SAW-less Transceiver for 4G/3G/2G Cellular Standards

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A single-chip multi-mode multi-band CMOS transceiver was designed and implemented for the 4G mobile platform. The transceiver supports both Long Term Evolution (LTE) frequency division duplexing (FDD) and time division duplexing (TDD) operation modes. It also supports 3G Wideband Code Division Multiple Access (W-CDMA) and 2G global system for mobile communication (GSM)/enhanced general packet radio service (EGPRS) operation with the same signal paths. The hardware supports FDD bands 1–21, TDD bands 33–40, W-CDMA bands I–VI and VIII–XI, and EGPRS bands Cell850, EGSM, DCS and PCS. The receiver has 9 primary and 5 diversity input ports that do not require external low-noise amplifiers (LNAs) or interstage surface acoustic wave (SAW) filters. The automatic gain control system is fully autonomous. The transmitter has 8 output ports that do not require interstage SAW filters. An integrated transmit predistortion path reduces the impact of offset modulations. An integrated ARM7 core controls transceiver sequencing and enables a high-level application programming interface (API) that greatly reduces radio development time. Two industry standard digital interfaces provide compatibility to LTE basebands as well as 2G/3G basebands. It is fabricated in 90 nm CMOS.

1. Introduction

Long Term Evolution, or LTE, is the latest cellular standard to be introduced into the cellular market space. It follows on the heels of global system for mobile communication (GSM) and Wideband Code Division Multiple Access (W-CDMA) which are the 2G and 3G components of the continually evolving 3rd Generation Partnership Project (3GPP) standards. LTE is the first generation that communicates using IP packets. It is directly developed as a data delivery network. GSM and W-CDMA were developed as voice networks that had improvements overlaid to support data.

The LTE radio signal is orthogonal frequency-division multiplexing (OFDM) modulated. In OFDM, the radio signal is not a single modulated radio frequency (RF), but a large number of closely spaced orthogonal sub-carriers. In LTE, these sub-carriers are spaced 15 kHz apart. The standard allows for channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz. The bandwidth is 90% occupied with sub-carriers. Each sub-carrier may be modulated with QPSK, 16QAM or 64QAM. The use of separate sub-carriers results in a uniform distribution of power spectral density across the radio channel which improves data throughput efficiency.

The communication channel bandwidth is further broken down into resource blocks (RBs) (**Figure 1**). Each RB is 180 kHz wide. In the time domain, communication is also subdivided into subframes. Each subframe is 1 ms. The number of RBs allocated to a given user is actively managed and varies from subframe to subframe as throughput demands change.

This characteristic of LTE places unique requirements on a transceiver. The receiver must receive a fully populated channel bandwidth with good performance in all RBs as

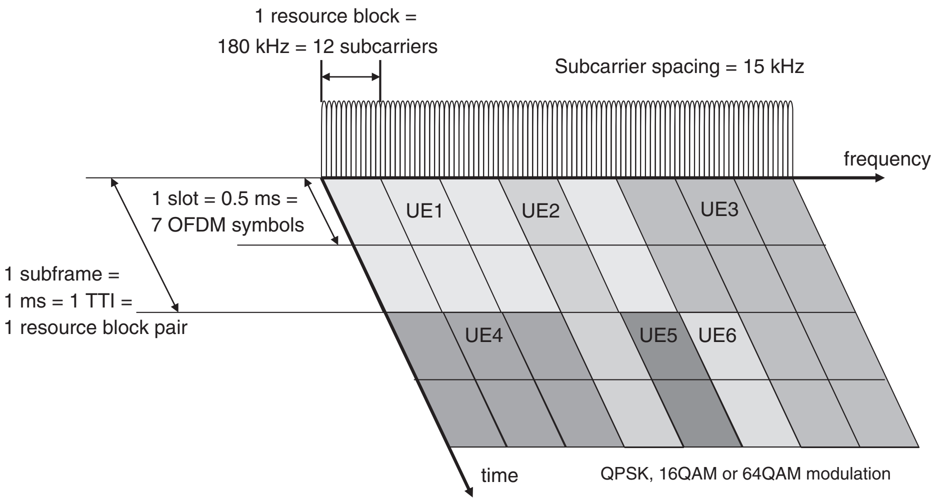

Figure 1
LTE communication channel.

the desired receive data could be at the band-edge or near DC for a direct conversion receiver. This requirement places tight constraints on quadrature and input-referred second order intercept point (IIP2). The transmitter must be able to create a single sideband or offset modulated signals without generating disruptive spurious signals related to the offset frequency.

