9.7 An LTE SAW-Less Transmitter Using 33% Duty-Cycle LO Signals for Harmonic Suppression

Yen-Horng Chen[1], Neric Fong[2], Bing Xu[3], Caiyi Wang[3]

[1]MediaTek, Hsinchu, Taiwan, [2]MediaTek, San Jose, CA, [3]MediaTek, Austin, TX

With limited frequency allocation in the radio spectrum, spectral efficiency has always been the core development of communication systems. To accommodate the increase in demand for wireless data services, RF systems have been challenged to provide better in-channel SNR (EVM) and lower out-of-channel emission. As performance requirements become more stringent, second-order RF circuit impairments, that were previously insignificant, have become major design considerations. One example is the Long-Term-Evolution (LTE) [1]. Compared with previous generations, channel bandwidth has been expanded to 9MHz in most of the sub-GHz bands and 18MHz in the GHz bands. For spectral efficiency, the TX OFDM subcarriers are grouped into Resource Blocks (RBs) that can be dynamically allocated within the channel bandwidth. Noise and spurious emission requirements have become more challenging in the sub-GHz bands, so that Counter 3rd-order Intermodulation products (CIM3) has been recognized as an important design parameter [2-4] for LTE RF systems. CIM3 is the result of the lower 3rd-order intermodulation (IM3) product of signals at around 1xLO and 3xLO by using mixers with 25% or 50% duty-cycle LO. If an f_{BB} tone is being fed to the TX baseband input, after the mixer and the RF amplifier, the TX RF output will produce the desired signal tone at f_{LO}+f_{BB} and an unwanted CIM3 tone at f_{LO}-3f_{BB} [3]. The adverse effects of CIM3 are shown in Fig. 9.7.1, using LTE Band 13 as an illustration. Band 13 has User-Equipment (UE) TX band from 777 to 787MHz, and RX band at -31MHz away from TX. Extreme cases of full RB and single RB are considered. At full RBs, modulated CIM3 has a bandwidth three times the desired signal, and it folds directly into the TX channel, degrading the TX EVM and the 1st ACLR (E-UTRA). Furthermore, the ACLR of bandwidth-expanded CIM3 falls into the RX band causing desensitization. When single RB is transmitted, the CIM3 may fall into the restricted bands and violate the spectral emission requirement. Consider the Public Safety Band, where the LTE standard dictates that the emission from 769 to 775MHz has to be less than -57dBm/6.25KHz [1]. If the output power at the antenna is +23dBm and only single RB is being transmitted, the power density is 23dBm/180kHz. Normalizing to power density from 180KHz to 6.25KHz, the power density is 8.4dBm/6.25KHz, resulting in a CIM3 requirement of -65.4dB/6.25KHz. This is challenging for linearity, and also for noise requirement in the case of a SAW-less system. CIM3 suppression techniques such as harmonic rejection and power mixing have been proposed [2-5], but these techniques require extra calibrations and/or off-chip filtering components, which will be described in later paragraphs. This work presents a CIM3 suppression technique by removing the undesired 3rd-harmonic component in the LO signal through LO duty-cycle selection. With this direct root-cause elimination method, the TX meets CIM3 and RX band noise requirements for SAW-less LTE RF systems over process and temperature without calibration and off-chip filtering.

Consider the odd harmonic components of the two LO waveforms as shown in Fig. 9.7.2. For 25% duty-cycle LO, the amplitude of the 3rd harmonic 3f_{LO} is only 10dB below the fundamental f_{LO}. After mixing with the baseband signal f_{BB}, assuming lower sideband I-Q rejection, the mixer output contains f_{LO}+f_{BB} and 3f_{LO}-f_{BB}. These two components are intermodulated by the amplifier non-linearity, and the lower IM3 falls at f_{LO}-3f_{BB}. For 33% duty-cycle LO, the waveform expression is given by

$$LO = (3/\pi)\sum(1/n)\sin(n\pi/3)\cos(n\omega_{LO}t),$$

where n is the harmonic number. The LO 3rd harmonic and its integer multiples become null due to the term sin(nπ/3), subsequently suppressing the CIM3 at the RF output. Unlike the harmonic rejection methods in [3], this suppression is not sensitive to device matching, and calibration is not required for robust performance. Furthermore, this architecture does not require 3×LO component filtering to reduce the CIM3 contribution, for example, with an LC tuned load at the mixer output [5] which has limited rejection and area penalty, or 3×LO filter between TX and PA [2,4] which adds to BOM cost. Without the need for filtering, this technique can also be employed for broadband applications.

