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doi:10.15199/48.2025.03.07

Application of temporal analysis of high-frequency signals in a distributed asset management system

***Abstract**. This thesis addresses the temporal analysis of ultra-wideband signals in a real-time localization system (RTLS). The main focus is laid on tag hardware solutions, miniaturization and energy optimization. It also addresses the algorithms responsible for estimating the user's location, how to manage the acquired data, and the methodology for its transfer and processing. The type of location network presented can find application in all kinds of WMS systems.*

***Streszczenie.** Niniejsza rozprawa dotyczy wykorzystania analizy czasowej sygnałów ultra-szerokopasmowych w systemie lokalizacji czasu rzeczywistego (RTLS). Główny nacisk położono na rozwiązania sprzętowe znaczników oraz ich miniaturyzację i optymalizację zużycia energii. Omówiono również algorytmy odpowiedzialne za szacowanie lokalizacji użytkownika, sposób zarządzania pozyskanymi danymi oraz metodologię ich przesyłania i przetwarzania. Przedstawiony typ sieci lokalizacyjnej może znaleźć zastosowanie we wszelkiego rodzaju systemach WMS (**Zastosowanie analizy czasowej sygnałów wysokoczęstotliwościowych w rozproszonym systemie zarządzania majątkiem**).*

Keywords: ultra-wideband signals; time analysis of signals; indoor localization; WMS systems.
Słowa kluczowe: sygnały ultra-szerokopasmowe; analiza czasowa sygnałów; lokalizacja wewnątrzbudynkowa; systemy WMS.

Introduction

The work presented is devoted to a proprietary hardware and software solution for efficient asset management in large-scale warehouses or related facilities. It describes the structure and components used to build the UWB (ultra-wideband) marker and anchor PCB (printed circuit board) and the location algorithms [1-8] with and without machine learning support to increase the efficiency of locating the minor possible items [9-12]. A number of different algorithms can be used in the localization process [13-21]. The topic is directly related to the increased but insufficient maturity of radio technologies for intra-body localization and navigation systems.

Development of the hardware layer

The envisaged structure of the equipment network included two types of elements: so-called anchors and markers. Anchors are elements with a known and fixed position in space and permanent and unrestricted access to the building's power supply and local network. Tags, on the other hand, are elements attached to objects tracked and localized by anchors. Both types incorporate the use of Qorwo's DWM microcontrollers. Different types of data transmitted outside the UWB band can be considered as readings from environmental sensors installed on each tag. The only exception is the accelerometer, whose signal is only used to wake the device from deep sleep in order to save the tag's built-in battery. This is a crucial procedure as it prevents the battery from being consumed in the absence of object movement. The accelerometer's trip threshold is adjustable over a wide range depending on the application conditions. Other key features include an integrated UWB antenna optimized for frequencies characteristic of this technology, a series of power and signal filters, and a separate transmission line with matching circuits and antenna for 2.4 GHz band operation. The final appearance of the devices is shown in Figure 1 and Figure 2.

For operation, the presented system uses a variable frequency radio signal source from 3.5 to 6.5 GHz with a split characteristic of the UWB band. This corresponds to the classification of ultra-wideband signals from the entire low band (channels 0 - 2) and the first channel of the high band (3). The channel width is typically 500 MHz. The DWM1000 microcontroller is responsible for signal generation and measurement data acquisition. Depending on the device (anchor or tag), it is connected to various other functional blocks. In the case of the anchor, an STM32 microcontroller from the F7 series is equipped with an Ethernet connection. In the case of the tag, it is a fusion with the nRF52832 microcontroller, designated to transport environmental data acquired from temperature, humidity and pressure sensors on the PCB.

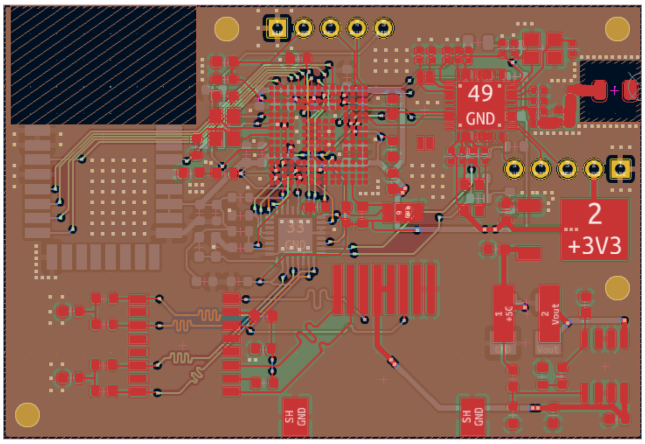

Fig. 1. Author's coupling solutions created in the project – a mosaic of electrical connections of the ultra-wideband anchor

