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Analysis of Measurements of UWB PDoA Local Navigation System with Different Baselines

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Abstract— **Today global navigation satellite systems are the most affordable and efficient source of information on geographic coordinates, speed and precise time. However, GNSS-based solutions are not capable to meet accuracy and availability requirements of most applications of indoor navigation. The ultrawideband radio systems are considered as the most promising solution for indoor positioning, since they have the highest range resolution and potential accuracy. A great number of UWB-based solutions for indoor positioning are known but systems implementing phase-based angle of arrival estimation are considered as very promising and more advantageous and preferable in comparison with time-based approaches like time of flight and time difference of arrival methods. In this regard this paper is devoted to investigation and analysis of performance of commercial ultrawideband phase difference of arrival local navigation system with 3 different baselines. Conducted experiment allows to increase angle of arrival resolution of considered system. Standard deviation of angle of arrival estimates calculated from obtained in experiment phase difference of arrival measurements decrease with increasing baseline length. In future work it is planned to develop method which helps to deal with phase ambiguities when phase measurements wrap around at a multiple of 2π for baselines greater than half of wavelength.**

Keywords—phase difference of arrival (PDoA), angle of arrival (AoA), ultrawideband (UWB), indoor positioning system, phase direction finder

I. INTRODUCTION

Global navigation satellite systems (GNSS) [1, 2] are playing an increasingly important role in the global economy and the daily lives of many people. Today there are a number of GNSS applications in various market segments, including navigation and monitoring of aerial, maritime, ground and railway transport, contribution to the implementation of highly effective farming management in agricultural sphere and frequency and time synchronization in communications networks, power grids, and financial systems.

As the most affordable and efficient source of information on geographic coordinates, speed and precise time, GNSS devices have become essential elements of a number of modern technical solutions, including solutions such as IoT, Big Data, augmented reality, as well as solutions for mobile medicine, smart cities and multimodal logistics.

GNSS devices and navigation devices in particular are becoming more widespread and are constantly being improved. A new trend is the development of the production of mass-produced GNSS devices operating at several frequencies simultaneously, which significantly improves the accuracy of positioning.

Despite this fact it is impossible for GNSS-based solutions to meet accuracy and availability requirements of most applications of indoor navigation. This is explained by the obvious reason: signals transmitted from GNSS satellites are not capable to pass through the walls and roofs of buildings. Even though some sensitive GPS devices can sometimes get a fix (receive signals from enough satellites to determine a location) inside a building, the resulting location is typically not accurate enough to be useful because signals from the satellites are attenuated and scattered by obstacles in the propagation paths.

In this regard, there is an increasing need in development indoor positioning systems. The indoor positioning market is predicted to show double-digit growth rates every year and there is a high demand for solving the following indoor positioning problems: locating patients and visitors in hospitals, optimizing staff workers routes and collision avoidance of augmented guided vehicles in warehouse, quality assurance and managing inventory in manufacturing, players positioning in location-aware VR/AR applications and others.

To date, all known solutions of indoor positioning problem can be divided into the following groups:

- optical systems;
- ultrasound systems;
- narrowband radio systems;
- ultrawideband radio systems;
- inertial systems;
- odometry systems;
- magnetometry systems.

Strengths and weaknesses of each of the listed group of indoor positioning systems are discussed in detail in [3,4].

Indoor radio systems are the most widespread cluster from all mentioned groups including various solutions based on several radio technologies: Ultra-WideBand (UWB), Bluetooth/Bluetooth Low Energy (BLE), Wi-Fi, ZigBee, NFER (Near-Field Electromagnetic Ranging), Radiofrequency identification (RFID). The ultrawideband radio systems are considered as the most promising solution for indoor positioning, since they have the highest range resolution and potential accuracy providing positioning error less than 10 cm [5].

