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A Concurrent Triple-Band Digital Transmitter Using Feedforward Noise Cancellation for Delta-Sigma Modulation

SungWon Chung[1,3], Rui Ma[1,*], Shintaro Shinjo[2], Koji Yamanaka[2], and Koon Hoo Teo[1]
[1]Mitsubishi Electric Research Laboratories (MERL), Cambridge, MA 02139, USA
[2]Information Technology R&D Center, Mitsubishi Electric Corporation, Ofuna, Kamakura 247-8501, Japan
[3]University of Southern California, Los Angeles, CA 90089, USA
[*]E-mail: rma@merl.com

***Abstract*—A concurrent triple-band digital transmitter architecture with relaxed RF output filter requirement is presented in this paper. With non-contiguous inter-band carrier aggregation, all digital transmitters based on delta-sigma modulation and pulse-width modulation have suffered from out-of-band noise and spurious tones, requiring extremely demanding RF output filter design. We demonstrate a feedforward noise cancellation technique in order to suppress the out-of-band quantization noise of concurrent triple-band delta-sigma modulation for the first time. An experimental prototype based on an asymmetric RF power combiner and a 5-bit 7-GS/s DAC for noise cancellation realizes concurrent triple-band transmission of LTE Advanced signals, which consist of 710 MHz, 1750 MHz, and 2510 MHz bands with 30-MHz aggregated total bandwidth. The prototype achieves better than 42-dB spurious-free dynamic range (SFDR) and -47-dBc adjacent channel power ratio (ACPR), enabled by up to 12-dB out-of-band noise suppression.**

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

I. INTRODUCTION

Advanced mobile communication technologies such as LTE-Advanced are utilizing all available spectrum in order to increase the data rate and the number of simultaneous users in service. Towards this trend of efficient spectrum usage to enhance network capacity, concurrent multi-band (CMB) transmission [1]-[4] is of particular interests, such as non-contiguous inter-band carrier aggregation in LTE Advanced technology. The need of a low-cost implementation with high performance in a small form-factor is driving the recent development of digital-intensive architecture for CMB transmitters.

Advanced digital transmitters (Fig. 1) using highly efficient digital power amplifiers (PAs) [18], [19] are largely based on either RF pulse-width modulation (PWM) [6], [7], [9], delta-sigma modulation (DSM) [5], [11]-[15], or a combination of PWM and DSM [3], [10]. The CMB digital transmitters based on RF PWM typically suffer from spurious tones while the CMB transmitters based DSM commonly show high out-of-band noise. To address these design challenges, digital-intensive transmitters with advanced signal processing as well as analog assistance have been recently introduced. For example, digital predistortion using a look-up table [8], and analog filtering [9], [12] have been applied to digital transmitters based on RF PWM to suppress undesirable spurious tones. Different techniques such as using replica DSMs [4], time-interleaved multi-DSMs [13], and band pass noise cancellation [16] have been reported in an attempt to reduce the out-of-band quantization noise of digital transmitters based on DSM. Nevertheless, although these techniques suppress the spurious tones and out-of-band noise, the suppression level of these previous works is not yet sufficient. As a result, the design requirements on the multi-band RF output filter [3] are still very challenging, which not only introduce a large insertion loss and but also constrain flexibility with band selection.

*This work was done while SungWon Chung was an intern with MERL.

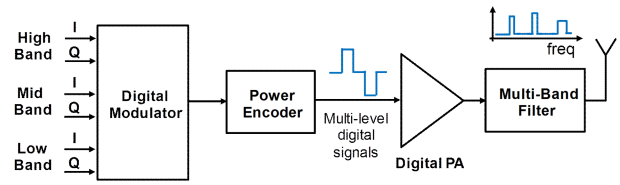


Fig. 1. General concurrent triple-band digital transmitter [3].

This paper introduces a new wideband out-of-band quantization noise cancellation technique for digital-intensive transmitters based on multi-level CMB-DSM. Although the resolution of the present high-efficiency digital power amplifiers in GaN HEMT technologies stays no more than 3-4 bits [22], [23], it is expected that advanced GaN HEMT process technologies such as [20] will allow a higher resolution (5-6 bits) GaN digital PA such as one corresponding to 6-bit digital PAs in a silicon technology [21]. Even the future GaN digital PAs with 5-6-bit resolution, however, will not satisfy the demanding spectral mask requirements of 4G LTE/5G with wideband modulation. The role of a wideband feedforward noise cancellation technique is therefore instrumental. To generate a wideband noise cancellation signal with over 3-GHz bandwidth, rather than using replica delta-sigma modulators [4], [10] whose bandwidth is typically limited below 1 GHz, we use a high-efficiency wideband digital PA such as [17], [25] whose peak output power is 6-10 dB lower than the desired peak transmitter output power. The complexity and power consumption of such a digital PA with 4-5-bit resolution are significantly lower compared to very high-resolution (12-14 bits) RF DACs [24], which commonly consume a watt-level power, and the overhead in power consumption and complexity for the noise cancellation is not significant.

