Crystal-Free Narrow-Band Radios for Low-Cost IoT

Brad Wheeler, Filip Maksimovic, Nima Baniasadi, Sahar Mesri, Osama Khan, David Burnett,
Ali Niknejad, Kris Pister
Department of Electrical Engineering and Computer Sciences
University of California, Berkeley
Email: brad.wheeler, fil, baniasadi, smesri, oukhan, db, niknejad, ksjp @berkeley.edu

***Abstract*—A transceiver was designed and fabricated in 65 nm CMOS to verify the feasibility of using a free running, on-chip LC tank as the local oscillator in an IEEE 802.15.4 transceiver. The elimination of the off-chip frequency reference is possible while still using a standards based narrow-band architecture. A free running LC tank is shown to have frequency stability better than 40 ppm in the absence of temperature changes. Demodulator-based feedback is implemented to allow a receiver to track transmitter drift due to varying environmental factors and phase noise. The modulation accuracy of a free-running open loop Minimum Shift Key (MSK) transmitter is shown to be within the limits set by IEEE 802.15.4.**

Keywords—Low power radio, Wireless Sensor Networks, Crystal-Free Radio

I. INTRODUCTION

The ubiquitous use of crystal-referred oscillators in wireless communication has enabled radios to operate with little concern for variations in local oscillator and timer frequencies arising both from long-term environmental changes and close-in phase noise. However, with the trend toward complete monolithic integration of an entire wireless sensor node, the crystal becomes an unaffordable luxury. MEMS provides an alternative to the quartz crystal for high quality oscillators, but still requires additional process integration beyond CMOS. A CMOS-only solution is thus preferable to enable large scale deployments of wireless nodes by reducing the costs of integration. The removal of the highly accurate time and frequency reference creates design challenges in channel selection, transceiver performance, and timing synchronization.

Traditional radios typically use two high quality references, one for timekeeping and one to phase lock the RF oscillator. It was shown in [1] that network level calibration algorithms can allow the timekeeping reference to be replaced with an on-chip relaxation oscillator. Network feedback can also be used to calibrate shifts in RF LO frequency due to slowly varying environmental factors [2], but the free-running oscillator must be stable enough over the duration of a packet to successfully communicate. Previous crystal-free approaches either suffer from reduced sensitivity due to large receiver bandwidths [3] or utilize non-standard modulation approaches [4]. In this paper we investigate the feasibility of using a free running LC tank as the LO for an IEEE 802.15.4 transceiver. How accurately the system can tune to a specific channel will determine the additional tolerance required for the receiver bandwidth in order to ensure communication. The instability of the LO will also affect the modulation accuracy of the proposed implementation of a open loop direct modulation transmitter. Measurement results presented here focus specifically on LO stability as it relates to channel selection and modulation accuracy.

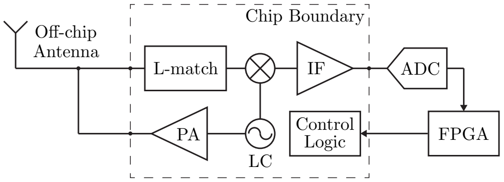

Fig. 1. System level block diagram of the transceiver.

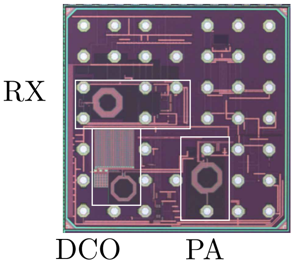

Fig. 2. Die photo of the 1.83 mm * 1.83 mm flip-chip IC, of which the radio occupies 1.2 mm^2.

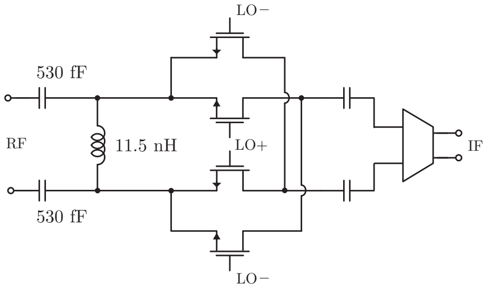

Fig. 3. Receiver front end schematic. Not pictured are off-chip RF balun and baseband filters. The mixer switches were minimum length devices with 3 μm channel widths.

