A Localisation and Telemetry LoRa Node for Rockets

Marta Brzynska
Faculty of Computing and Telecommunications
Poznan University of Technology
Poznan, Poland
marta.brzynska@student.put.poznan.pl

Krzysztof Klimaszewski
Institute for Multimedia Telecommunications
Poznan University of Technology
Poznan, Poland
krzysztof.klimaszewski@put.poznan.pl

Krzysztof Martin
Faculty of Computing and Telecommunications
Poznan University of Technology
Poznan, Poland
krzysztof.martin@student.put.poznan.pl

***Abstract*—Accurate localisation of flying objects has become increasingly important in a variety of applications including navigation, public safety and air defence. Traditional methods have limitations in terms of cost, complexity and reliance on active transmitters. In contrast, passive radio signal detection offers a viable solution for object location. This paper presents a dedicated hardware node designed for the development of a telemetry and localisation system based on LoRa modulation technology. It provides an overview of passive radio signal detection and its potential applications in locating flying objects, particularly in rocket tracking and positioning systems.**

***Index Terms*—Time Difference of Arrival (TDoA), localisation, LoRa, hardware, multilateration**

I. Introduction

Traditional methods for object localisation, such as radar, often rely on active transmitters, which can be costly, complex, and limited in their range. In contrast, passive radio signal detection provides a promising solution for locating objects without the need to emit additional signals. This technology relies on detection and analysis of radio signals emitted by the objects of interest. By measuring the time difference of arrival (TDoA) of these signals at multiple reference points, it is possible to determine the position of the object.

As rocket technology has advanced, so has the need for accurate tracking and positioning systems. During a rocket's flight, it is crucial to have accurate information about its location and trajectory. The most common method of localisation today - the use of a Global Navigation Satellite System (GNSS) - has some drawbacks in such an application. GNSS localisation requires additional hardware, such as a special module and antenna, which must function correctly despite the rocket's rotation. This increases the cost of the equipment, the power consumption of the electronic module and the weight.

In such a case, multilateration, a well-established technique in the field of navigation, offers a solution to accurately determine the rocket's position based on TDoA measurements from multiple reference points. The article describes a custom printed circuit board that provides a compact, cheap and reliable solution for object localisation. It is a good alternative for expensive solutions, often only available to the military or aerospace industry. The article also provides an overview of TDoA-based multilateration for rocket localisation. It examines the principles of passive radio signal detection, the calculation of TDoA and the application of multilateration algorithms to determine the position of the rocket. It also discusses the challenges and considerations specific to rocket tracking systems, and presents potential applications and future directions in the field.

A. Possible applications

Rocket localisation systems based on TDoA and multilateration using low-cost hardware solutions have many applications and offer exciting possibilities for future development. Some of the potential applications are

- **Rocket testing:** Accurate localisation enables detailed performance analysis during test flights.
- **Safety and tracking:** TDoA and multilateration-based systems provide real-time rocket position to monitor and ensure safet
- **Research and development:** Accurate position data supports scientific experiments, payload deployment and trajectory optimisation.

II. Existing localisation methods

Three common methods are often used to track rockets, especially sounding rockets: TDoA-based multilateration, GPS/GNSS-based localisation, and inertial navigation systems (INS). Other methods include Time of Arrival (ToA) and Angle/Direction of Arrival (AoA/DoA). TDoA-based multilateration involves measuring the time difference of arrival of radio signals emitted by the rocket at multiple reference points [1]. At the same time, these transmissions can be used to transmit the telemetry data from the rocket. The method provides real-time tracking and reasonable accuracy but requires synchronised receivers and careful placement of reference points (anchors) [2]. In many recent studies the authors choose for these applications modules using LoRa modulation [3], which is specially designed to provide a long range of transmission with low transmitting power. LoRa modulation offers different settings and spreading factors that can be used to balance the trade-off between bandwidth, range and available bit rate. LoRa is a robust modulation, resistant to Doppler frequency shift [4] and interference. This makes it a good choice for many IoT applications and sensor networks.

