An Alternative Double-Sided Two-Way Ranging Method

Conference Paper · October 2016

DOI: 10.1109/WPNC.2016.7822844

Dries Neirynck
Decawave

Michael Mclaughlin
DecaWave Limited

An Alternative Double-Sided Two-Way Ranging Method

Dries Neirynck, Eric Luk and Michael McLaughlin
Decawave Ltd
Dublin, Ireland
Email: first_name.last_name@decawave.com

***Abstract*—Symmetric double-sided two-way ranging is a well-known technique to deal with clock drift in time-of-flight measurements between unsynchronised devices. However, the requirement for symmetric reply delays is often not feasible. This paper presents an alternative way to process double-sided two-way ranging measurements that eliminates the need for this impractical constraint. The error of the proposed method is of the same order of magnitude as the best case error of symmetric double-sided two-way ranging. Crucially, the error depends only on the clock drift of one of the devices, which can be exploited if one of the device has a better timing reference than the other.**

I. Introduction

In order to provide accurate positioning, the underlying distance measurements need to be as good as possible. Ultra-wideband (UWB) ranging is a natural fit for indoor real time location systems (RTLS). The large bandwidth allows for high resolution channel impulse response estimation and accurate time-of-flight measurements in dense multipath environments.

Accurate ranging and positioning were one of the main motivations behind the IEEE 802.15.4a standard [1]. A UWB physical layer (PHY) was selected, which in 2011 was integrated in the main 802.15.4 standard as the UWB PHY [2]. Recently, commercial implementations of the standard have become available, in the form of Decawave's DW1000 ScenSor integrated circuit (IC) [3].

As will be shown in section II, two-way ranging allows two devices without common clock synchronisation to perform time-of-flight measurements. However, clock drift in the timing references of the devices gives rise to unacceptably large errors in the estimated time-of-flight. [1] proposes a symmetric double-sided two-way ranging scheme that reduces the error caused by clock drift. To achieve this, an extra transmission is introduced, as well as a constraint that the reply delay at both devices should be the same, hence the name symmetric double-sided two-way ranging. This method will be discussed in section III.

While symmetric double-sided two-way ranging reduces the timing errors for practical clock drifts to acceptable levels, the requirement for symmetric reply delays is restrictive. The desire to eliminate this constraint gave rise to an alternative double-sided two-way ranging processing method, presented here in section IV.

The removal of the need for symmetry isn't the only advantage of the new method. Its error due to clock drift equals the minimum error achievable with symmetric double-sided two-way ranging under all circumstances. In addition, the error depends solely on the clock drift of only one of the devices, rather than a mix of both clock drifts for symmetric double-sided and simple two-way ranging.

II. Two-Way Ranging

The core of a two-way ranging exchange is depicted in figure 1. Here, the left vertical arrow represents time as measured by the first device. The right vertical arrow is the time as measured by the second device. It is assumed that the clocks are independent and unsynchronised.

The exchange starts with the first device sending a packet to the second, which is indicated by the slanted arrow. When a defined part of the packet leaves the device's antenna, it starts its round-trip timer R_a. That timer will be stopped when the reply from the second device is received.

The time of flight between both devices is denoted as T_f. Typically, since 1 ns corresponds to roughly 30 cm at the speed of light, T_f in indoor RTLS systems is in the order of tens of nanoseconds.

Upon reception of the initiating packet, the second device will calculate the time of arrival at its antenna and then construct an acknowledgment packet. The second device embeds in this packet the time delay from the reception of the initiating packet until the transmission of the reply, denoted here as D_b.

Typically, D_b is several orders of magnitude larger than T_f. The length of the packets to be transmitted is usually in the order of hundreds of microseconds. The processing speed of the device will determine how fast the time of arrival can be calculated and embedded in a reply. While this is very implementation dependent, it is safe to assume this will also be in the order of hundreds of microseconds. The dotted lines in the time axes in figure 1 are used to indicate the difference in scale between T_f and D_b and R_a.

It is clear that with ideal timing references,

$$R_a = 2T_f + D_b \tag{1}$$

From which T_f is easily extracted.

