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Abstract

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Outphasing Multi-Level RF-PWM Signals for Inter-Band Carrier Aggregation in Digital Transmitters

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***Abstract* — A novel non-contiguous concurrent multi-band digital-RF transmitter architecture is presented, which is based on outphasing the multi-level RF pulse-width modulated signals (MLRF-PWM) for digital Class-S power amplifiers. In order to improve the transmitter power efficiency, the outphasing modulation in the proposed architecture effectively increases the number of MLRF-PWM signal output levels. In addition, a multi-band multi-bit band-pass delta-sigma modulator (BPDSM) with a hard clipping technique is introduced, which further improves power coding efficiency by trading off distortion performance with coding efficiency. Experimental results with a dual-channel 25-GSPS arbitrary waveform generator (AWG) demonstrate non-contiguous carrier aggregation for 3-level Class-S PAs with inter-band LTE signals at 874 MHz and 1501 MHz for the channel bandwidth of 10-MHz and 20-MHz, respectively. The proposed outphasing MLRF-PWM technique achieves 59.5% power coding efficiency, which is significant improvement from the 8.6% coding efficiency of conventional 3-level BPDSM with the experimental dual-band LTE signal transmission.**

***Index Terms* — Class-S power amplifier, concurrent dual-band transmitter, digital-RF transmitter, multi-band delta-sigma modulator, non-contiguous carrier aggregation.**

I. Introduction

Non-contiguous inter-band carrier aggregation (CA) techniques [1] have been recently developed for 4G LTE-A and 5G mobile broadband communication, which utilize concurrent inter-band transmission for a very high wireless data rate (>1Gbps at peak) as well as efficient spectrum usage. The flexibility and demanding performance requirements for the non-contiguous CA are very challenging to achieve in practice.

All digital-RF transmitters for concurrent multi-band transmission (Fig.1) [2]–[6] have demonstrated promising potential to realize compact and versatile wireless communication. Nevertheless, there are several design challenges with non-contiguous carrier aggregation. For example, the high performance multi-level IFPWM (ML-IFPWM) originally reported by our group for single-band transmission [2], becomes less suitable for inter-band CA. With the ML-IFPWM, the spurious tones from one band appear as in-band distortions to another band, which is difficult to mitigate. Band pass delta-sigma modulation

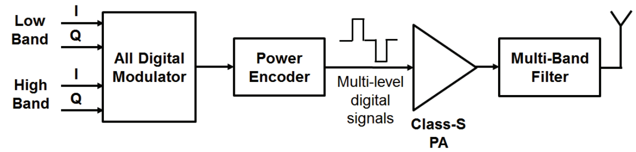

Fig. 1. Digital-RF transmitter architecture for concurrent multi-band transmission.

(BPDSM) [3] achieves non-contiguous concurrent multi-band transmission with a poor coding efficiency (<10%). Because the whole transmitter power efficiency is closely related to power coding efficiency of input signals [2],[4], which is defined as a ratio of the in-band power to the whole band power, this work focuses on improving the power coding efficiency while enabling concurrent dual-band transmission.

This paper presents a novel outphasing multi-level RF pulse-width modulation (MLRF-PWM) technique on the basis of BPDSM, in order to achieve both high coding efficiency and linearity. Although conventional outphasing modulation provides a wideband capability, the outphasing modulation has few applications for communication signals with a high peak-to-average power ratio (PAPR). The main drawbacks of the outphasing modulation are with limited dynamic range and high sensitivity to mismatch between the two signal paths for outphasing. Maintaining outphasing angles below a certain limit can avoid the undesirable sensitivity [5]. By using PWM as an additional degree-of-freedom in modulation, [6] demonstrated that outphasing PWM can provide enough dynamic range and linearity for WCDMA signals. Nevertheless, the outphasing is applied to only a single carrier frequency in [5], [6], thus inter-band CA cannot be supported. By applying limited outphasing angles between two MLRF-PWM signals, the digital-RF transmitter presented in this paper enables the inter-band CA with the efficient use of outphasing while providing flexible re-configurability with the band selection.

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

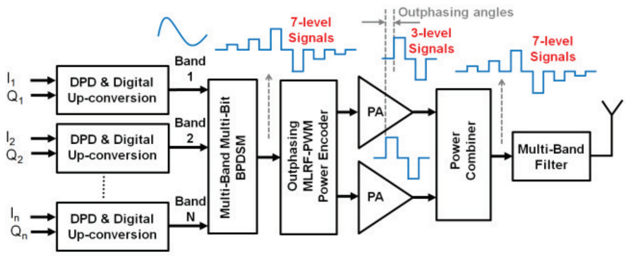

Fig. 2. Proposed outphasing multi-level RF-PWM (MLRF-PWM) transmitter architecture for inter-band CA.

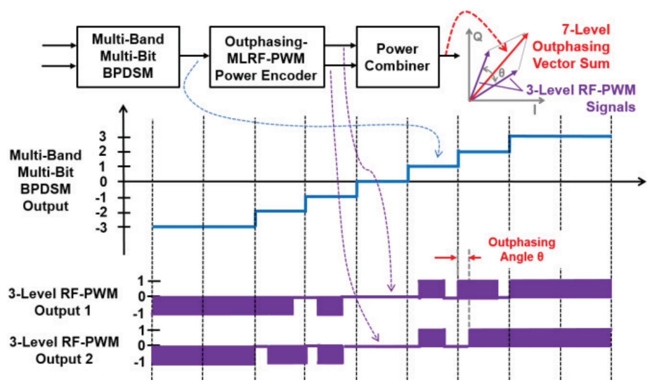

Fig. 3. Power encoder operation for outphasing multi-level RF pulse-width modulation (MLRF-PWM).

