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INDOOR UWB POSITIONING IN EIGER LOCALIZATION SYSTEM

Jerzy Kolakowski [1], Angelo Consoli [2], Vitomir Djaja-Josko [1], Jaouhar Ayadi [2], Lorenzo Morrigia [3], Francesco Piazza [3]

[1] Institute of Radioelectronics, Nowowiejska 15/19; 00-665 Warsaw, Poland, j.kolakowski@ire.pw.edu.pl, v.djaja@stud.elka.pw.edu.pl, www.ire.pw.edu.pl
[2] Eclexys SAGL, Via dell'Inglese 6, 6826 Riva San Vitale, Switzerland, angelo.consoli@eclexys.com, jaouhar.ayadi@eclexys.com, www.eclexys.com
[3] Saphyrion SAGL, Strada Regina 16, 6934 Bioggio, Switzerland, lorenzo.moriggia@saphyrion.ch, francesco.piazza@saphyrion.ch, www.saphyrion.ch

Abstract: The EIGER project proposes a global approach for the exploitation of the efficient joint use of Global Navigation Satellite System (GNSS) signals and Ultra-Wide Band (UWB) positioning in order to allow permanent and reliable outdoor/indoor localization. This paper is focused on the UWB positioning subsystem designed within the project. The architecture of the subsystem, design of its components and the transmission scheme leading to the time difference of arrival determination are described. Results of system laboratory tests are presented and discussed.

Keywords: indoor localization, TDOA, UWB positioning.

1. INTRODUCTION

Nowadays, the technological progress creates an opportunity for provision of Localization Based Services (LBS) in large outdoor and indoor areas. Unfortunately due to limitations of Global Navigation Satellite Systems (GNSS), being not able to provide accurate localization in indoor environments, typical implementations are based on a few different technologies. The main components of such hybrid solutions are GNSS systems, well performing outdoors, but requiring support in environments where the reception of satellite signals is difficult or even impossible.

This implies that classical GNSS receivers should cooperate with other systems such as ranging or location ones and GNSS assistance data sources. The classification of GNSS based outdoor/indoor systems is presented in Fig. 1.

A-GNSS solution depends on the use of wireless technology to provide aiding information to the GNSS receiver in order to improve acquisition speed and sensitivity. In case of indoor GNSS pseudolites the proposed approach consists in development of the local indoor infrastructure of transmitters emitting GNSS signals [1, 2].

Solutions that jointly use GNSS and Inertial Navigation Systems (INS) depend on the integration of both technologies. The inertial system uses accelerometers and gyroscopes to continuously calculate the position, orientation, and velocity of the sensor. This hybrid system can provide position during a short outage of the GNSS. The disadvantage of this approach is that the localization error increases with time [3].

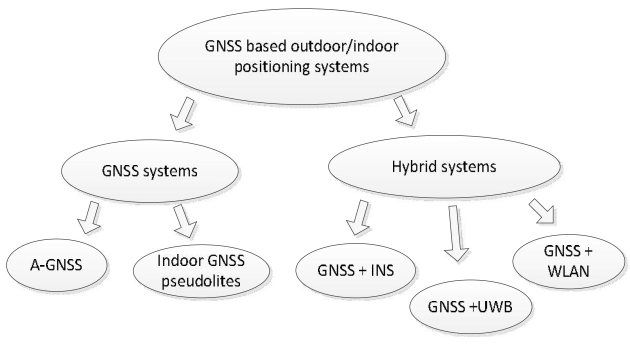


Fig. 1 – Classification of GNSS based outdoor/indoor positioning technologies

Nowadays, Wireless Local Area Networks (WLANs), mostly compliant with 802.11 standards, are spread all over the world. A majority of WLAN based positioning systems rely on Received Signal Strength (RSS) measurements. The benefit of using RSS measurements is that RSS information is available in typical WLAN devices [4, 5].

Impulse Radio (IR) Ultra Wideband technology (IR-UWB) seems to be especially relevant for positioning purposes. Transmission of narrow pulses improves systems accuracy and increases immunity to interference and multipath propagation. Due to the excellent time measurement resolution, positioning techniques implemented in UWB systems usually rely on measurements of travel times of signals between the target and reference nodes. UWB seem to be a very good candidate for indoor supplement of GNSS technology. So far, implementations of solutions that jointly use of GNSS and UWB are limited to research experiments.