II. SYSTEM OVERVIEW

The transceiver was designed in TSMC 65 nm using a CMOS LC tank DCO shared between the low-IF receiver and direct modulation transmitter. The system block diagram and die photo are shown in Fig. 1 and Fig. 2 respectively. Image rejection was sacrificed for lower power consumption and simplicity in this design, but could be incorporated by switching to a quadrature LC oscillator [5] at the expense of increased design complexity. The transceiver takes advantage of the equivalency of OQPSK-HSS and Minimum Shift Key modulation [6] in order to simplify the system design. The receiver design is based on [7] using a passive front end with reactive components for voltage gain before down-conversion by the double balanced passive mixer as shown in Fig. 3. The mixer gate capacitance is resonated in the LC tank which also sets the bias point for the switches. A differential pair with common-mode feedback buffers the IF and drives the signal off-chip. A third-order Butterworth low-pass filter with automatic gain control is implemented off-chip followed by a 100 Msps ADC. This oversampling rate is chosen to enable the use of a zero-crossing counter as an MSK demodulator. Once the signal is digitized it is processed in an FPGA using a Cortex-M0 based digital system which implements IEEE 802.15.4 packet handling. MSK transmissions are generated by open loop digital modulation of the LO which directly drives a class D PA.

III. LOCAL OSCILLATOR PERFORMANCE

The local DCO is a CMOS LC tank that employs a degenerated capacitive DAC [8] for high frequency tuning resolution. As shown in Fig. 5 the phase noise at 100 kHz is -92.1 dBc/Hz relative to the carrier. The DCO consumes 1 mA from a 1 V supply which results in a figure of merit of 182.1 dB. The DCO is also tunable from 2.6 GHz to 3.1 GHz. The coarse tuning characteristic is shown in Fig. 4. The fine tuning, which has an LSB of approximately 10 kHz is enabled by a g_m reduction in the capacitance seen at the tank. This DAC is used to compensate for temperature variations.

Phase noise degrades receiver performance through reciprocal mixing with interferers and by adding frequency variation to down-converted signals. The interference tolerance requirements of IEEE 802.15.4 are not stringent and the phase noise requirement due to reciprocal mixing is easily met by a free running LC tank [9]. Fig. 6 shows the result of down-converting the free running LO to a low intermediate frequency of approximately 2 MHz and evaluating the variation in cycle-to-cycle frequency. The phase noise of the LO causes frequency variation at IF with a standard deviation of 22 kHz which is significantly smaller than the 1 MHz tone separation used by the IEEE 802.15.4 modulation. Low frequency phase noise appears constant over the duration of a packet, but causes drift which complicates channel selection and is addressed in the next section.

IV. PHASE NOISE AND FREQUENCY DRIFT

The oscillator frequency will drift over time due to both temperature and phase noise. To separate the drift effects of temperature from other sources of noise the oscillator was placed in a temperature chamber overnight at $25°C$. Frequency stability was measured using a Rohde & Schwarz FSP analyzer with the frequency counter set to 100 Hz resolution. The average frequency was repeatedly measured over a 100 ms window using a 10 MHz RBW with approximately 5 ms of dead time between measurements. This experiment was run for LC tank bias currents of 1 mA and 500 μA with the results shown in Fig. 8 and Fig. 9.

Over 13 hours the free running oscillator drifts less than 40 ppm from noise alone which is within the +/- 40 ppm specification of IEEE 802.15.4. The temperature coefficient of the oscillator was measured by subjecting it to a $0°C$ to $50°C$ temperature ramp at a rate of $7°C$/min. Fig. 7 shows more than 4000 ppm of variation over the 50° range. The measured temperature coefficient of 95 ppm/$°C$ near room temperature is higher than the simulated value of 25 ppm/$°C$. This value is comparable to other LC tanks found in literature and can be improved by the use of compensation schemes at the expense of increased power consumption [11].

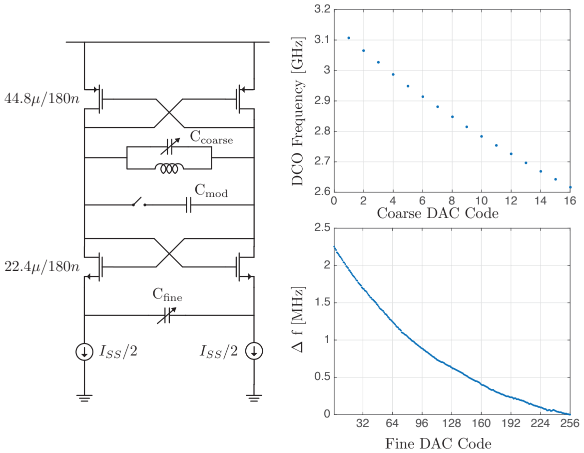

Fig. 4. DCO schematic with coarse and fine frequency tuning characteristics. Each binary weighted DAC code was implemented with a parallel tank capacitance similar to [10]. I_{SS} is 1 mA. The inductor is 3.2 nH with a Q factor of 9.2.