UWB-based indoor positioning systems usually utilize intersection navigation methods. These methods can be implemented in systems with various architectures and differ in measured parameters which are the following: Time of Flight (ToF), Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), etc [5]. All intersection navigation methods are based on determining the unknown user location by one (or several) measured parameters, carried out by receiving a signal from radio navigation reference points (frequently called anchors) with previously known coordinates.

A great number of UWB-based solutions for indoor positioning are known but systems implementing phase-based AoA estimation are considered as very promising and more advantageous and preferable in comparison with time-based approaches like ToF and TDoA [6,7]. The main advantage of such system that only one anchor is required for 2D-positioning. However, the major drawback of solutions implementing phase-based AoA estimation is complexity of system design and therefore manufacturing cost, due to the fact that physical principle requires two receivers synchronized with one crystal oscillator and two receiving antennas.

II. Problem Statement

In this work we considered AoA system based on PDoA measurements. Such system is also called phase direction finder. It usually contains two (or more) identical antenna elements separated in space by a known distance *L*, called a baseline (Fig. 1).

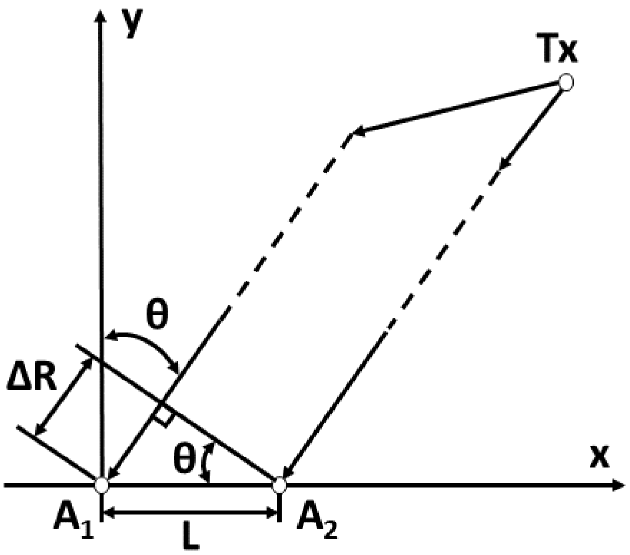

Fig. 1. Principles of AoA estimation based on PDoA measurement.

Let us assume that the distance from the direction finder to the signal source (Tx) is much greater than the baseline L. Then the wave incident on the antenna system can be considered as a plane wave. Thus, the difference in distance traveled by the two waves from signal source to antenna elements can be found as:

$$\Delta R = L\sin(\theta) \ . \tag{1}$$

PDoA α of two waves is related to path difference ΔR as:

$$\alpha = \frac{2\pi}{\lambda}\Delta R \ , \tag{2}$$

where λ is notation of signal wavelength defined as ratio of speed of light to signal frequency.

From (1) and (2) AoA θ can be expressed as:

$$\theta = \arcsin\left(\frac{\Delta R}{L}\right) = \arcsin\left(\frac{\alpha\lambda}{2\pi L}\right). \tag{3}$$

Formula (3) is the basis for determining the AoA θ based on PDoA measurements α.

In [8] authors show the following relationship between standard deviation of AoA estimates and standard deviation of PDoA measurements:

$$\sigma_\theta = \frac{\sigma_\alpha}{2\pi\frac{L}{\lambda}\cos(\alpha)} \ . \tag{4}$$

This formula reveals one of the most important advantages of phase direction finder: for a fixed phase error σ_α, the angular error σ_θ can be made arbitrarily small if the ratio $\frac{L}{\lambda}$ is large enough. An obstacle to increasing baseline length *L* in two-channel direction finders is the ambiguity of phase measurements.

In this work we research dependence of σ_α and σ_θ on ratio $\frac{L}{\lambda}$ by varying baseline length *L* in real experiment.

III. Experiment

To evaluate statistical characteristics of PDoA measurements we carried out field experiment which described below (Fig. 2).

