Effect of Local Oscillator Performance on Ultra-wideband Indoor Localization System

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***Abstract* —We discuss the performance of a commercial ultra-wideband (UWB) ranging technique for indoor localization. We study the influence of the local oscillator's phase noise and frequency drift due to temperature variations on the range estimation and ranging stability. We analyzed the ranging stability in terms of Allan deviation, instead of conventional statistics such as standard deviation.**

Keywords— Allan deviation; indoor location; phase noise; ranging; ultra-wideband (UWB)

I. INTRODUCTION

Robust, reliable, and accurate positioning systems for indoor location is of utmost importance for mapping and emergency first responder localization. Positioning systems such as the Global Positioning System (GPS) do not work indoors because radio signals from the GPS satellites are too weak to penetrate efficiently through building walls. Other radio frequency (RF) based systems such as radio-frequency identification (RFID), Wi-Fi, Bluetooth, and cellular provide coarse indoor localization but each have their own advantages and disadvantages [1-6]. Some of them estimate distance from relative signal strength indicators (RSI). However, they cannot distinguish line-of-sight (LOS) signals from non-line-of-sight (NLOS) multipath signals, so the measurement of signal strength is not an ideal indicator of distance. In addition, these are shared narrow band systems that are prone to interference. Another widely used technique is ultra-wideband (UWB) [1, 7-9], which measures distance accurately by measuring the radio-wave time-of-flight between a transmitter (Tx) and a receiver (Rx). It utilizes radio-waves with very short-duration pulses that increase precision and make it easier to separate the LOS signal from NLOS signals in the time-domain. In this context, RF-based technologies are highly desired since optical/imaging techniques are easily defeated by smoke and debris, and miniature wearable inertial, pressure, and magnetic sensors can drift and require frequent calibration.

In this paper, we present the performance of a commercial transceiver based on ultra-wideband (UWB) radio communications. We chose the decaWave's TREK1000/EVK1000 chipset [9], hereafter referred to as the device under test (DUT). We evaluated the ranging performance of the DUT in terms of phase noise and frequency drift due to temperature variations of the local oscillator (LO) at 38.4 MHz. The LO is used as the reference clock for the digital and analog sub-circuits. In addition, we characterized the ranging stability using the Allan deviation (ADEV) statistic [10].

II. TWO-WAY RANGING SCHEME

The DUT comprises two transceivers as shown in Fig. 1, one assigned as the anchor and other as the tag. The pair utilizes two-way ranging and estimates the distance between anchor and tag from the time-of-flight of the signal. The ranging measurement includes the following three steps [9]: first, the tag sends a poll message; second, after receiving this poll message the anchor sends a response; third, after receiving this response message, the tag sends a final message with embedded timestamps for poll, response and final message. The anchor then uses this information along with its own transmit and receive time stamps to calculate two-way round-trip time, which is in turn used to estimate the one-way time-of-flight. The one-way time of flight equals the distance between the transceivers multiplied by the speed-of-light. This entire process requires accurate time-stamping of message transmission and reception in both transceivers.

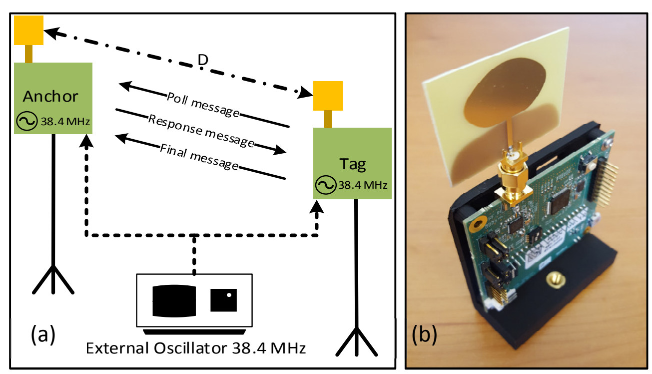

Fig. 1: Two-way ranging scheme used by the DUT. The range is calculated from the time-of-flight obtained from the receive and transmit time stamps of three messages. The DUT was evaluated with internal as well as external 38.4 MHz local oscillators. (b) Picture of one of the transceiver.

The DUT has a specified ranging accuracy of less than 10 cm [9]. Sources of error can originate from the frequency offsets or frequency drifts between the oscillators in the transceivers. The maximum accuracy of the receiver is realized when there is no frequency error between the transmitted signal and the receiver's LO.

