30.3 A SAW-Less NB-IoT RF Transceiver with Hybrid Polar and On-Chip Switching PA Supporting Power Class 3 Multi-Tone Transmission

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The Narrowband-Internet-of-Things (NB-IoT) is a narrowband wireless communication technology that benefits from the advantages of both cellular networks and narrowband transmission. Since the NB-IoT specification was finalized by 3GPP in 2016, several SoCs [1,2] and an RF transceiver [3] as well as power amplifiers (PA) [4-5] for NB-IoT have been reported. Highly integrated, low-power and low-cost design with the same transmission power levels as existing LTE systems are required. This paper demonstrates a SAW-less NB-IoT RF transceiver with a hybrid polar transmitter and an on-chip switching PA supporting Power Class 3 multi-tone transmission.

The system diagram of the RF transceiver is shown in Fig. 30.3.1. The RF transceiver can support all NB-IoT bands in the 450MHz-to-960MHz and 1561MHz-to-2220MHz frequency ranges, with two separate RF ports for high-band (HB) and low-band (LB), respectively. The RF matching can be optimized for each band by adjusting the components of an off-chip matching network. The receiver adopts a low-IF architecture with a 2nd-order complex filter as a channel-selection filter (CSF) for channel selection and image rejection, and a PGA with a gain step of 1dB for fine gain control. A 10bit asynchronous SAR ADC samples the IF signal centered at 480kHz with a 15.36MHz sampling clock, followed by a decimation filter to downsample the IF signal to 1.92MHz and increase the digital-output bit-width to 12bits. A polar transmitter with an on-chip switching PA is used to achieve a low-power and low-cost implementation for an NB-IoT uplink signal with 5-to-6dB PAPR. Low transmission noise can be achieved with the polar transmitter by avoiding using an upconversion mixer so that the SAW filter can be eliminated. As shown in Fig. 30.3.1, 11bit-I/Q-baseband data are firstly converted to phase-modulation (PM) and amplitude-modulation (AM) data by a CORDIC module. Then 27bit PM data and 9bit data are passed into a look-up table (LUT) for digital pre-distortion followed by PM-to-frequency-modulation (FM) conversion. There are a total of 16 look-up tables (LUT) corresponding to 64 different power levels, to save the total LUT size. Each table has 9bits for AM-AM predistortion mapping and 7bits for AM-PM predistortion mapping. After AM-path and FM-path timing alignment, FM data are passed into the frequency synthesizer, and AM data are upsampled and passed into a 9bit DAC followed by an image-rejection filter for amplitude modulation. One buck DC-DC converter converts input battery voltage from a range of 2.1 to 3.6V, to 1.1V and then supplies several LDOs for internal modules operating under 0.9V. Another buck-boost DC-DC converter is dedicated to supply the on-chip switching PA. The on-chip DCXO achieves more than +/-20ppm frequency-tuning range with 1.3mA current consumption.

The hybrid polar transmitter combines both analog modulation in the PA power supply for high output-power level and digital modulation in PA cells for low output-power level. Figure 30.3.2 shows the architecture of the hybrid polar transmitter. For a high-output-power level of 10 to 23dBm, AM data are input into a Class-AB amplifier and both amplitude modulation and power-level control are implemented in the Class-AB amplifier. The Class-AB amplifier modulates the power supply of the PA (solid line) together with a Class-D amplifier via an off-chip 2.2uH inductor. The Class-AB amplifier provides the small modulation current while the Class-D amplifier provides the large DC current for the PA. For a low-output-power level of 0 to 10dBm, the Class-AB amplifier is bypassed, the Class-D amplifier is turned off and amplitude modulation is directly achieved by direct on/off modulation in the PA cells (dashed line). The buck-boost DC-DC converter is used for low-power-level control, which can provide output as low as 312.5mV with a step of 12.5mV for accurate output-power control. The MSB, MSB-1 and MSB-2bits of the 9bit AM data can be forced to 0 individually for even lower output power level down to -40dBm. Voltage ripple at the Class-AB amplifier output must be less than 20mV$_{pp}$ to pass the SEM requirement and spurious-emission limits without a SAW filter. As shown in Fig. 30.3.2, a Class-E PA with cascode protection is adopted with external L load and LC filter for flexible support of global NB-IoT bands with various off-chip matching configurations. A total 9bit control code with 5bit thermometer code and 4bit binary code are used to control on/off of PA cells. The maximum LB and HB output powers under various temperatures are up to 27.3dBm with 38.6% drain efficiency and 26.7dBm with 44% drain efficiency, respectively. Complete deep N-well isolation is used to separate noise sources such as PA and DC-DC converters and noise victims such as the VCO and LNA, which significantly mitigates the PA-VCO pulling effect and noise coupled to the LNA and VCO.