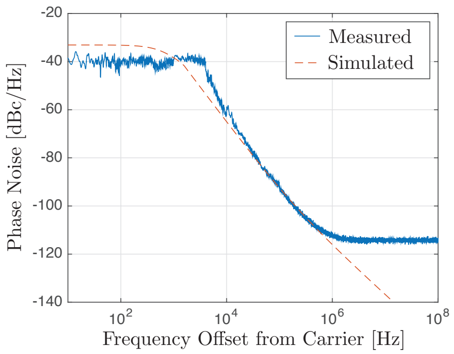

Fig. 5. LC tank phase noise measurement.

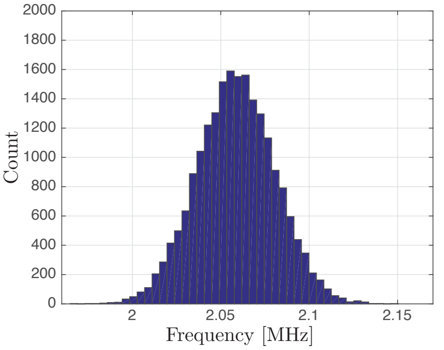

Fig. 6. Histogram ($\sigma = 22kHz$) of instantaneous IF frequency down-converted by free-running LC tank over 10 ms time span.

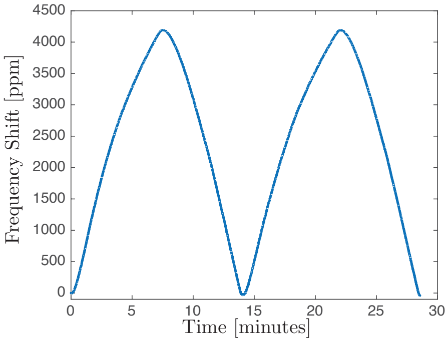

Fig. 7. Frequency deviation during two 0°C to 50°C temperature ramps at 7°C/min rate.

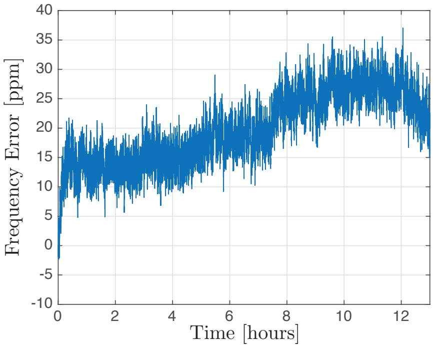

Fig. 8. Measured LO stability with 1 mA bias current.

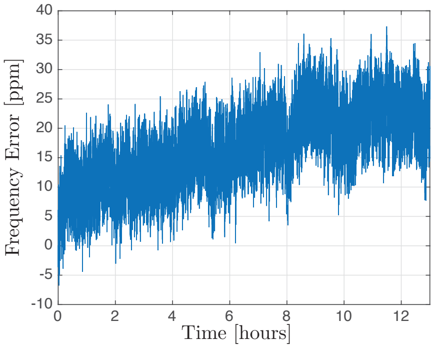

Fig. 9. Measured LO stability with 500 μA bias current.

In order to tolerate temperature fluctuations, a feedback mechanism was implemented which uses the demodulated output of incoming packet transmissions to correct the LO frequency. Using the demodulator output obtained from down-conversion via the mixer avoids the power penalty of a full PLL with a frequency divider. More importantly this makes the incoming RF signal the reference for the receiver which allows it to track a drifting transmitter even while drifting itself.

The demodulator used is a simple zero-crossing based MSK discriminator which utilizes a counter running at 100 MHz to distinguish between the two MSK tones. A simple correction scheme was implemented which determines the average value of the demodulator counter and then digitally tunes the LO until this count value falls in some specified range. This tuning mechanism will cause the receiver to track the transmitter if the drift is slow compared to the update rate which was set to be 5 Hz.