Fig. 2. Author's coupling solutions created in the project – actual prototypes of the UWB anchor (left) and UWB tags (right)

Both devices assume the use of FR4 laminate with a total thickness of 1.6 mm. The copper thickness of both layers (top and bottom) of the PCB is 0.035 mm. The PCB laminate has been stripped of the polygon in all PCB-sensitive sectors, which could adversely affect RF layer performance. Connections operating at high frequencies have been smoothed and differential lines impedance equalised. This is especially true when implementing Ethernet communication and passing differential signals through a symmetrizer in the antenna path.

Comparison of positioning algorithms & results

Two newly developed algorithms with a reference point in the form of a trilateration method for determining points in space using a system of triangles (trilateration) are analyzed. The first can be called machine learning-assisted trilateration (MLET), while the second is localization by optimization (LBO). The method using MLET takes each pair of anchors and their corresponding distances and then finds the corresponding circle intersections. An unsupervised machine learning algorithm – DBSCAN (Density-Based Spatial Clustering of Applications with Noise) – then takes the set of intersections and divides the points into relevant and outliers. The center of the appropriate cluster is the localized position returned by the method. The second method – LBO – uses a different approach. It constructs a goal function from the distance equations of each anchor. Ideally, this function would completely disappear for the solution. However, it should be stressed again that the algorithm is dealing with noisy data, so the global minimum of the objective function corresponds to the best approximation of the user's position

The LBO and MLET algorithms are two advanced methods designed to enhance the accuracy and reliability of indoor positioning systems utilizing UWB technology. LBO is an optimization-based approach that minimizes the discrepancy between measured and theoretical distances from multiple UWB anchors to a transmitter. By formulating an objective function that captures these discrepancies, LBO employs techniques such as gradient descent or genetic algorithms to iteratively adjust the estimated coordinates of the transmitter. This method is particularly effective in handling complex environments and mitigating errors caused by non-line-of-sight conditions and other interferences, providing a robust solution for precise indoor localization.

In contrast, the MLET algorithm integrates machine learning techniques to improve traditional trilateration methods. It starts with collecting distance measurements from UWB anchors and preprocessing this data to reduce noise and outliers. Circle equations are then formulated based on these measurements to identify potential intersections that indicate the transmitter's location. MLET leverages the DBSCAN algorithm to cluster these intersection points, effectively distinguishing relevant data from noise. This approach significantly enhances the reliability and precision of the localization system, making it highly effective in dynamic and challenging environments. Both LBO and MLET represent significant advancements in indoor positioning technology, offering improved accuracy and robustness across various real-world scenarios.

However, before implementing the measurement algorithms, it was first necessary to quantify the errors for the usual distance calculations based on the ToF (Time of Flight) method. It involves comparing and calculating the difference between the start and end timestamps of a transmission between two devices. Knowing the speed of light and dividing the result by half makes it possible to calculate the distance between two devices. Then, using classic trilateration, the 2D coordinates of the tracked objects were calculated and compared with the coordinates calculated from the values measured with a laser rangefinder. The results are presented in Figure 3.

Figure 4, in turn, shows a summary of the positioning error values for a series of 80 samples. The resulting diagrams clearly show that trilateration returns worse results than the other two methods. The error reaches up to 50 cm for trilateration, while MLET and LBO do not exceed 30 cm. Table 1 summarises the averaged error values for all measurement series and calculation algorithm types. These show a 25% advantage of the MLET and LBO algorithms over traditional trilateration.

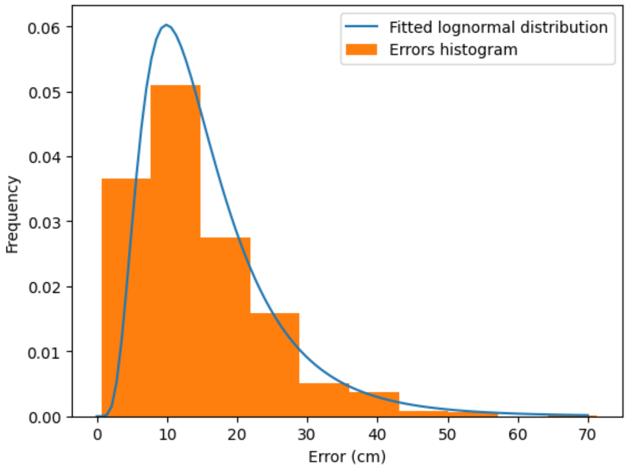

Fig. 3. Histogram of algorithm errors with fitted log-normal distribution

Table. 1. Comparisons of localization errors obtained by three different algorithms

