# Frequency Reference For Crystal Free Radio

Osama Khan[1], Brad Wheeler[2], David Burnett[3], Filip Maksimovic[4], Sahar Mesri[5], Kris Pister[6]
SWARM Lab, UC Berkeley
Berkeley, CA, USA
[1]oukhan@*, [2]brad.wheeler@*, [3]db@*, [4]fil@*, [5]smesri@*, [6]ksjp@*, *berkeley.edu

Ali Niknejad
BWRC, UC Berkeley
Berkeley, CA, USA
niknejad@berkeley.edu

***Abstract*—To reduce the cost of a sensor node, complete system integration implies zero external components. A system solution is therefore presented to calibrate the frequency of an on-chip relaxation oscillator to be used as a frequency reference for low power crystal free wireless communication.**

**Keywords—** ***Crystal free radio, frequency reference, Internet of Things (IoT), low power radio, mesh network, relaxation oscillator, time synchronization, wireless communication.***

## I. Introduction

We present a system solution as how a crystal free wireless sensor node can be designed in the absence of a crystal reference. We make one assumption that the nodes in a wireless network are operating in a Time-Synchronized Mesh Protocol (TSMP) [1] with at least one node in a network having a crystal reference. In the absence of any quartz crystal oscillator at our disposal, we are left with an on-chip relaxation oscillator as our frequency reference. As frequency reference is characterized by its frequency stability and the frequency stability of relaxation oscillators published in the literature, as measured by the Allan deviation directly in the time domain, shows that beyond 1 s better than 20 ppm frequency stability is achieved at nW power for 18.5 kHz [2] and 33 kHz [3] RC oscillators and < 100 ppm for 11 Hz [4] RC oscillator beyond 100 s. It is clear that the frequency stability of relaxation oscillators is not limited by the pure random noise but in fact due to sensitivity to environmental factors e.g. temperature and supply voltage sensitivity. Measured temperature accuracy of ±2100 ppm (-20 to 90 °C) and ±1000 ppm (-20 to 100 °C) while voltage accuracy of 900 ppm and 600 ppm per volt has been reported for [3] and [5] respectively. Therefore the sensitivity to environmental factors sets the lower limit on the frequency accuracy of the relaxation oscillators.

It is plausible to assume, after calibrating for static errors, e.g. process variations, ~1% (~10000 ppm) initial frequency accuracy of relaxation oscillators keeping environmental factors into account. Then in a wireless network if one node has a crystal-referenced oscillator used as a clock (called Root) then all other nodes in the network can synchronize their local reference (relaxation oscillator) clock to the Root clock by exchanging packets and using the time-stamp information to track their clock drift with respect to a crystal clock [6]. However the problem with this approach is in order for the nodes to initially communicate (listen) to a Root node to get the time information, they need to tune their LO to a precise RF frequency (typically <100 ppm accuracy) which is traditionally achieved with an on-chip PLL using an accurate crystal based frequency reference.

In the next section we will present an algorithm that allows a sensor node to communicate with a Root node with inaccurate frequency reference (~10000 ppm). Once communication with a Root node is established and time-information exchanged, this initial frequency accuracy can be improved (< 100 ppm) and in principle is limited only by the noise of the relaxation oscillators for a given power as quantified by the Allan deviation and the time synchronization algorithm accuracy.

## II. Frequency Calibration

An Internet of Things (IoT) sensor node can employ simple counters for an on-chip frequency measurement of RF (LC/Ring) oscillators to tune their frequency. The measurement interval $T$ is defined by the $N1$ count of the reference frequency (RC oscillator) measured by counter 1. The RF frequency $f_{RF,}$ can then be estimated by,

$$f_{RF} = \frac{N \times N2}{N1} f_{REF} \qquad [1]$$

Where $N2$ is the counter 2 count value for the interval $T$ measuring the divided RF frequency by the frequency divide value $N$. The accuracy with which the RF frequency can be determined is dictated by the accuracy of the reference frequency $f_{REF}$ which is initially assumed to be ~1%. The 2.4 GHz ISM band is ~83 MHz wide which correspond to 3.4% of the band center frequency of 2450 MHz. With 1% frequency accuracy all the nodes in the network are guaranteed to find the 2.4 GHz ISM band and can tune their LOs to be within ~1% (24.5 MHz) of the desired channel. Depending on the communication channel bandwidth, a frequency resolution ($\Delta R$) can be selected to tune the RF frequency of an IoT sensor node that guarantees to find the Root node transmit frequency in the 24.5 MHz search band ($SB$) in a reasonable time. The number of potential RF channels to search would be $SB/\Delta R$. If the Root node sends a beacon signal every $T_B$ seconds on a predetermined RF channel then an IoT node needs to listen at least $1.0202 \times T_B$ seconds on each potential RF channel to guarantee finding a beacon signal if it happens to be on that frequency. $T_B$ is defined with respect to a crystal clock and the factor 1.0202 takes into account the initial ~1% (10000 ppm) clock error with respect to a Root node clock. Therefore the maximum time ($T_F$) that it would take for an IoT node to find the Root node is bounded by,