II. FEEDFORWARD NOISE CANCELLATION FOR CONCURRENT MULTI-BAND DELTA-SIGMA MODULATION (CMB-DSM)

A. Concurrent Triple-Band Delta-Sigma Modulation

Fig. 2 shows a concurrent multi-band delta-sigma modulation (CMB-DSM) for triple-band transmission, which has three inputs each for different frequency bands but produces a single multi-level output to drive a multi-level Class-S or Class-D

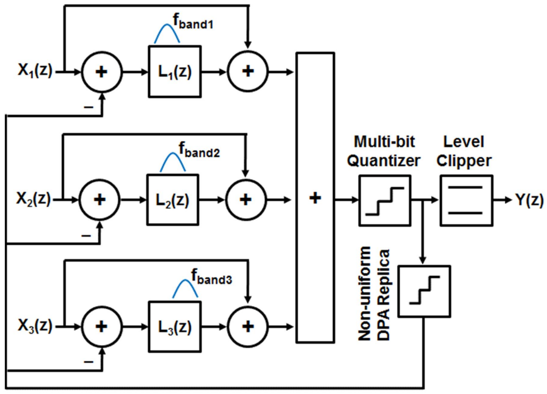


Fig. 2. Concurrent multi-band delta-sigma modulator (CMB-DSM) for triple-band transmission.

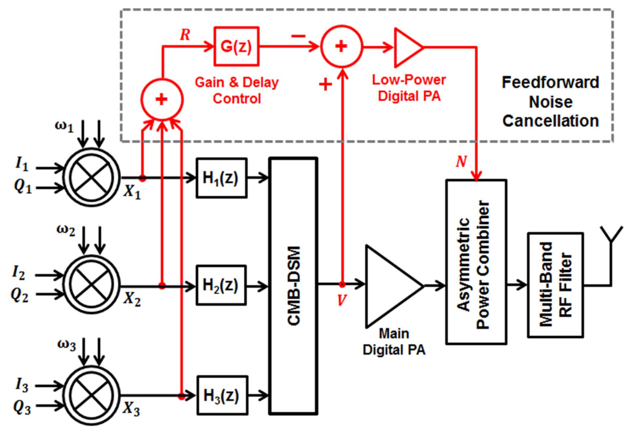


Fig. 3. Feedforward noise cancellation for triple-band transmission using concurrent multi-band delta-sigma modulation (CMB-DSM).

PA. Each of the digital loop filters $L_n(z)$ have three pole-zero pairs that are tuned to resonate at each frequency band. The noise transfer function, which can be shown as

$$NTF(z) = \left(1 + \sum_{i=1}^{M} L_i(z)\right)^{-1}, \qquad (1)$$

therefore has a null at each frequency band. To achieve a higher efficiency by sacrificing modulation accuracy to an acceptable level, an output clipper [3] is employed, which reduces the number output levels in the CMB-DSM output by clipping out the maximum and the minimum amplitude levels. The main design challenge with CMB-DSM is to maintain the modulator stability when the multiple frequency bands are close to each other and also when the digital loop filters have a higher-order structure.

B. Feedforward Out-of-Band Noise Cancelltion

Fig. 3 illustrates the proposed feedforward out-of-band noise cancellation technique for multi-level CMB-DSM. A high-efficiency low-power digital PA generates a wideband noise cancellation signal. The gain and delay control as well as the

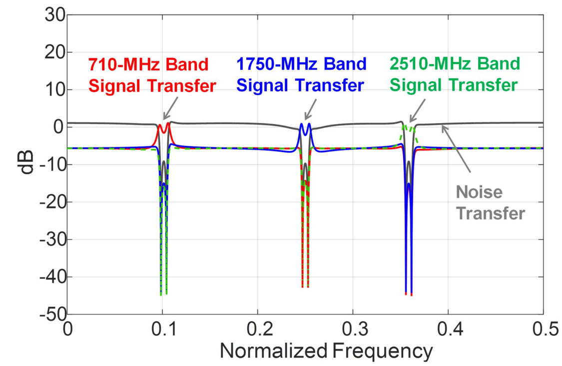


Fig. 4. Simulated noise and signal transfer functions of a CMB-DSM for concurrent triple-band transmission.