As a hardware which allows to measure bearing angle based on phase difference of signal arrival, we used PDoA Beta kit produced by Decawave [9,10]. This kit contains DWM 1002 (Node) radio module with two antennas and two DW1000 receivers synchronized from the same 38.4 MHz reference clock input. The appearance of described modules is shown in Fig. 3 and Fig. 4.

The PDoA node and tags hardware and software are designed to operate on channel 5 of UWB frequency range with a central frequency of 6489.6 MHz and, accordingly, signal wavelength of 4.62 cm.

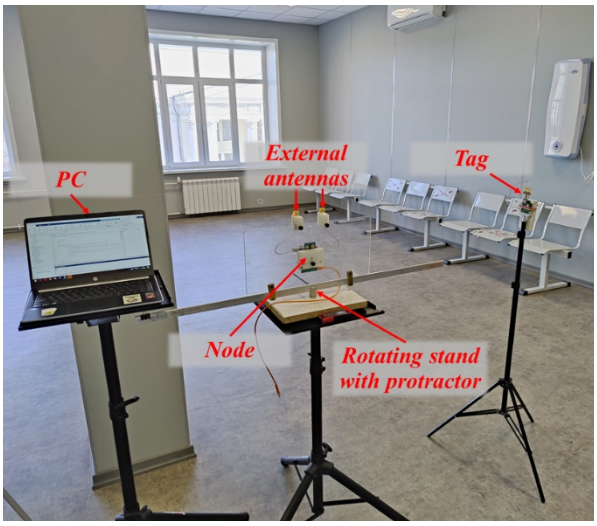

Fig. 2. Experimental equipment.

Fig. 3. Appearance of tag module (Tag) DWM 1003.

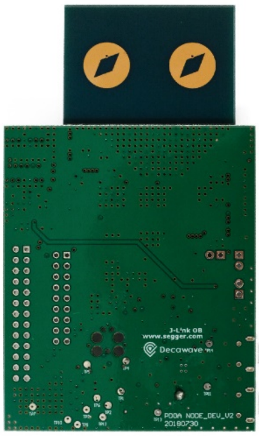

Fig. 4. Appearance of node module (Node) DWM 1002.

During conducted experiment the tag, fixed on tripod at the same height as node, was placed consecutively at distances (R) of 1 meter, 5 meters and 10 meters from node. At each of these three distances we recorded 10 datasets of phase difference measurements (500 samples in each dataset), while rotating the node relative to the tag by angles from 0° to 90° in steps of 10°. Such procedure we repeat for three different distances between the external antennas (baselines) multiple of half of signal wavelength λ: λ/2, λ and 2λ.

IV. Results and Discussion

Datasets of phase difference measurements obtained during conducted experiments were summarized in six boxplots (Fig. 5 - Fig. 13). On each box, the central mark indicates the median. The bottom and top edges of each box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points and outliers are not considered. The outliers are plotted

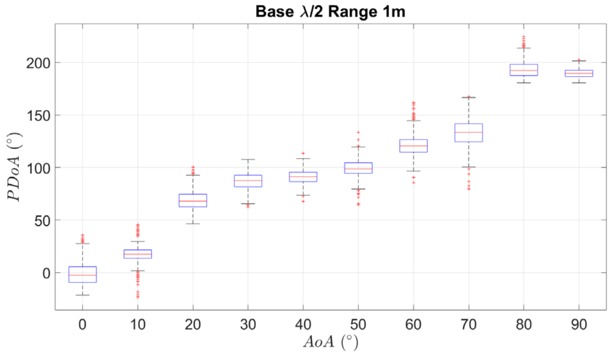

Fig. 5. Distribution of phase measurements for baseline = λ/2 and R=1m.

