Calibration Method of Antenna Delays for UWB-based Localization Systems

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***Abstract*—Wireless sensor networks are gaining ground due to their low cost. Among them, solutions exist, that use the UWB (Ultra-Wideband) physical layer, which is ideal for localization by the nature of the technology. The accuracy of one of the most commonly used time measurement-based method depends on the accuracy of the timestamps provided by the devices. In this article, the authors propose a time measurement and UWB-based calibration method, which provides more accurate receiver and transmitter delays than commonly used methods. Using this approach, the calibrated devices utilized for positioning will provide more accurate time of arrival (ToA)—commonly called time of flight (ToF)—timestamps, which results in a significantly more accurate position calculation. First, the mathematical description of this calibration method is introduced followed by an enhanced version of that, then the system calibration algorithm is disclosed. Finally, a closed formula is presented which shows the error propagation of the presented methods.**

I. Introduction

Nowadays it would be hard to imagine our daily routines without wireless network devices (e.g. Wi-Fi access points, cell phones, Bluetooth headsets, etc.), they are part of our lives. Apart from to the previously listed technologies, low-cost wireless sensors, which provide various functionalities (e.g. humidity or temperature measurements, alerting, etc.) are emerging in small form factor as standalone or networked devices. Likewise, there is an increasing demand in civil and industrial areas to find, log and even continuously monitor the precise location of certain objects (e.g. cars, people, devices).

An ideal option for positioning could be a ToA or TDoA-based ultra-wideband impulse radio (UWB-IR), which could provide accurate time measurement with short impulses while staying robust against multipath signal propagation. The precise measurement of the events of transmission and reception is vital for ranging-based localization. The antenna delay, which is introduced by manufacturing differences (and environmental effects) can cause errors in the time of flight measurements.

This article introduces a device calibration method which determines the receiver and transmitter antenna delays based on UWB communication. The method determines the sum of transmitter and receiver delays to decrease the error originating from the measurement of time and hence results in a more accurate distance measurement and position value. (It will be proved, that determining the sum of the receiver and transmitter delays is sufficient.) First, Section II shows the commonly used calibration methods, then Section III and IV the proposed calibration method is introduced along with a further refinement of the method. After that, Section V shows how to extend the new calibration scheme to calibrate the whole positioning system. Then in Section VI the error propagation of these new methods are formalized, and finally, the paper is concluded.

II. Related works

This section introduces UWB device calibration methods found in the scientific literature, which can be divided into two categories. The first category contains methods, which attempt to compensate the error originating from antenna delays. The second category consists of algorithms for anchor device placement.

Paper [1] introduces the calibration method suggested by the popular DW1000 UWB chipmaker DecaWave Ltd. The authors propose the use of consecutive two-way ranging measurements. In each iteration, the transmitter and receiver delays should be altered to find the local optimum, which produces the least difference between the measured and the actual distances with the help of two already calibrated devices.

Similarly to the previous article, in paper [2] the engineers of Time Domain shows an estimation method, which aims to decrease the distortions caused by manufacturing in the radio and antenna circuitry. The amount of delay is determined using the linear least squares regression, which requires solving $n(n-1)$ equations for n devices (one equation per connection).

The authors of article [3] disclose a flexible and easy to use calibration algorithm, which facilitates 3D positioning by determining time delay values of the devices. These time delay values are determined by starting from maximum likelihood estimation and nonlinear least-squares method. Utilizing their ToA measurement method, the authors can calibrate a device in a matter of minutes.

Paper [4] propose a method to measure clock drift of a device by stroboscopic (periodic) sampling and maximum likelihood estimation. The stroboscopic method requires the appropriate sampling frequency, which is achieved by sending the messages repeatedly. This approach is not recommended in case of sensor networks, where the energy efficiency is the most important factor due to the high number of required repetitions.

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Article [5] introduces a method, which can be used to compensate the errors originating from the differences in antenna orientation of the devices in case of LoS (Line of Sight) environment. The effects of antenna orientation are not the scope of this paper.

