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Abstract

This work introduces a digital outphasing transmitter architecture, which is based on a hybrid architecture taking the advantage of Bandpass delta-sigma modulation, RF-Pulse width modulation, and outphasing. Digital outphasing PA based on GaN switching amplifier improves the average power efficiency of non-contiguous multi-band transmitters. This paper also apply GaN switching amplifier to the supply modulator of the envelope tracking power amplifiers (ET-PA), and we have developed a high efficiency and multiband ET-PA using GaN for both RF-PA and the supply modulator. By testing this ET-PA using a Real-Time DPD (RT-DPD) system, we demonstrated that ACLR was improved to below -45dBc, even under a 80MHz LTE signal with 6.5 dB PAPR, while maintaining its high efficiency for multi-band operation. This, to the best of the authors' knowledge, is the widest modulation bandwidth yet reported for an efficient and multi-band ET-PA.

Microwave Workshops & Exhibition

GaN スイッチング増幅技術を活用した デジタル送信機とエンベロープトラッキング増幅器
Digital Transmitter and Envelope Tracking Power Amplifier using GaN Switching Mode Power Amplifiers

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和文概要

次世代通信機で使用される変調波信号は、複数のキャリアが結合しているため(Carrier Aggregation)、そのピーク対平均電力比(PAPR)は 10-12dB と巨大である．そのような PAPR の大きな信号に対しても高効率に信号を増幅する増幅器技術として GaN スイッチング増幅器が注目されている．本稿では GaN スイッチング増幅器を用いたデジタル送信機とエンベロープトラッキング増幅器について報告を行う．デジタル送信機については, GaN スイッチング増幅器を用いて、Out-phasing 技術、Bandpass delta-sigma 変調, RF パルス幅変調を組み合わせたデジタル送信機の試作・評価結果について報告する．エンベロープトラッキング増幅器については、GaN スイッチング増幅器を増幅器の電源変調器として使用した増幅器の試作・評価結果について報告する．

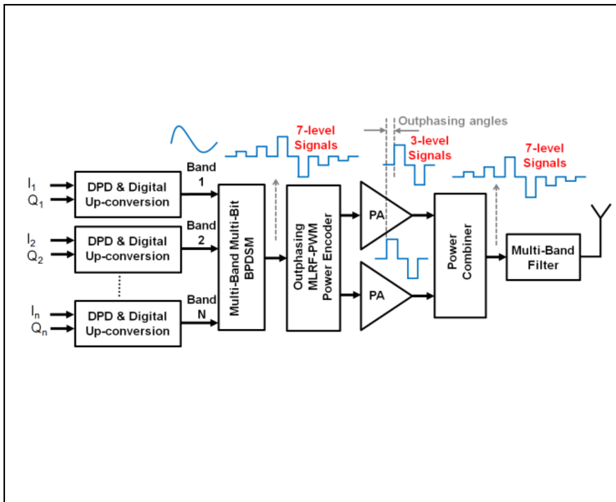

図１　デジタル送信機の概略図

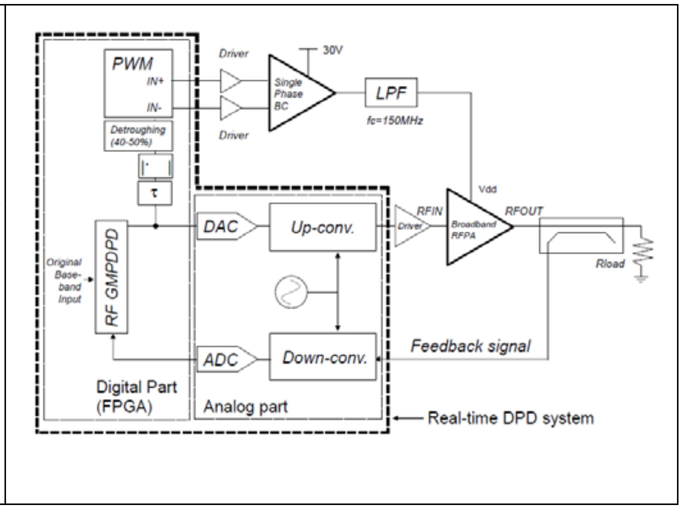

図２　エンベロープトラッキング増幅器の概略図

Abstract

This work introduces a digital outphasing transmitter architecture, which is based on a hybrid architecture taking the advantage of Bandpass delta-sigma modulation, RF-Pulse width modulation, and outphasing. Digital outphasing PA based on GaN switching amplifier improves the average power efficiency of non-contiguous multi-band transmitters.