In some countries where there is a developed LoRaWAN network, TDoA location is supported by the provider's infrastructure and can be easily used, as has been demonstrated in many papers, e.g. [5]. A LoRaWAN network is unfortunately not available in most places, so a bespoke (or "private") network of receivers is required [6]. Some other methods can also be used, one of which is the Received Signal Strength (RSS) method, which is simpler than TDoA, can be implemented with the same limited set of hardware, but is less accurate [7] [8]. For both methods, the placement of anchor nodes can significantly affect the accuracy of localisation [9]. The TDoA method can be supplemented by the Angle of Arrival/Direction of Arrival method when more complex antenna arrays are used in the receivers. In these systems, the direction to the transmitter is estimated based by analysing the signal phase shifts in an antenna array of the receiver. The location of the transmitter can then be estimated using the information about antenna array direction of receivers and their locations to triangulate the location of the transmitter. At the cost of complex receiver hardware, the receivers do not need to be synchronised. Another system, called Time of Arrival, requires the transmitter to be synchronised with the receivers. A timestamped packet is sent and the receivers can calculate the time of flight from the difference between the time of the timestamp and the time of reception.

GPS/GNSS-based positioning is based on satellite signals received by the rocket's GNSS receivers. It provides global coverage and high accuracy but can have limitations in certain environments and can be susceptible to signal loss or interference. As mentioned in the introduction, this method also increases the overall cost of the device, increasing its weight, size and power consumption compared to a device sufficient for TDoA positioning. There may also be some problems with good antenna placement.

INS systems estimate the position of the rocket using accelerometers and gyroscopes, providing autonomous tracking capabilities. This method is self-sufficient as the position can be calculated by the rocket's computer without any information from other sources, unlike TDoA and GNSS methods which rely on other devices located away from the rocket. This method also increases the overall cost of the equipment compared to the TDoA method and increases the power consumption, both of which increase significantly, especially if high accuracy is expected. A major disadvantage of this method is that it inherently suffers from the accumulation of errors over time.

III. System requirements

The method selected for further development is TDoA-based localisation.

The principle that is used in this case is the passive detection and analysis of radio signals emitted by an object of interest, such as a rocket. To do this, the object is fitted with a radio transmitter, that emits signals at regular intervals. These signals can be detected by a network of receivers (anchors) strategically placed in the surrounding area.

To accurately determine the position of a rocket, it is essential to measure the exact times at which the radio signals were received by the anchors. Te TDoA can then be calculated for the same transmission received by several of anchors. Differences in the time of arrival of a signal at different reference points are caused by differences in the distance between the transmitter and receiver. By measuring the TDoA, it is possible to triangulate the position of the rocket relative to the reference points.

To obtain the most accurate results, the receivers must be placed in a circle with a radius from the test object that allows for sufficiently strong signal to be received, which depends on using antennas with sufficient gain and placing them as high as practically possible.

A. *Calculation of Time Difference of Arrival (TDoA)*

The calculation of TDoA involves precise timestamp measurements of the arrival time of the radio signals at multiple reference points. These reference points can be ground-based stations or even airborne platforms equipped with appropriate receivers. The TDoA calculation typically consists of the following steps:

- **Receiver location:** The accurate location of the receivers must be determined. These locations are reference points for the further processing steps.
- **Signal Detection:** The receivers capture the radio signals emitted by the rocket.
- **Signal synchronisation:** The captured signals are synchronized using a common time reference to ensure accurate timestamp measurements.
- **Timestamp measurement:** The arrival time of the synchronised signals is measured with high accuracy at each reference point.
- **TDoA calculation:** The TDoA is calculated by taking the time differences between the arrival times of the signals at each pair of reference points.

The TDoA values obtained from the calculations serve as input to the multilateration algorithm, which determines the rocket's position [11].