Paper [6] describe a 2D and 3D calibration method, which does not compensate the amount of clock difference among the anchors but determine their position. The solution defines a Calibration Unit, in which the distances (ranges) are determined, and the position of the anchors is calculated with least squares methods.

The authors of article [7] introduce a so-called “bilateration” network, which is capable of automatic anchor positioning based on noisy measurement data.

Similarly to the previous article, the authors of [8] show an algorithm, which is capable of positioning the anchors without prior information. The solution uses an iterative estimation of their actual positions based on Newton’s method with a predefined limit value.

The solutions which use the least square method face the problem that they distribute the receiver and transmitter delays among the devices. This approach can significantly decrease the amount of accuracy in positioning through time measurements in case the tag is ranging with other devices to whom it was not calibrated. It would be required to calibrate all devices with other devices and store these values; therefore the (re)calibration is time and energy consuming.

The other presented papers dealing with anchor calibration decrease the amount of a priori knowledge and can introduce more uncertainty in the system and position estimation.

The calibration method proposed in our paper increases the accuracy of time measurement by determining the sum of the receiver and transmitter delays for the current device under calibration independently from the other (helper) devices taking part in the calibration process; therefore the helper devices do not require calibration. This approach allows calibrating the devices individually without distributing the error of the antenna delays among them.

III. Calibration of antenna delay

There is a delay present in the process of transmitting and receiving an UWB signal. The timestamps reported by the radio chip is different from the actual transmission and reception timestamp. This delay, which is device dependent, is caused by manufacturing differences in the chips, the surrounding circuitry, the antenna and even environmental effects (e.g. temperature). The delay is very small; however, in UWB positioning the distance measurement is based on the ToF of the radio signal (where the timestamp differences are converted to distances by multiplying with the speed of light). Even the smallest delay can introduce significant error; therefore the determination and compensation for this effect are necessary.

Although the transmitter and receiver delays exist separately and can be compensated individually, in the calibration process it is enough to determine the sum of these values (for a certain device) because during the distance measurement process these values always affect the measurement together. Figure 1 shows the message sequence of extended two-way ranging (commonly called symmetric double-sided two-way ranging [9]) marking the transmission and reception time intervals. According to this figure, the time measurements of the Anchor and Tag can be compensated with transmitter and receiver delays as

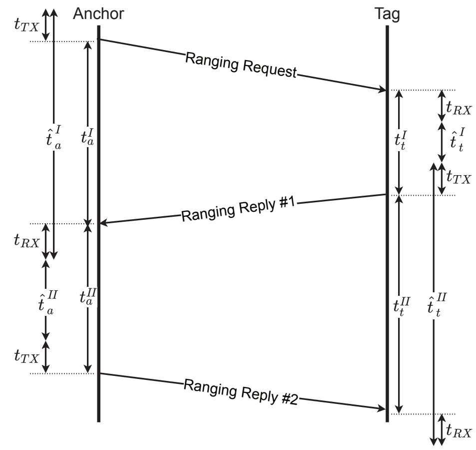

Figure 1. Extended two-way ranging

$$t_a^I = \hat{t}_a^I - t_{RX} - t_{TX} = \hat{t}_a^I - \tau \ , \quad (1)$$
$$t_a^{II} = \hat{t}_a^{II} + t_{RX} + t_{TX} = \hat{t}_a^{II} + \tau \ , \quad (2)$$
$$t_t^I = \hat{t}_t^I + t_{RX} + t_{TX} = \hat{t}_t^I + \tau \ , \quad (3)$$
$$t_t^{II} = \hat{t}_t^{II} - t_{RX} - t_{TX} = \hat{t}_t^{II} - \tau \ , \quad (4)$$

where the parameters with the hat sign represent the measured parameters, t_{RX} is the receiver, and t_{TX} is the transmitter delay. Their sum is noted with τ.

The UWB chips provide an independent setting of transmitter and receiver delays—these compensation values offset the measured timestamps of packet transmission and reception. Figure 2 shows that substituting either the transmitter or receiver delay values with their sum, and the measured time differences stay the same. If the compensation with τ amount is applied to the receiver delay, it makes the events appear to be earlier with t_{TX} compared to reality. Similarly applying a compensation of τ to the transmitter delay, it makes the events appear to be later with t_{RX}.