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.

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 outphasing MLRF-PWM signals. Discrete outphasing is applied to each pulse, so that the power combiner can recover the original 7-level BPDSM output signals. The number of output levels can be determined depending on

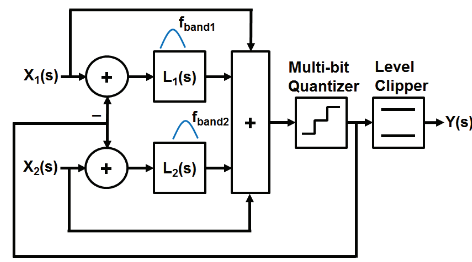

Fig. 4. Multi-band multi-bit band-pass delta-sigma modulator (BPDSM) with level clipping.

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 delta-sigma 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 $L_1(s)$ and $L_2(s)$ have a different resonant frequency tuned for each carrier frequency. The dual-band input signal $X_1(s)$ and $X_2(s)$ are scaled such that the quantizer is not saturated in order to maintain the BPDSM feedback stability and linearity.

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

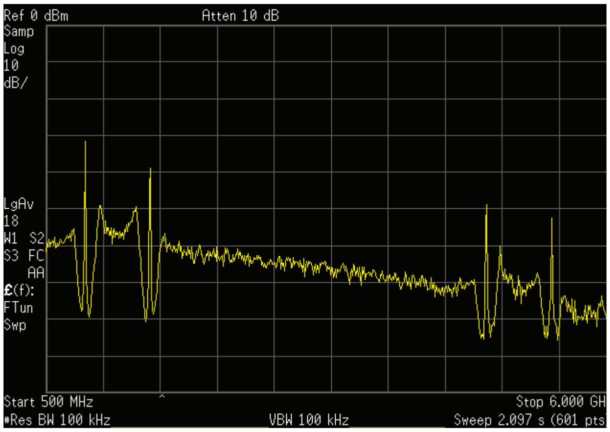

Fig. 5. Measured wideband spectrum of LTE inter-band CA for 10-MHz bandwidth at 874 MHz and 20-MHz bandwidth at 1501 MHz.

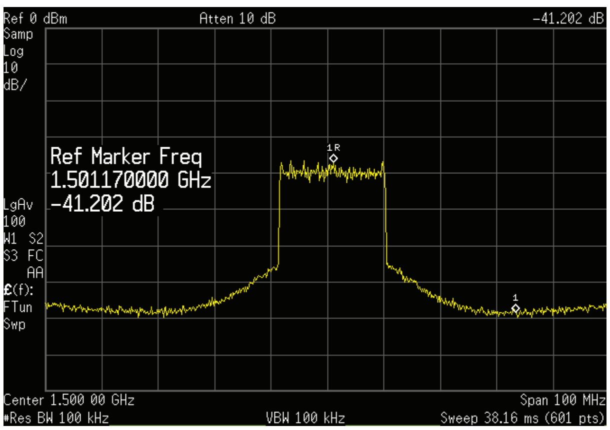

Fig. 6. Measured 1501-MHz band spectrum of the 20-MHz bandwidth LTE signals from the inter-band CA.

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.

III. Experimental Performance Evaluation

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. Fig. 6 and Fig. 7

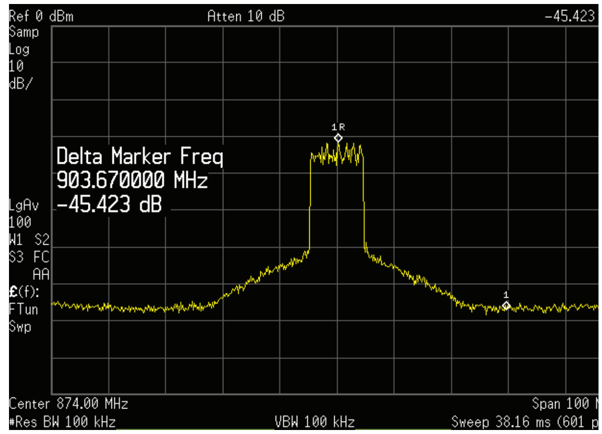

Fig. 7. Measured 874-MHz band spectrum of the 10-MHz bandwidth LTE signals from inter-band CA.

show the zoom-in spectrum of each band. 59.5% coding efficiency is achieved, providing significant improvement compared to the 8.6% coding efficiency with a single-stream dual-band 3-level BPDSM.

IV. Conclusion

The proposed digital-RF transmitter architecture demonstrated the advantages of introducing outphasing techniques combined with MLRF-PWM in providing a high linearity and high coding efficiency for 4G LTE-Advanced inter-band carrier aggregations. Approximately 7 times higher power coding efficiency is obtained in comparison to multi-level BPDSM for inter-band CA.

In the future, we plan to improve the outphasing power combining efficiency as well as digital pre-distortion algorithms to improve the overall transmitter linearity.

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