Improving Range Accuracy of IEEE 802.15.4a Radios in Presence of Clock Frequency Offsets

Sahinoglu, Z.

TR2011-019 February 2011

Abstract

Two-way time-of-arrival (TW-ToA) is a ranging protocol that provides distance between two devices in absence of synchronization, but it suffers from range estimation errors when clock frequency offset is present. In this work, we provide a timing counter management scheme for TW-ToA that suppresses ranging errors induced by any clock frequency offset between a transmitter and receiver pair. The suggested scheme is shown to be superior both theoretically and empirically to the one that is recommended in the IEEE 802.15.4a standard.

IEEE Communications Letters

Improving Range Accuracy of IEEE 802.15.4a Radios In Presence of Clock Frequency Offsets

Zafer Sahinoglu, *Senior Member, IEEE*

***Abstract*—Two-way time-of-arrival (TW-ToA) is a ranging protocol that provides distance between two devices in absence of synchronization, but it suffers from range estimation errors when clock frequency offset is present. In this work, we provide a timing counter management scheme for TW-ToA that suppresses ranging errors induced by any clock frequency offset between a transmitter and receiver pair. The suggested scheme is shown to be superior both theoretically and empirically to the one that is recommended in the IEEE 802.15.4a standard.**

***Index Terms*—Two-way time-of-arrival (TW-ToA), ultra-wideband (UWB), IEEE 802.15.4a, clock frequency offset.**

I. INTRODUCTION

VARIOUS real-time location systems (RTLSs) are commercially available for indoor scenarios [1], [2]. They consist of transmit-only tags and time-synchronized anchors, since they adopt a time-difference-of-arrival (TDoA) based positioning scheme. Synchronization of anchors can be handled either via transmitting periodic beacons from a designated device so-called *coordinator*, or wiring all anchors and feeding them with a common clock, which is quite labor intensive. Alternatively, a two-way time-of-arrival (TW-ToA) based scheme [3] does not have any stringent time synchronization requirement. In practice, frequency generated by a non-ideal oscillator is different from its nominal value. This unknown frequency offset, quantified in ppm (parts per million), between transmitter and receiver oscillators is inevitable, because transmitters and receivers use separate crystal oscillators in their sampling clocks [4]. In impulse radio ultra-wideband (IR-UWB) systems [5], this frequency offset causes received pulses to gradually drift from their sampling positions that are set at the transmitter. This makes acquisition difficult at low signal-to-noise ratios (SNR), and also causes two ranging devices to observe the turn-around time unequally [6]. For instance, in IEEE 802.15.4a networks, the preamble itself of a ranging packet can be up to $4\,\mathrm{ms}$ long [5]. Then, the accumulated timing offset could reach $160\,\mathrm{ns}$ under a frequency offset of $\pm 40\,\mathrm{ppm}$. Using a delay-lock-loop (DLL) or phase-lock-loop (PLL) may compensate for sample timing errors during acquisition and decoding, but they do not help mitigate timing errors in estimating the long turn-around time, because there is no reference signal to track or lock onto while turning around.

A simple and efficient mechanism is needed to mitigate frequency offset induced range errors, and thus to make TW-ToA based scheme commercially viable. Recent attempts include differential two way ranging protocols [5],[7] that eliminate the need to transmit a separate time-stamp packet required in TW-ToA to report the turn-around time. However, these techniques have a major drawback: It is impractical to force a physical layer to transmit precisely at a preset time instant, especially if the required precision is in the order of nanoseconds or sub-nanoseconds and the clock frequency is imperfect. Another approach, called double symmetric ranging protocol [8], aims to minimize the effect of finite clock frequency imperfection in ranging, but at a cost of an extra transmission.

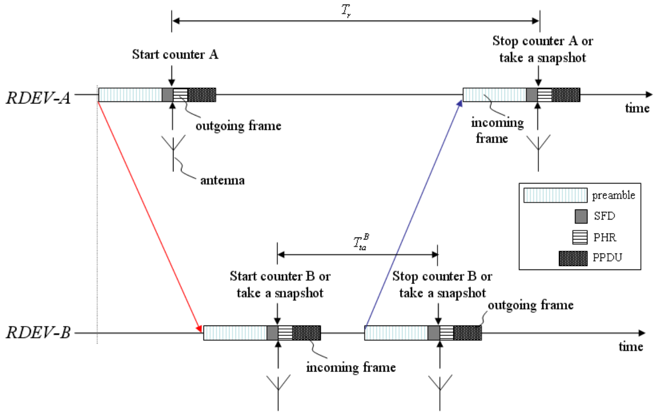

Fig. 1. Illustration of the TW-ToA ranging protocol and counter management in IEEE 802.15.4a.