Considering a two-dimensional Euclidean space, there is a transmitter located at $\vec{x}$, which transmits at time t_0 with a propagation speed of $v\frac{m}{s}$. The transmission is received by n stations. The station that first receives the transmission is located at $\vec{p_c}$ with a reception time of t_c. The remaining $n-1$ stations are located at $\vec{p_i}$ with reception times t_i. For the first station $\vec{p_c}$, the distance between the transmitter $\vec{x}$ and the station can be expressed as the propagation velocity multiplied by the flight time:

$$||\vec{x} - \vec{p_c}|| = v(t_c - t_0) \tag{1}$$

For the remaining stations:

$$\begin{aligned} ||\vec{x} - \vec{p_i}|| &= v(t_i - t_0) \\ &= v(t_i - t_c + t_c + t_0) \\ &= v(t_i - t_c) + v(t_c - t_0) \end{aligned} \tag{2}$$

By combining these expressions, we obtain a single equation where the only unknown is $\vec{x}$:

$$||\vec{x} - \vec{p_c}|| = ||\vec{x} - \vec{p_i}|| - v(t_i - t_c) \tag{3}$$

A set of $n - 1$ equations for n stations can be derived:

$$||\vec{x} - \vec{p_c}|| - ||\vec{x} - \vec{p_i}|| + v(t_i - t_c) = 0 \qquad , \quad i = 1, ..., n-1 \tag{4}$$

Each of these equations represents a hyperbola. To plot these hyperbolic curves using the intersection of circles method, the intersection points between two circles must be calculated. The aim is to find two points of intersection P_3 and P_3', if they exist (Fig. 1).

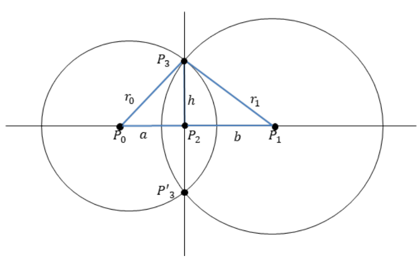

Fig. 1. Illustrated example of finding the intersection of two circles

For $r_0 \in (0, \infty)$ and $r_1 = r_0 + v(t_i - t_c)$ the following steps are performed. Calculate the distance d between the centres of the circles:

$$d = ||P_1 - P_0|| \tag{5}$$

Additionally, if:

$d > r_0 + r_1$, the circles are separated and there is no solution. $d < |r_0 - r_1|$, one circle contains the other and there is no solution. $d = 0$ and $r_0 = r_1$, the circles overlap and there are infinitely many solutions. Considering the two triangles $P_0P_2P_3$ and $P_1P_2P_3$, we can write the following equations:

$$\begin{aligned} a^2 + h^2 &= r_0^2 \\ b^2 + h^2 &= r_1^2 \end{aligned} \tag{6}$$

Using $d = a + b$, we can determine a as:

$$a = \frac{r_0^2 - r_1^2 + d^2}{2d} \tag{7}$$

The equation simplifies to $d = r_0 \pm r_1$ if the circles touch at a single point. Substituting a into the first equation gives $h^2 = r_0^2 - a^2$, and we can calculate:

$$P_2 = P_0 + \frac{a(P_1 - P_0)}{d} \tag{8}$$

This leads to the final solution from the triangle similarity $P_3(x_3, y_3)$, $P_3'(x_3', y_3')$ for $P_0(x_0, y_0)$, $P_1(x_1, y_1)$, $P_2(x_2, y_2)$:

$$\begin{aligned} x_3 &= x_2 + \frac{h(y_1 - y_0)}{d} & x_3' &= x_2 - \frac{h(y_1 - y_0)}{d} \\ y_3 &= y_2 - \frac{h(x_1 - x_0)}{d} & y_3' &= y_2 + \frac{h(x_1 - x_0)}{d} \end{aligned} \tag{9}$$

For 2D localisation, a minimum of 3 spatially separated receivers are required to estimate the state of the object. For 3D tracking, as would be required to locate a rocket in flight, a minimum of 4 spatially separated receivers are required. When tracking an object in 3D space with more than 5 stations, the system becomes over-determined. By introducing an intermediate variable, the non-linear equation can be transformed into a set of equations that are linear for the unknown parameters and the intermediate variable. Their solution can be obtained by the method of least squares(LS). Using the known relationship between the intermediate variable and the position coordinates, the weighted least squares method (WLS) can be applied to obtain the final localisation position [12]. Some other, heuristic optimization algorithms can also be used, like the one described in [13], [16].

