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Abstract

Digital-intensive RF transmitters using delta-sigma modulation have a compact physical footprint, enabling a low-cost mobile MIMO transmitter for 5G systems, but suffer from a high noise floor due to quantization errors. In order to eliminate the need of high-Q multi-band RF filters for attenuating such high noise floor, this paper for the first time presents a multi-band noise cancellation technique for digital-intensive transmitters based on concurrent multi-band delta-sigma modulation. Using an asymmetric RF power combiner, an experimental implementation realizes the bandpass noise cancellation for non-contiguous interband carrier aggregation of 835 MHz and 1450 MHz bands. For 40-MHz aggregated bandwidth, the proposed noise cancellation technique achieves ACPR better than -47 dB and -42 dB for the low-band and the high-band, respectively. With the dual-band prototype with a 6-GHz sampling rate, the proposed technique needs three times less bandwidth for noise cancellation signal compared to conventional feed-forward techniques, and thus the sampling rate requirement on noise cancellation path can be significantly relaxed.

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Cancelling Noise in Multi-Band Digital-Intensive Transmitters

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***Abstract*—Digital-intensive RF transmitters using delta-sigma modulation have a compact physical footprint, enabling a low-cost mobile MIMO transmitter for 5G systems, but suffer from a high noise floor due to quantization errors. In order to eliminate the need of high-Q multi-band RF filters for attenuating such high noise floor, this paper for the first time presents a multi-band noise cancellation technique for digital-intensive transmitters based on concurrent multi-band delta-sigma modulation. Using an asymmetric RF power combiner, an experimental implementation realizes the bandpass noise cancellation for non-contiguous inter-band carrier aggregation of 835 MHz and 1450 MHz bands. For 40-MHz aggregated bandwidth, the proposed noise cancellation technique achieves ACPR better than -47 dB and -42 dB for the low-band and the high-band, respectively. With the dual-band prototype with a 6-GHz sampling rate, the proposed technique needs three times less bandwidth for noise cancellation signal compared to conventional feed-forward techniques, and thus the sampling rate requirement on noise cancellation path can be significantly relaxed.**

***Keywords*—Digital transmitter, RF filter, feedforward noise cancellation, non-contiguous inter-band carrier aggregation, concurrent multi-band delta-sigma modulation.**

I. INTRODUCTION

Non-contiguous inter-band carrier aggregation (NCIB-CA) for 4G/5G communication systems [1] are essential to maximize the utilization of available spectrum in multi-user environment. The compact form factor and the low-cost implementation of digital-intensive RF transmitters for NCIB-CA are enabling high-performance MIMO phased array technology, which requires a large number of RF transceivers in a single system. Compared to all-digital RF transmitters [2], [3], digital-intensive RF transmitters [4], [5] provide a higher efficiency and allows a RF output filter with relaxed design requirement. It should be noted that digital-intensive RF transmitters have several design challenges in order to provide competitive performance in the market. For example, the inherent quantization noise of delta-sigma modulation, which requires either a high-Q RF output filter [5] or a high-performance active noise cancellation [6], introduces power efficiency degradation. Nevertheless, recent development in advanced digital RF power amplifiers [7], [8] have continuously improved the performance of digital-intensive transmitters, increasing the potential of digital-intensive RF NCIB-CA transmitters for future deployment in 5G communication infrastructure.

This paper presents a novel multi-band quantization noise cancellation technique for digital-intensive RF transmitters (Fig. 1) based on concurrent multi-band delta-sigma modulation (CMB-DSM) for NCIB-CA. Active cancellation of CMB-DSM quantization noise can be achieved by a replica modulator [9], [10] or a feed forward technique [6]. Replica-modulator based quantization noise cancellation has a limited noise cancellation bandwidth while feed forward noise cancellation technique requires a high-performance DAC, whose power consumption may dominate an overall transmitter employing advanced modulation techniques with a high peak-to-average power radio (PAPR). The proposed noise cancellation technique provides a larger cancellation bandwidth compared to the replica modulator based noise cancellation techniques while allowing a low-complexity and low-power implementation compared to the feed-forward techniques.