The frequency synthesizer adopts two-point modulation since the bandwidth of FM data is extended after IQ-to-AM/FM conversion. Narrower loop bandwidth of the frequency synthesizer leads to better phase noise, thus better spectrum. However, it will filter the high-frequency FM component in multi-tone transmission if only single-point modulation in the delta-sigma divider is used, thus degrading EVM of the output signal. Two-point modulation enables large-bandwidth frequency modulation with narrower loop bandwidth of the frequency synthesizer. Figure 30.3.3 shows the diagram of the frequency synthesizer. The FM data are separated into a low-frequency (LF) path for delta-sigma divider modulation and a high-frequency (HF) path for VCO modulation. Since NB-IoT must support single-tone 3.75kHz modulation, a 27bit delta-sigma divider is used to achieve 0.57Hz frequency resolution. For the high frequency path, a 12bit DAC followed by a differential-to-single-ended conversion buffer converts FM data to analog voltage for control of the FM varactor in the VCO. The DAC has 7bits for calibration to tune the gain mismatch between the LF path and HF path. A counter calculates the VCO frequency at two boundaries of DAC input, and calibrates the gain of the modulation-frequency vs DAC-input-code, which combines contributions from both DAC and FM varactor to make it consistent with the gain of the delta-sigma divider. The timing mismatch can be adjusted in either the HF path or LF path before FM data are input into the DAC or delta-sigma divider. Figure 30.3.3 also shows part of the system-level simulation platform to model two-point modulation in the frequency synthesizer.

To achieve a SAW-less receiver, a passive mixer followed by a transimpedance amplifier and a 25%-duty-cycle LO are used to achieve -4dBm output P_{1dB} with 5mA current consumption. Furthermore, to pass the most stringent out-of-band (OOB) blocking requirement of -15dBm at +/-150MHz offset for LB and -15dBm at +/-200MHz for HB without SAW filter, LNA gain should be lowered to increase the linearity when a strong blocker exists. Figure 30.3.4 shows the architecture of "smart" AGC in this design. Two identical analog RSSI modules with 8bit ADC are used to detect a blocker at the RF front-end. With the presence of a blocker, there will be a large difference between the two RSSI output codes. Therefore, the digital baseband can utilize this information to decrease LNA gain, thus increasing the linearity of the RF front-end. The measured LB and HB OOB blocking results are -12dBm at +/-150MHz offset and -14dBm at +/-200MHz offset, respectively. Figure 30.3.4 also shows a key part of chip EVB, in which neither an external PA nor a PMU chip is needed. The measured LB and HB receiver EVM are 1.9% and 3.5%, respectively.

Figure 30.3.5 shows key parameter measurements of the transmitter with multi-tone 12-tone transmission, which is the most stringent requirement in NB-IoT transmission. For the Power Class 3 requirement, the nominal output power is 23dBm with +/-2dB tolerance. With consideration of 2dB MPR for 12-tone transmission and 0.7dB testing tolerance, the minimum-output-power requirement for Power Class 3 is 18.3dBm. As shown in Fig. 30.3.5, the chip can output 19.2dBm in 12-tone transmission with EVM of 7.7% and ACLR is 26dBc for GSM and 40dBc for UTRA. The SEM requirement and spurious-emission limit can also be passed. Figure 30.3.5 also shows constellation and EVM measurement for single-tone 15kHz transmission. The output power is 22.2dBm with EVM of 1.7%, which also meets the Power Class 3 requirement (20.3dBm) with 1.9dB margin. The measured LB and HB receiver power consumption are 53mW and 56mW, respectively. The measured LB and HB transmitter power consumption for 12-tone transmission are 675mW@19.2dBm and 585mW@18.6dBm with analog polar modulation, and 396mW@10dBm and 332mW@10dBm with digital polar modulation, respectively. The performance comparison with state-of-the-art technologies is summarized in Fig. 30.3.6 and the die micrograph is shown in Fig. 30.3.7.

Acknowledgements:
The authors would like to thank Kin Cheung Au, Tin Ho Wu, Chun Kit Chan and Jinghong Zhu for their physical implementation and other colleagues in ASTRI for their technical discussions and contributions.