B. Concept of the project

The chosen method has several requirements that the designed hardware must meet. The most basic requirements are the following:

- The hardware must be able to correctly timestamp the received data. This requires the means to synchronise a set of receivers.
- The hardware shall provide a method of accurately locating the receiver.
- The hardware must be mobile - small in size and battery powered.

Although specialised standalone modems for LoRa transmissions are available and widely used, such as [14], a different approach was taken. To simplify the hardware and make it as compact as possible, the designed hardware uses a microcontroller with an integrated LoRa modem. Instead of using a separate microcontroller and radio module this makes it possible to design a smaller, simpler and cheaper board. The envisaged TDoA system setup consists of a transmitter, multiple receivers, and data collection nodes for location estimation. The transmitter sends messages and the receivers record the received data with a timestamp directly onto laptops, via a USB connection, or store it on an SD card.

The time differences in packet reception times between two stations were measured, with one station remaining stationary while the other underwent location changes, as shown in Fig. 2. A GPS module is used in this study to locate the

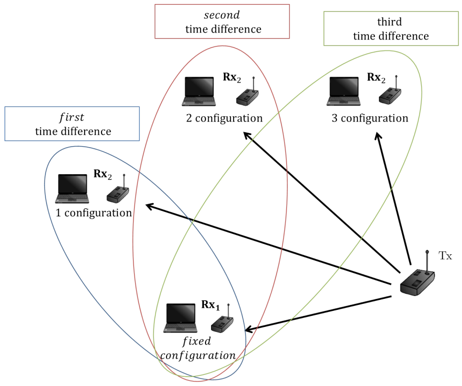

Fig. 2. Architecture of the experimental setup

receiver and to synchronise the receivers. For future research on synchronisation, the GPS module can also be used for benchmarking the developed algorithms, or it can be switched off completely once the position of the receiver has been established. There are some works on the calculation of TDoA with different means of synchronisation [15] [17] which may be tested in the future.

IV. Description of Hardware Construction

The microcontroller chosen, the STM32WL55CCU7 from STMicroelectronics [18], is a 32-bit dual-core integrated circuit with built-in LoRa modulation capability and various features suitable for communicating with peripherals.

The main components of the board are a microcontroller with an integrated radio module, an antenna amplifier (PA and LNA) for transmission and reception [19], a GPS module Quectel L96-33 [20], and two antennas for GPS and the LoRa network. The chosen microcontroller, the STMicroelectronics STM32WL55CCU7, is equipped with a LoRa capable modem with a wide frequency range of 150 to 960 MHz. This range covers a significant portion of the radio spectrum commonly used for TDoA-based positioning systems. It allows the device to receive signals from multiple transmitters and perform accurate TDoA calculations. The device developed uses the 433MHz frequency band. A pair of the developed devices is shown in Fig. 3.