The EIGER project focuses on the design of a GNSS/UWB based system for indoor/outdoor localization.

Majority of commercially available localization systems targets services that depend on the localization of a large number of assets or people on relatively small area. Such approach justifies the usage of simple, cheap target nodes (tags) whose extremely low power requirements guarantee long service without the exchange of batteries. The infrastructure of such systems consists of many receivers responsible for signal reception, time interval measurements and transfer of results to positioning server. All these systems control their tags and gather information on their localization in location servers.

The EIGER system targets services that are available in large areas, covering many distant buildings, often belonging to different institutions or enterprises. In such case the UWB system infrastructure should be distributed.

In the EIGER system the innovative infrastructure consisting of many “islands” deployed in different premises is proposed. All these subsystems will operate independently. Such approach significantly improves the system scalability. Extension of the system operation area by “covering” another building becomes very simple. The same infrastructure can be shared by navigation devices offered by different operators. All these factors should enable wider system implementation.

Of course, the UWB positioning system is more expensive than positioning systems based on other radio technologies (e.g. Bluetooth, WiFi or ZigBee), as it requires distribution of dedicated anchor nodes.

However the recent advances in technology resulting in availability of UWB transmission modules (e.g. Decawave's DWM1000) which price is comparable with the price of the typical WiFi modules has diminished this difference.

Nevertheless, benefits of UWB solution, depending on better localization accuracy and precision, may be a good counterweight for a higher cost.

2. EIGER SYSTEM ARCHITECTURE

The general EIGER system architecture is shown in Fig. 2. In order to provide outdoor and indoor localization, two separate localization subsystems are used: the GNSS one and the UWB one.

The navigation device consists of two modules: positioning module and a standard device (smartphone or tablet). The positioning module is intended for gathering location related data, processing and sending data to the smartphone for position calculation and results visualization.

The positioning module can be used alone in applications requiring recording tracking data. In this mode, localization data are stored in an internal memory and can be post-processed using an application run on an external computer.

Due to current UWB regulations, the UWB infrastructure operation is limited to the indoor environment. The EIGER positioning module operates in areas where signals from both infrastructures or only one infrastructure are available. The module is able to choose the subsystem guaranteeing position determination.

The EIGER UWB infrastructure consists of a set of wirelessly synchronized transmitters subsequently sending packets, each after a predefined delay. The EIGER positioning module receives packets and measures times of packets arrivals.

The EIGER UWB positioning system is illustrated in Fig. 2.

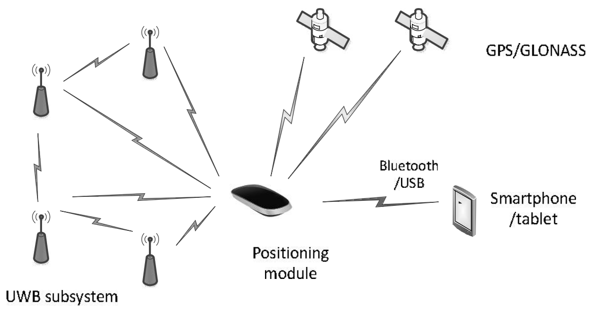


Fig. 2 – EIGER system architecture

The devices roles are limited to reception of GNSS or UWB signals. Therefore the problem of intersystem interference is negligible. Moreover such approach allows for a limitless number of devices to be served. In commercially available systems, where transmitters are localized, the increasing number of tags can significantly decrease the system performance.

3. UWB POSITIONING SUBSYSTEM

3.1 SYSTEM INFRASTRUCTURE

The UWB architecture is built from anchor nodes, which block diagram is presented in Fig. 3.

The UWB transmitter is based on the DW1000 integrated chip [8] In order to provide sufficient transmitter clock stability, the external TCXO oscillator was used.