Fig. 10 shows the frequency deviation of an LC oscillator in uncontrolled ambient lab conditions with and without feedback applied. The RF input to the system was a modulated signal from a function generator which resulted in a baseband SNR of 14.7 dB. The LO fine tune DAC was updated at a 5 Hz rate with the target of producing a 2.5 MHz average IF signal. The feedback mechanism reduces the effect of the temperature variation from 150 ppm to less than 10 ppm over the duration of the test. It should be noted that this level of accuracy is obtained due to a MEMS oscillator on the FPGA which runs the 100 MHz counter. While this example demonstrates the feasibility of performing temperature compensation based on a received RF reference, it is not realistic in that it has a continuously available RF input and a very stable low frequency reference.

A more realistic frequency correction mechanism was then implemented which only performed updates upon reception of an IEEE 802.15.4 packet. The low frequency MEMS reference on the receiver FPGA was replaced by a clock with jitter representative of a relaxation oscillator (1σ period deviation of 200 ps) thus making the receiver completely reliant on only CMOS oscillators. Both the TX and RX RF oscillators were free-running LC tanks and packets were sent via open-loop modulation of the transmitter every 200 ms. This RF signal was coupled into the receiver such that the IF signal after down-conversion had an SNR of 15 dB. Each time the receiver detected a packet it estimated the intermediate frequency using a counter driven by its poor quality low frequency reference. The fine tune DAC on the receiver was then used to adjust the LO to force the mixing product of the RX LO and TX LO to be the desired intermediate frequency of 3 MHz. The RX LO coarse tune was fixed in place so that only the fine tune DAC could be used to adjust frequency, resulting in a tunable range of 2.2 MHz. The TX LO was then subjected to a 2°C/min temperature ramp while the RX LO remained in ambient lab conditions. Fig. 11 shows the measured intermediate frequency during the temperature ramp. At the start of the test the TX LO is beyond the tuning range of the DAC and the IF frequency is too high. As the temperature increases the TX LO frequency decreases. When the IF reaches the target of 3 MHz, the feedback adjusts the RX LO to track the changing TX frequency until it reaches the end of the RX DAC range and the IF begins to drop again.

V. TRANSMITTER PERFORMANCE

The signal is transmitted using a class D power amplifier with two stages of pre-amplification and MSK modulated using direct modulation on the local oscillator frequency. While transmitting a single tone at 2.615 GHz, the transmitter provides -5.3 dBm to a 50 Ω load. The transmitter itself consumes 1.537 mW from a 1V supply (a drain efficiency of 19.2%). The system efficiency of the entire transmitter system, counting the power consumed by the oscillator, is 11.6%. The transmitter EVM was measured by implementing a reference OQPSK receiver in MATLAB which had a carrier recovery loop with a bandwidth of 200 kHz. The EVM is shown in

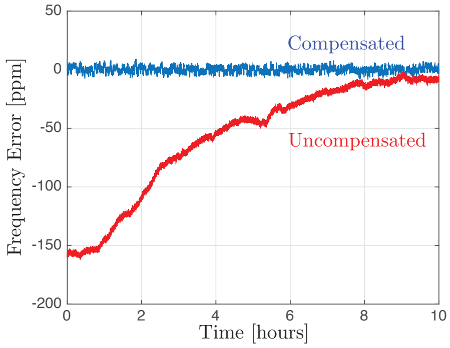

Fig. 10. Frequency stability measured on lab bench top overnight with and without feedback.

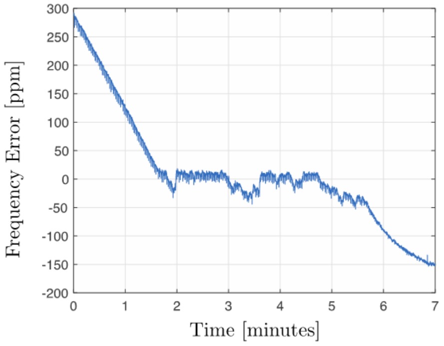

Fig. 11. Intermediate frequency of a receiver using feedback based on packets received from a transmitter whose temperature varies at 2° C/min.

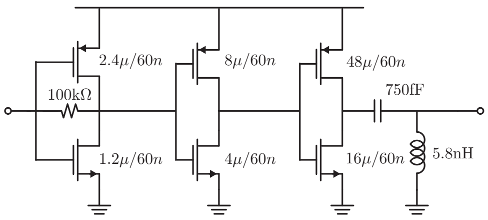

Fig. 12. Class D PA schematic.

