New synchronization method for UWB TDOA based localization system utilizing two reference nodes

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***Abstract* — Nowadays indoor localization systems are getting more and more attention as there is a rising need for indoor location-based services. Different approaches to this problem can be found in the literature, with the UWB (ultrawideband) technique being one of the most promising. Most commonly it utilizes measurement of TDOA (Time Difference of Arrival) between the tag and the fixed-positioned, synchronized nodes. In the paper a novel approach to the synchronization of the anchor nodes is presented, which uses two reference nodes. Synchronization method is described along with the derivation of TDOA estimation equations and discussion on performed experimental verification.**

***Keywords* — indoor localization, two-reference nodes synchronization, ultrawideband**

I. Introduction

Nowadays with the constantly growing interest for indoor location based services (Indoor LBS) a need for accurate indoor positioning system is rapidly arising. As contemporary outdoor positioning systems such as GPS, GLONASS or GALILEO are not capable of providing such data, new indoor location solutions are being developed. There are various specific requirements, that need to be taken into account in the design phase, such as desired accuracy (depending on the scenario, ranging from dozens of centimetres to single meters), number of supported users, size of the area where system will be deployed, energy efficiency of localized tags (if applicable) and others. Additionally, indoor environment is quite demanding as it consists of walls, furniture and other objects that may impact localization estimation or calculation.

There are different techniques that can be utilized in indoor localization systems. Vision solutions can use a set of depth cameras to estimate the position of objects within a room [1]. Accuracy of such systems can reach even dozens of centimetres, if there are not many objects obstructing the vision. However, such approach is not practical when multiple rooms need to be covered, as it requires LOS (Line of Sight) between the cameras and the localized objects. Also, localizing multiple objects may pose a problem. Laser-based solutions share similar limitations [2]. They are used rather for autonomous navigation of robots/vehicles than for localization of multiple objects/persons. Another approach involves use of ultrasounds to locate persons. ToF (Time of Flight) between the fixed infrastructure and localized tag is measured and based on that position of signal's source is determined. There are various systems utilizing such approach such as ActiveBAT [3] or Cricket [4], however only Sonitor's solution is commercially available [5].

Techniques using either ToF or RSS (Received Signal Strength) measurements can be also utilized in the radio-based localization systems. Due to possibility of the electromagnetic waves to propagate through walls and other obstacles they are promising when it comes to indoor positioning. WiFi or BLE (Bluetooth Low Energy) based systems are most widespread due to the popularity of both technologies. Both of them use measurements of RSS for localization – either by creating radio map and performing so called fingerprinting [6][7] or by estimating distance between nodes forming the infrastructure and localized tags [8][9]. Accuracy that can be achieved by those systems is in range of single meters, which may be enough to point the room with localized object or person.

Another technique utilizing radio waves is UWB (ultrawideband) [10]. It relies on the transmission of narrow pulses with very short rise times (in range of hundreds of picoseconds), which allows for accurate measurements of their ToA (Time of Arrival) or TDOA (Time Difference of Arrival) [11].

Most UWB indoor localization systems consist of localized tags (which most commonly, in case of TDOA technique, serve as transmitters), fixed infrastructure comprised of nodes placed in known positions and system controller responsible for position calculation based on the data received from anchor nodes. In order for the system to work properly, anchor nodes need to be synchronized – their clocks need to be aligned, drifts and differences in clocks' frequencies need to be compensated. In commercially available systems such as Zebra's Dart [12] or Ubisenses' Dimension4 [13] this is achieved by providing wired connections between the nodes. Such approach allows for precise synchronization and accurate localization (even dozens of centimetres, if the propagation environment is not much obstructed), however it is rather inconvenient in terms of installation. The solution to this problem is wireless synchronization. It can be accomplished