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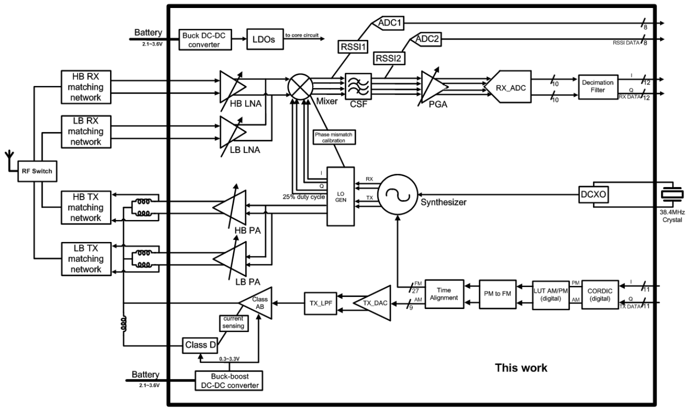

Figure 30.3.1: System architecture of NB-IoT RF transceiver.

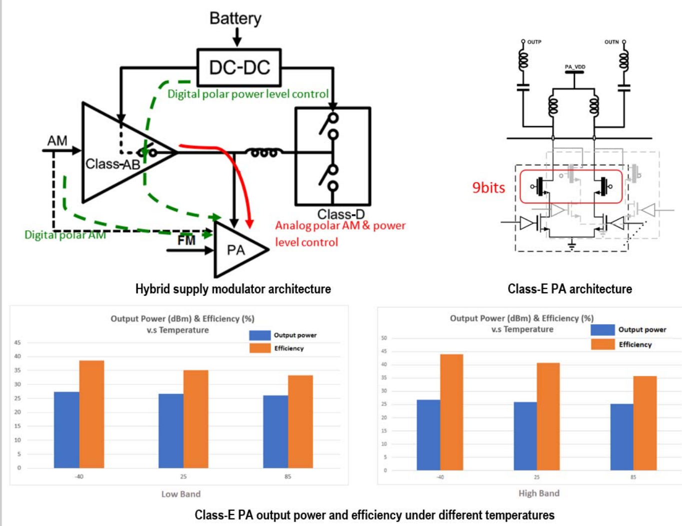

Figure 30.3.2: Hybrid supply modulator, PA architecture and PA measurement.

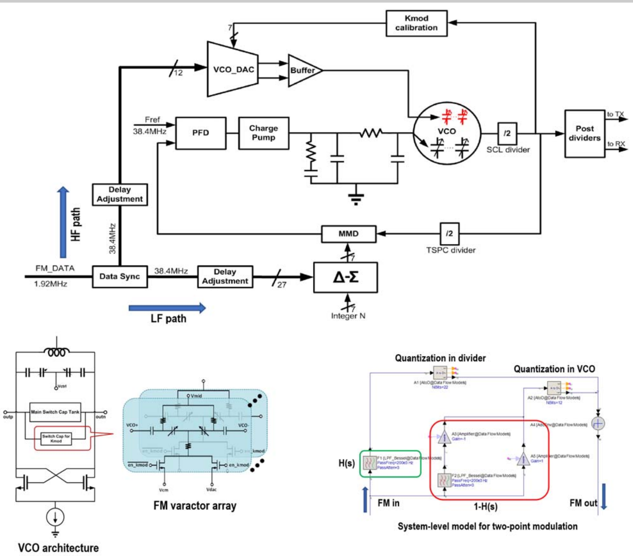

Figure 30.3.3: Two-point modulation in frequency synthesizer.

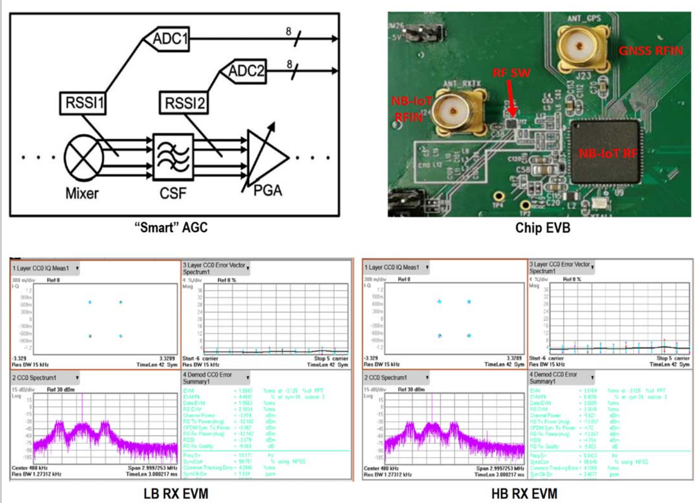

Figure 30.3.4: RX AGC, chip EVB and RX EVM measurement.