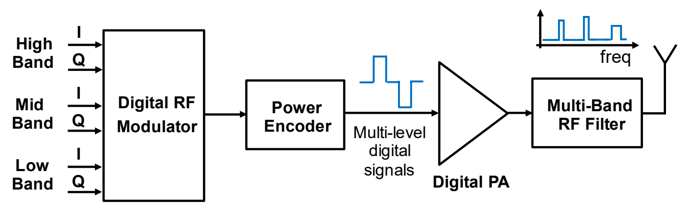


Fig. 1. General architecture of a concurrent multi-band digital-intensive RF transmitter.

Section II describes the concept and the operation of the proposed multi-band quantization noise cancellation technique for a dual-band NCIB-CA transmitter, in comparison with the previous works. Measured results from an experimental prototype are reported in Section III, with concluding in Section IV.

II. MULTI-BAND NOISE CANCELLATION FOR CONCURRENT MULTI-BAND DELTA-SIGMA MODULATION

Fig. 2 illustrates an improved concurrent multi-band delta-sigma modulation (CMB-DSM), which transforms quadrature baseband signals with a high resolution for low-band and high-band into a single-stream digital signal to drive a multi-level digital RF PA. Compared to conventional CMB-DSM [11], the level clipper improves a coding efficiency and the non-uniform digital feedback gain provides nonlinearity correction with a multi-level digital PA. Although Fig. 2 is illustrated for dual-band CA applications, CMB-DSM can be applied to triple-band while maintaining modulator stability [6]. Fig. 3 shows simulated signal and noise transfer functions of a 4-th order CMB-DSM for NCIB-CA with 835-MHz low band and 1450-MHz high band each for 20-MHz LTE channel bandwidth, providing overall 40-MHz aggregated bandwidth.

A digital-intensive RF transmitter architecture using CMB-DSM with the proposed band-pass quantization noise cancellation technique is depicted in Fig. 4. The wideband quantization

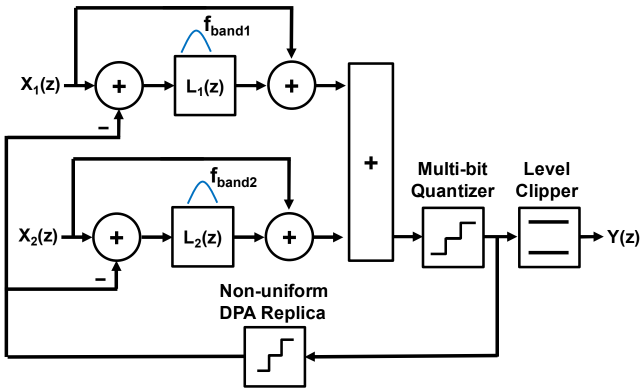


Fig. 2. Concurrent multi-band delta-sigma modulation (CMB-DSM) with level clipping and digital feedback linearization.

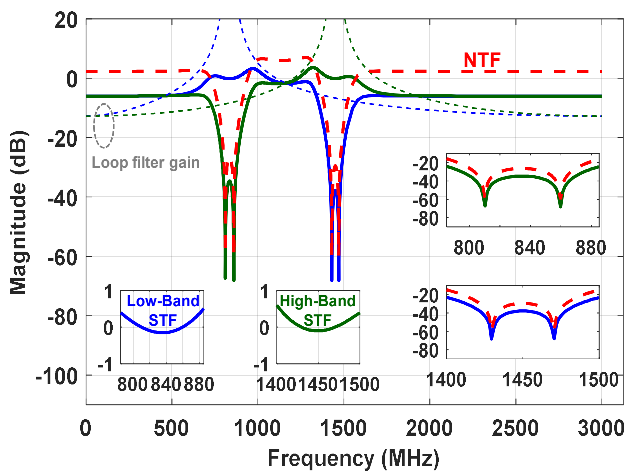


Fig. 3. Simulated noise and signal transfer function of a CMB-DSM with 6.0 GHz sampling rate for 40-MHz aggregate bandwidth combining 835 MHz and 1450 MHz frequency bands.