In this paper, we address management of timing counters to mitigate ranging error due to clock frequency offsets. Section II provides theoretical analysis of a new counter management scheme. In Section IV, an experimental set-up is explained and performance results are given. Finally, Section V contains concluding remarks.

II. TW-TOA RANGING PROTOCOL

In this article, we adopt the terminology used in a recently published IEEE 802.15.4a standard [9], and refer to a ranging capable device and the signals used for ranging as *RDEV* and *RFRAME* respectively. The *RFRAME* consists of a synchronization header (SHR) preamble, a physical layer header (PHR) and a data field. The SHR preamble is composed of the (ranging) preamble and the start of frame delimiter (SFD). The SFD signals the end of the preamble and the beginning of the PHY header. Therefore, its detection is critical for frame timing and synchronization.

The range between two *RDEV*s can be determined simply via two-way exchanging of *RFRAME*s and tracking their arrival times as illustrated in Fig. 1.

A. ToF Estimation with Ideal Clocks

Assume that *RDEV A* wants to perform ranging with *RDEV B*. A true elapsed time, T_r, between departure of the SFD of an

Manuscript received October 25, 2010. The associate editor coordinating the review of this letter and approving it for publication was H. Wymeersch.

Z. Sahinoglu is with the Mitsubishi Electric Research Laboratories, 201 Broadway, Cambridge, MA 02139 USA (e-mail: zafer@merl.com).

Digital Object Identifier 10.1109/LCOMM.2011.09.102034

outgoing *RFRAME* from A and arrival of the SFD of a reply *RFRAME* from B is given by $T_r = 2T_f + T_{ta}^B$, where T_f is the one-way time-of-flight (ToF) of the signal, and T_{ta}^B is the turn-around time introduced at *B*. The corresponding counter management scheme for TW-ToA in the IEEE 802.15.4a is illustrated in Fig. 1.

It is possible to measure off-line the time instant that the SFD of an outgoing frame leaves its transmit antenna via a loop-back test and time calibration for a given communication hardware design. Therefore transmit time-stamps can be assumed error-free. Thus, any error in detecting the ToA of an incoming SFD determines the accuracy of the estimate of the turn-around time, $\hat{T}_{ta}^B$. Timing imperfections even in the order of nanoseconds, multipath fading and NLoS propagation can easily induce undesirably large positive bias in a range estimate (30 cm per nanosecond). In [10], the ToA based range estimation error n_i made by device i is modeled as $n_i \sim \mathcal{N}(0, \sigma_i^2)$, and ToA estimation errors at two different devices are assumed to be independent.[1] Using the same error model, the round-trip-time $\hat{T}_r$, measured at A, is then given by

$$\hat{T}_r = 2T_f + T_{ta}^B + n_A \ , \tag{1}$$

where n_A is a measurement error.

In practice, B obtains an estimate of the turn-around time, $\hat{T}_{ta}^B$, by calculating the difference between the estimated arrival time of the incoming SFD and recorded departure time of the outgoing SFD. Then, B reports $\hat{T}_{ta}^B$ to A in the payload of the reply packet. During (long) preamble transmission (order of milliseconds for IEEE IEEE 802.15.4a), payload formation is possible. Note that the estimation of $\hat{T}_{ta}^B$ at B involves the ToA estimation of the incoming SFD and the measurement of the time instant that the outgoing SFD leaves the transmit antenna. As discussed above, ToA estimation is accompanied with a zero mean Gaussian error, namely, $n_B \sim \mathcal{N}(0, \sigma_B^2)$, whereas the recorded departure time can be considered as the true value since it can be accurately determined via loop-back tests and time calibrations. Therefore, the estimate of the turn-around time is modeled as $\hat{T}_{ta}^B \sim \mathcal{N}(T_{ta}^B, \sigma_B^2)$.