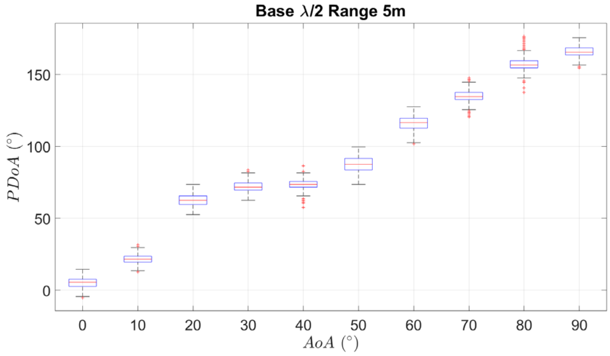

Fig. 6. Distribution of phase measurements for baseline = λ/2 and R=5m.

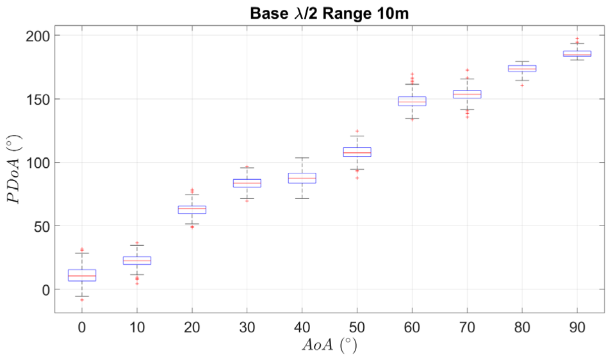

Fig. 7. Distribution of phase measurements for baseline = λ/2 and R=10m.

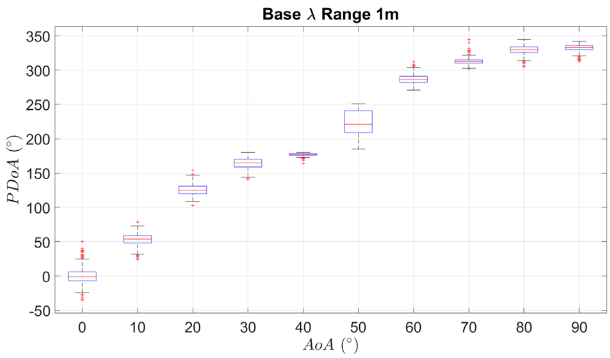

Fig. 8. Distribution of phase measurements for baseline = λ and R = 1 m.

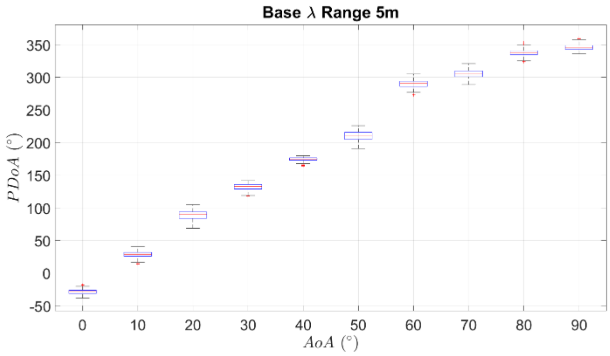

Fig. 9. Distribution of phase measurements for baseline = λ and R = 5 m.

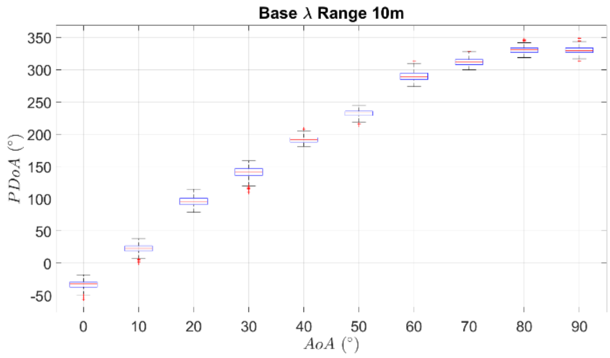

Fig. 10. Distribution of phase measurements for baseline = λ and R = 10 m.