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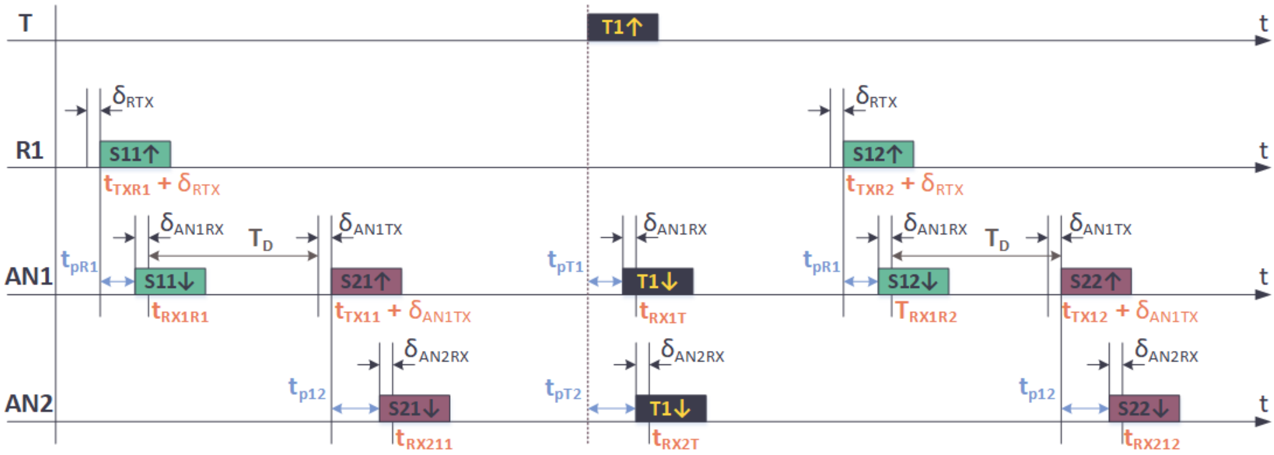

Fig. 2. Transmission scheme

in various ways, for example by sequentially transmitting synchronization packets [14] or by providing single source of synchronization data [11]. The latter is easier to achieve and allows for more precise synchronization, however, may significantly limit the system's area of operation, as in such approach every anchor node needs to have direct connection with the reference node. In the paper a novel approach is presented, where a pair of reference nodes is used, which allows for extension of the systems coverage. Both reference nodes are synchronized and transmit synchronization signals to other anchor nodes.

The paper is organized as follows. In section II proposed method is described along with the derivation of the TDOA measurement formulas. In section III experimental examination of the method is presented. The paper is concluded in section IV.

II. Two-Reference Nodes Synchronization

A. *Proposed architecture*

Proposed synchronization method utilizing two reference nodes is meant to be used in the ultrawideband positioning system comprised of anchor nodes, localized tags and the system controller responsible for position calculation. Proposed architecture is shown in Fig. 1.

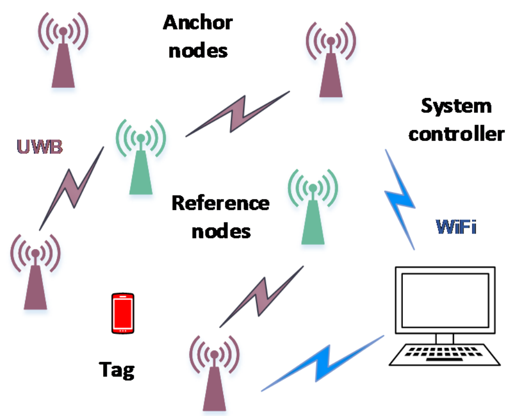

Fig. 1. Proposed architecture of the UWB localization system

Standard anchor nodes serve as UWB receivers, which measure times of arrival of packets transmitted by the tags and by the reference nodes. Measurement results are sent using the WiFi interface to the system controller, where position is calculated.

One reference node serves as the master node. The goal is to align clocks in all other nodes (including the second reference node) to its clock. By the term "aligning clocks", both estimation of the offset of the inner counters in the nodes and compensation of their clocks' drifts is assumed. Second reference node serves as the signal extender – it retransmits with small and fixed delay the synchronization packets transmitted by the master. It is assumed that reference nodes are equipped with high stability and tolerance clock signal sources (e.g. TCXO – Temperature Compensated Crystal Oscillator). It is worth mentioning, that second reference node can be either a standalone device or one of the standard anchor nodes can take this role (assuming that it is equipped with proper clock signal source.

B. *Proposed Transmission scheme*

Proposed transmission scheme is presented in Fig. 2. In this scenario there are three anchor nodes (master reference node – R1 and two standard nodes – AN1 and AN2, one of them (AN1) having also the role of the second reference node) and one tag – T. It is assumed that AN2 is too far from master reference node and does not receive its packets and therefore is synchronized using the second reference node.