III. Experimental Results

The DUT supports four RF center frequencies ranging from 3.5 GHz to 6.5 GHz with bandwidths (BW) of 500 MHz or 900 MHz. For our experiment, the operating frequency and the distance (*D*) between the anchor and tag were chosen to be 4.0 GHz and ~8 m respectively. Other parameters used for this evaluation are as follows: Center frequency = 4.0 GHz (500 MHz BW), Pulse Repetition Frequency (PRF) = 64 MHz, Data Rate = 110 kB/s, Preamble Length (Symbol repetitions) =1024.

A. Local Oscillator Phase Noise

The distance (*D* = ~8 m) between the anchor and the tag was first measured with the default on-board oscillators. The phase noise of the default oscillator was not measured directly because the signal was not conveniently available. Therefore, we replaced the default oscillator of the tag and anchor with an external oscillator with noise modulation capability. Using the external oscillator, we generated three LO noise profiles to test.

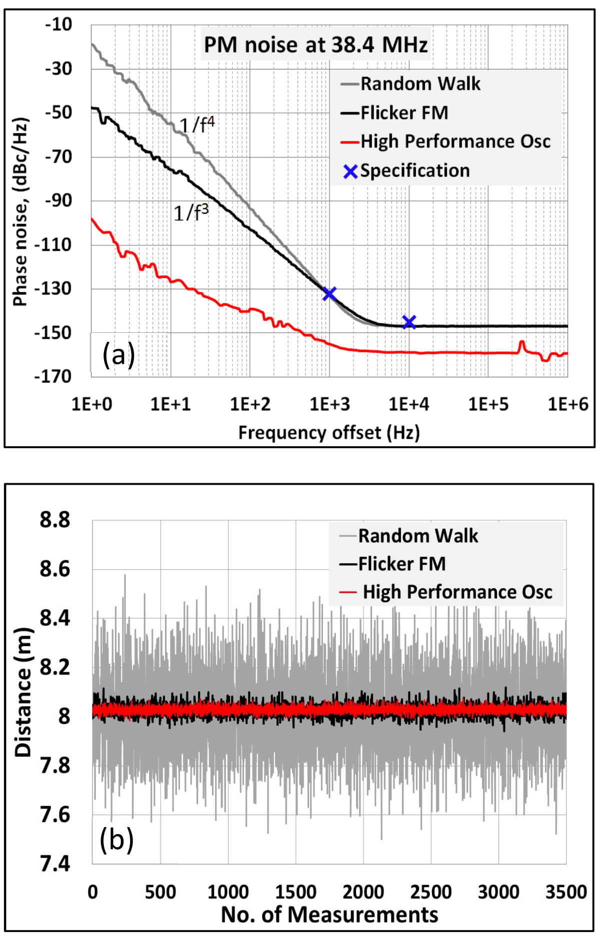

Fig. 2: (a) Three different phase noise levels of the local oscillator at 38.4 MHz (b) corresponding distance measurement.

The black trace in Fig. 2(a) meets the noise specification in the data sheet and has a dominantly flicker FM noise profile ($1/f^3$) close-to-the-carrier. For this noise profile, the performance of the transceivers agreed closely with that achieved with the default oscillators. The gray trace also meets the noise specifications; however, it follows a random-walk FM ($1/f^4$) profile near the carrier. Finally, the red trace shows the third noise profile which is significantly better than the datasheet specifications. Fig. 2(b) depicts the ranging measurement of the DUT with three different LO phase noise levels. It indicates that the instantaneous measurement has higher uncertainty when the LO phase noise is higher. The measurement eventually averages to almost the same range value as that obtained with a low phase noise LO, but it takes longer to do so.

Furthermore, we used Allan deviation (ADEV) to characterize the short- and long-term range stability (σ_R). The ADEV is a two-sample deviation often used by the time and frequency community to analyze the frequency stability of clocks [10]. ADEV is a measure of stability of a quantity measured vs measurement time (τ) at a sample rate of $T = \tau_0$. It allows for the detection and analysis of non-white noise processes that may not be convergent for the standard deviation. In Fig. 3, the ADEV plots indicate that the instantaneous range measurement is white in nature ($\tau^{-1/2}$ slope) and statistics like standard deviation are sufficient to determine the short-term range stability. In addition, the stability achieved with the high-performance oscillator is limited by the signal-to-noise ratio (SNR) and it could be further improved by increasing the transmitted power.