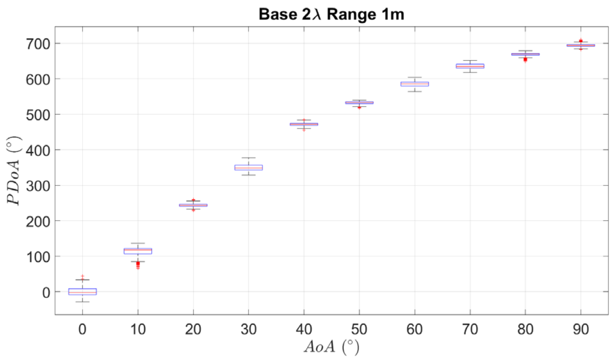

Fig. 11. Distribution of phase measurements for baseline = 2λ and R = 1 m.

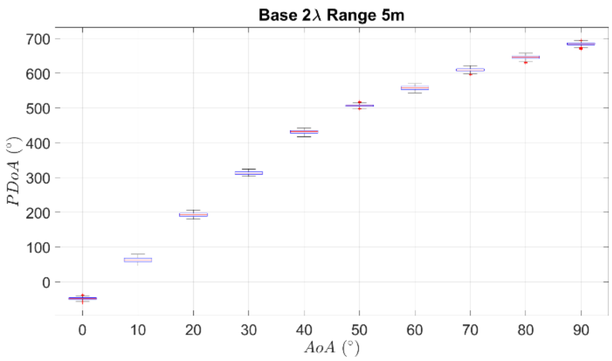

Fig. 12. Distribution of phase measurements for baseline = 2λ and R = 5 m.

individually using the '+' symbol. In Fig. 5 – Fig. 13 vertical axis shows the phase difference of the received signal in the corresponding experiment in degrees.

In all conducted experiments we made a calibration procedure for each baseline length: device readings at a distance of 1 meter and at an angle of 0° are considered as zero offsets and all obtained measurements were corrected on these values.

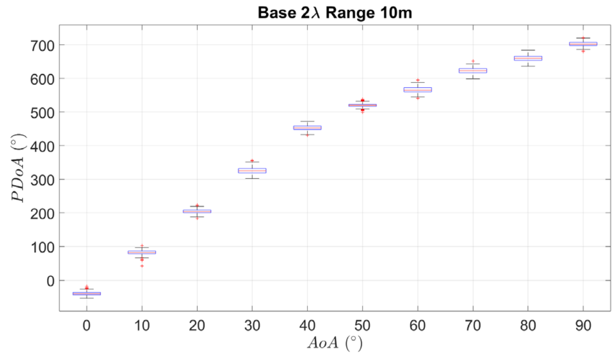

Fig. 13. Distribution of phase measurements for baseline = 2λ and R = 10 m.

From expression (3) it is clear that in order for α and θ to have one-to-one mapping in θ from -π/2 to π/2, baseline L must be less than λ/2. Since, in our experiment we spaced external antennas at greater distance, violating inequality above, PDoA measurements began to wrap around extending beyond range of [-π, π]. In this regard we manually have adjusted some datasets for values multiple of 2π.

As we can see from boxplots above, discriminator curve of considered system does not change its form essentially even with connected external antennas, but slope of curve is higher (and value of slope increases with higher baseline length). This fact allows to state that despite PDoA measurements have almost the same standard deviation σ_α regardless of baseline length, standard deviation of AoA measurements σ_θ is less than σ_α and its value inversely depends on baseline length.

In order to prove abovementioned statement about dependences of σ_α and σ_θ on baseline length and expression (4), we calculate these standard deviations for 3 baseline length at angles from 0° to 90° in steps of 10° and at a distance of 5 meters. All obtained results were summarized in Table I presented below.