The concept of direct upconversion using 33% LO duty cycle is illustrated in Fig. 9.7.3. The I-path differential signals are upconverted by the LO with phase of 0°, and the Q-path differential signals are upconverted by the LO with phases of 120° and 240°. With the vector operation, the in-phase components are cancelled, and the quadrature-phase components are constructively summed, resulting in the Q-path signal magnitude being $\sqrt{3}$ times larger than the I-path signal. To make I- and Q-signals equal in magnitude at RF, the Q-path signals are first being attenuated by $\sqrt{3}$ in baseband before upconversion. To avoid the non-identical I-Q paths and complicated I-Q calibration that would affect EVM performance, a symmetric topology with complementary paths is proposed.

The transmitter block diagram is shown in Fig. 9.7.4. The high-speed DAC outputs, located in the Modem/AP SoC, are first filtered by the lowpass network (LPF+RCF). The filtered output is fed to RF segments, where the output current is summed at the transformer to drive 50Ω. With the segmentation, RF units can scale according to the required output power for power saving while keeping consistent linearity over wide dynamic range. Each RF segment consists of four sets of voltage-mode mixers and one g_m cell. The CK signals of the mixers are generated by CLKGEN. In 33% duty-cycle mode, the VCO frequency is first divided by 2 to generate differential quadrature clocks. Each quadrature clock is further divided by 3 to generate 33% duty-cycle LOs, resulting in a total of twelve CK phases from 0° to 330° at a step of 30°. Each RF segment receives three CK phases that are 120° apart (Fig. 9.7.3), and one of the mixers is disabled (CK<3>). In 25% duty-cycle mode, CLKGEN generates 25% duty-cycle LO and all the mixers are enabled. To enable worldwide band coverage from 700MHz to 2.7GHz, two radio paths are implemented with one path optimized for sub-GHz band operation (LB) and the other optimized for GHz operation (HB). A total of 8 TX output ports are supported.

This chip was fabricated in the TSMC 40nm CMOS LP process, and the TX core circuit occupies 0.93mm^2 including the full function paths to support multimode (GSM/GPRS/EDGE, WCDMA/HSDPA/HSPA+, TDSCDMA, LTE) multiband operation. Figure 9.7.5 shows the Band-13 TX output spectra at +2dBm output power. At full RBs, the EUTRA ACLR is better than -54dBc, and the RX band noise at -31MHz away is -157.9dBc/Hz. The noise is 1.5dB lower if the RX band is at the upper sideband due to gain asymmetry from the passive mixer upconvert architecture. An example is Band 12, where the RX band is +30MHz away from the TX band. Note that it is important to include synthesizer (SX) and LO distribution noise in the measurement, as they can be the major noise and power consumption contributor. For example, to achieve -158dBc/Hz, and assume noise is budgeted equally between TX and SX, each block needs to achieve noise at -161dBc/Hz at 30MHz offset. At single RB, CIM3 better than -70dBc at +2dBm output power is achieved. Residual CIM3 is a result of second-order effects, such as LO mixing of baseband harmonic distortions (3f_{BB}) and higher-order inter-modulation (IM5 of 5f_{LO}+f_{BB} and f_{LO}+f_{BB}). The 3×LO at TX output is -56dBc, so no external 3×LO filter is required between TX and PA. The TX performance is summarized in Fig 9.7.6. If 25% duty-cycle is employed, CIM3, ACLR, RX band noise and 3×LO leakage are degraded by 18dB, 4dB, 3dB and 35dB respectively. The transmitter operates under a switched-mode 1.8V power supply. It consumes 216mW in Band 13 at maximum output power (P_{max}), and the current is reduced by 60% at P_{max}-12dB. Compared with previous literatures, the higher power consumption is attributed to the stringent noise requirement and competitive silicon area restriction in SX and LO distribution. (It contributes 33% of the overall power at P_{max}.)

This paper demonstrates a low-cost and compact transmitter by using the method of 33% duty-cycle to suppress the 3rd harmonic of the LO. This concept can be further expanded to suppress the Nth harmonic of the LO by using 1/N duty-cycle.