$$T_F < (1.0202 \times T_B) \times \frac{SB}{\Delta R} \qquad [2]$$

For example if we assume a communication channel bandwidth of 2 MHz then a frequency resolution of $\Delta R$ = 0.5 MHz is acceptable and with a beacon interval of $T_B$ = 1 s, the maximum time it would take for an IoT node to find the root node transmit frequency would be < 50 seconds. Once communication with a Root node is established, an IoT node can then calculate its frequency error by receiving two beacon signals from the Root node separated in time by $T_B$ seconds. Each beacon packet contains the precise time-stamp in terms of counter value $c_R(t)$ of the Root node's clock. An IoT node can then compare this counter value against its own counter value $c_N(t)$ to estimate the current average relative frequency error by using [7],

$$f_{err} = \frac{\{c_R(t = T_B) - c_N(t = T_B)\} - \{c_R(t = 0) - c_N(t = 0)\}}{c_R(t = T_B) - c_R(t = 0)} \qquad [3]$$

The accuracy of the frequency error estimation is limited by the rate at which the environmental factors change over the synchronization period.

## III. MEASUREMENT RESULTS

Commercial off-the-shelf hardware platform OpenMote was used to verify the feasibility of the frequency calibration algorithm. The measurement setup for the experiment is shown in Fig. 1 along with its conceptual illustration. There are three motes where one is configured as the transmitter (Tx), and the other two motes are emulating a crystal free wireless node. Two motes are needed to emulate a crystal free wireless node since commercial hardware platforms don't allow the radio to communicate without Xtal oscillator running. Therefore one mote is configured as receiver (Rx) to communicate with the Tx while the other mote is configured as RC (Xtal oscillator disabled) on which relaxation oscillator is running. The three motes are placed inside a temperature chamber to exclude any temperature dependent frequency variation.

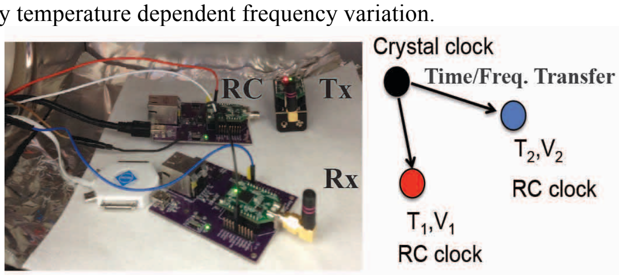


Fig. 1 Measurement setup inside temperature chamber.

The Tx mote is configured to periodically send RF packets with 100 ms time interval (synchronization interval) defined by a crystal clock that acts as a time reference for the network. The crystal free node (Rx & RC) is connected to an FPGA. A counter is setup in the FPGA to measure the relaxation oscillator frequency. The Rx node sends an interrupt to the FPGA on receiving the RF packet from the Tx. The FPGA records the current value, resets the counter and the measurement is repeated. The top plot in Fig. 2 shows the measured RC oscillator frequency over 12 hrs at a constant temperature of 23 °C. The counter value is recorded every 100 mS, which is then compared with its ideal value, and the frequency error is thus estimated as shown in the middle plot. The computed error is then used to calibrate the RC oscillator frequency, which is shown in the bottom plot. The maximum residual frequency error is less than 1000 ppm due to random noise. To demonstrate that the RC oscillator frequency can be calibrated for environmental factors, a fast temperature ramp was setup from 0 °C to 70 °C with a slope of ~9 °C/min. The synchronization interval is again 100 mS. The top plot in Fig. 3 shows the effect of temperature ramp on the RC oscillator frequency, the middle plot shows the estimated frequency error and the bottom plot shows the calibrated residual error in the RC oscillator frequency. The temperature ramp resulted in about 25,000 ppm frequency deviation which has been calibrated to less than 1000 ppm limited by the random noise. The standard deviation of the residual error is 134 ppm. A Finite Impulse Response (FIR) filter was then used to filter the residual frequency error. The FIR filter was designed to compute the cumulative moving average (MAVG) and the filtered response is plotted on top of the residual frequency error in the bottom plot. The FIR filter reduced the standard deviation to about 70 ppm. Similar results were obtained by varying the synchronization interval on a log scale from 100 mS up to 10 s at room temperature and at a communication Line-of-Sight (LoS) distance of 1 m between the Root node (Tx) and the crystal free node (Rx & RC).