The LTE standard supports frequency division duplexing (FDD) and time division duplexing (TDD) modes of operation. FDD uses separate frequency allocations for uplink and downlink data paths. Transmit and receive operations occur concurrently. TDD uses a single frequency allocation for both uplink and downlink data paths. To avoid interference between the data paths, transmit and receive operations are interleaved in time.

2. IC description

2.1 Outline

A block diagram of the integrated circuit is shown in **Figure 2**. It is a highly integrated, single-chip CMOS transceiver. The transceiver includes a high-performance, low-noise transmit modulator with no interstage SAW filter; dual receivers for MIMO/diversity operation with no external low-noise amplifiers (LNAs) or interstage surface acoustic wave (SAW) filters; receive analog-to-digital converters (ADCs) and receive digital signal processing hardware; transmit digital-to-analog converters (DACs) and associated transmit digital signal processing; D4G and D3G[1), 2)] digital interfaces for full digital communication to baseband ICs; an ARM7 microprocessor for sequence/hardware control; and a high-level application programming interface (API) for faster radio platform development time.

The transceiver supports both LTE FDD and TDD operation. It also supports 3G W-CDMA and 2G GSM/enhanced general packet radio service (EGPRS) operation with the same signal paths. The hardware supports FDD bands 1-21, TDD bands 33-40, W-CDMA bands I-VI and VIII-XI, and EGPRS bands Cell850, EGSM, DCS and PCS. All LTE channel bandwidths are supported.

2.2. Receiver

Three capabilities distinguish this receiver from the competition:

1) SAW-less operation
2) common RF signal paths for LTE, 3G and 2G
3) autonomous automatic gain control (AGC)