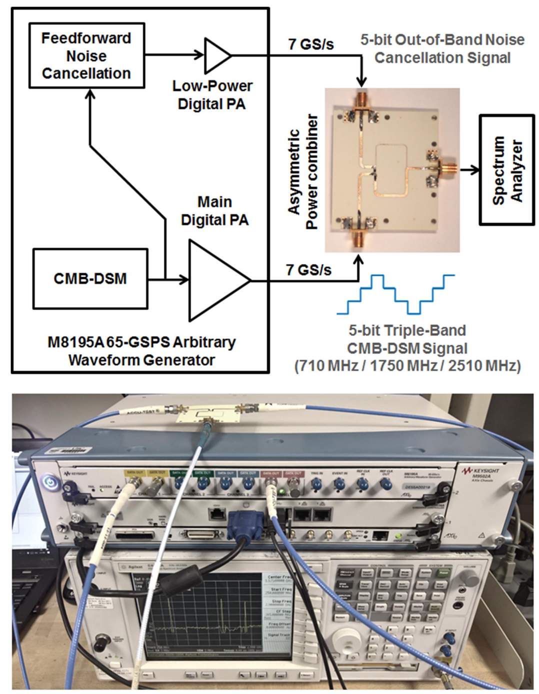


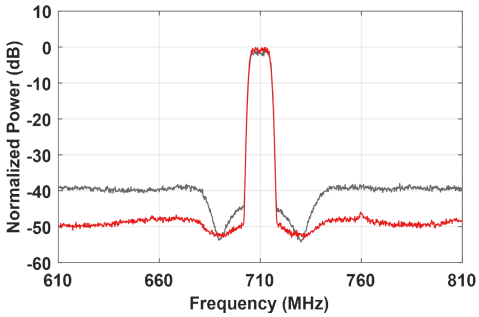
Fig. 5. Measurement setup of feedforward noise cancellation for concurrent triple-band transmission with LTE Advanced signals using 30-MHz aggregated bandwidth.

CMB-DSM predistortion function $H_n(z)$ are adjusted to reduce the output power requirement on the digital PA for noise cancellation. The efficiency η of the overall transmitter is given by

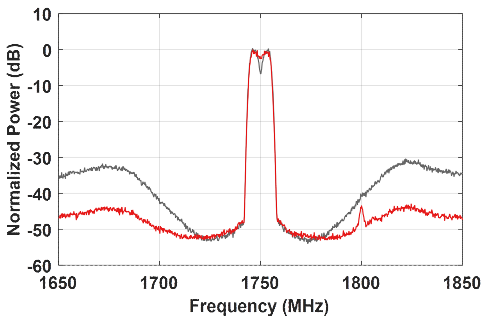
$$\eta = (\eta_1{}^{-1} + k\,\eta_2{}^{-1})^{-1}, \qquad (2)$$

where η_1 and η_2 are the efficiencies of the main digital PA and the noise cancellation PA, respectively, and k is the average noise cancellation signal power normalized to the average main digital PA output power.

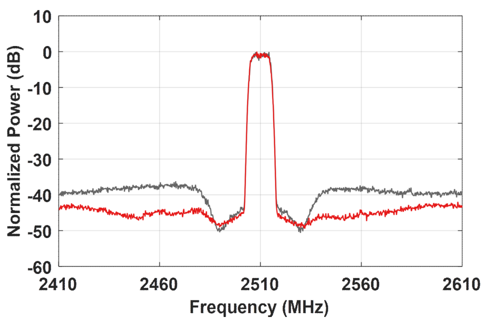
Since the noise cancellation signals are computed as the difference between the CMB-DSM output and the reference output, the CMB-DSM is designed for stability at the expense



(a)



(b)



(c)

Fig. 6. Measured close-in spectrum of concurrent triple-band LTE-Advanced transmission with 30-MHz aggregated bandwidth: (a) 710 MHz band, (b) 1750 MHz band, (c) 2510 MHz band (dark gray: without noise cancellation, red: with feedforward noise cancellation).

of flat frequency response in the signal band, assuming the noise cancellation signal will provide necessary correction on the frequency response. This design technique resolves the noise peaking problem of a concurrent multi-band digital transmitter [4].