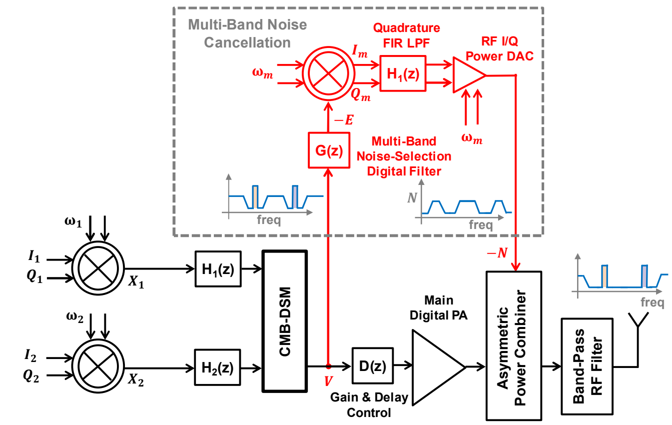


Fig. 4. Proposed multi-band noise cancellation technique employed a digital-intensive RF transmitter for non-contiguous inter-band carrier aggregation.

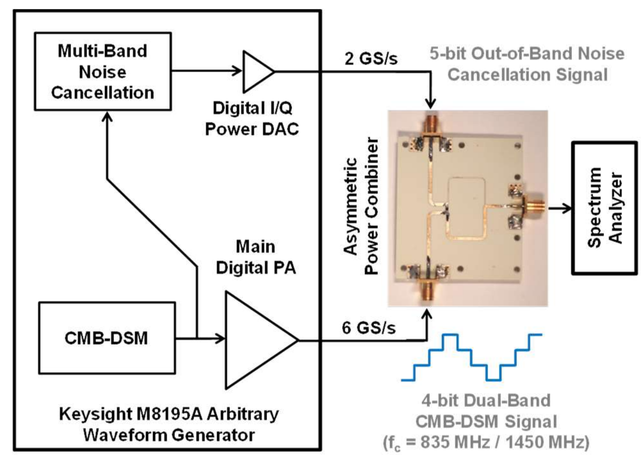


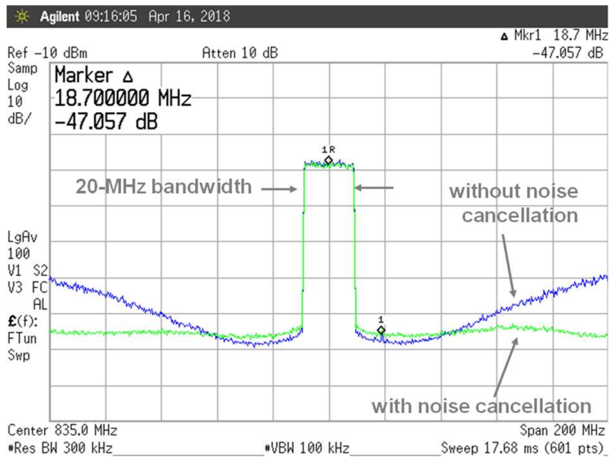
Fig. 5. Experimental demonstration of multi-band noise cancellation using an asymmetric power combiner to accommodate 8.7-dB power disparity between the main PA and the digital RF IQ power DAC.

noise of CMB-DSM is obtained by the multi-band noise-selection filter. This noise selection process is fundamentally different from the feed-forward technique [6] since the bandwidth of the noise cancellation signal is much smaller, which not only reduces the design requirement of noise cancellation path, but also allows the usage of a low-resolution main digital PA. For a dual-band prototype operating with 835-MHz and 1450-MHz bands, the noise-selection transfer function $G(z)$ is designed to have three passbands consisting of 645-790 MHz, 880-1405 MHz, and 1495-1645 MHz. The digital quadrature mixer down-converts the multi-band noise into a baseband I/Q signal. The digital low-pass filter with a cut-off frequency f_c limits the bandwidth of the quantization noise such that the RF output filter does not need any rejection between the low band edge $f_L + B_L/2$ and the high band edge $f_H - B_H/2$. Since the noise cancellation bandwidth, which is given by $2f_c$, can be reconfigured by the digital low-pass filter cut-off frequency, a conventional RF output filter can be used by properly adjusting the digital filter bandwidth.