Since both devices have their own independent and unsynchronised clocks, both will be affected by imperfections in the timing references. It is assumed that clock drift is the dominant component in the imperfections. The magnitude of the clock

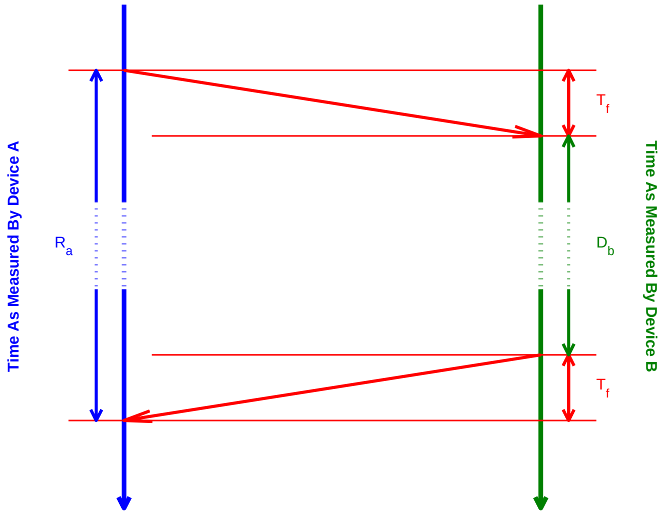

Fig. 1. Two-way ranging exchange

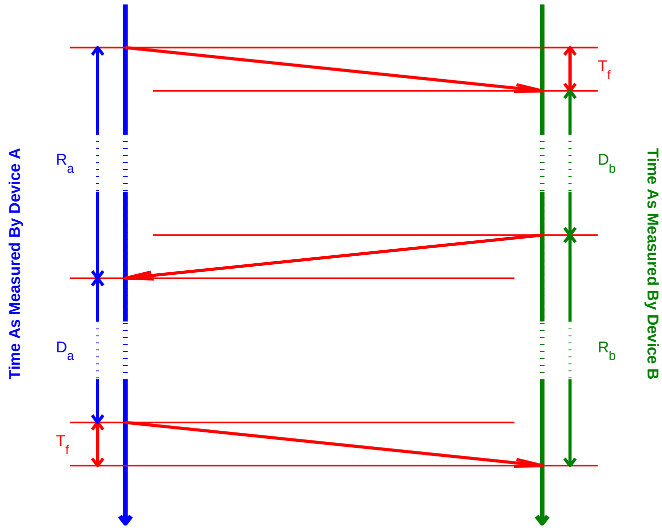

Fig. 2. Double-sided two-way ranging exchange

drift depends very much on the chosen timing reference but as an indication, the IEEE 802.15.4a standard provides for clock drifts up to ±20 ppm [1].

The clock drift will be modelled as

$$\hat{R}_a = (1 + e_a)\, R_a = k_a R_a \tag{2a}$$
$$\hat{D}_b = (1 + e_b)\, D_b = k_b D_b \tag{2b}$$

where X and $\hat{X}$ represent the nominal and actual values respectively. e_x models the deviation from the nominal frequency and is typically expressed in parts per million (ppm).

Using (1), the estimated time of flight $\hat{T}_f$ now becomes

$$\hat{T}_f = \frac{1}{2}\left(\hat{R}_a - \hat{D}_b\right) \tag{3}$$

and the error equals

$$\hat{T}_f - T_f = \frac{1}{2}\left(\hat{R}_a - \hat{D}_b\right) - \frac{1}{2}\left(R_a - D_b\right) \tag{4a}$$
$$= \frac{1}{2}\left(e_a R_a - e_b D_b\right) \tag{4b}$$

Classically, R_a in equation (4b) is replaced using (1) to yield

$$\hat{T}_f - T_f = \frac{1}{2}\left(e_a R_a - e_b D_b\right) \tag{5a}$$
$$= \frac{1}{2}\left(e_a\left(2T_f - D_b\right) - e_b D_b\right) \tag{5b}$$
$$= e_a T_f + \frac{D_b}{2}\left(e_a - e_b\right) \tag{5c}$$

Whether expressed as (4b) or (5c), it is clear that the reply delay D_b is the dominant factor determining the size of the error. Typically, the time of flight T_f is in the order of nanoseconds, while D_b is in the order of milliseconds. The reply delay D_b is determined by the length of the packets to be transmitted and the processing speed of the measurement circuit and its control logic.

Assuming that the reply delay D_b can be as low as 1 ms and with $(e_a - e_b)$ worst case ±40 ppm in IEEE 802.15.4a implies that the error in equation (5c) is at least 20 ns, which corresponds to a distance of almost 7 metres at the speed of light. Such an error is clearly unacceptable for indoor RTLS systems. In many cases, the total distance will be less than 7 metres.