Acknowledgement:
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References:

[1] 3GPP TS 36.101 V9.3.0
[2] O. Oliaei, et al., "A Multiband Multimode Transmitter Without Driver Amplifier," *ISSCC Digest Tech. Papers*, pp. 164-165, Feb. 2012.
[3] M. Ingels, et al., "A Multiband 40nm CMOS LTE SAW-Less Modulator with -60dBc C-IM3," *ISSCC Digest Tech. Papers*, pp. 338-339, Feb. 2013.
[4] P. Rossi, et al., "An LTE Transmitter Using a Class-A/B Power Mixer," *ISSCC Digest Tech. Papers*, pp. 340-341, Feb. 2013.
[5] T. Kihara, et al., "A Multiband LTE SAW-Less CMOS Transmitter with Source-Follower-Drived Passive mixers, Envelope-Tracked RF-PGAs, and Marchand Baluns," *IEEE Radio Frequency Integrated Circuits Symp.*, pp. 399-402, June 2012.

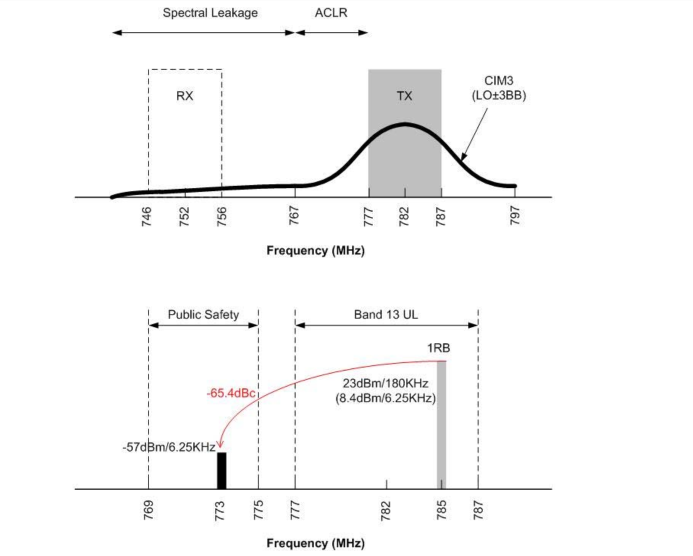

Figure 9.7.1: CIM3 and spectral leakage.

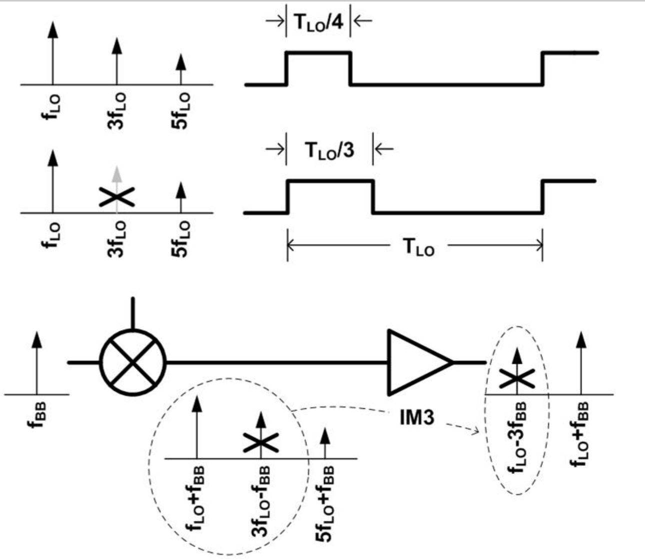

Figure 9.7.2: CIM3 improvement by 33% duty-cycle LO.

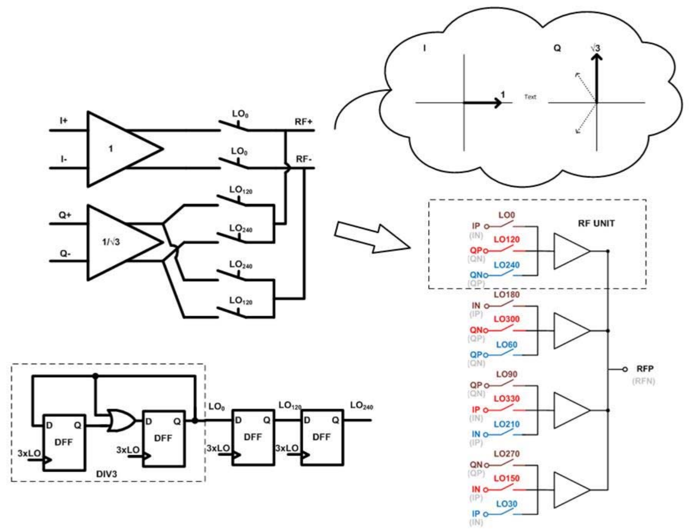

Figure 9.7.3: Concept of direct upconversion using 33% LO duty cycle.