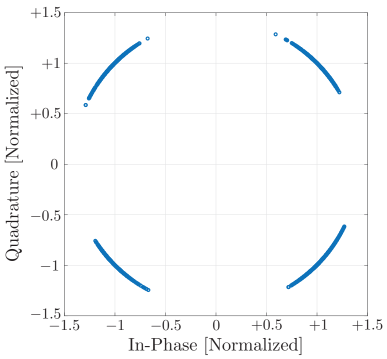

Fig. 13. OQPSK constellation with EVM of 11% obtained via reference receiver in MATLAB with 200 kHz carrier recovery loop.

Fig. 13 and was measured to be 11% which is within the IEEE 802.15.4 specified limit of 35%.

VI. CONCLUSIONS

The feasibility of using free-running LC tank oscillators in an IEEE 802.15.4 transceiver has been investigated. The frequency drift from noise alone was found to be less than 40 ppm over a 13 hour time period. Temperature variations cause significant frequency shifts, but are generally slowly varying and can be compensated for using feedback from the error between TX and RX frequency, or IF frequency. It was shown that a free-running transmitter which is drifting due to a $2°C$/min temperature change can be tracked by a receiver. Furthermore an open loop direct modulation transmitter was shown to achieve 11% EVM for OQPSK modulation. The use of fully integrated free running RF oscillators enables a reduction in power with the elimination of the PLL, reduced system cost due to lack of a crystal reference, and a step towards fully on-chip wireless system integration.

ACKNOWLEDGMENT

The authors would like to thank Lorentz PeakView, Integrand EMX, and the students, faculty, and sponsors of the Berkeley Wireless Research Center and the Berkeley Sensor & Actuator Center. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. 1106400, the DARPA Vanishing Programmable Resources Program, and also in-part by support from Intel Corporation.

REFERENCES

[1] O. Khan, et al. ”Frequency reference for crystal free radio”, *IEEE International Frequency Control Symposium (IFCS)*, 2016.

[2] T. Watteyne, et al. ”OpenWSN: A Standards-Based Low-Power Wireless Development Environment,” *European Transactions on Telecommunications*, 2013.

[3] N. M. Pletcher, et al. ”A 52 μW wake-up receiver with -72 dBm sensitivity using an uncertain-IF architecture.” *IEEE Journal of Solid-State Circuits*, 44.1 (2009): 269-280.

[4] S. Drago, et al. ”A 2.4 GHz 830 pJ/bit duty-cycled wake-up receiver with -82 dBm sensitivity for crystal-less wireless sensor nodes.” *Solid-State Circuits Conference Digest of Technical Papers (ISSCC)*, 2010 IEEE International. IEEE, 2010.

[5] A. Mirzaei, et al. ”The quadrature LC oscillator: A complete portrait based on injection locking.” *IEEE Journal of Solid-State Circuits*, 42.9 (2007): 1916-1932.

[6] J. Notor, et al. ”CMOS RFIC architectures for IEEE 802.15.4 networks.” Cadence Design Systems, Inc 41 (2003).

[7] B. Cook, et al. ”Low-Power 2.4 GHz Transceiver With Passive RX Front-End and 400 mV Supply,” *IEEE Journal of Solid-State Circuits*, Vol. 41, No. 12, Dec. 2006, pp. 2757-2766.

[8] L. Fanori, et al. ”Capacitive Degeneration in LC-Tank Oscillator for DCO Fine-Frequency Tuning,” *IEEE Journal of Solid-State Circuits*, Vol. 45, No. 12, Dec. 2010, pp. 1-9.

[9] N. Oh and S. Lee. ”Building a 2.4 GHz radio transceiver using IEEE 802.15.4.” *IEEE Circuits and Devices Magazine* 21.6 (2006): 43-51.

[10] A. D. Berny, et al. ”A 1.8 GHz LC VCO With 1.3 GHz Tuning Range and Digital Amplitude Calibration,” *IEEE Journal of Solid State Circuits*, Vol. 40, No. 4, Apr. 2005, pp. 909-917.

[11] N. Sinoussi, et al. ”A single LC tank self-compensated CMOS oscillator with frequency stability of ±100 ppm from $-40°C$ to $85°C$” *IEEE International Frequency Control Symposium (IFCS)*, 2012.