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13.4 All-Digital RF Transmitter in 28nm CMOS with Programmable RX-Band Noise Shaping

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The crowdedness of the radio spectrum allocated for 3G/4G mobile communication, together with the growing demand for higher data rates, has led to the situation where transceivers need to support FDD operation in multiple frequency bands with different TX-RX duplex spacing. In order to reduce costs and enable SAW-less operation, many recent transmitter implementations have thus targeted stringent out-of-band (OOB) emission levels. Analog-intensive TX architectures achieve low OOB noise at the price of large area consumption, as complex reconstruction filters are used to suppress DAC quantization noise and image replicas [1,2]. On the other hand, due to the lack of analog filtering, digital-intensive TX architectures need 12-14 bits of DAC resolution for low OOB noise, which complicates DAC design and typically requires DPD or calibration [3-5]. This work presents an RF transmitter implementing a fully digital solution to the aforementioned challenge. Instead of using bulky analog filtering or high resolution DAC, the disclosed TX employs digital $\Delta\Sigma$ modulation and mismatch shaping to attenuate the DAC noise at a programmable duplex distance. This solution enables -160dBc/Hz noise in the RX-band, by using only 10-bit DAC without DPD, calibration or analog filtering.

The system architecture is depicted in Fig. 1. It is based on direct-conversion I/Q modulation, but all signal processing is performed in the digital domain, preceding the DAC. The key observation is that a 10-bit oversampling DAC is sufficient to meet the in-band and ACLR performance requirements of 3G/4G mobile radio standards, but fails at achieving low OOB emissions due to excessive unfiltered quantization noise reaching the TX output [6]. Nevertheless, OOB emissions need to be particularly low only at duplex distance, and the quantization noise spectral density can be shaped accordingly. The solution is to use a digital bandpass $\Delta\Sigma$ modulator, with the programmable NTF stopband centered on the RX-band. The performance of multibit $\Delta\Sigma$ modulation is limited by mismatch noise, caused by static amplitude and timing mismatches between DAC conversion cells. Fortunately, mismatch noise can be also spectrally shaped in the digital domain, by employing a bandpass mismatch shaping (MS) encoding scheme. The MS block, illustrated in Fig. 2, encodes the 1-bit signals c0, ..., C27 in a pseudorandom fashion, such that the spectrum of each signal is shaped by the same NTF used in the $\Delta\Sigma$ modulator. Hence, by combining the aforementioned techniques, RX-band noise filtering can be accomplished in a fully digital fashion.

Each of the 54 switching blocks in the MS encoders needs an individual sequence generation circuit (Fig. 3), consisting of a programmable digital filter connected in feedback with a special quantizer (SQ). The SQ quantizes the filter output according to the equations in Fig. 2, and can be modeled as additive random error. Therefore, the circuit generates a pseudorandom sequence shaped by the NTF given in Fig. 3. The NTF notch can be centered freely over the Nyquist range by tuning coefficient α , providing up to 20dB noise attenuation at the programmed duplex distance.

The MS encoded signals are fed to the digital mixer (DMIX), which performs upconversion to RF carrier fc in the digital domain. The DMIX block is clocked at 2fc by an externally generated LO signal, and calculates the DAC cell enables en_p/en_n with 25% duty-cycle. The DAC is based on a current-steering architecture, where each conversion cell branch is built of a cascoded current source (CS) in series with a switch. A 4 MSB + 6 LSB segmentation approach is adopted, resulting in 28 conversion cells divided into 16 MSB unaries and 6 LSB binaries, with the LSB segment doubled to create redundancy for MS. Because of 25% duty-cycling, the I-DAC is active only during the 0° and 180° LO phases, whereas the Q-DAC is active during the 90° and 270° phases, thus avoiding any cross-interaction between the two signal paths. No overdesigning is needed to achieve linearity better than 10bits, since the effective resolution in the RX-band is improved digitally by the $\Delta\Sigma$ and MS blocks.

The TX prototype was fabricated in 28nm CMOS and packaged with flip-chip technology. The die micrograph is shown in Fig. 7, and the core area measures 0.82mm². The digital BB data is loaded into a 16k-word memory, from where it can be streamed at a sample rate equal to fc. The outputs of the I and Q paths are combined on-chip through an RF balun, designed to match 50 Ω external load in the low band (LB) of the cellular radio spectrum. The circuit uses 1.5V supply for the DACs, and 0.9V supplies for the digital part. The overall power consumption is 150mW, of which 75mW are taken by the DACs, 22mW by the LO divider and DMIX blocks, and 53mW by the $\Delta\Sigma$ and MS blocks.

The measured output spectrum of a 9MHz CW tone at 900MHz carrier frequency is shown in Fig. 4. At +3dBm output power, the image and LO feedthrough are at -36 and -61 dBc respectively. The CIM3 and CIM5 are both below -67dBc, barely visible above the noise floor. Fig. 4 also plots the output spectrum with a +0.9dBm LTE20 signal at 850MHz (Band 20), showing excellent E-UTRA ACLR performance of less than -60dBc.

Fig. 5 combines the results of several RX-band noise measurements, performed with modulated LTE carriers at varying duplex distances from the 895MHz TX band. In order to evaluate the effectiveness of all-digital RX-band noise shaping, each measurement was repeated three times: with $\Delta\Sigma$ and MS bypassed, with only MS bypassed, and with both $\Delta\Sigma$ and MS in use. In the third mode, the averaged RX-band noise is between -155 and -163 dBc/Hz, showing up to 20dB improvement when compared to the first two modes. The results are worst at 45 and 80 MHz duplex distances, due to intermodulation with the fc/16 memory internal clock. The notch center frequency is not restricted to the 895MHz carrier frequency.

Fig. 6 compares the TX performance with previous implementations. This work stands out for its superior linearity and compact die area, while exhibiting stateof-art overall performance. Enabled by the low cost of DSP logic in modern CMOS processes, the TX demonstrates the feasibility of all-digital RX-band noise filtering, requiring only 10-bit DAC to achieve -160dBc/Hz noise without need for DPD, calibration or analog filtering.

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Figure 13.4.5: Measurement of RX-band noise at various duplex distances, repeated for different LTE signals and bypass modes.

-165 190 195 185 190 195 Offset from TX band [MHz]



Figure 13.4.7: Die micrograph.