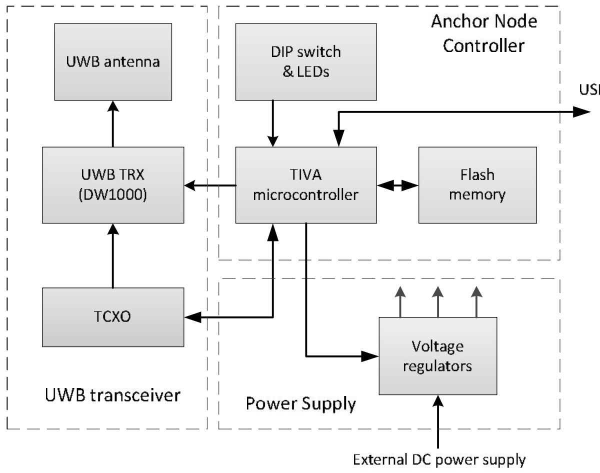


Fig. 3 - EIGER anchor node block diagram

The anchor node is controlled by a TIVA family TM4C123GH6PM ARM microcontroller. Its configuration is stored in the flash memory.

3.2 POSITIONING MODULE

EIGER positioning module subsystems are shown in Fig. 4. The GNSS subsystem is based on ST Microelectronics TeseoII single chip GNSS receiver (GPS/Galileo/Glonass L1). It provides the GNSS functionality but also it is the main control processor for the positioning module. It controls DW1000 transceiver and auxiliary subsystem modules.

The auxiliary subsystem includes all non UWB nor GNSS related functionalities such as: the accelerometer, the Bluetooth 4.0 module, the power supply, the battery charger and the microSD card.

The DW1000 used in the positioning module operates only as the receiver. It is responsible for the packet reception and packet time of arrival measurements. The measurements are performed with 15.65 ps resolution. The rate of positioning depends on the number of anchor nodes used (in an infrastructure comprising 5 anchors ten measurements per second can be easily achieved).

3.3 RADIO INTERFACE DESIGN

The EIGER UWB interface conforms to the IEEE802.15.4a standard [7]. At the level of the selection of center frequencies and bandwidths provided by DW1000 chip, the 5th channel corresponding to 6.4896 GHz and 499.2 MHz bandwidth was chosen (due to European regulations concerning deployment of UWB positioning systems, the EIGER system should operate in 6-8.5 GHz band). The levels of UWB signals emitted by the transmitters fulfill requirements specified in regulations.

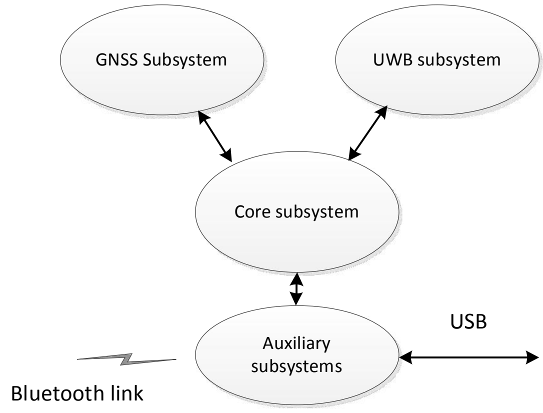


Fig. 4 – EIGER positioning module

The DW1000 radio interface is based on high speed pulses. Information is transmitted with Burst Position Modulation – Binary Phase Shift Keying (BPM-BPSK) modulation where the symbols value is encoded in the position of burst of UWB pulses. The DW1000 supports physical layer and a few functions from the MAC layer.

A general structure of the UWB frame is shown in Fig. 5. It starts with a preamble after which the start of frame delimiter is transmitted. According to IEEE 802.15.4a specification [7] both parts constitute a synchronization header. A frame header (PHR) contains information on data rate, frame length and preamble duration. It is protected by a single error correct, double error detect parity check sequence.

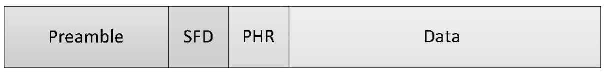


Fig. 5 – General structure of the UWB frame [8]

The EIGER system protocol messages will be transmitted in the EIGER frames (Fig. 6). The EIGER frame (up to 127 bytes) occupies the Data field of the UWB frame.

The frame begins with an EIGER Frame header (EFH), after which a node information block is transmitted. The last field is intended for user data transmission.