IV. The steps of calibration

To calibrate a certain device, the help of two other devices is required; however, the calibration of the helper devices is not necessary at this point. This is possible because the helper devices only transmit (A) or receive (C) packets during the calibration process; therefore their transmitter or receiver delays do not affect their time difference measurements. The calibration process is shown in Figure 3 with the time differences to be measured.

Device A sends a packet to device B, then consequently B send a packet to C. Device C also listened and received the

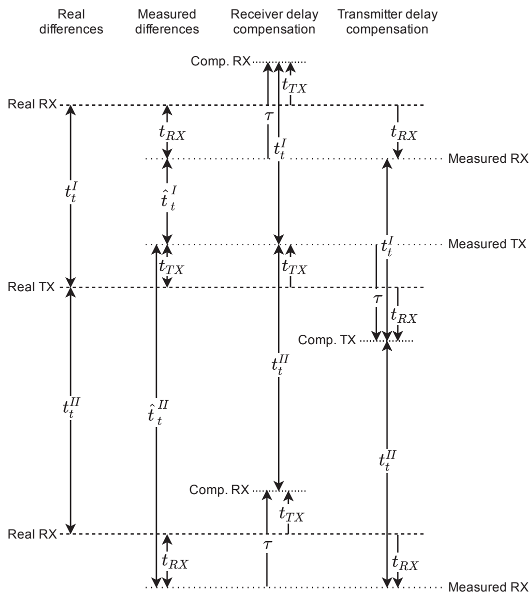

Figure 2. Effect of compensation with transmitter or receiver delay

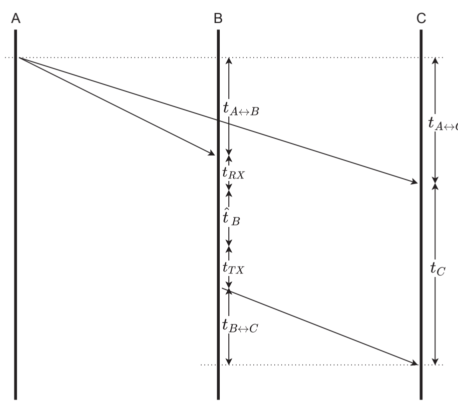

Figure 3. Calibration process

first packet sent from A. Devices A and C are the helpers for determining the aggregated delay value ($\tau = t_{RX} + t_{TX}$) to calibrate device B. Device A does not measure time differences; device C measures the time difference of receiving two packets, which is not affected by the delay. The knowledge of the distances between all the participating devices is necessary for calibration, so $t_{A\leftrightarrow B}$, $t_{B\leftrightarrow C}$, and $t_{A\leftrightarrow C}$ are known, $\hat{t}_B$ and t_C are measured by the devices. According to the previous description, the following equation is derived:

$$t_{A\leftrightarrow B} + t_{RX} + \hat{t}_B + t_{TX} + t_{B\leftrightarrow C} - t_C - t_{A\leftrightarrow C} = 0 \ . \quad (5)$$

Reordering the previous formula, the unknown parameter is expressed as

$$\tau = t_C - \hat{t}_B + t_{A\leftrightarrow C} - t_{A\leftrightarrow B} - t_{B\leftrightarrow C} \ . \quad (6)$$

A. *Enhancing the accuracy of calibration*

Utilizing the same idea as extended two-way ranging improves the accuracy of two-way ranging, it is possible to augment the calibration process to three message exchange to decrease the amount of error originating from the clock drift differences during time measurements to achieve more accurate calibration.

The previous process can be considered as the following: the second packet is sent from B to A, but C overhears the packet (and device A drops the packet). Using this interpretation of the calibration process, it is natural to extend it the same way as two-way ranging was extended. The extended process is shown in Figure 4. In this case, B answers the packet sent from A, and then A sends a new packet to B while all the packets are overheard by C.