Finally, A computes the time of flight (ToF) $\hat{T}_f$ by subtracting $\hat{T}_{ta}^B$ from $\hat{T}_r$, and dividing the result by 2. Since $\hat{T}_{ta}^B \sim \mathcal{N}(T_{ta}^B, \sigma_B^2)$ and (1) implies that $\hat{T}_r \sim \mathcal{N}(2T_f + T_{ta}^B, \sigma_A^2)$, and the $\hat{T}_f$ is distributed as $\hat{T}_f \sim \mathcal{N}\left(T_f \ , \ \frac{\sigma_A^2 + \sigma_B^2}{4}\right)$.

B. ToF Estimation with Clock Frequency Offsets

The instantaneous frequency $f(t)$ of a clock circuit at time t is referred to as the *mean frequency*, and is given by [11] $f(t) \approx f_s + D(t)$, where f_s is the natural frequency of the crystal (or, LC circuit), and $D(t)$ is the frequency drift caused by aging, temperature variation, and mechanical stress. $D(t)$ can be assumed an unknown constant during ranging, because it models slow changes.

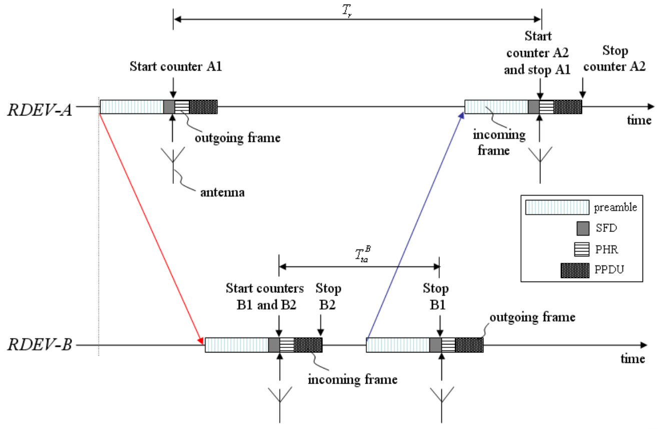

Fig. 2. Illustration of the TW-ToA ranging protocol with the modified counter management scheme to reduce range estimation errors due to clock frequency offsets.

Assume that e_i stands for the clock frequency offset of device i with respect to an ideal clock. Then, (1) is rewritten as

$$\hat{T}_r^o = (1 + e_A)(2T_f + T_{ta}^B) + n_A \ , \tag{2}$$

where the superscript 'o' is used to indicate the presence of clock frequency offset. Similarly, the turn-around time estimated at B, $\hat{T}_{ta}^{B,o}$, is given by

$$\hat{T}_{ta}^{B,o} = (1 + e_B)T_{ta}^B + n_B \ . \tag{3}$$

Then, the estimate of the one way flight time, $\hat{T}_f^o = (\hat{T}_r^o - \hat{T}_{ta}^{B,o})/2$, is modeled as

$$\hat{T}_f^o \sim \mathcal{N}\left((1 + e_A)T_f + \epsilon \ , \frac{\sigma_A^2 + \sigma_B^2}{4}\right) \ , \tag{4}$$

where $\epsilon \doteq T_{ta}^B(e_A - e_B)/2$. It is seen in (4) that due to imperfect clocks the mean of $\hat{T}_f^o$ becomes a function of the turn-around time.

III. MINIMIZING CLOCK FREQUENCY INDUCED RANGE BIAS

By using the timer management scheme illustrated in Fig. 2, the bias ϵ in (4) can be removed. This scheme requires management of two counters at each ranging device. Assume that counters A_1 and A_2 are managed by A, and counters B_1 and B_2 by B.