This paper also apply GaN switching amplifier to the supply modulator of the envelope tracking power amplifiers (ET-PA) , and we have developed a high efficiency and multiband ET-PA using GaN for both RF-PA and the supply modulator. By testing this ET-PA using a Real-Time DPD (RT-DPD) system, we demonstrated that ACLR was improved to below -45dBc, even under a 80MHz LTE signal with 6.5 dB PAPR, while maintaining its high efficiency for multi-band operation. This, to the best of the authors' knowledge, is the widest modulation bandwidth yet reported for an efficient and multi-band ET-PA.

1. Motivation

Non-contiguous multiband transmission techniques for interband carrier aggregation (CA) [1] have been recently developed for 4G LTE-A and 5G mobile broadband communication, which achieve a multigigabit wireless data rate as well as efficient spectrum usage. The flexibility and demanding performance requirements for the interband CA are very challenging to achieve. Furthermore, the peak-to-average power ratio (PAPR) of a non-contiguous multiband signal is typically larger than 10–12-dB, so that the average power efficiency of a linear power amplifier (PA) significantly suffers.

All-digital non-contiguous multiband RF transmitters [2] with Class-S operation have shown a promising potential to provide high average power efficiency. All-digital architecture (Fig. 1) replaces RF/analog front-ends, which drive the PA in Class-S operation, with high-speed digital circuits, allowing a compact and low-cost implementation. Class-S operation demonstrated in [3] typically achieves the output envelope amplitude modulation with a switching-mode Class-D amplifier by applying time-domain modulation on the two-level digital input signals. Pulse-width modulation (PWM) [3], and bandpass delta–sigma modulation (BPDSM) [4] have been popularly used to modulate the digital input signal for Class-S operation. Although ideal Class-S operation achieves 100% power efficiency independent of power back-off, the nonideal switch characteristics of a transistor at a high frequency, particularly when the input pulses have a large variation in duty cycle, degrades the power efficiency.

The average power efficiency of an Class-S transmitter can be determined as a product of the PA peak power efficiency and power coding efficiency, which is defined as a ratio of the in-band power to the total output power both at the transmitter output. Compared to the linear PAs whose average power efficiency depends on the instantaneous envelope amplitude of the RF signals in transmit, the power efficiency of an ideal Class-D PA in Class-S operation remains constant. Therefore, to improve the average power efficiency of all-digital non-contiguous multiband transmitters, it is essential to improve power coding efficiency.

To improve the power coding efficiency of all-digital Class-S transmitters, various pulse modulation techniques have been introduced, such as Multilevel RFPWM(ML-RFPWM) [5], Multilevel RF delta-sigma modulation (ML-RFDSM) [6], and Multilevel IF PWM (ML-IFPWM) [7].

This work introduces a digital outphasing transmitter architecture, which is based on a hybrid architecture taking the advantage of BPDSM, RFPWM, and outphasing. Digital outphasing PA based on GaN switching amplifier improves the average power efficiency of non-contiguous multi-band transmitters [8].

This paper also apply the Class-S operation of GaN switching amplifier to supply modulator of the envelope tracking power amplifiers (ET-PA) , and we have developed a high efficiency and multiband ET-PA using GaN for both RF-PA and EA [9]. By testing this ET-PA using a Real-Time DPD (RT-DPD) system, we demonstrated that ACLR was improved to below -45dBc, even under a 80MHz LTE signal with 6.5 dB PAPR, while maintaining its high efficiency for multi-band operation. This, to the best of the authors' knowledge, is the widest modulation bandwidth yet reported for an efficient and multi-band ET-PA.