The receiver block diagram is shown in

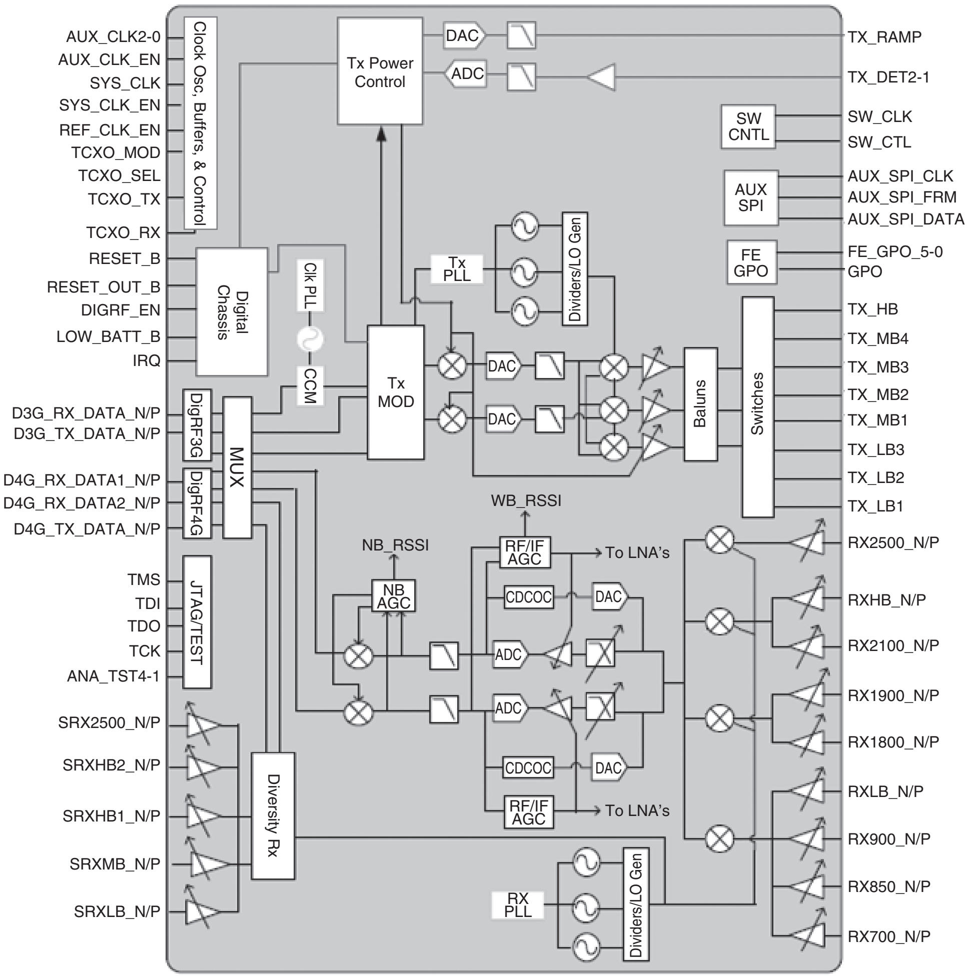

Figure 2
IC block diagram.

Figure 3.

The primary purpose for an interstage SAW filter in a receiver is to attenuate the transmit signal before it reaches the sensitive receiver input. The receiver must be sensitive enough to receive signals smaller than −106.7 dBm in the presence of a +24 dBm transmit signal at the antenna. The radio duplexor attenuates the transmit signal by approximately 48 dB, but the transmit signal remains as the single largest blocking signal to the receiver. The presence of this modulated blocking signal places four principle constraints on the receiver.

1) The LNA must have a high third order intercept point (IIP3) to prevent the generation of RF products with narrow band blockers at 0.5× and 2× the duplex frequency spacing.
2) The mixer must have excellent IIP2 to prevent the generation of interference in the direct conversion receiver from transmit signal self-mixing.
3) The receive synthesizer and quadrature local oscillator generation must have very low phase noise at the duplex frequency spacing.
4) The filter and gain profile of the receiver must maximize dynamic range while preventing clipping in the signal path due to the transmit signal.

The LNA is designed as a current-mode stage to meet the stringent IIP3 requirements.

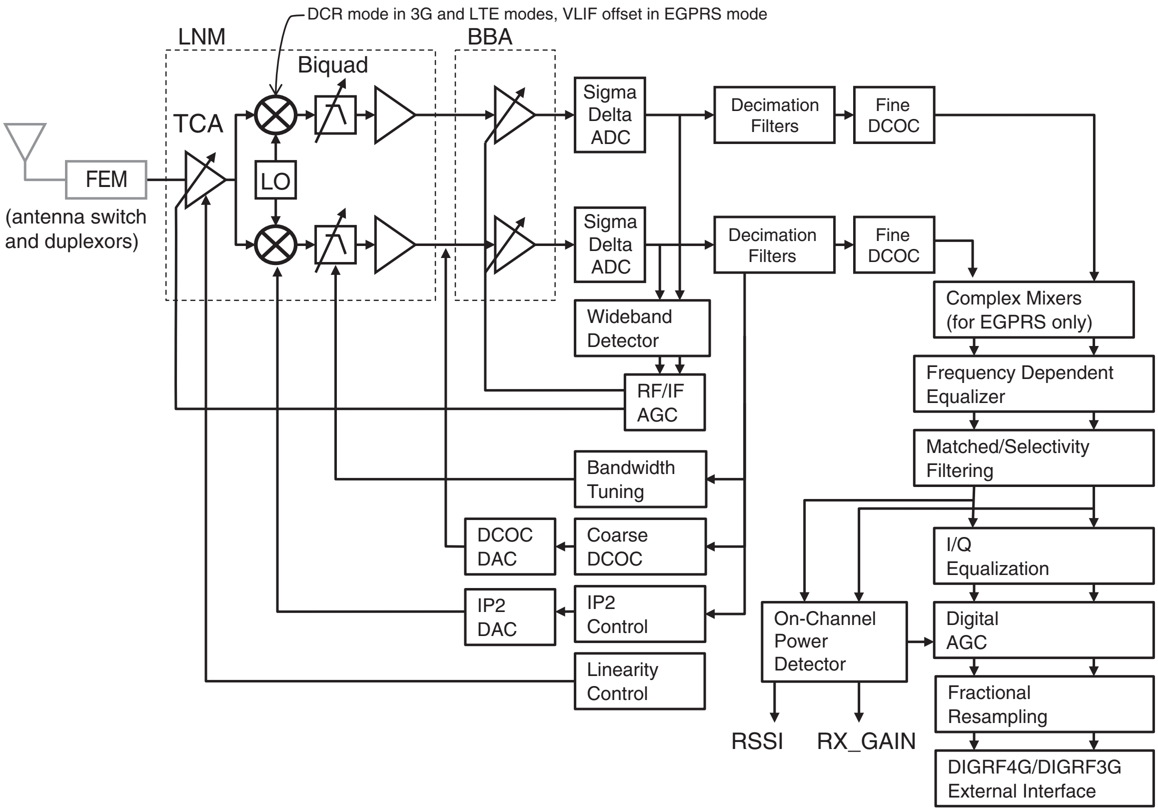

Figure 3
Receiver block diagram.