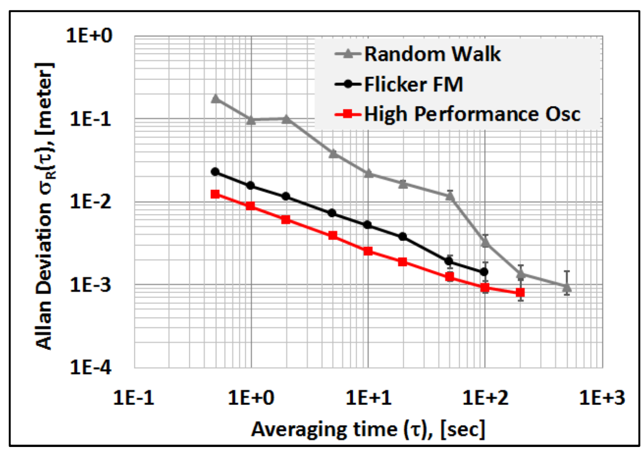

Fig. 3: Plot of ranging stability σ_R obtained from ADEV for different phase noise values of the local oscillator .

B. Frequency Drift due to Temperature

The distance (*D* = ~8 m) between the anchor and the tag was also measured when the LO frequency of the anchor was drifting with respect to the LO frequency of the tag. The anchor was mounted inside an environmental chamber (Fig. 4a) and its temperature was ramped up from 0^0 to 60^0C and back down with a square wave control. The corresponding temperature of the anchor integrated circuit is shown on the secondary *y*-axis of Fig. 4b. The antenna was kept outside the chamber and it was connected to the anchor's printed circuit board (PCB) with an approximately 1.0 m long coaxial cable and connectors. This corresponds to an effective distance of 1.5 m since the speed of an electrical signal in coaxial cable is 2/3 of the speed of light. Therefore, for this test the actual distance between the anchor and the tag was ~9.5 m. Fig. 4b shows that when the temperature of the chamber is continuously changing from 0^0 to 60^0C, there is a variation of ~24 cm in the distance as measured by the DUT, which corresponds to a change of ~0.4 cm/^{0}C. A ranging error of approximately +0.4 cm to - 2 cm was observed. In addition, a static range error of ~14 cm was detected when the temperature was kept constant at two extreme values. This indicates that the LO frequency drift due to extreme temperatures changes can introduce ranging errors if the LO is not properly insulated.

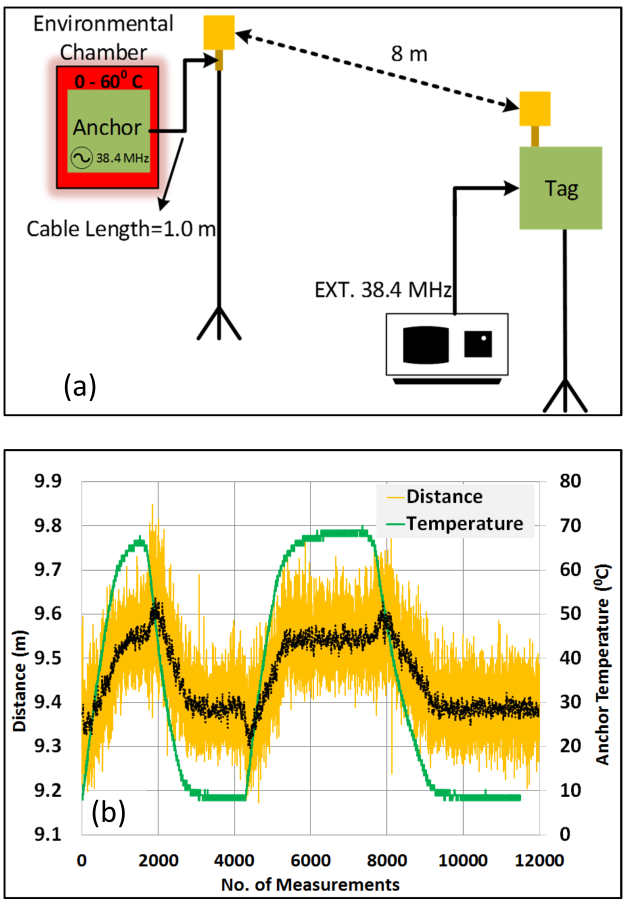

Fig. 4: (a) Mounting of the anchor inside the environmental chamber. (b) Effect of frequency drift of the LO due to temperature on the distance measurement. The black dotted curve is obtained from 20 moving averages.

IV. Summary

We studied the influence of local oscillator (LO) phase noise on ranging and we found that the performance of the DUT is primarily limited by the received SNR. No significant improvement in accuracy was observed with lower phase noise LOs due to the continuous synchronization of the DUT's two-way ranging algorithm. However, we observed ranging errors due to the LO frequency drift introduced by large temperature variations. In the future, we plan to test the DUT under higher SNR conditions, as well as study the effect of phase noise on longer distance LOS and NLOS range accuracy.

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