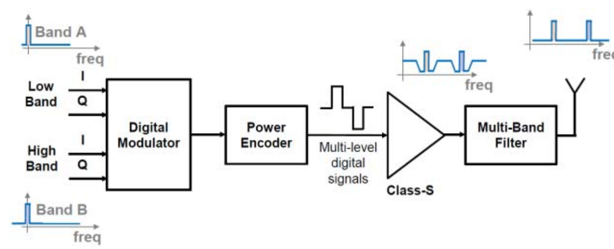

Fig. 1. Digital-RF transmitter architecture for non-contiguous multi-band transmission. [8]

2. Non-Contiguous Multi-Band Digital-RF Transmitter Architecture

Fig. 2 shows the proposed outphasing MLRF-PWM digital-RF transmitter architecture for non-contiguous multi-band transmission. The quadrature baseband signals are up-converted to each band (component carrier in CA) in digital domain. Multi-band multi-bit BPDSM combines the high-resolution multi-band inputs (>10 bits) into a single-stream multi-level digital signal (e.g. 7 level) with high linearity. Because the design of Class-S digital power amplifiers (PAs) is increasingly demanding with a large number of output levels (>7 levels), the single-stream multi-level BPDSM output signal is transformed into dual-stream multi-level (e.g. 3 levels) PWM signals that are outphased to each other, so that the PAs can produce only a small number of output levels. By maintaining the outphasing angles small, non-isolated Chireix power combiners can be used with a very high efficiency in summing the output power of the two PAs. Therefore, both high efficiency and high linearity can be obtained with non-contiguous inter-band CA.

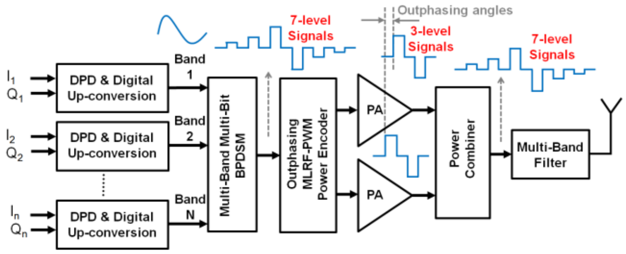

Fig. 2. Proposed outphasing multi-level RF-PWM (MLRFPWM) transmitter architecture for inter-band CA[8]

A. Outphasing Multi-level RF Pulse-Width Modulation (MLRF-PWM) Power Encoder

Fig. 3 shows an example operation of the power encoder, which transforms the single-stream 7-level BPDSM output signals into dual-stream 3-level PWM performance requirements on linearity and out-of-band emission.

The sampling rate of the power encoder determines the minimum outphasing angles. A higher sampling rate allows smaller minimum outphasing angles, so that a larger number of BPDSM output levels can be transformed into MLRF-PWM signals with the same number of output levels. Advanced CMOS technologies for 40 Gb/s serial link [7] and time-interleaved deltasigma modulation will allow outphasing angles less than 20° at 2-GHz cellular frequency bands.

The duty cycles of the MLRF-PWM signals are maintained higher than 25% of the carrier with the highest frequency among multiple aggregated bands. Although allowing a lower duty cycle allows a larger number of BPDSM output levels, the power coding efficiency degrades as the duty cycle decreases. In hardware implementation, carrier frequencies can be reconfigured by updating the digital loop filter coefficients with a set of pre-calculated values. Since the signal path to the PA inputs is all in digital domain, a wide frequency range can be supported.

B. Multi-Band Multi-Bit BPDSM with Level Clipping

Fig. 4 shows the multi-band multi-bit BPDSM with level clipping for high power coding efficiency, which is used in the proposed transmitter architecture. Two digital loop-filters L1(s) and L2(s) have a different resonant frequency tuned for each carrier frequency. The dual-band input signal X1(s) and X2(s) are scaled such that the quantizer is not saturated in order to maintain the BPDSM feedback stability and linearity.