III. Implementation and Measured Results

For the experimental demonstration of the proposed band-pass noise cancellation technique for CMB-DSM, a dual-band NCIB-CA LTE transmission is realized with 6-GHz sampling rate. A main 4-bit digital RF PA clocked at 6 GHz and a 5-bit digital RF IQ power DAC [12] for band-limited noise cancellation running at 2 GHz is emulated by Keysight M8195 arbitrary waveform generator, as shown in Fig. 5. An asymmetric power combiner [6], which is fabricated on FR-4 substrate, allows the noise cancellation power backed off from the main digital RF PA output power.

The measured noise cancellation performance of the 835-MHz low-band (Fig. 6a) and the 1450-MHz high-band (Fig. 6b) shows that more than 15-dB cancellation is achieved within the noise cancellation bandwidth of 90 MHz around each band. With the noise cancellation band, better than -47 dB and -43 dB ACPR is achieved with the low-band and the high-band, respectively. Fig. 7 shows the wideband spectrum of the NCIB-CA



(a)

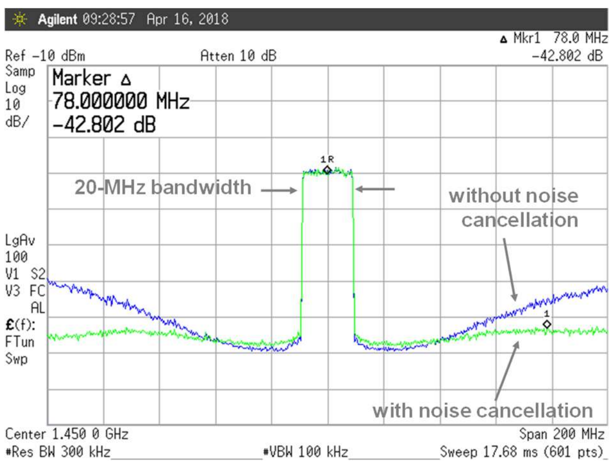


Fig. 6. Measured multi-band noise cancellation on concurrent dual-band transmission with 40-MHz aggregate bandwidth. (a) 835-MHz band, which achieves better than -47 dB ACPR after the multi-band noise cancellation. (b) 1450-MHz band, which achieves better than -43 dB ACPR after the multi-band noise cancellation.

LTE transmission, demonstrating that the prototype noise cancellation eliminates the need of noise rejection between the low-band and the high-band.

IV. Conclusion

Digital-intensive RF transmitters for the non-continuous inter-band carrier aggregation of 4G LTE-Advanced and 5G communication systems have suffered from high quantization noise, which has mandated a lossy high-Q multi-band RF output filter or a high-performance noise cancellation with a high-power consumption. This work presents a low-power multi-band noise cancellation technique, which cuts down the RF output filter design requirement so that a conventional band-pass RF output filter can be used for multi-band digital-intensive transmitters. The proposed multi-band noise cancellation requires a narrower bandwidth for cancellation signal compared to feedforward cancellation techniques by more than a factor of two. Thus, design requirements and costs of high-performance digital-intensive RF transmitter can be significantly relaxed.

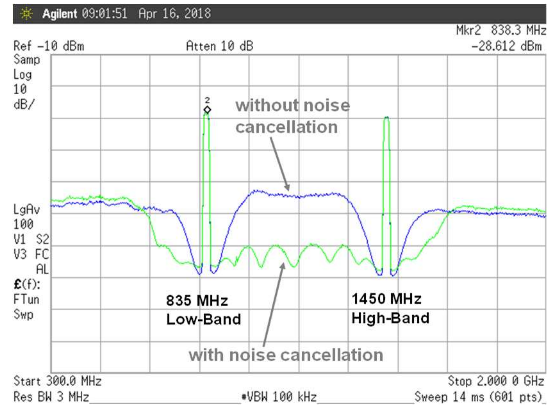


Fig. 7. Measured mid-band noise cancellation more than 15 dB, which allows a band-pass RF output filter for multi-band transmitters.

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