Careful device sizing and judicious use of current bias enable the required phase noise performance. The autonomous AGC and calibrated filter bandwidths deliver the maximized dynamic range. The extremely high mixer IIP2 performance is accomplished by calibrating the performance at transceiver power-up.[3] A two-tone signal generated in the transmitter is routed through the receiver. The receive digital signal processing monitors the nonlinear products and minimizes the non-linearity by rebiasing the mixer operating point using a pair of DACs. A search algorithm ensures that peak performance is achieved.

There are three additional requirements placed upon the receiver by the LTE standard.

1) The first is the addition of band 7 at 2.7 GHz. Careful design is required to ensure a good noise figure performance at this higher frequency.
2) TDD operation requires improved synthesizer settling times to quickly turn-around from transmit to receive modes.
3) The range of bandwidth settings imposed by LTE adds a number of new, wider bandwidths to the analog filters. To reduce the amount of current drain increase at wider bandwidths, current-mode filters are used to realize critical filter poles. Current-mode filters are not constrained by the fixed gain-bandwidth product limitations of voltage-mode filters.

In LTE operation, the gain control is done completely by the transceiver chip. The transceiver determines the received signal strength indicator (RSSI) level and sets the appropriate gain for the receiver. The baseband IC is only required to provide a timing accurate strobe that tells the transceiver when the start of subframe occurs.

2.3. Transmitter

A block diagram of the direct launch transmitter is shown in **Figure 4**. Similar to the receiver, there are new requirements placed on the transmitter by both SAW-less and LTE operations. The TX interstage SAW is primarily used to limit the impact of the transmitter on the receiver. In the transmit case, it limits the transmitter noise in the receive frequency. The transmit synthesizer and quadrature local oscillator generation must have very, very low phase noise at the duplex frequency spacing (>−160 dBc). Again, this is achieved through careful design and judicious use of current.

LTE operation adds four new requirements to the transmitter. Three are common with the receiver: 1) band 7; 2) variable bandwidths; and 3) TDD operation. These requirements are met in a similar way as with the receiver. The fourth requirement is unique and challenging. Since the direct launch transmitter must support single, or low, RB counts offset from the channel center, new intermodulation products that do not occur in 2G and 3G modulators must be addressed.

Figure 5 shows the frequency spectrum for a transmitter with an offset RB. The offset RB is equivalent to a signal modulated at an IF or intermediate frequency. If the channel center is identified as the RF, then the desired signal appears in the output spectrum at RF+IF. A signal image appears at RF-IF due to non-ideal quadrature modulation. A carrier feed-through signal appears at RF. Two additional terms appear in the spectrum at RF−3IF (C-IMR3) and RF+5IF (C-IMR5), primarily due to mixer non-linearities.

The baseband to RF up-mixing process can produce a complex distortion, unlike either the baseband or RF. This is a consequence of the interleaved switching mixer[4]; simple in concept, low in noise, intrinsically linear and wideband. Resistive nonlinearities in the component t-gate switches, whose response is a function of both the sequentially selected input +I, −Q, −I, +Q voltages and the instantaneous output RF voltage, results in an RC charging behavior of the load capacitance which depends on both current and past values of the $I(t)$ and $Q(t)$ modulation. This nonlinear behavior results in complex transient mixing of the I and Q signals to form intermodulation products that are unusual admixtures of both I and Q signals, as shown in **Figure 6**. It has been empirically determined that this non-linearity can be described as a cubic function of I and Q.