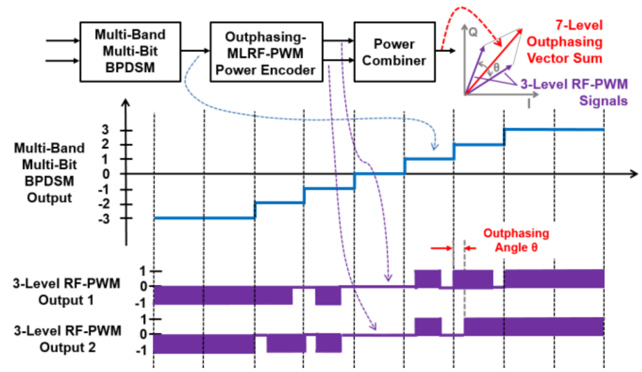

Fig. 3. Power encoder operation for outphasing multi-level RF pulse-width modulation (MLRF-PWM). [8]

The level clipper reduces the number of BPDSM output levels, which improves the coding efficiency at the expense of linearity and out-of-band emission. With 6-th order loop filter design, smaller than -50-dBc out-of-band emissions can be achieved with a 9-level quantizer without clipping. Simulation results show that clipping the 9-level quantizer output signals into 7-level improves the coding efficiency by more than 10% with acceptable EVM performance and out-of-band emissions for dual-band LTE signals with 10-MHz + 20-MHz bandwidth.

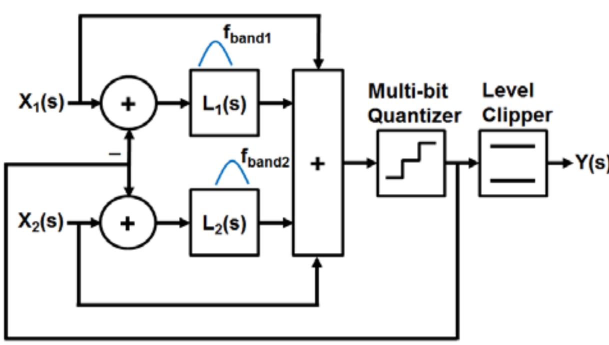

Fig. 4. Multi-band multi-bit band-pass delta-sigma modulator (BPDSM) with level clipping. [8]

The proposed outphasing MLRF-PWM technique is experimentally evaluated using a 25-GSPS Tektronics AWG70000 arbitrary waveform generator. 6.25-GSPS 7-level clipped BPDSM output signals are transformed into dual-stream 3-level RF-PWM signals and downloaded into AWG70000. A Wilkinson power combiner attached to the two output channels of the AWG70000 is measured. Fig. 5 shows the measured spectrum of LTE inter-band carrier aggregation for 10-MHz bandwidth at 874 MHz and 20-MHz bandwidth at 1501 MHz. 59.5% coding efficiency is achieved, providing significant improvement compared to the 8.6% coding efficiency with a singlestream dual-band 3-level BPDSM.

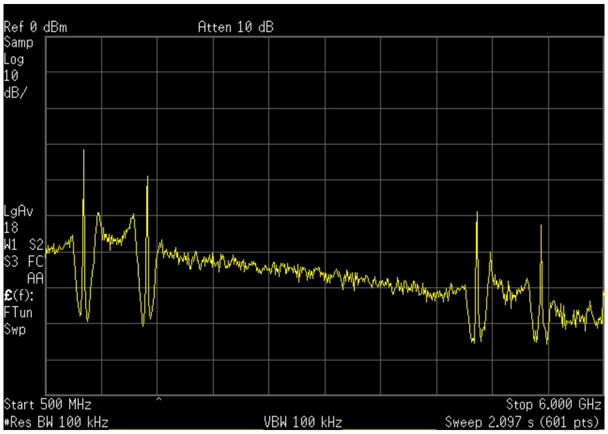

Fig. 5. Measured wideband spectrum of LTE inter-band CA for 10-MHz bandwidth at 874 MHz and 20-MHz bandwidth at 1501 MHz. [8]