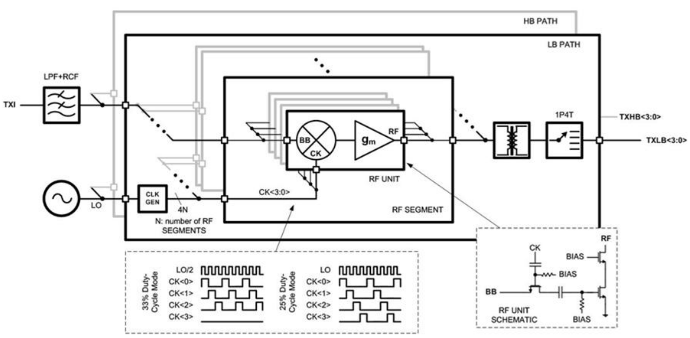

Figure 9.7.4: Segmented TX and LO diagram.

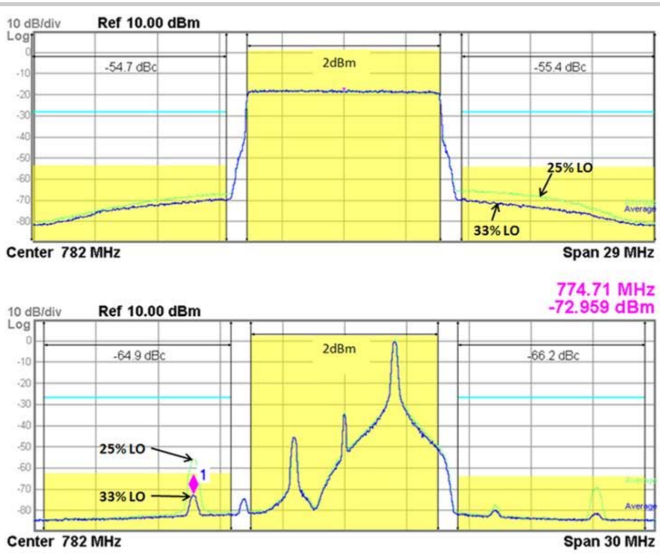

Figure 9.7.5: TX output spectrum (B13 RB=50; B13 RB=1).

LTE TX performance Band 13 10MHz BW	This work	[2]	[3]	[4]
Pout (dBm)	2	-1.5	3.1	2.4
EVM (%)	0.8	0.66	1.6	1.4
ACLR (dB)	-54	-40.3	-46	-45
CIM3 (dBc)	< -70	-70	-65	-57.1
RX noise (dBc/Hz)	-157.9*/-159.4**	-155	-158.7**	-154
Supply voltage (V)	1.8	1.55 / 2.7	1.1 / 2.5	1.8
Power consumption (mW)	216	186	157	101***
Area (mm^2)	0.93 (40nm)	5.06 (90nm)	1.4 (40nm)	1.3 (55nm)

* At -1dBm Pout (including SX noise)
** Band 12 data
*** LO generation circuit is not included

Figure 9.7.6: Performance summary table.

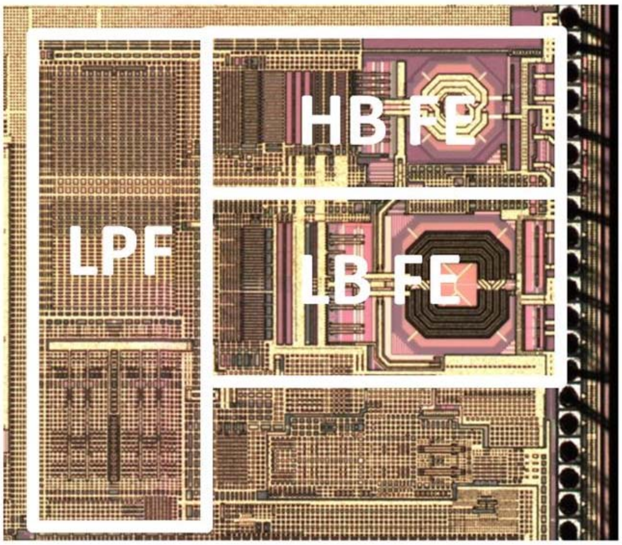

Figure 9.7.7: Die micrograph.

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