In certain applications, such as band 1 in Japan and band 13 in the United States, these complex non-linear terms present regulatory challenges. Therefore mitigation is required. This transceiver includes a digital predistortion path. The digital predistortion circuit, shown in **Figure 7**, creates a signal that is equal in amplitude and opposite in phase to the undesired non-linear products. It allows for the use of any

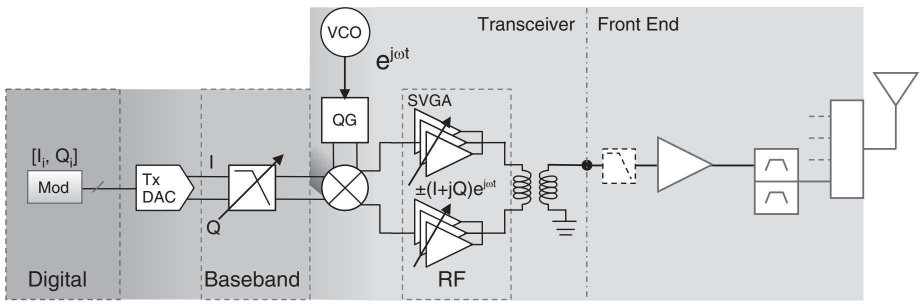

Figure 4
Transmitter block diagram.

one of the cubic pre-distortion terms $\alpha \cdot Q^n I^{3-n}$ for I and $\beta \cdot I^n Q^{3-n}$ for Q and can be bypassed via MUX. The pre-emphasis filter compensates for the magnitude and phase response of the analog baseband filter. It uses up to 15 taps in an FIR configuration and can be bypassed through a stage with matching delay and gain, so that pre-distortion can be enabled/disabled without gain or delay anomalies in the transmitter.

2.4. Application programming interface

The transceiver IC includes an ARM7 core microprocessor. The microprocessor plus associated peripheral blocks control operation of the transceiver. Sequences and timing are under firmware control. This is the fourth generation of transceiver ICs with a common API.

The integrated processor and firmware control tremendously reduces the complexity required by a phone manufacturer to incorporate the transceiver in a radio platform. The common API eases the transition from one transceiver generation to the next. Together, the firmware and API reduce the time required to ship a cellular radio.

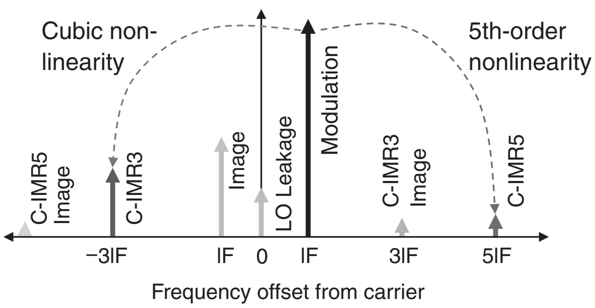

Figure 5
Offset transmit spectrum.

2.5. Digital interfaces

Two industry-standard digital interfaces are integrated into the transceiver IC. This is the third generation of transceiver ICs with a D3G interface. The D3G interface supports a data rate of 312 Mb/s which is enough throughput to handle all versions of 2G and 3G signaling including HSPA+. The D4G interface adheres to the MIPI DigRF v4 standard. It supports a bit rate of 1248 Mb/s per lane. Two downlink lanes are included, raising data throughput to 2496 Mb/s. The D4G interface can handle commands and data for 2G, 3G, and 4G signaling.

This transceiver is able to support two baseband ICs. The coexistence of the D3G and D4G interfaces on the transceiver are advantageous in terms of time to market (TTM)