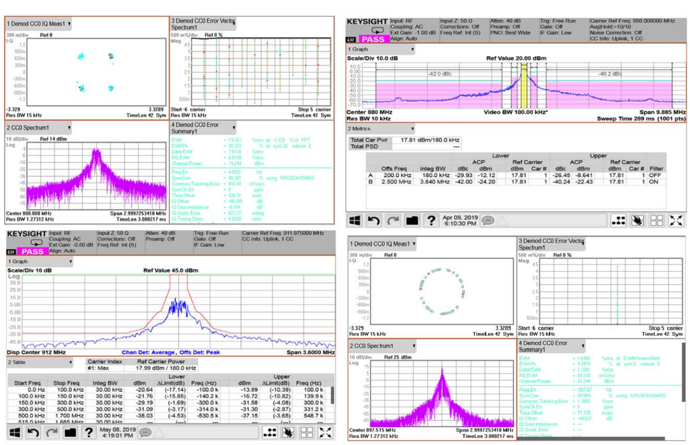

Figure 30.3.5: TX EVM, ACLR, SEM measurement for multi-tone 12-tone and EVM measurement for single-tone 15kHz transmission.

		ESSCIRC-18 [1]	RFIC-19 [2]	TCAS-I-17 [3]	ISSCC-18 [4]	JSSC-19 [5]	This work
Frequency range		700-900MHz; 1.7-2.1GHz	450-2220MHz	750-960MHz	850MHz/1.7GHz	699-915MHz	**450~960MHz; 1561-2220MHz**
Supporting mode		NB-IoT (both single-tone and multi-tone) /EC-GSM	NB-IoT (both single-tone and multi-tone)	NB-IoT RX & NB-IoT TX (single-tone 3.75kHz only)	NB-IoT (PA only)	eMTC/NB-IoT (PA only)	**NB-IoT (both single-tone and multi-tone)**
Technology		110nm CMOS	55nm CMOS	180nm CMOS	55nm CMOS	40nm CMOS	**40nm CMOS**
Die size		N/A	2.23mm²	N/A	1.11mm² (PA only)	5.0 mm² (PA+interface)	**7.1 mm²**
Integrated PA		No	No	Yes	Yes (PA only)	Yes (PA only)	**Yes**
Integrated PMU		N/A	No	No	No	No	**Yes**
Supply voltage		N/A	0.9/1.1V	1.7V	1.2/2.4V	2.2V	**2.1~3.6V; 0.9V for core modules**
TX	Pout	N/A	4dBm	23.2dBm (single-tone, 3.75kHz)	24.4dBm/23dBm	27.1dBm (for continuous wave)	**19.2dBm (LB) / 18.6dBm (HB) for multi-tone 12-tone transmission / 22.2dBm (LB) /22dBm (HB) for single-tone 15kHz transmission**
	EVM	N/A	3.5% for multi-tone 12-tone transmission / 0.73% for single-tone 3.75kHz transmission	3.87@18.87dBm (single-tone, 3.75kHz)	-21.6dB (8.3%)	3.1% (for eMTC)	**7.7% (LB) / 8.3% (HB) for multi-tone 12-tone transmission / 1.5% (LB) / 2.9% (HB) for single-tone 15kHz transmission**
	SAW-less	Yes	Yes	No	No	No	**Yes**
	Power consumption	N/A	25.8mW	~480mW (by addition of each module)	N/A	N/A	**675mW@19.2dBm (LB) / 585mW@18.6dBm (HB) for multi-tone 12-tone transmission**
RX	Sensitivity	-115.9dBm	-140dBm with repetition	N/A (NF=4dB)	N/A	N/A	**-112.5dBm (LB) / -111.9dBm (HB) without repetition**
	EVM	N/A	N/A	N/A	N/A	N/A	**1.9% (LB) / 3.5% (HB)**
	SAW-less	Yes	Yes	N/A	N/A	N/A	**Yes**
	Power consumption	N/A	11.8mW	25mW@1.7V	N/A	N/A	**53mW (LB) / 56mW (HB)**

Figure 30.3.6: Performance comparison with state-of-the-art technologies.