At the moment of the transmission of the first synchronization packet (S11), values of inner counters in both anchor nodes AN1 and AN2 are unknown. Their offsets with respect to the counter in the R can be calculated as shown in equations (1) – (2) and (3) – (4) respectively.

$$t_{TXR1} + \delta_{RTX} + \Delta T_{R1Offset} = t_{RX1R1} - \delta_{AN1RX} - t_{pR1} \quad (1)$$

$$\Delta T_{R1Offset} = t_{RX1R1} - t_{TXR1} - t_{pR1} - \delta_{RTX} - \delta_{AN1RX} =$$

$$= \Delta T_{R1OffsetN} - \delta_{RTX} - \delta_{AN1RX} \quad (2)$$

Where t_{RX1R1} is reception time of the packet S11 in AN1, t_{TXR1} is transmission time of the packet S11, t_{pR1} is propagation time between the R1 and AN1 and δ_{AN1RX} and δ_{RTX} are inner reception and transmission delays introduced by the radio modules.

$$t_{TXR1} + \delta_{RTX} + \Delta T_{R2Offset} = t_{RX211} - \delta_{AN2RX} +$$

$$-t_{p12} - \delta_{AN1TX} - T_D - \delta_{AN1RX} - t_{pR1} \quad (3)$$

$$\Delta T_{R2Offset} = t_{RX211} - t_{TXR1} - T_D - t_{p12} - t_{pR1} +$$

$$-\delta_{AN2RX} - \delta_{AN1TX} - \delta_{AN1RX} - \delta_{RTX} =$$

$$= \Delta T_{R2OffsetN} - \delta_{AN2RX} - \delta_{AN1TX} - \delta_{AN1RX} - \delta_{RTX} \quad (4)$$

Where t_{RX211} is reception time of the packet S21 in AN2, t_{TXR1} is transmission time of the packet S11, T_D is known transmission delay in anchor AN1, t_{pR1} is propagation time between the R and AN1, t_{p12} is propagation time between AN1 and AN2 and δ_{AN1RX}, δ_{AN1TX}, δ_{AN2RX} and δ_{RTX} are inner reception and transmission delays introduced by the radio modules.

It can be assumed that at the moment of the reception of synchronization packet, anchor nodes' clocks drift is equal 0 and reaches its maximum value right before the reception of the next synchronization packet. Based on that, the correction factor at the moment of the reception of the tag's packet can be calculated for anchor AN1 as shown in equation (5).

$$\Delta T_{CT1AN1} =$$

$$(t_{RX1T} - t_{RX1R1}) * \frac{(t_{RX1R2} - t_{RX1R1}) - (t_{TXR2} - t_{TXR1})}{(t_{RX1R2} - t_{RX1R1})} \quad (5)$$

Where t_{RX1T}, t_{RX1R1}, t_{RX1R2} are reception times in AN1 and t_{TXR1} and t_{TXR2} are transmission times in R. Correction factor for anchor AN2 is shown in equation (4).

$$\Delta T_{CT1AN2} =$$

$$(t_{RX1T} - t_{RX2R1}) * \frac{(t_{RX2R2} - t_{RX2R1}) - (t_{TXR2} - t_{TXR1})}{(t_{RX2R2} - t_{RX2R1})} \quad (6)$$

Where t_{RX2T}, t_{RX2R1}, t_{RX2R2} are reception times in AN2 and t_{TX11} and t_{TX12} are transmission times in AN1.

TDOA value can be derived from the equation (7).

$$t_{RX1T} - \delta_{AN1Rx} - t_{pT1} = t_{RX2T} - \delta_{AN2RX} - t_{pT2} \quad (7)$$

After taking into account calculated clock offsets, equation (7) can be rewritten as follows:

$$t_{pT2} - t_{pT1} = t_{RX2T} - \delta_{AN2RX} - \Delta T_{R2Offset} +$$

$$-t_{RX1T} - \delta_{AN1RX} - \Delta T_{R1Offset} =$$

$$= t_{RX2T} - \Delta T_{R2OffsetN} - t_{RX1T} + \Delta T_{R1OffsetN} +$$

$$+\delta_{AN1TX} + \delta_{AN1RX} \quad (8)$$

Final equation allowing for TDOA calculation which includes correction factors is shown in (9).

$$t_{pT2} - t_{pT1} = t_{RX2T} - \Delta T_{R2OffsetN} - \Delta T_{CT1An2} +$$

$$-t_{RX1T} + \Delta T_{R1OffsetN} + \Delta T_{CT1AN1} +$$

$$+\delta_{AN1TX} + \delta_{AN1RX} \quad (9)$$

As inner delays in the anchor nodes (δ_{AN1TX} and δ_{AN1RX}) are unknown, their sum needs to be determined. It can be easily achieved in the calibration process by placing reference nodes in known positions and performing a set of ToA measurements using UWB receiver. Appropriate calculation is shown in (10).

$$\delta_{AN1TX} + \delta_{AN1RX} = t_{RX211} - t_{RX2R1} - T_D +$$

$$-t_{p12} - t_{pR1} - t_{pR2} \quad (10)$$

Where t_{RX211} and t_{RX2R1} are reception times of packets transmitted by both reference nodes, T_D is transmission delay in the second reference node, t_{p12} is propagation time between the reference nodes and t_{pR1} and t_{pR2} are propagation times between the receiver and first and second reference node respectively.