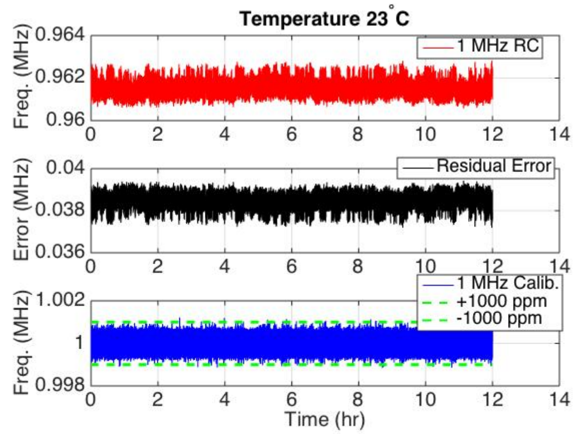


Fig. 2 Measured calibrated RC oscillator frequency.

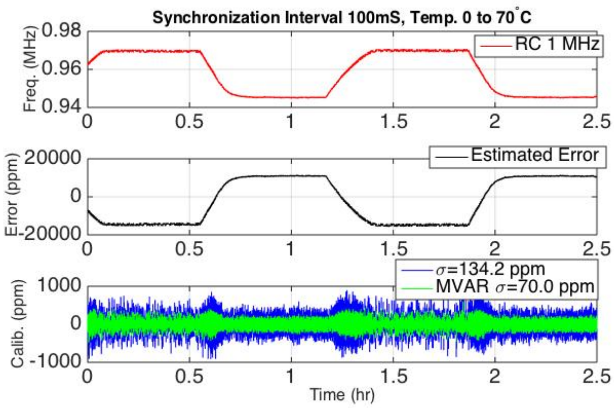


Fig. 3 Measured calibrated RC oscillator residual frequency error.

## CONCLUSION

The proposed frequency calibration algorithm can calibrate the RC oscillators on two Xtal free nodes with ~70 ppm accuracy. Then for 99.7% (three-sigma) of the cases the two nodes will be off in RF frequency at most by 420 ppm. This corresponds to roughly 1 MHz for the 2.4 GHz ISM band. If the receiver front-end acquisition range is designed to be greater than 1 MHz, then the two crystal free nodes will be able to communicate over a wireless channel.

## REFERENCES

[1] K. Pister, et al., "TSMP: Time synchronized mesh protocol," in *IASTED Distributed Sensor Networks*, 2008, pp. 391-398.

[2] A. Paidimarri, et al., "A 120nW 18.5kHz RC oscillator with comparator offset cancellation for ±0.25% temperature stability," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2013 IEEE International*, Feb. 2013, pp. 184-185.

[3] D. Griffith, et al., "A 190nW 33kHz RC oscillator with ±0.21% temperature stability and 4ppm long-term stability," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2014 IEEE International*, Feb. 2014, pp. 300-301.

[4] Seokhyeon Jeong, et al., "A 5.8 nW CMOS Wake-Up Timer for Ultra-Low-Power Wireless Applications," *Solid-State Circuits, IEEE Journal of*, vol. 50, no. 8, pp. 1754-1763, Aug. 2015.

[5] Keng-Jan Hsiao, "A 32.4 ppm/°C 3.2-1.6V self-chopped relaxation oscillator with adaptive supply generation," in *in VLSI Circuits (VLSIC), 2012 Symposium on*, June 2012, pp. 14-15.

[6] Tengfei Chang, et al., "Adaptive synchronization in multi-hop TSCH networks," *Computer Networks*, vol. 76, pp. 165-176, Jan. 2015.

[7] Thomas schmid, et al., "On the Interaction of Clocks, Power, and Synchronization in Duty-Cycled Embedded Sensor Nodes," *ACM Transactions on Sensor Networks (TOSN)*, vol. 7, no. 3, Sept. 2010.