Most RTLS systems target an error of ±10 cm, or roughly 1/3 ns, an improvement of at least a factor 60 compared to the performance of the system under the current assumptions. Since it is unlikely that the reply delay D_b can be reduced further, most of this improvement would have to come from more accurate timing references. However, to achieve less than 1 ppm accuracy requires expensive and power-hungry temperature compensated crystal oscillators (TCXOs), which are not viable in many mobile systems.

III. Symmetric Double-Sided Two-Way Ranging

It is possible to improve the ranging accuracy by including another ranging exchange as shown in figure 2. The double-sided two-way ranging exchange starts of with a normal two-way ranging exchange as before. However, upon reception of the reply, the first device sends an extra reply back to the other device with information about the reply delay D_a that it required. The second device is then able to calculate the round-trip time R_b.

Similar to (1), the following equations are easily derived from figure 2:

$$R_a = 2T_f + D_b \tag{6a}$$
$$R_b = 2T_f + D_a \tag{6b}$$

Adding both equations in (6) and rearranging to extract the time of flight T_f results in

$$T_f = \frac{1}{4}\left(R_a - D_a + R_b - D_b\right) \tag{7}$$

Again, clock drift is assumed to be the dominant source of errors affecting the measurements and is modelled analogous to (2) as

$$\hat{R}_a = (1 + e_a)\, R_a = k_a R_a \tag{8a}$$
$$\hat{R}_b = (1 + e_b)\, R_b = k_b R_b \tag{8b}$$
$$\hat{D}_a = (1 + e_a)\, D_a = k_a D_a \tag{8c}$$
$$\hat{D}_b = (1 + e_b)\, D_b = k_b D_b \tag{8d}$$

The resulting estimate for the time of flight $\hat{T}_f$ can then be expressed as

$$\hat{T}_f = \frac{1}{4}\left(\hat{R}_a - \hat{D}_a + \hat{R}_b - \hat{D}_b\right) \tag{9}$$

Comparing (7) and (9), the error between the estimated and actual time of flight is

$$\hat{T}_f - T_f = \frac{1}{4}\left(\hat{R}_a - \hat{D}_a + \hat{R}_b - \hat{D}_b\right) \tag{10a}$$
$$- \frac{1}{4}\left(R_a - D_a + R_b - D_b\right) \tag{10b}$$
$$= \frac{1}{4}\left(e_a\left(R_a - D_a\right) + e_b\left(R_b - D_b\right)\right) \tag{10c}$$

Next, R_a and R_b can be replaced by (6) and some manipulation similar to (5c) yields

$$\hat{T}_f - T_f = \frac{1}{2} T_f\left(e_a + e_b\right) + \frac{1}{4}\left(e_a - e_b\right)\left(D_b - D_a\right) \tag{11}$$

The error in equation (11) will be minimal when the reply delays D_a and D_b are equal. In that case, they cancel each other out and the second half of the right-hand term is reduced to zero — hence the name symmetric double-sided two-way ranging.

Practically, it is very hard to make D_a and D_b truly symmetrical. The reply delays start when the packet is received, which occurs at a random time with respect to the system clock edges. The delays end however with the transmission of the reply packet, which happens at a deterministic time with regards to the system clock. For example, Decawave's DW1000 IC uses a 125 MHz clock, so the difference between D_a and D_b is uniformly distributed from 0 up to 8 ns.

If, as before, the worst case $(e_a - e_b)$ of ± 40 ppm from the IEEE 802.15.4a standard is used in combination with a worst case error $(D_b - D_a)$ of 8 ns, the second half of the error term in equation (11) reduces to 80 fs, rougly 24 μm. The overall error is therefore dominated by the part proportionate to the time of flight. While the actual time of flight is potentially in the order of hundreds of nanoseconds, $(e_a + e_b)$ is still worst case ± 40 ppm, bringing the overall error well below a picosecond.

From the numerical example, it is clear that symmetric double-sided two-way ranging is able to bring the error due to clock drift within a range where it will no longer be the dominant source of error in the final reported range. However, in many practical applications, the requirement for equal reply delays is a real hindrance. Three packets have to be transmitted with precise timing, but in an uncoordinated network packet collisions easily occur. The whole procedure then has to start all over, further aggravating network congestion.

The reply delay includes the time taken to transmit the packet and the packets lengths might need to be different. The two devices might have different amounts of housekeeping to do between receiving a packet and sending a response, so requiring both delays to be equal means the whole exchange needs to be longer than absolutely necessary.