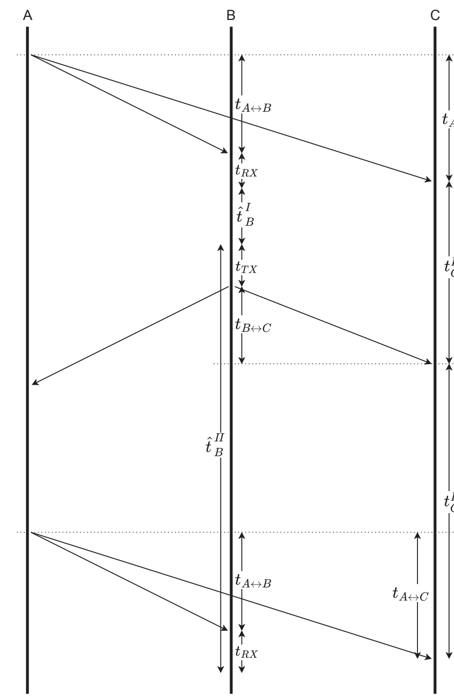

Figure 4. Extended calibration process

In the case of extended calibration, device A transmits and receives packets; however, it is not necessary that it was previously calibrated because it does not measure time differences, the same way as in the basic calibration process.

The equations for extended calibration are

$$t_{A\leftrightarrow B} + t_{RX} + \hat{t}_B^{I} + t_{TX} + t_{B\leftrightarrow C} - t_C^{I} - t_{A\leftrightarrow C} = 0 \ , \quad (7)$$
$$\hat{t}_B^{II} - t_{RX} - t_{A\leftrightarrow B} + t_{A\leftrightarrow C} - t_C^{II} - t_{B\leftrightarrow C} - t_{TX} = 0 \ . \quad (8)$$

The difference of the previous equations give the following expression for τ:

$$\tau = \frac{t_C^{I} - t_C^{II}}{2} - \frac{\hat{t}_B^{I} - \hat{t}_B^{II}}{2} + t_{A\leftrightarrow C} - t_{A\leftrightarrow B} - t_{B\leftrightarrow C} \ . \quad (9)$$

It should be noted, that the result is equivalent to the original statement (Equation (6)) with the substitution of $t_\bullet \rightarrow \frac{t_\bullet^{I} - t_\bullet^{II}}{2}$.

V. System calibration

The previously presented calibration method calibrates one device; however, in a positioning system, there are more devices. Therefore, in practical applications, it is required to calibrate all the fix placed devices (anchors) automatically. This section provides a possible algorithm for this problem utilizing the previously presented calibration method.

The calibration of a multi-anchor positioning infrastructure can be achieved by using this algorithm:

```
1:  function SystemCalibration
2:      K ← [0, 0, ..., 0]
3:      while 0 ∈ K do
4:          i ← min(K == 0)
5:          j ← random(0 .. N − 1, ≠ i)
6:          k ← random(0 .. N − 1, ≠ i, j)
7:          A[0] ← calibrate(i, j, k)
8:          A[1] ← calibrate(j, k, i)
9:          A[2] ← calibrate(k, i, j)
10:         cond_1 ← range(i, j) == d_ij
11:         cond_2 ← range(j, k) == d_jk
12:         cond_3 ← range(k, i) == d_ki
13:         if cond_1 && cond_2 && cond_3 then
14:             C[i] ← A[0], C[j] ← A[1], C[k] ← A[2]
15:             K[i] ← 1, K[j] ← 1, K[k] ← 1
```

The strategy of the algorithm is to select the first device in the list of uncalibrated devices (the state of calibration is stored in logical vector K) and randomly pick two other devices for mutual calibration (there are N devices in the system). The device calibration method is carried out by the function $calibrate(i, j, k)$ which calibrates device i using device j and k as helpers.

After the mutual calibration phase, the calibration values are validated, because it cannot be guaranteed, that the devices are line of sight. In worst case scenario, a reflection occurred during the communication signal path, which could tamper the measurements. The validation is based on $range(i, j)$ function and the previously known distances d_{ij}. Function $range(i, j)$ determines the distance between device i and j using the parameters mentioned above. After successful validation, the $C[i]$ calibration values and vector K are updated.

The previously described scheme is repeated until the appropriate calibration values are determined for all the target devices.