Let $\triangle_{k_i}$ denote the difference between the stop and start times of counter i of device k. As illustrated in Fig. 2, counters $\triangle_{A_1}$ and $\triangle_{B_1}$ measure the round-trip-time and the turn-around time, respectively, as in the conventional case in Fig. 1. Therefore, the time estimates obtained from counter values $\triangle_{A_1}$ and $\triangle_{B_1}$ are given by (2) and (3), respectively. On the other hand, counter $\triangle_{A_2}$ measures the length of the PHR and PPDU of the frame received from B, and counter $\triangle_{B_2}$ the length of the PHR and PPDU of the frame received from A. Assume that T_p denotes the length of the PHR and PPDU combined together at an ideal clock rate f_s, and that T_p is the same for both frames. Then, $\triangle_{A_2}$ and $\triangle_{B_2}$ are given by

$$\triangle_{A_2} = f_s \frac{T_p}{(1 + e_B)} (1 + e_A) \ , \tag{5}$$

$$\triangle_{B_2} = f_s \frac{T_p}{(1 + e_A)} (1 + e_B) \ . \tag{6}$$

Consider $\triangle_{A_2}$, which is the counter value that measures the length of the PHR and PPDU of the frame received from B.

---

[1] $\mathcal{N}(x_1, x_2)$ represents a Gaussian random variable with mean x_1 and variance x_2.

TABLE I
MITIGATION OF RANGING ERROR INDUCED BY CLOCK FREQUENCY OFFSET - EXPERIMENT.

					Traditional	Proposed	DSTWR [8]
Device Index	Δ_{A_1}	Δ_{B_1}	Δ_{A_2}	Δ_{B_2}	$\hat{r}$(m), $\epsilon_{\hat{r}}$(m)	$\hat{r}$(m), $\epsilon_{\hat{r}}$(m)	$\hat{r}$(m), $\epsilon_{\hat{r}}$(m)
Anchor, R$_1$	$214 + 10^6$	$14 + 10^6$	294355	294366	27.45, 2.55	30.25, 0.25	30.02, 0.02
Anchor, R$_2$	$200 + 10^6$	10^6	294351	294370	25.35, 4.65	29.85, 0.15	30.02, 0.02
Anchor, R$_3$	$314 + 10^6$	$113 + 10^6$	294384	294336	42.45, 12.45	30.22, 0.22	30.03, 0.03

According to the ideal clock rate, the length of the PHR and PPDU is equal to T_p seconds or, $T_p f_s$ counter ticks. However, due to its clock frequency offset, device B generates a frame that has the length of the PHR and PPDU equal to $T_p/(1+e_B)$ in seconds after $T_p f_s$ counter ticks. When this frame is received by device A, the length of the PHR and PPDU is measured in number of clock ticks as $f_s(1+e_A)T_p/(1+e_B)$. Hence, (5) is obtained. The expression in (6) can be justified similarly.

It should be noted that (5) and (6) do not involve any ToA estimation errors for two reasons. First, there is no need to detect ToA of the direct path for these counter measurements. Second, the SFD processing gain is much higher than that of a single preamble symbol. In other words, the signal-to-noise ratio (SNR) for detecting the SFD peak is sufficiently high. Therefore, no measurement noise is incorporated in (5) and (6). Device B should report $\triangle_{B_2}$ and $\triangle_{B_1}$ to A. Now, define a correction factor α_c that is computed by A, which is given by $\alpha_c \doteq \sqrt{\frac{\triangle_{A_2}}{\triangle_{B_2}}} = \frac{1+e_A}{1+e_B}$. Then, A calculates the corrected turn-around time as $\hat{T}_{ta}^{B,oc} \doteq \hat{T}_{ta}^{B,o}\alpha_c$, where the superscript 'c' is added to indicate 'after correction'. Finaly, the ToF estimate in the proposed scheme is obtained as

$$\hat{T}_f^{oc} = \frac{\hat{T}_r^o - \hat{T}_{ta}^{B,oc}}{2} = (1+e_A)T_f + \frac{n_A}{2} - \frac{n_B}{2\alpha_c}. \quad (7)$$

Comparison of (4) and (7) reveals that the proposed technique can reduce the large errors inherent in the ToF estimate by removing the ϵ in (4).

IV. EXPERIMENTAL SETUP AND RESULTS

Four 1GHz sinewave saw based ±100ppm clock oscillators (CCSO-914X-1000) are used in our ranging experiment. Oscillator output waveforms are recorded for 1ms on the LeCroy WaveMaster 8600A Oscilloscope at 10GHz sampling rate and processed offline using Matlab to determine their frequency offsets. One of the oscillators is used as a target device, and the remaining three as anchors. The measured CFOs are $e_{R_1} = 14 \times 10^{-6}$, $e_{R_2} = 0$, $e_{R_3} = 113 \times 10^{-6}$ for the anchor devices and $e_T = 31 \times 10^{-6}$ for the target device, respectively. The distance between the target and each anchor is set to 30m.