If, on the other hand, the timing of the packets becomes unimportant, the throughput of the network can easily be increased. Transmissions can be combined to serve several nodes at once, reducing the air occupancy.

This desire to eliminate the requirement for equal reply delays gave rise to the alternative processing presented in the next section.

IV. Alternative Double-Sided Two-Way Ranging Method

First, let's start by considering perfect timing references.

The double-sided two-way ranging exchange remains the same as shown in figure 2. Hence (6) still holds:

$$R_a = 2T_f + D_b \tag{12a}$$
$$R_b = 2T_f + D_a \tag{12b}$$

However, rather than adding, R_a and R_b are multiplied as follows

$$R_a R_b = \left(2T_f + D_b\right)\left(2T_f + D_a\right) \tag{13}$$

which can easily be expanded and rearranged to obtain

$$R_a R_b - D_a D_b = 2T_f(2T_f + D_a + D_b) \tag{14}$$

Then, equation (12) is used to replace the appropriate terms within the brackets to yield either of

$$R_a R_b - D_a D_b = 2T_f\left(R_a + D_a\right) \tag{15a}$$
$$R_a R_b - D_a D_b = 2T_f\left(R_b + D_b\right) \tag{15b}$$

and hence leads to the following two expressions for the time of flight

$$T_f = \frac{R_a R_b - D_a D_b}{2\left(R_a + D_a\right)} \tag{16a}$$
$$= \frac{R_a R_b - D_a D_b}{2\left(R_b + D_b\right)} \tag{16b}$$

Note that equations (12) and (15) imply that $(R_a + D_a)$ equals $(R_b + D_b)$, so (16) could also be written as

$$T_f = \frac{R_a R_b - D_a D_b}{R_a + D_a + R_b + D_b} \tag{17}$$

As before, clock drift is assumed to be the main source of timing error. With the relationship between the nominal and actual values given by (8) the estimates of the time of flight $\hat{T}_f$ based on equation (16) become

$$\hat{T}_f = \frac{\hat{R}_a \hat{R}_b - \hat{D}_a \hat{D}_b}{2\left(\hat{R}_a + \hat{D}_a\right)} \tag{18a}$$
$$= \frac{\hat{R}_a \hat{R}_b - \hat{D}_a \hat{D}_b}{2\left(\hat{R}_b + \hat{D}_b\right)} \tag{18b}$$

which relates to the true value as

$$\hat{T}_f = \frac{k_a k_b}{k_a} \frac{R_a R_b - D_a D_b}{2\,(R_a + D_a)} = k_b T_f \tag{19a}$$

$$= \frac{k_a k_b}{k_b} \frac{R_a R_b - D_a D_b}{2\,(R_b + D_b)} = k_a T_f \tag{19b}$$

The error between the true and estimated values is therefore

$$\hat{T}_f - T_f = k_a T_f - T_f = e_a T_f \tag{20a}$$

$$\hat{T}_f - T_f = k_b T_f - T_f = e_b T_f \tag{20b}$$

By comparing (11) and (20), it becomes clear that both methods have best case errors in the order of eT_f. As the numerical example in section III showed, this brings the error due to clock drift well below the level where it affects the reported range. However, the alternative achieves this performance under all circumstances, while traditional symmetric double-sided two-way ranging requires the reply delays to be the same. Using (18) to estimate the time of flight minimises the effect of clock drift on the accuracy of the estimate.

Furthermore, (11) averages the error of both devices. (20) on the other hand depends only on the error of one device, implying that all ranges can be measured in the same time domain. This can be exploited if one device has a much better timing reference than the other to yield superior performance. Because all distances can have the same error, a simple calibration allows to convert to the true distances.

V. Conclusions

This paper presented an alternative to symmetric double-sided two-way ranging that removes the symmetry constraint on the reply delays. Both methods manage to reduce the error due to clock drift below the level where it will be noticeable in the reported range estimates. However, the alternative method presented has the advantage that the error dependent on the clock drift of only one device. This will improve performance if the timing reference of one device is much better than the other.

References

[1] *Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs), Amendment 1: Add Alternate PHYs*, IEEE Std. 802.15.4a, August 2007.

[2] *Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE Std. 802.15.4, June 2011.

[3] *Decawave ScenSor*, DW1000, Decawave, 2013. [Online]. Available: www.decawave.com