The EIGER Frame Header structure contains information describing the frame and its source. The Frame control carries information on the infrastructure operating mode. The SQN field denotes the sequence packet number. The ANS and AN IDs identify the infrastructure and the anchor node that sent a packet. The point of origin corresponds to location of the local Cartesian coordinate system origin in WGS84 format.

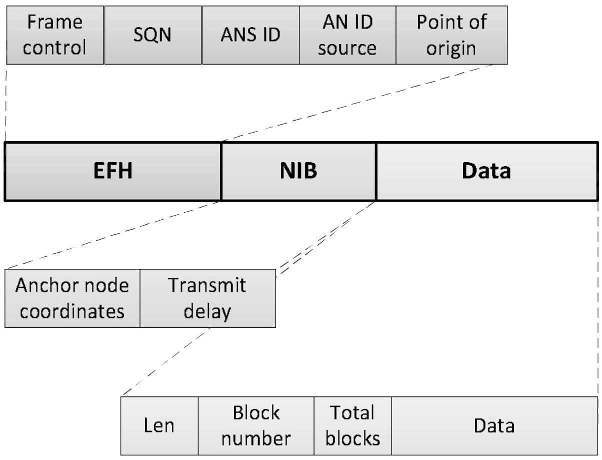


Fig. 6 – EIGER packet

The Node Information Block (NIB) includes anchor node coordinates and delay information necessary for TDOA calculation. The Data field contains data required by EIGER services (e.g. building plans).

3.4 TRANSMISSION SCHEME

The EIGER localization determination relies on TDOA measurements. Such approach allows for precise positioning, but needs very accurate measurements of the packets time of arrival. Therefore, a synchronization between the anchors is needed, to maintain constant and strict timing between consecutive packets. Wireless synchronization is an innovation introduced by the EIGER system to UWB indoor localization systems.

In order to precisely synchronize all devices within the infrastructure a specific packet transmission scheme has been developed. The idea of the system operation is presented in Fig. 7.

The transmission is initiated by the first anchor, which sends the packet with its unique identifier (AN ID source) and a new sequential number (SQN). All nodes in the vicinity of the AN_1 receive this packet, but only the one with AN ID higher by 1 reacts to it. It programs so called "delayed transmission" and after predefined time interval a packet with new data, but the same SQN is sent. It is received by other anchors, yet only the one with AN ID higher by one responds. This chained transmission continues until the last anchor is reached. After that it starts all over again.

The PND receives packets from the anchors and measures their time of arrival. The position calculation algorithm, also utilizes data contained in the packet, such as a transmitting anchor's position and ID, packet burst's SQN and calibration data.

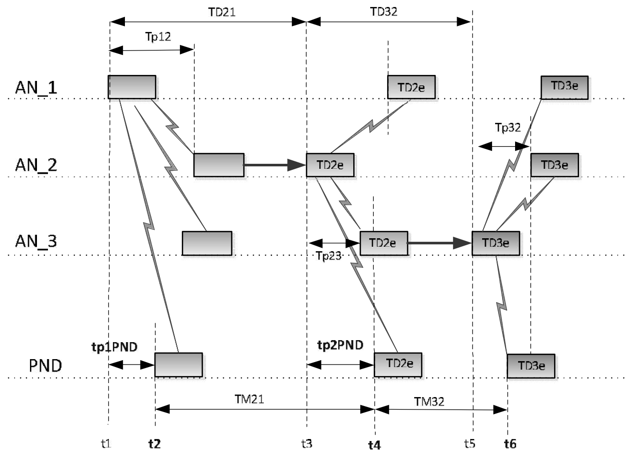


Fig. 7 – System operation scheme

3.5 TDOA EVALUATION

The position calculation relies on TDOA technique. Therefore, a TDOA values for consecutive anchors have to be determined. An exemplary calculation for TDOA21, between anchors 2 and 1 is described below.