An IEEE 802.15.4a packet with 64μs long preamble is emulated. The total length of the SFD, PHR and PPDU parts of the packet is set to 294.36μs, which is the portion of the packet to be measured by Δ_{A_2} and Δ_{B_2}. The emulated ideal turn-around and round-trip times are $T_{ta}^B = 1$ms and $T_r = 1\text{ms} + 200\text{ns}$, respectively. The Δ_{A_1} and Δ_{B_1} for each anchor and target pair are measured by the number of clock cycles of the anchor and target oscillators, respectively.

For an ideal 1GHz clock generates a 294.36μs long packet in $294,360$ clock cycles, each anchor device and target device also forms the same packet after $294,360$ cycles via their local clocks. However, the true duration of the packet (after the preamble) that each generates is different from 294.36μs, because their CFO is not zero. The counter values Δ_{A_2} and Δ_{B_2} are determined at the anchors and the target from the packets generated using $294,360$ local clock cycles by the target and the corresponding anchor, respectively. The measured counter values for each anchor and target pair are given in Table I. The resulting range estimate $\hat{r}$ and the range error $\epsilon_{\hat{r}}$ are given for conventional, the DSTWR [8] and the proposed techniques. It is clear that the conventional counter management scheme is vulnerable to CFO and it results in large range errors, whereas the proposed scheme mitigates the CFO induced range error to centimeter levels even with clocks with very large ppm.The proposed scheme approaches the performance of DSTWR with one less transmission.

V. CONCLUDING REMARKS

A timing counter management scheme for IEEE 802.15.4a networks using TW-ToA has been shown to provide accurate range estimation analytically and via experiments.

REFERENCES

[1] D. Kelly, G. Shreve, and D. Langford, "Fusing communications and positioning–ultrawideband offers exciting possibilities," Time Domain Corporation, Aug. 1998.

[2] R. Fontana and S. J. Gunderson, "Ultra-wideband precision asset location system," in *Proc. IEEE Conf. on Ultra-wideband Syst. and Technol.*, May 2002, pp. 147-150.

[3] Z. Sahinoglu and S. Gezici, "Ranging in the IEEE 802.15.4a standard," in *Proc. IEEE Wireless and Microwave Tech. Conf.* , pp. 1-5, May 2006.

[4] L. Huang, N. E. Ghouti, O. Rousseaux, and B. Gyselinckx, "Timing tracking algorithms for impulse radio (IR) based ultra wideband (UWB) systems," in *Proc. IEEE Wireless Commun. Networking and Mobile Computing Conf.*, pp. 570-573, Sep. 2007.

[5] Z. Sahinoglu, S. Gezici, and I. Guvenc, *Ultra-Wideband Positioning Systems: Theoretical Limits, Ranging Algorithms and Protocols*. Cambridge University Press, 2008.

[6] A. Fort, M. Chen, C. Desset, P. Wambacq, and L. V. Biesen, "Clock offset tracking for subsampling UWB architectures in a body area network," in *Proc. IEEE Int. Conf. Ultrawideband*, pp. 229-234, Sep. 2007.

[7] J.-Y. Lee and R. A. Scholtz, "Ranging in a dense multipath environment using an UWB radio link," *IEEE J. Sel. Areas Commun.*, vol. 20, no. 9, pp. 1677-1683, Dec. 2002.

[8] R. Hach, "Symmetric double sided two-way ranging," IEEE 802.15.4a standard, doc. IEEE P.802.15-05-0334-00-004a, June 2005.

[9] IEEE P802.15.4a/D4 (Amendment of IEEE Std 802.15.4),"Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LRW-PANs)," July 2006.

[10] N. Patwari, J. N. Ash, S. Kyperountas, A. O. Hero III, R. L. Moses, and N. S. Correal, "Locating the nodes: cooperative localization in wireless sensor networks," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 54-69, July 2005.

[11] D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls, "Characterization of clocks and oscillators," National Institute of Standards and Technology, Technical Note 1337, Mar. 1990.