TABLE I. DEPENDENCES OF σ_α AND σ_θ ON BASELINE LENGTH, OBTAINED IN EXPERIMENT

	λ/2		λ		2λ	
	σ_α	σ_θ	σ_α	σ_θ	σ_α	σ_θ
0°	3.6449	1.1609	3.4231	0.5465	3.3268	0.2653
10°	3.3204	1.0653	4.5239	0.7223	6.3363	0.5062
20°	4.0679	1.3815	6.8243	1.1201	6.1589	0.5041
30°	3.6454	1.2671	5.0526	0.8640	4.0203	0.3206
40°	3.9707	1.3803	2.8980	0.5269	5.5080	0.4405
50°	5.1323	1.8646	6.5220	1.1403	3.0708	0.2496
60°	4.8786	2.0263	5.5636	0.9027	5.3972	0.4409
70°	4.4268	2.1219	6.0790	0.9792	4.6768	0.3766
80°	5.2960	3.8432	4.6578	0.7428	5.1153	0.4093
90°	3.7811	3.1436	4.4755	0.7128	4.4537	0.3549

As can be seen from Table 1 obtained results gave good agreement with formula (4) for each angle and standard deviation of AoA measurements σ_θ decreases with declining ratio L/λ.

V. Conclusion

In this paper we investigate performance of commercial UWB PDoA local navigation system with 3 different baselines. Conducted real field experiment and subsequent calculations show that discriminator curve of considered system retains its form essentially even with connected external antennas, but slope of curve increases with baseline length. This fact allows to state that increasing baseline length we managed to increase AoA resolution of considered system or in other words we decreased standard deviation of AoA estimates. We proved this statement presenting table with calculated standard deviation of AoA estimates for different baseline length.

In future work it is planned to develop method which helps to deal with phase ambiguities when phase measurements wrap around at a multiple of 2π for baselines greater than half of wavelength.

References

[1] A. Perov, V. Kharisov, "GLONASS. Construction and functioning principles," Radiotekhnika, Moscow, 2010, pp. 3-23.

[2] Y. Bar-Shalom, X.-R. Li, T. Kirubarajan, "Estimation with Applications to Tracking and Navigation: Theory, Algorithms and Software," John Wiley & Sons, Inc., USA, 2001.

[3] A. Chugunov et al., "Integration of Local Ultrawideband ToA/AOA Phase Difference of Arrival System and Inertial Navigation Systems," 2020 27th Saint Petersburg International Conference on Integrated Navigation Systems (ICINS), Saint Petersburg, Russia, 2020, pp. 1-8, doi: 10.23919/ICINS43215.2020.9133989

[4] F. Zafari, A. Gkelias and K. K. Leung, "A Survey of Indoor Localization Systems and Technologies," in IEEE Communications Surveys & Tutorials, vol. 21, no. 3, pp. 2568-2599, thirdquarter 2019.

[5] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. Al-Ammar, H. Al-Khalifa, "Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances," in *Sensors*, vol. 16, no.5, pp. 1-36, May 2016, doi: 10.3390/s16050707.

[6] M. Heydariaan, H. Dabirian, and O. Gnawali, "Anguloc: Concurrent angle of arrival estimation for indoor localization with uwb radios," in 2020 16th International Conference on Distributed Computing in Sensor Systems (DCOSS). IEEE, 2020.

[7] N. Smaoui, M. Heydariaan and O. Gnawail, "Single-Antenna AoA Estimation with UWB Radios," 2021 IEEE Wireless Communications and Networking Conference (WCNC), 2021, pp. 1-7, doi: 10.1109/WCNC49053.2021.9417526.

[8] V. P. Denisov, D. V. Dubinin "Phase direction finders: Monograph," – Tomsk: Tomsk State University of Control Systems and Radioelectronics. - 2002. - 251 p.

[9] Beta PDoA kit User Manual, Decawave, 2018.

[10] I. Dotlic, A. Connell, H. Ma, J. Clancy and M. McLaughlin, "Angle of arrival estimation using decawave DW1000 integrated circuits," 2017 14th Workshop on Positioning, Navigation and Communications (WPNC), 2017, pp. 1-6, doi: 10.1109/WPNC.2017.8250079.