According to Fig. 7, a standard TDOA equation can be written:

$$TDOA21 = tp2_{PND} - tp1_{PND} = t4 - t3 - (t2 - t1) \quad (1)$$

From Fig. 7 the following equation can be derived:

$$t2 - t1 + TM21 = t4 - t3 + TD21 \quad (2)$$

By rearranging components in (2), the equation takes the form:

$$TDOA21 = t4 - t3 - (t2 - t1) = TM21 - TD21 \quad (3)$$

Generally, for every pair of anchors:

$$TDOA_{NM} = TM_{NM} - TD_{NM} \quad (4)$$

The TD_{NM} period is unique for each pair of the anchors and consist of the following components:

$$TD_{NM} = Tp_{MN} + Tdel + ANdel + \varepsilon_{RX} + \varepsilon_{TX} \quad (5)$$

where, Tp_{MN} is the constant propagation time between anchors, which can be calculated based on their locations, Tdel is a transmit time delay, constant for all anchors, ANdel time is a constant delay time introduced by each anchor, and both ε_{RX} and ε_{TX} are random components resulting from clock signal instabilities, the method for signal detection etc.

3.6 ANCHORS CALIBRATION

For the proper TDOA estimation, anchor node delay (ANdel) value is needed. Therefore a calibration leading to evaluating this value is required for each anchor node. It can be performed by placing the receiver and two anchors in known positions (Fig. 8) and performing a series of TDOA measurements.

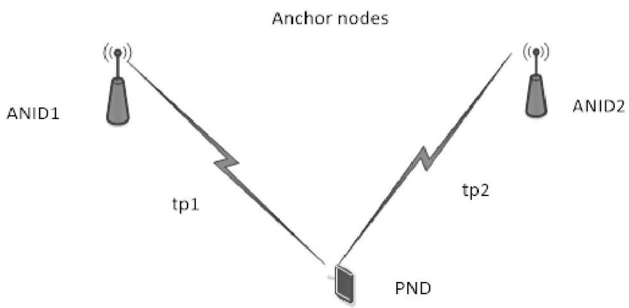


Fig. 8 – Calibration procedure

Since all devices' positions are known, a real TDOA value can be calculated:

$$TDOAr = tp2 - tp1 \tag{6}$$

Measurement results can be averaged which would lead to reduction of random components' influence. Required ANdel value can be obtained from equation (5).

3.7 POSITION CALCULATION

The position determination algorithm is based on Extended Kalman Filter [10]. The filter calculates estimation of the state vector including receiver coordinates and receiver velocity components. In each iteration the predicted state vector values are corrected taking into account the measurement vector containing measured TDOA values. In the proposed filter implementation the measurement vector length is not fixed, it depends on the number of available results.

4. UWB SUBSYSTEM INVESTIGATION

4.1 SCOPE OF TESTS

The UWB subsystem has been developed from scratch. Therefore its investigation was of prime importance. As the positioning process relies on two steps: the TDOA measurements and the position determination, these two processes were investigated. The exemplary results, presented in this paper, were obtained in laboratory conditions.

4.2 TDOA MEASUREMENTS

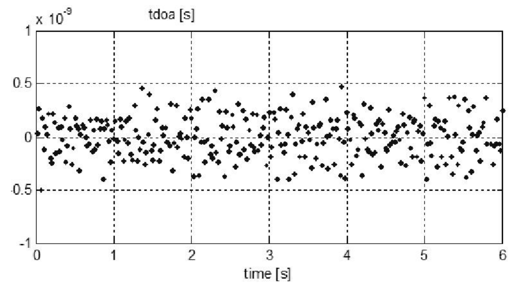
The first tests were focused on the determination of accuracy and precision of TDOA measurements. Tests with various clock signal sources were performed: a standard crystal oscillator, a TCXO and a rubidium standard. The test consisted in the reception of a series of packets transmitted by the anchor node at the predefined rate (rates were changing from 5 to 50 packets per second). The receiver measured time intervals between incoming packets and calculated TDOA values.

Three main TDOA error components were identified:

- time offset caused by clock frequency offsets (it was especially seen in crystal oscillator case),
- relatively slow clock frequency drift observed in modules with crystal oscillators (the largest changes were in the order of a few nanoseconds),
- TDOA random components.