III. Experimental verification of the method

A. Test setup

Proposed synchronization method was experimentally tested in the laboratory conditions. Test setup is presented in Fig. 3. It consists of two reference nodes, two anchor nodes and one tag. Reference nodes were equipped with the DW1000 [15] ultrawideband transceiver with clock signal supplied from TCXO generator. Other anchor nodes and the tag were equipped with DWM1000 modules with standard crystal oscillators.

Tests were carried out in the laboratory room of size 6 by 6 meters with many reflective objects inside.

Reference nodes were placed 2.5 meters apart at the same height of 2.1 meters. Anchor nodes were placed 3.6 metres apart at the height of 2.2 meters. Tag was placed at the height of 1.8 meters in 6 different positions in the room. First measurement (point P0) was done in such position, that propagation time to both anchor nodes was the same. This measurement was used to estimate the difference in the reference nodes' clocks frequencies which manifested as constant bias in calculated TDOA values. In all test points two sets measurements were performed. In the first set, both anchors (AN1 and AN2) were synchronized using only master reference node (R1). In the second set, anchor AN1 was synchronized to the R1 and anchor AN2 was synchronized to the R2. In all test points around 3000 measurements per set were performed.

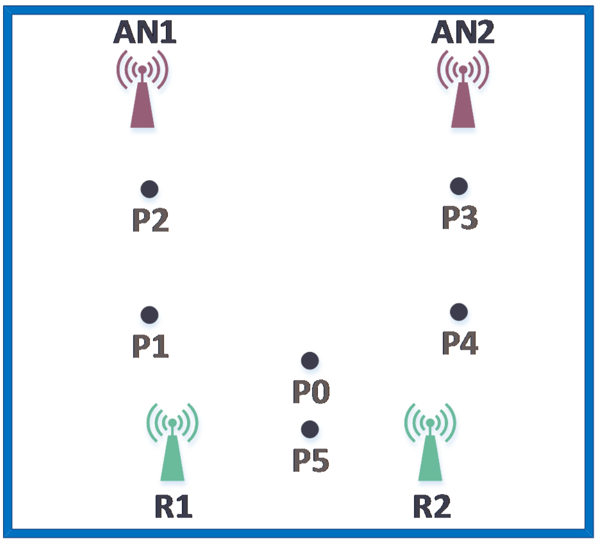

Fig. 3. Test setup

B. Test results

Before further analysis, outliers of gathered results were removed using the median method. Empirical cumulative distribution functions (ECDFs) of errors of TDOA measurements (calculated as the difference between measured TDOA and real TDOA) for all test points in the first set of measurements are shown in Fig. 4 and for the second set of measurements in Fig. 5.

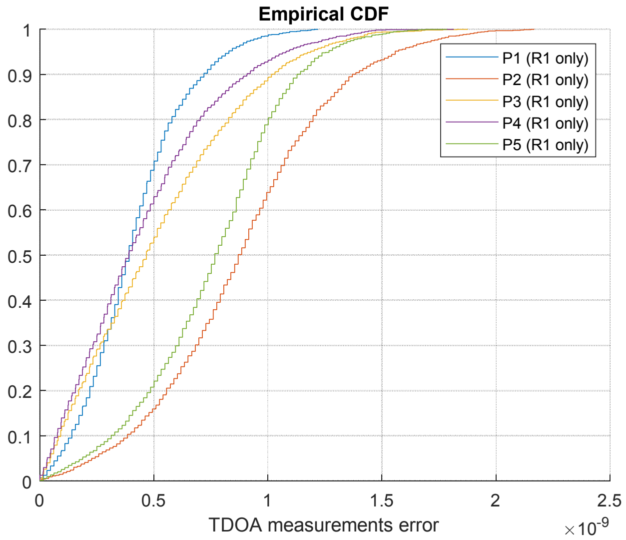

Fig. 4. CDF of errors of TDOA measurements (both anchors synchronized with R1)