It should be noted that in the hereby introduced pseudo code symbol $==$ in lines 10–12 refers to equality within the desired range for practical purposes instead of exact match.

VI. Propagation of error

A. Basic calibration

In the case of the basic (2-message) method the τ calibration value depends on the error of time measurement in device B and C according to the following equations based on Equation (6):

$$\Delta\tau^{\Delta t_C} = \frac{\partial\tau}{\partial t_C}\Delta t_C = \Delta t_C \ ,$$
$$\Delta\tau^{\Delta\hat{t}_B} = \frac{\partial\tau}{\partial\hat{t}_B}\Delta\hat{t}_B = -\Delta\hat{t}_B \ . \tag{10}$$

The error of distance measurement between the devices (to enable the calculations) is not examined in this article because it was assumed that distance measurement is significantly more accurate than the error originating from time measurement. This assumption is not unlikely because the distance of the devices can be measured with a laser rangefinder with high accuracy. The moving tag can also be measured with high accuracy at a predefined calibration point. Consequently, the systematic error of calibration originating from the clock drifts of the devices can be expressed as

$$\Delta^s\tau = \Delta^s t_C - \Delta^s\hat{t}_B = e_C^s t_C - e_B^s\hat{t}_B \ , \tag{11}$$

where e_C and e_B are the relative errors (clock drifts) of time measurements in devices C and B. Reordering Equation (6) gives

$$t_C = \hat{t}_B + t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau \ , \tag{12}$$

which can be substituted into the systematic error of the calibration as

$$\Delta^s\tau = \left(e_C^s - e_B^s\right)\hat{t}_B + e_C^s\left(t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau\right) \ . \tag{13}$$

Both calibration value τ and the time of flight values ($t_{A\leftrightarrow B}$, $t_{B\leftrightarrow C}$, and $t_{A\leftrightarrow C}$) are in the magnitude of ns, while $\hat{t}_B$ is in the magnitude of ms. Hence the first part of the previous equation is the significant one, and the error of clock drift influences the measurement proportional to the response time.

For the random error (e.g. jitter, error of signal detection, etc.) signed summation cannot be employed; instead, the absolute summation of error components is required for worst case error calculation:

$$\Delta^r\tau = \left|\Delta^r t_C\right| + \left|-\Delta^r\hat{t}_B\right| = e_C^r t_C + e_B^r\hat{t}_B \ . \tag{14}$$

Using Equation (12) the formula is similar to the systematic error is constructed:

$$\Delta^r\tau = \left(e_C^r + e_B^r\right)\hat{t}_B + e_C^r\left(t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau\right) \ . \tag{15}$$

B. Extended calibration

According to Equation (9), the error of extended calibration is affected by the error of time differences measured in devices B and C as

$$\Delta\tau^{\Delta t_C^I} = \frac{1}{2}\Delta t_C^I \ , \qquad \Delta\tau^{\Delta t_C^{II}} = -\frac{1}{2}\Delta t_C^{II} \ ,$$
$$\Delta\tau^{\Delta\hat{t}_B^I} = -\frac{1}{2}\Delta\hat{t}_B^I \ , \quad \Delta\tau^{\Delta\hat{t}_B^{II}} = \frac{1}{2}\Delta\hat{t}_B^{II} \ . \tag{16}$$

Summing up the error components the systematic error of all time measurements is:

$$\Delta^s\tau = \frac{1}{2}\left(\Delta^s t_C^I - \Delta^s t_C^{II} - \Delta^s \hat{t}_B^I + \Delta^s \hat{t}_B^{II}\right)$$
$$= \frac{1}{2}\left(e_C^s\left(t_C^I - t_C^{II}\right) - e_B^s\left(\hat{t}_B^I - \hat{t}_B^{II}\right)\right) \ . \quad (17)$$

t_C^I and t_C^{II} can be expressed by Equations (7) and (8):

$$t_C^I = \hat{t}_B^I + t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau \ , \quad (18)$$
$$t_C^{II} = \hat{t}_B^{II} - t_{A\leftrightarrow B} - t_{B\leftrightarrow C} + t_{A\leftrightarrow C} - \tau \ . \quad (19)$$