Exemplary results obtained with TCXO are shown in Fig. 9. TDOAs were normalized by subtracting the TDOA mean value. The TDOA standard deviation observed during measurements was in the range from 200 to 250 picoseconds. This value does not depend on the measured period and clock source. The first path component detection technique implemented in the DW1000 chip is probably the main contributor to this error.

a)



b)

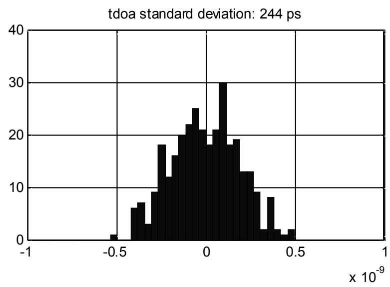


Fig. 9 – Normalized TDOA results: a) versus time b) histogram

4.3 POSITIONING RESULTS

The tests were carried out in three laboratory rooms in the Electronics and Information Technology Faculty building. The rooms are equipped with laboratory equipment and metal cabinets, so the propagation environment is very challenging. Anchor nodes were located at heights ranging from 1.6 m to 2.5 m.

The test consisted in measurement of TDOAs with the test receiver. The collected results were processed with positioning algorithm based on Extended Kalman Filter.

Anchor node delays were determined in LOS propagation conditions. In a real environment, where the system is deployed, the propagation times between anchor nodes was different from times calculated from anchor nodes coordinates. It is mainly caused by objects introducing additional delays when signals are passing through or by reflecting objects changing path of signal propagation. Therefore the measurement of real delays was performed.

The test setup consisted of two EVB1000 nodes and application allowing for distance measurement with TWR technique. Both modules as well as software are included in EVK1000 Decawave's evaluation kit [11, 12]. The measurements consisted in placing the modules in anchor node locations and performing measurements.

Introduced corrections resulted in small accuracy and precision improvement, especially in side rooms. In the center room the significant improvement was not observed. In this case transmission from four anchor nodes is sufficient to provide good localization accuracy.

The results of positioning are shown in Fig. 10. Location of anchor nodes is marked with black stars. Small dots correspond to raw positioning results. Averaged positions are marked with circles, test point locations with diamonds. The mean positioning errors, correspond to the distance between test points and averaged positions. Error values expressed in meters are placed close to the lines connecting averaged and test point positions. Circular error probability (CEP) (calculated for 50% of points) was used as a measure of obtained positioning results precision. Particular CEP values are placed on the gray background, the circles illustrate this measure.

Cumulative distribution function (CDF) calculated for localization error and precision are presented in Fig. 11. Mean positioning error lower than 1 m was obtained in 90% of test locations. The precision of all recorded results is better than 0.4 m.

The system has a very good accuracy and precision in the center room (room 28). In many points positioning errors and CEP values are lower than 10 cm. Two test points are located close to objects obscuring signal propagation, but even in these cases the positioning error is lower than 1m.

Bigger errors occur in both side rooms because of lower number of signals reaching the receiver and calculation of position using results of measurements carried out for reflected signals.

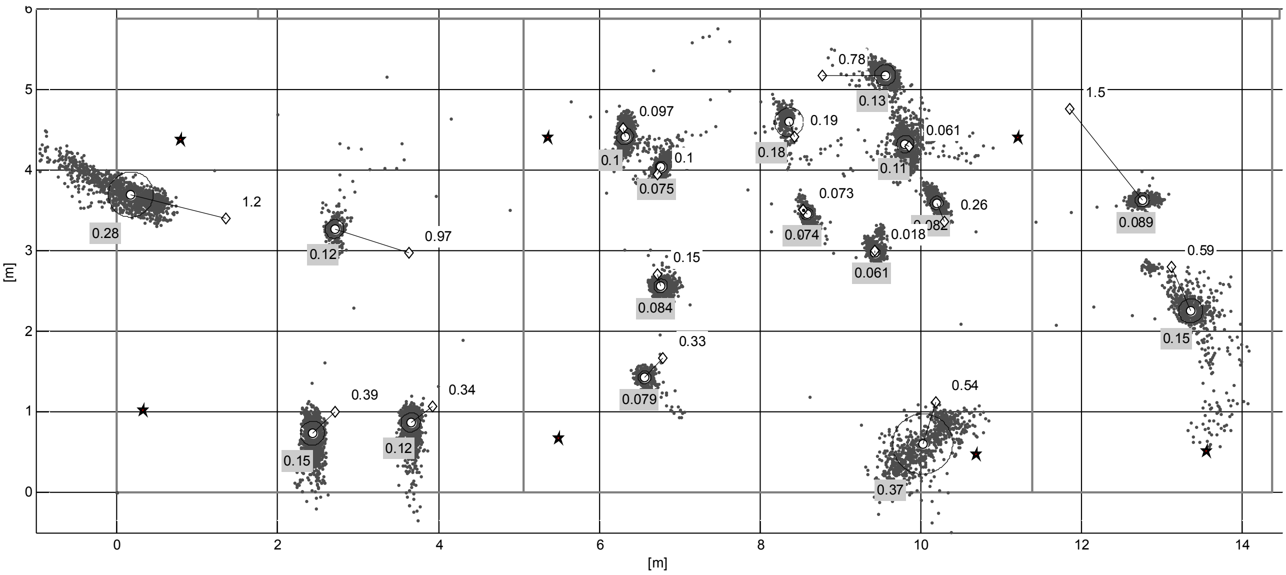
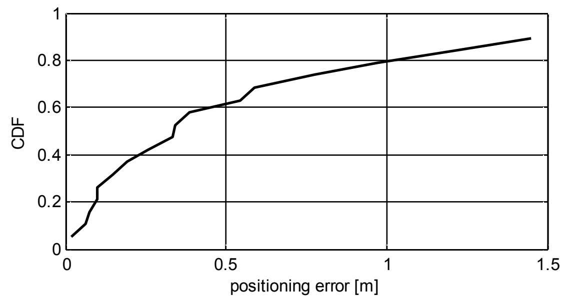