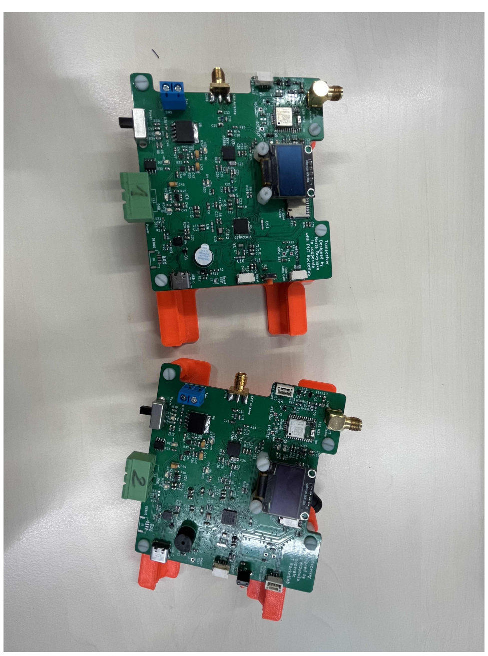

Fig. 3. Designed Transceiver PCB

TDoA methods rely on precise time measurements to accurately calculate the time differences between signal arrivals at different receivers. The current state of the art is to synchronise and locate modules using signals from GPS modules. Time is measured using a built-in timer in the STM32WL55 microcontroller with a clock frequency of 48 MHz. The smallest possible time resolution was 20.83 ns, which corresponds to 6.25 m of radio signal propagation.

V. Description of the Software

In its current state, the software running on the microcontroller in the receiver module is responsible for maintaining timestamp synchronisation with other receivers, receiving and timestamping the received packets and recording them on an SD card or sending them via a USB connection to a computer. The data can then be analysed offline. In the future, the development of localisation algorithms will focus on moving towards real-time localisation on the development hardware. This will make it possible to present the results in real time, together with debug information, for faster algorithm development and optimisation of system parameters.

During the initial phase of the study, when the receivers were not synchronised, a time drift in the differences in signal arrival times was observed (see Fig. 4).

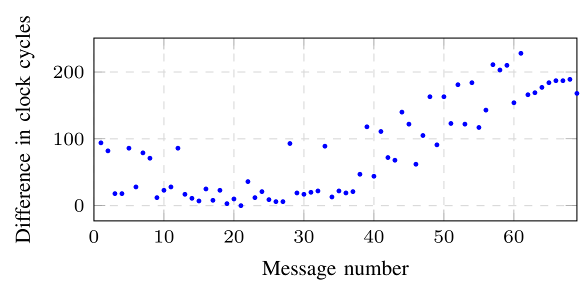

Fig. 4. Clock cycle drift between two clock oscillators in two different receivers

Drift occurs because the oscillators are not perfectly identical. To compensate for this drift, synchronisation is performed every second. Before using the 1PSS signal, the receivers were synchronised once at the start of each test.

Synchronisation is achieved using a 1PPS signal from the satellite-based GPS radio navigation system. When the 1PPS pulse is received, the counter on the receiver is reset. The 1PPS signal is received once per second. The subsequent test showed that for stationary equipment, the 1PPS signal significantly improved the synchronisation of the receivers, so that this very simple technique, although not perfect (rollover error is possible), allowed measurements that were sufficiently accurate. Some further developments in synchronisation software are possible in the future. One idea is to calculate the difference between the oscillators (i.e. the difference between their actual frequencies) and make appropriate synchronisation adjustments. Another idea is to change the clock source for the receivers to a more accurate one and do the frequency synchronisation at the oscillator level.

VI. Measurements results

The preliminary simulation results were obtained using custom developed software to locate the transmitting node. It was found that for randomly generated arrival times and locations, as the number of base stations increased beyond seven, the computation time increased significantly without a significant improvement in the accuracy of the estimated location [10]. Following successful algorithm testing, further studies were initiated using actual base station configurations and signal arrival time differences.

For this study, a simplified architecture was implemented consisting of a single transmitter using the NUCLEO-WL55JC board [21], with custom transceivers acting as receivers. Antennas of the devices were placed at a height of 2m. The gain of the antennas was 2dBi. In these conditions the receiver received the signal with the lowest RSSI value of -114 dBm as reported by our system. Please note that we are using a SKY 65366 frontend in the signal chain.

For artificial, idealised timestamp data, an accuracy of 13.2 m was achieved. The error in this case is due to the inaccuracies of the available internet maps and possible errors introduced by conversions between Cartesian and WGS coordinates. For the real data obtained during the experiment from the actual transmitter and receiver locations (the same locations as in the idealised case), the average error was only 40.2 m.