Subtracting the equations gives

$$t_C^I - t_C^{II} = \hat{t}_B^I - \hat{t}_B^{II} + 2\left(t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau\right) \ . \quad (20)$$

This difference substituted into Equation (17) the systematic error of extended calibration is

$$\Delta^s\tau = \frac{e_C^s - e_B^s}{2}\left(\hat{t}_B^I - \hat{t}_B^{II}\right) +$$
$$e_C^s\left(t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau\right) \ . \quad (21)$$

For device B the time differences can be estimated (assuming that the response times of devices A and B are close to equal) by

$$t_B^I - t_B^{II} \approx -2t_{A\leftrightarrow B} \ . \quad (22)$$

However, the device does not measure this time difference. Utilizing $\hat{t}_B^I = t_B^I - \tau$ and $\hat{t}_B^{II} = t_B^{II} + \tau$, the measured time difference can be estimated by the following formula:

$$\hat{t}_B^I - \hat{t}_B^{II} \approx -2\left(t_{A\leftrightarrow B} + \tau\right) \ . \quad (23)$$

Employing the previous equation, Equation (21) can be rephrased as

$$\Delta^s\tau = \left(e_B^s - e_C^s\right)\left(t_{A\leftrightarrow B} + \tau\right) +$$
$$e_C^s\left(t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau\right)$$
$$= e_B^s\left(t_{A\leftrightarrow B} + \tau\right) + e_C^s\left(t_{B\leftrightarrow C} - t_{A\leftrightarrow C}\right) \ . \quad (24)$$

The calibration value τ and the $t_{A\leftrightarrow B}$, $t_{B\leftrightarrow C}$ and $t_{A\leftrightarrow C}$ time of flight values are in the magnitude of nanoseconds; therefore the clock drift of the devices affects the measurements up to the magnitude of the time of flight values, hence extended calibration decreases the systematic error significantly.

To analyze the worst case scenario of the random error the components are summed by absolute values:

$$\Delta^r\tau = \frac{1}{2}\left(\Delta^r t_C^I + \Delta^r t_C^{II} + \Delta^r \hat{t}_B^I + \Delta^r \hat{t}_B^{II}\right)$$
$$= \frac{1}{2}\left(e_C^{rI}\, t_C^I + e_C^{rII}\, t_C^{II} + e_B^{rI}\, \hat{t}_B^I + e_B^{rII}\, \hat{t}_B^{II}\right) \ . \quad (25)$$

Opposed to systematic error $e_C^{rI} \neq e_C^{rII}$ and $e_B^{rI} \neq e_B^{rII}$, so they should not be simply denoted by e_C^r and e_B^r. After substituting t_C^I and t_C^{II} according to Equations (18) and (19), the random error of extended calibration is

$$\Delta^r\tau = \frac{1}{2}\left(\left(e_C^{rI} - e_C^{rII}\right)\left(t_{A\leftrightarrow B} + t_{B\leftrightarrow C} - t_{A\leftrightarrow C} + \tau\right) +\right.$$
$$\left.\left(e_C^{rI} - e_B^{rI}\right)\hat{t}_B^I + \left(e_C^{rII} - e_B^{rII}\right)\hat{t}_B^{II}\right) \ . \quad (26)$$

It can be seen by comparing this result with Equation (15) that the significant component of the random error is not suppressed by extended calibration; however, opposite to systematic error, random error can be decreased by averaging the results of more measurements.

VII. Conclusion

This article introduced a method for calibrating the transmitter and receiver delays of UWB radios used for time measurement based positioning. The proposed method can determine the unique calibration values by devices, unlike traditionally used methods (based on least squares optimization), which distribute the error among the devices. Hence the new calibration method provides independence of helper devices and recalibration-free utilization in new networks. Besides, the developed method can be utilized for the calibration of all devices present in a network, which is also shown in the paper.

The authors showed an enhanced version of their calibration method, which makes the measurement more accurate by adding a new message exchange. The results of the error propagation discussion in the article show that the extended calibration method significantly suppresses the systematic error.

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