Fig. 10 – Positioning results after inter-anchor propagation time correction



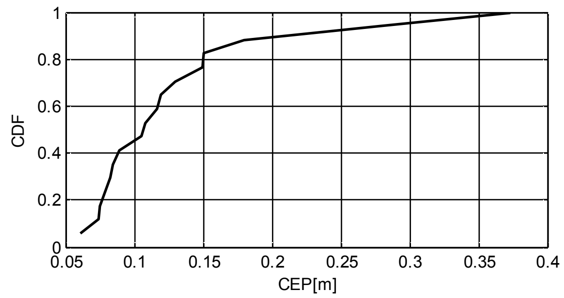


Fig. 11 – Positioning error and precision cumulative distribution functions

5. CONCLUSION

The paper contains a description of the indoor and outdoor positioning system developed within the EIGER project. The performance of the system indoors depends on the UWB positioning system.

The novelty of the proposed solution consists in wireless synchronization of anchor nodes. It reduces system cost and simplifies the deployment.

The laboratory tests showed that the proposed solution provides TDOA measurements with 250 ps precision, which impacts the positioning accuracy that can be obtained.

The obtained results demonstrate that quality of positioning results depends not only on the availability of signals, but the quality of these signals also plays an important role. A significant shifts in obtained positions were observed in cases where direct path components of transmitted signals were blocked by the laboratory equipment (e.g. metal cabinets). Thorough distribution of nodes or increasing their number will allow for the system accuracy and precision improvement.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] A. Fluerasu, A. Vervisch-Picois, G. Boiero, G. Ghinamo, P. Lovisolo, N. Samama, “Indoor positioning using GPS transmitters: Experimental results,” in *Proceedings of the International Conference on Indoor Positioning and Indoor Navigation (IPIN’2010)*, 2010, pp. 1-9.

[2] A. Vervisch-Picois, I. Selmi, Y. Gottesman, N. Samama, “Current status of the repealite based approach: A sub-meter indoor positioning system,” in *Proceedings of the 5th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC’2010)*, 2010, pp. 1-6.

[3] R. Mautz, “Combination of indoor and outdoor positioning,” in *Proceedings of the 1st International Conference on Machine Control & Guidance*, 2008, pp. 1-9.

[4] L. Reyero, G. Delisle, “A pervasive indoor-outdoor positioning system,” *Journal of Networks*, vol. 3, no. 8, November 2008, pp. 70-83.

[5] D. Fernandez, F. Barcelo-Arroyo, I. Martin-Escalona, M. Ciurana, M. Jofre, E. Gutierrez, “Fusion of WLAN and GNSS observables for positioning in urban areas: The position ambiguity,” in *Proceedings of the IEEE Symposium on Computers and Communications (ISCC’2011)*, 2011, pp. 748-751.