Seq. number	Method	Mean error
[-]	**[-]**	**[cm]**
1	Classic trilateration	15.21
2	LBO	11.66
3	MLET	11.31

During the development of the system, several synthetic environments and one real environment were created. The artificial environments involved mapping storage rooms of different sizes or logistics centers. One such visualization is depicted in Figure 5. Each of the maps created had an infinitely variable number of markers it could handle, making it possible to perform load tests on the system. The same applies to a real test environment but with the consideration of real devices and a database created in SQL. One such load test is presented in Figure 6, where the simultaneous shuffling of more than 100 tags was simulated. All distance readings obtained from the ToF technique and the corresponding environmental parameters were fed into the LAN via a wired connection. All results, on the other hand, were clustered in a dedicated service. Figure 7, in turn, is an approximation of the environmental data labels coupled to a specific tag. This provided a convenient way to monitor the storage parameters for each load. Exceeding a preset value triggered a system response and immediate notification to the system operator.

In contrast to synthetic tests, real-world tests additionally take into account scenarios such as going outside the test zone until the tag's range breaks with most anchors, making tracking impossible. This is one of the features that distinguishes this type of system from networks using tomographic methods, which are limited by the circumference of the probe belt.

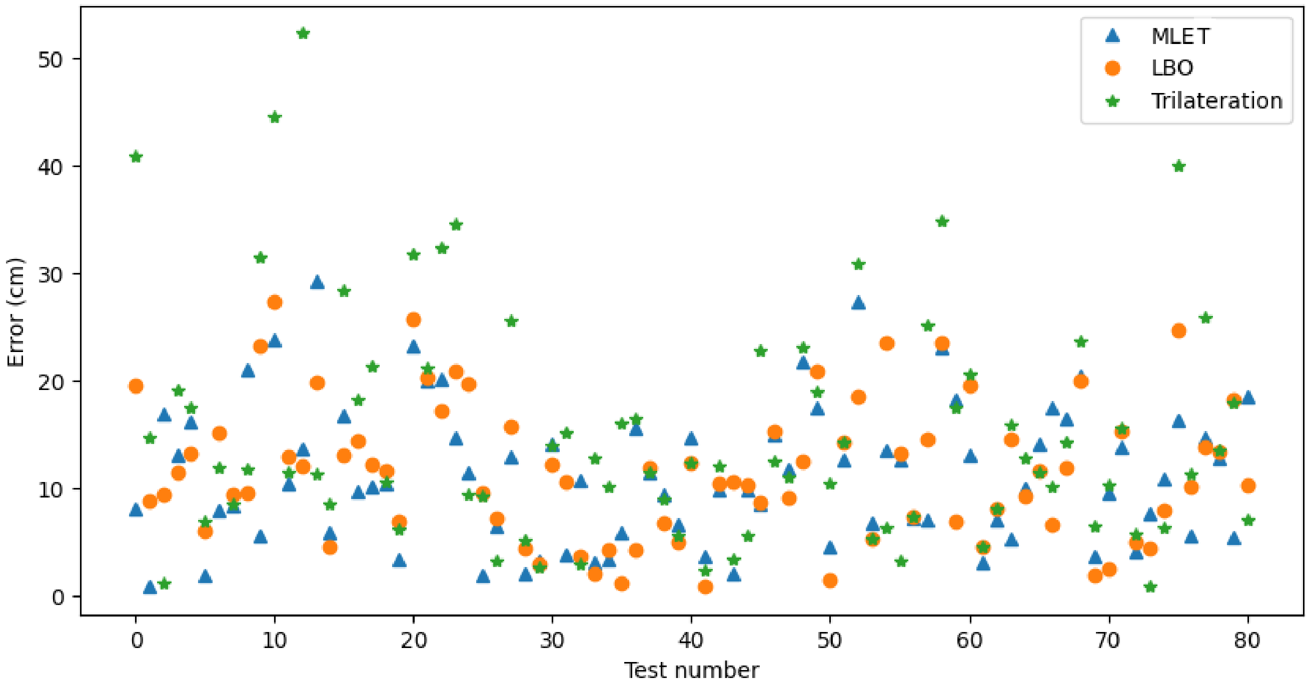

Fig. 4. Position errors - the distance between the actual and calculated position of the device for the three selected methods