3. All GaN Envelope Tracking Power Amplifier

Fig. 6 shows the the measurement setup of the ETPA including the RT-DPD system. The ET-PA consists of the single GaN supply modulator based on switching operation and the broadband RF-PA described, and a low pass filter (LPF), which has a cut off frequency of 150MHz. The original baseband signal for 20-80MHz LTE was generated through Matlab in a remote computer and stored in the memory of the RT-DPD system. Based on the baseband signals, the input signals for the modulator and RF-PA were generated. The input signal for the modulator was generated with simple Pulse Width Modulation (PWM) using a 245.76MHz base clock frequency at 6.39Gbps (oversampling ratio of 26).

An LTE signal with 80MHz bandwidth, 6.5dB PAPR at 2.15GHz was then applied. As described in Fig. 6, output signals from the PA were captured by the same RT-DPD system, and used to perform RF Generalized Memory-Polynomial DPD (RF-GMPDPD) in the FPGA implemented in the system. The distorted signals were also used to calculate signals for the BC. This allowed us to perform the DPD on a real-time basis, since signal generation and capturing, and predistortion were all done in the same system.

Fig. 7 shows measured spectra with and without DPD at 2.15GHz under 80MHz LTE signal with 6.5dB PAPR (after Crest Factor Reduction). By using the real-time DPD system with a correction BW of 180MHz, we demonstrated that ACLR was improved from -37.6dBc to -45.1 dBc, even under a 80MHz LTE signal. Output power and PAE of the ET-PA were 30.7dBm and 35.3% respectively. This, to the best of the authors' knowledge, is the widest modulation bandwidth yet reported for an efficient ET-PA.

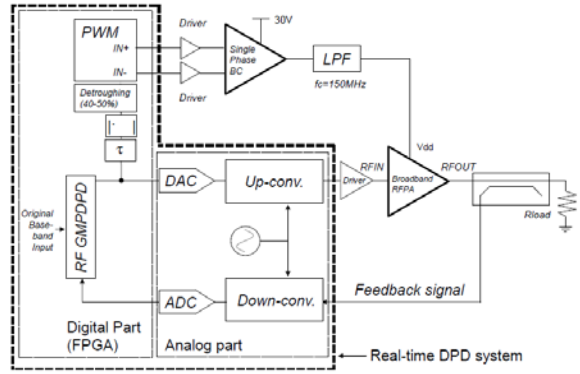

Fig. 6: ET measurement setup and signal generation algorithm[9]

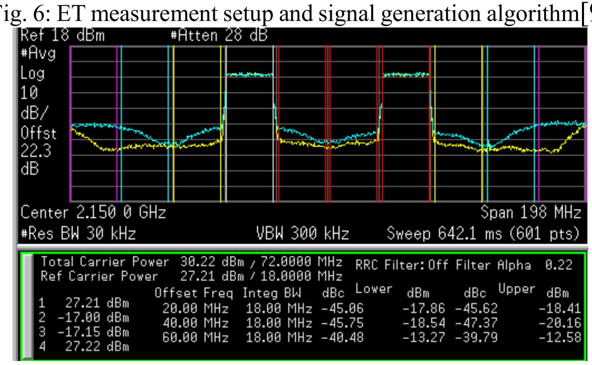

Fig. 7: Measured spectra with and without DPD at 2.15GHz under 80MHz LTE signal, with 6.5dB PAPR. (yellow and cyan respectively); the correction BW is 180MHz[9]

4. Summary

This paper introduces a digital outphasing transmitter architecture, which is based on a hybrid architecture taking the advantage of BPDSM, RFPWM.

This paper also extend the digital technique to the envelope tracking power amplifiers (ET-PA) , and we have developed a high efficiency and multiband ET-PA using GaN for both RF-PA and Envelope Amplifier

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