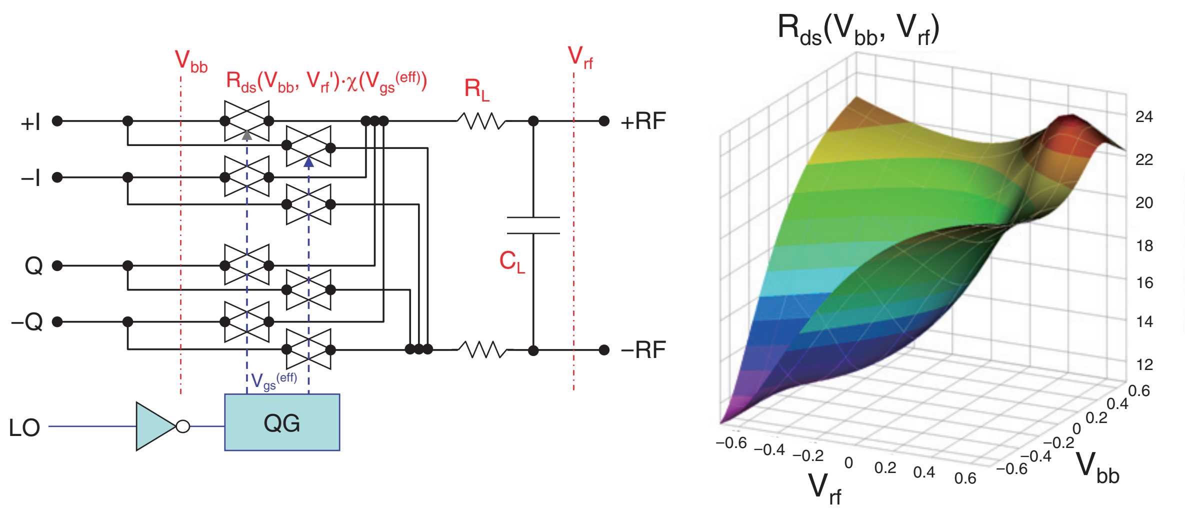

Figure 6
Interleaved switching mixer and non-linear resistance.

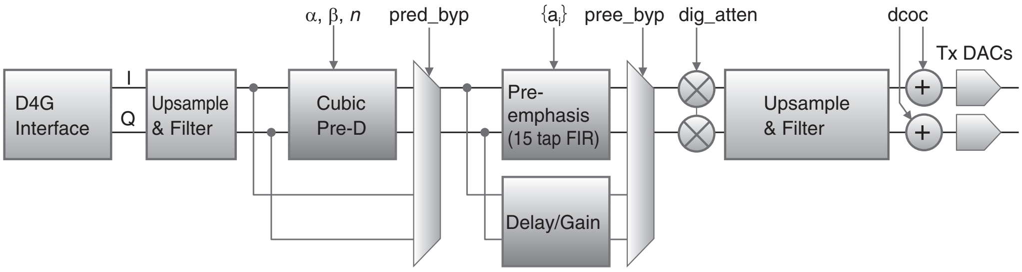

Figure 7
Transmit predistortion system.

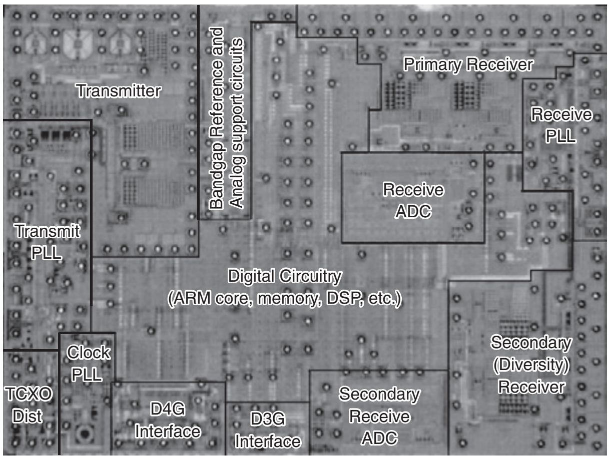

Figure 8
Die photo.

Table 1
Chip specifications.

Technology	90 nm triple well CMOS 6 metals (1 ultra-thick) + AP cap MIM capacitors
Package	6.5 mm × 9.0 mm 4 layer LGA
Supply Voltage	RF: 2.7, 1.85 V Digital: 1.8, 1.2 V
Ports	9 differentialprimary receive 5 differential secondary receive 8 single-ended transmit
GSM bands	Cell850, EGSM, DCS, PCS
W-CDMA bands	I–VI, VIII–XI
LTE bands	1–21, 33–40
LTE bandwidths	1.4, 3, 5, 10, 15, 20 MHz
Interfaces	DigRF 4G DigRF 3G

because each baseband has its own interface to the transceiver.

3. Measured results

A microphotograph of the transceiver with major blocks defined is shown in **Figure 8**. **Table 1** shows the transceiver IC specifications. **Figure 9** shows the C-IMR3 performance versus RF power out and temperature for an RF subsystem (transceiver IC plus power amplifier). Note that the top 12 dB of power range is out of specification for C-IMR3 without predistortion. With predistortion enabled, the radio meets the specification with a margin. **Tables 2** to **5** list the measured RF performance of the transceiver IC.