III. Implementation

The digital loop-filters of CMB-DSM with 5-bit output resolution are designed for the simultaneous LTE Advanced transmission of 710 MHz, 1750 MHz, and 2510 MHz band signals with overall 30-MHz aggregated bandwidth. Fig. 4 shows the signal transfer function and the noise transfer function with the three digital loop filters in the CMB-DSM. For

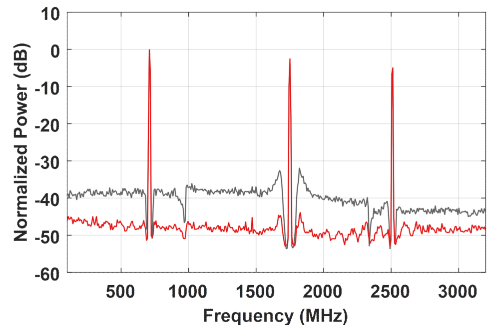


Fig. 7. Measured wideband spectrum of the concurrent triple-band LTE transmission (dark gray: without noise cancellation, red: with feedforward noise cancellation).

Table I
Comparison of concurrent multi-band digital transmitters.

Ref.	[2] 2013	[3] 2015	[14] 2017	This work
# of Concurrent Carriers	2	2	2	3
Modulation Resolution	1 bit	1.5 bit	1 bit	5 bits
Carrier Frequency	800 MHz / 1500 MHz	856 MHz 1450 MHz	2620 MHz 5240 MHz	710 MHz 1750 MHz 2510 MHz
Sampling Frequency	3.9 GHz	25 GHz	24.5 GHz	7 GHz
Transmit Signal	LTE	LTE	LTE / Wi-Fi	LTE
PAPR	6.5 dB	11.7 dB	5 dB	11.7 dB
Channel Bandwidth	5 MHz / 5 MHz	20 MHz / 20 MHz	5 MHz / 20 MHz	10 MHz / 10 MHz / 10 MHz
Aggregated Bandwidth	10 MHz	40 MHz	25 MHz	30 MHz
SFDR	< 5 dB	6 dB	34 dB / 30 dB	46 dB / 43 dB / 42 dB
ACPR	-51 dBc / -44 dBc	-46 dBc / -43 dBc	-48 dBc / -35 dBc	-50 dBc / -48 dBc / -47 dBc

the modulator stability, the order of the digital loop-filters is limited to no more than 6.

Fig. 5 shows an experimental setup on current triple-band transmission where an asymmetric power combiner, which is optimized for an uneven input power ratio [4], performs the noise cancellation. Agilent M8195A 65-GS/s arbitrary wave form generator (AWG) is configured to have a sampling rate of 7 GS/s to emulate a fourth-order concurrent triple-band CMB-DSM. 5-bit 7-GS/s noise cancellation low-power digital PA is emulated by a different output channel of the AWG. The noise cancellation signal power is 8.7 dB below the main digital power amplifier output power. If the setup includes a main digital PA and a noise cancellation PA both with 50% efficiency, the overall transmitter efficiency can be obtained from (2) as 44%. Considering the insertion loss of triple-band RF output filters (typically 2 dB or higher, which will degrade the transmitter efficiency from 50% to below 31%), the proposed noise cancellation technique provides more than 13% higher efficiency by removing the need of a multi-band RF output filter.

IV. Measured Results

Fig. 6 shows the measured wideband spectrum on the concurrent triple-band transmission of LTE Advanced signals where feedforward noise cancellation improves the noise floor up to 12 dB. The adjacent channel power radio (ACPR) for 700-MHz, 1750-MHz, and 2510-MHz band is -50 dBc, -48 dBc, and -47 dBc, respectively. Spurious free dynamic range (SFDR) for each band, which determines the filter design complexity, is 46 dB, 43 dB, and 42 dB, respectively. Fig. 6(b) exhibits the improvement of in-band signal frequency response as discussed in Section II-B concerning modulator stability.

Fig. 7 shows the wideband spectrum from 200 MHz to 3200 MHz, showing that the noise floor improvement by the feedforward noise cancellation varies over frequencies. This incomplete noise cancellation can be explained by the delay mismatch as well as gain/phase response mismatch between the main amplifier path and the noise-cancelling amplifier path.

Table I summarizes the performance of the prototype in comparison with previous works on concurrent multi-band digital transmitters. The multi-bit CMB-DSM of this work allows a relatively low sampling frequency for superior SFDR and a high peak-to-average power ratio (PAPR) of 11.7 dB.

V. Conclusion

For the first time, a concurrent triple-band transmitter based on digital architecture using multi-band delta-sigma modulation is demonstrated towards a low-cost implementation of advanced communication transmitters with a high-efficiency and a small form-factor. Wideband feedforward noise cancellation on the out-of-band noise of delta-sigma modulation can significantly relax the multi-band RF output filter design for concurrent multi-band digital transmitters. If the noise cancellation is enough to remove the RF output filters, digital transmitters can offer a greater flexibility in carrier frequency reconfiguration. Since the proposed noise cancellation technique does not depend on a particular digital modulation technique, it can be applied to general multi-level digital modulators.

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