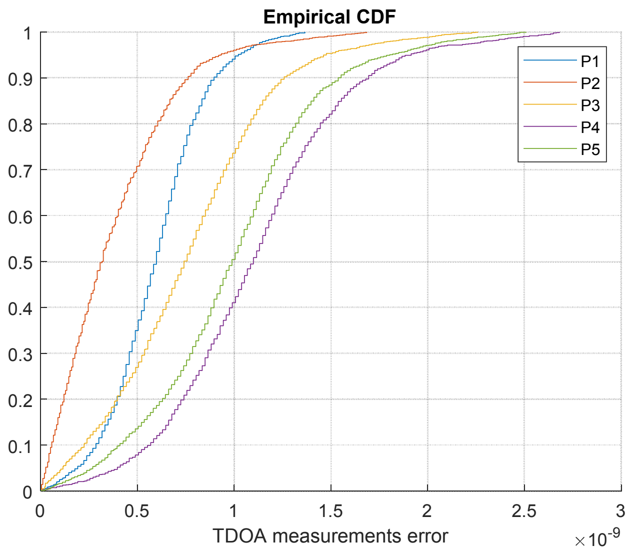

Fig. 5. CDF of errors of TDOA measurements (AN1 synchronized to R1, AN2 to R2)

Results are promising. For all test points for both sets of measurements in 90% of cases TDOA measurement error is lower than 1.6ns. As expected, when anchors are synchronized to different reference nodes, errors are slightly higher, due to the reference nodes' clocks differences.

IV. CONCLUSION

In the paper a novel method of wireless anchor nodes synchronization is presented. It utilizes two reference anchor nodes, one of them being the master node and second one serving as synchronization packets retransmitter. Proposed method allows for extension of the localization system's coverage while maintaining reasonable level of TDOA measurements accuracy.

In the paper a simple case was presented with only two reference nodes. Proposed solution could be possibly extended by adding one or more secondary reference nodes – all synchronized with the master node. Such case would require more extensive calibration and will be examined in the future work.

REFERENCES

[1] H. Song, W. Choi and H. Kim, "Robust Vision-Based Relative-Localization Approach Using an RGB-Depth Camera and LiDAR Sensor Fusion," in IEEE Transactions on Industrial Electronics, vol. 63, no. 6, pp. 3725-3736, June 2016.

[2] Y. Liu and Y. Sun, "Mobile robot instant indoor map building and localization using 2D laser scanning data," 2012 International Conference on System Science and Engineering (ICSSE), Dalian, Liaoning, 2012, pp. 339-344.

[3] A. Harter, A. Hopper, P. Steggles, A. Ward and P. Webster, "The Anatomy of a Context-Aware Application" in Proc. 5th ACM MOBICOM Conf., Seattle, WA, August 1999

[4] A. Smith, H. Balakrishnan, M. Goraczko, N. Bodhi Priyantha, "Tracking Moving Devices with the Cricket Location System", in Proc. Mobisys 2004, Boston, MA, June 2004

[5] Sonitor Sense RTLS Technology Brief, Sonitor Technologies, 2018 Available: https://static1.squarespace.com/static/59cac734cf81e0d666427339/t/5d5fe53e1cb86b00014898e8/1566565697966/Sonitor-Sonitor-Sense-Technology+Brief.pdf

[6] W. K. Zegeye, S. B. Amsalu, Y. Astatke and F. Moazzami, "WiFi RSS fingerprinting indoor localization for mobile devices," 2016 IEEE 7th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), New York, NY, 2016, pp. 1-6.

[7] T. Tsai, C. Hsu, H. Chiang and W. Wang, "Mobile Localization-Based Service Based on RSSI Fingerprinting Method by BLE Technology," 2018 IEEE 8th International Conference on Consumer Electronics - Berlin (ICCE-Berlin), Berlin, 2018, pp. 1-3.

[8] Y. Yun, J. Lee, D. An, S. Kim and Y. Kim, "Performance Comparison of Indoor Positioning Schemes Exploiting Wi-Fi APs and BLE Beacons," 2018 5th NAFOSTED Conference on Information and Computer Science (NICS), Ho Chi Minh City, 2018, pp. 124-127.

[9] A. Thaljaoui, T. Val, N. Nasri and D. Brulin, "BLE localization using RSSI measurements and iRingLA," 2015 IEEE International Conference on Industrial Technology (ICIT), Seville, 2015, pp. 2178-2183.

[10] 02.15.4a-2007 - IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirement Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)

[11] J. Kolakowski, V. Djaja-Josko, M. Kolakowski, "UWB monitoring system for AAL applications", Sensors, 2017, 17(9):2092

[12] Zebra Technologies. 2016. https://www.zebra.com.

[13] Ubisense. 2015. http://ubisense.net/en.

[14] J. Kolakowski, A. Consoli, V. Djaja-Josko, J. Ayadi, L. Morrigia and F. Piazza, "UWB localization in EIGER indoor/outdoor positioning system," 2015 IEEE 8th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Warsaw, 2015, pp. 845-849.

[15] DW1000 Data Sheet, DecaWave Ltd, Dublin, 2014 Available: https://www.decawave.com/support