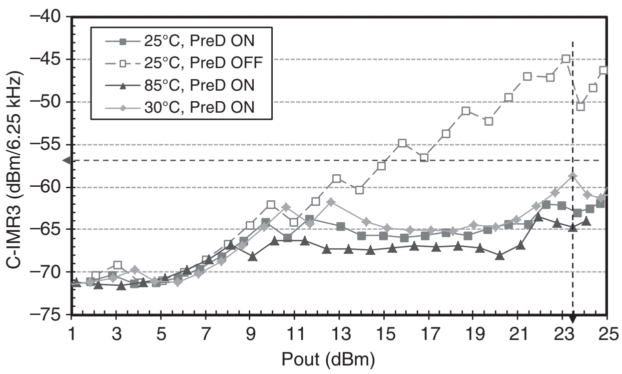

Figure 9
C-IMR3 performance.

Table 2
3G/4G receiver measurements.

Receive	LTE (20 MHz mode)				W-CDMA			Units
	B1	B4	B7	B17	B1	B5	B9	
Center Frequency	2140.0	2132.5	2655.0	740.0	2140.0	881.5	1862.4	MHz
NF	2.9	3.0	2.9	2.1	2.7	2.6	2.6	dB
Sensitivity	−100.3	−100.3	−99.7	−100.7	−114.1	−113.6	−113.4	dBm
EVM	2.7	2.8	2.5	2.9	2.8	2.9	2.6	% RMS
Duplex IIP2	73.3	72.9	71.9	70.0	76.7	70.9	71.2	dBm
Half Duplex IIP3	1.1	5.2	−1.2	0.1	1.1	−0.3	−0.8	dBm
Full Duplex IIP3	4.9	6.4	2.7	3.2	4.9	1.8	1.5	dBm
In-band IIP3	−5.7	−5.6	−4.4	−4.0	−5.1	−4.8	−6.2	dBm

Table 3
3G/4G transmitter measurements.

Transmit	LTE				W-CDMA			Units
	B1	B4	B7	B17	B1	B5	B9	
Center Frequency	1950.0	1727.5	2535.0	710.0	1950.0	836.5	1767.4	MHz
Pout	2.0	2.0	2.0	2.0	3.0	3.0	3.0	dBm
EVM	1.3	1.3	1.7	1.1	1.9	1.8	1.6	% RMS
ACLR	−48.8	−49.2	−53.6	−52.4	−44.8	−46.7	−48.6	dBc
ACLR2	−50.9	−51.4	−55.6	−57.5	−73.5	−74.2	−73.3	dBc
RX Band Noise	−160.0	−161.0	−158.0	−154.0	−160.0	−160.0	−159.5	dBc

Table 4
2G receiver measurements.

Receive	GSM	EGSM	DCS	PCS	Units
Center Frequency	881.5	942.5	1842.5	1960.0	MHz
NF	2.8	3.1	3.0	3.0	dB
Sensitivity	−111.8	−111.9	−111.4	−111.6	dBm
Image Rejection	−76.3	−74.5	−53.3	−51.0	dBc
IIP2	58.0	57.9	56.1	53.0	dBm
In-band IIP3	−13.8	−14.0	−13.9	−14.1	dBm

Table 5
2G transmiter measurements.

Transmit		GSM	EGSM	DCS	PCS	Units
Center Frequency		836.5	897.5	1747.5	1880.0	MHz
GMSK	Pout	5.2	5.1	4.9	4.7	dBm
	GPE	1.0	1.0	1.0	1.1	% RMS
	MODORFS@200 kHz	−34.5	−34.5	−34.6	−34.7	dBc
	MODORFS@400 kHz	−70.9	−70.8	−68.2	−67.2	dBc
8PSK	Pout (EDGE)	1.7	1.7	−0.7	−0.8	dBm
	EVM (EDGE)	1.4	1.4	1.8	1.4	% RMS

4. Conclusion

The world's first single-chip 2G/3G/4G CMOS transceiver was developed and presented. It is also the first commercially available transceiver in the world to support SAW-less 4G operation. The introduction of a transmit predistortion path has been shown to address the stringent nonlinearity requirements of bands 1 and 13 due to offset modulations inherent in LTE signaling. The fourth generation API greatly improves radio development time. The measured performance demonstrated the transceiver is a commercially viable 4G solution.

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4) K. Hausmann et al., A SAW-less CMOS TX for EGPRS and WCDMA. *IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, 2010, pp. 25–28.

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