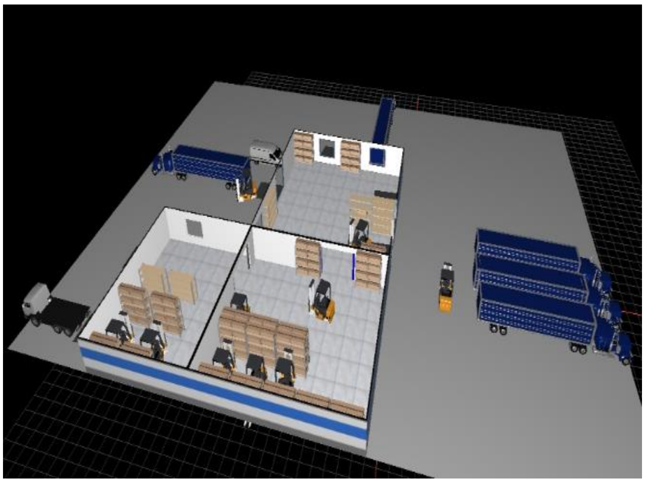

Fig. 5. Software with built-in 3D visualization environment for operating the system

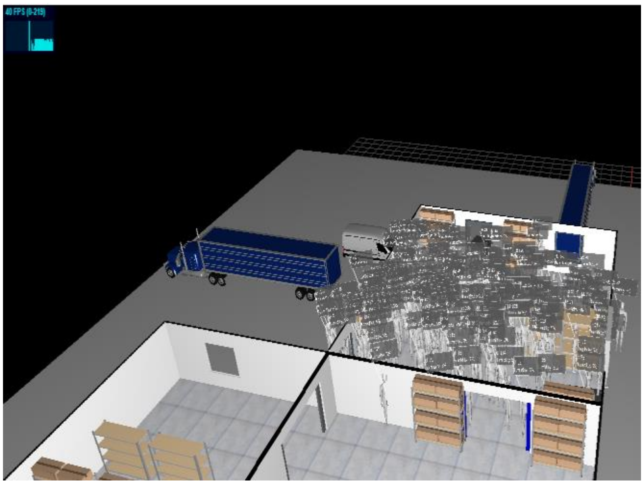

Fig. 6. View of synthetic system load tests with 1000 transmitting tags

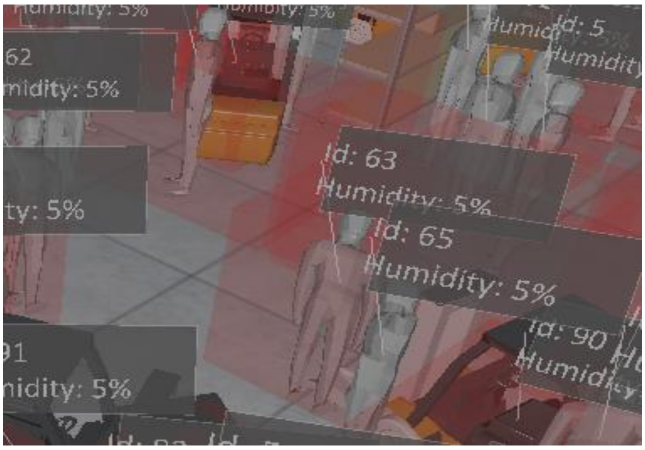

Fig. 7. View of tracked objects with consideration of environmental storage parameters

Results and conclusions

The study demonstrates the effectiveness of the LBO (Localization by Optimization) and MLET (Machine Learning Enhanced Trilateration) algorithms in enhancing the accuracy and reliability of UWB-based indoor positioning systems. Through rigorous testing under controlled conditions, the LBO algorithm showcased its robustness in minimizing discrepancies between the measured and theoretical distances by employing optimization techniques such as gradient descent and genetic algorithms. Similarly, the MLET algorithm improved traditional trilateration methods by integrating machine learning, specifically the DBSCAN algorithm, to cluster intersection points and reduce noise effectively. Although this research focused on evaluating core functionalities, future work will explore the performance of these algorithms under real-world conditions, including various interference factors. This will ensure their practical applicability in dynamic environments, contributing significantly to advancing precise indoor localization technologies.

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