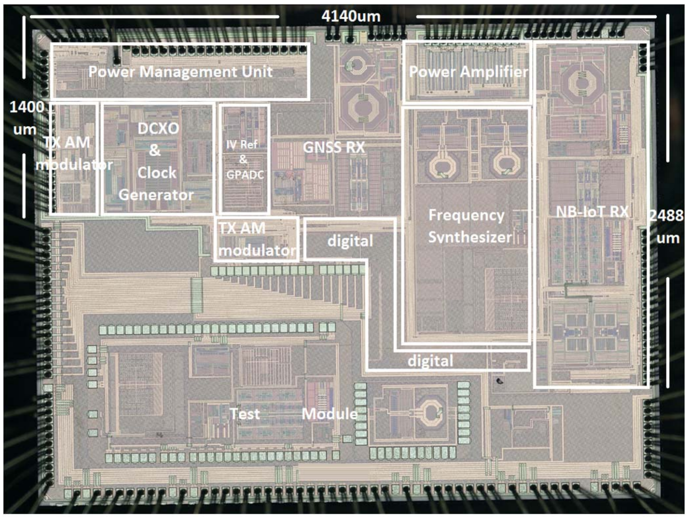

Figure 30.3.7: Die micrograph.

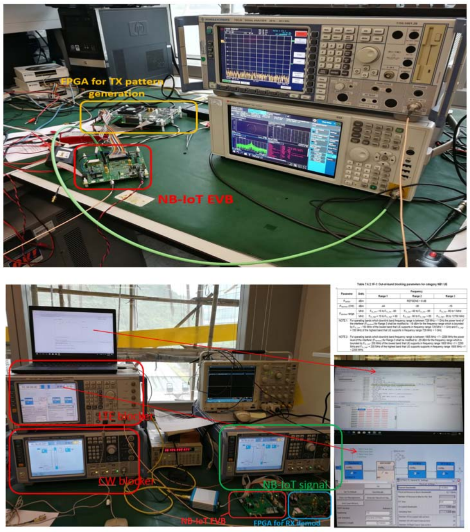

Figure 30.3.S1: Measurement setup for TX (top) and RX wideband intermodulation (bottom).

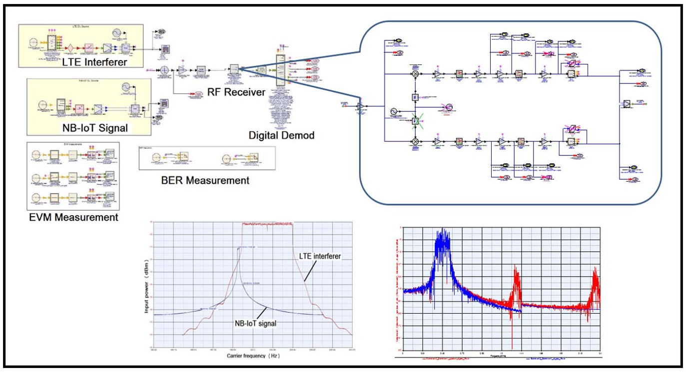

Figure 30.3.S2: System-level simulation platform for NB-IoT receiver.

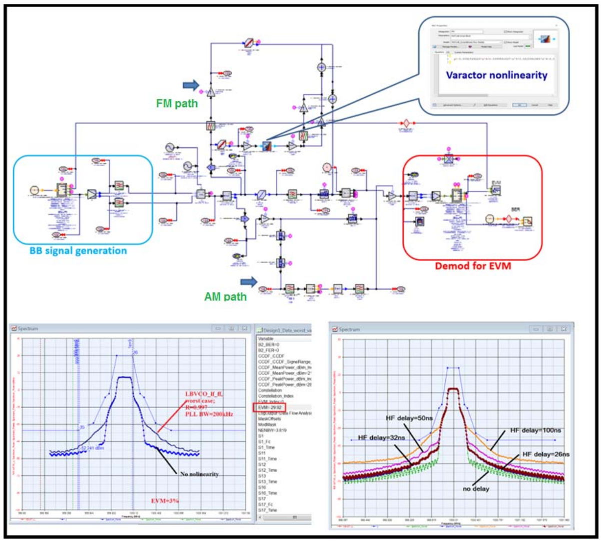

Figure 30.3.S3: System-level simulation platform for NB-IoT transmitter.