[6] Y. T. Chan, K. C. Ho, “A simple and efficient estimator for hyperbolic location,” *IEEE Transactions on Signal Processing*, vol. 42, issue 8, 1994, pp. 1905-1915.

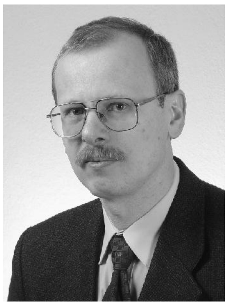
[7] IEEE Std 802.15.4a™-2007, “PART 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs),” “Amendment 1: Add Alternate PHYs”, August 2007.

[8] *DW1000 Data Sheet*, DecaWave, 2014.

[9] J. Kolakowski, A. Consoli, V. Djaja-Josko, J. Ayadi, L. Morrigia and F. Piazza, “UWB localization in EIGER indoor/outdoor positioning system,” in *Proceedings of IEEE 8th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS’2015)*, Warsaw, 2015, vol. 2, pp. 845-849.

[10] M. S. Grewal, A. P. Andrews, *Kalman Filtering: Theory and Practice Using MATLAB*, 3rd Edition, Wiley 2008.

[11] *EVK1000 User Manual*, v.1.11, Decawave, 2015.
[12] *DecaRanging (PC) User Guide*, v.2.5, DecaWave, 2014.



***Jerzy Kolakowski** received the M.Sc. ('88) and Ph.D. ('00) degrees in telecommunications from the Warsaw University of Technology. Since 1988 he has been with the Institute of Radioelectronics and Multimedia Technology where he holds a position of Assistant Professor. He is a Member of the Management Board of the Foundation for the Development of Radiocommunications and Multimedia Technology, His current research interests include positioning systems, ultra wideband technology, cellular systems.*

***Angelo Consoli** received MSc. in electronic engineering from ETHZ Zürich. Professor and a Head of the IT security laboratory at the University of Applied Science of Southern Switzerland. Industrial experience: Siemens AG (4.5 years), AIG (3y) and many years as freelance technology consultant. Aerospace Programme Manager, project leader and head of the space business unit for NemeriX (2001-2009). Founder and managing director of ECLEXYS Sagl. Since 2007, mandated by the Swiss Government as a member of the group of experts entitled by the Swiss Space Office for related projects.*

***Vitomir Djaja-Josko** received the BSc ('13) and M.Sc ('15) degrees in telecommunications from the Faculty of Electronics and Multimedia Technology, Warsaw University of Technology, Poland. He is pursuing the Ph.D. degree in the Institute of Radioelectronics and Multimedia Technology. He is currently a member of the research team working in the field of UWB technologies. His research interests include UWB signals, indoor localization and synchronization methods in positioning systems.*

***Jaouhar Ayadi** received the Engineer Degree ('94) in electrical engineering from the Ecole Nationale d'Ingénieurs de Tunis in 1994. He received the MSc ('95) and PhD ('99) in Computer Science and Communication from the Ecole Nationale Supérieure des Télécommunications (ENST)-René Descartes University, Paris. In 1999, he joined the Wireless Communication Section of the Centre Suisse d'Electronique et de Microtechnique (CSEM), Switzerland, Currently he is a R&D Manager at ECLEXYS. His research interests include Digital Signal Processing for mobile communications, wireless propagation, UWB systems.*

***Lorenzo Morrigia** received the BS degree in Electrical Engineering from the University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Manno in 2004. From 2004 to 2009 he worked as Researcher at the Department of Innovative Technologies of SUPSI. Since 2009 he is with Saphyrion Sagl as principal HW electronic engineer, where he works in the development of RF and digital boards.*

***Francesco Piazza** received the M.Sc. degree in Electrical Engineering from the Swiss Federal Institute of Technology (ETHZ), Zurich, and the Ph.D. degree from the Integrated Systems Laboratory at the same university in 1999 under the supervision of Prof. Qiuting Huang. From 2000 to 2002 he worked for TChip Semiconductor as RF/analogue IC designer and from 2002 to 2008 at NemeriX SA as chief scientist for RF design. Since 2009 he is with Saphyrion Sagl as chief scientist, where he works in the development and industrialization of rad-hard space qualified RF/analog integrated circuits.*