The time difference was measured for one of the pairs of receivers. The actual distance difference between the first station and the transmitter (1790 m) and the second station and the transmitter (86 m) was 1704 m.

The Fig. 5 represents measurements for a series of 350 measurements. The Y-axis represents the time difference in nanoseconds, while the X-axis represents the number of measurements. The second Y-axis represents the distance travelled by the radio signal during this time.

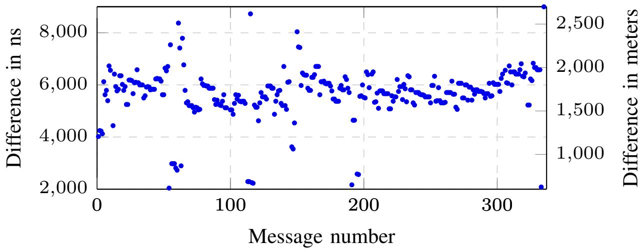

Fig. 5. The difference in clock cycles between two stations

From this series of measurements, the average measurement from the quantile space was calculated. This average value is 5707.08 ns, which corresponds to a distance of 1710.98 m. For this single measurement, the error was 7 m. Based on these measurements and the implemented TDoA algorithm, the position of the transmitter was calculated, resulting in a final position error of 40.2 m. Increasing the number of receivers should improve the location accuracy.

The resulting map was generated using a specially developed program. The programme used the collected data to plot the map in Google Maps, allowing a visual representation of the calculated results, as shown in Fig. 6.

Fig. 6. Resulting map with the plotted locations of the stations and hyperbolas. Blue dots - receivers, green dot - transmitter, red dot - the calculated position of the transmitter.

The results of the study will be used to further develop the system. The influence of different parameters of the system must be measured. These parameters include the time interval between transmissions, the bandwidth, the spreading factor and the transmission power. All these parameters can be easily adjusted in the designed board.

VII. Challenges and Considerations

As evidenced by the experiments performed and the literature review, the development of a rocket localisation system based on TDoA and multilateration faces several challenges and considerations. Some of the key factors to be considered are:

- **Accuracy and noise:** The accuracy of the TDoA measurements depends on the quality of the received signals and the presence of noise. Factors such as atmospheric conditions, signal propagation, and interference can affect the accuracy of the time of arrival measurements. It is important to use high gain antennas placed as high as possible.All these aspects need to be evaluated experimentally in an environment similar to that encountered during a sounding rocket flight.
- **Receiver placement:** An effective approach for estimating a 2D position using TDOA is to place three receivers in an equilateral triangle formation around the signal source. For 3D position estimation, it is advantageous to place four receivers in a tetrahedron formation. These

configurations minimise ambiguity and provide accurate localisation results in TDOA-based methods.

- **Synchronisation:** Synchronisation in the receivers is achieved by using a 1 pulse per second (1PPS) signal derived from the GPS satellite radio navigation system. When the 1PPS pulse is received, the receiver counter is reset. The 1PPS signal can also be used to calculate the discrepancy between the oscillators, which reflects the difference in their actual frequencies. This can then be used to obtain accurate TDOA measurements in the absence of an accurate 1PPS signal.
- **Real time processing:** Real-time processing of the TDoA measurements is essential for tracking a rocket's position during its flight. Efficient algorithms are required to process the measurements and estimate the rocket's position in real time. This also requires the development of a method for data exchange between the receivers (and a possible central processing unit).

VIII. Conclusion

TDoA-based multilateration has been shown to be a promising solution for rocket localisation systems. This paper presents a low-cost, simple, yet promising localisation system.

The results of the operation of the developed system demonstrate its effectiveness in accurately estimating the location of objects. The simple localisation algorithm was tested using both simulated and real data obtained with the developed hardware solution. Satisfactory accuracy was achieved in both cases. The calculated positional accuracy from accurate data was found to be 13.2 m, with any errors attributed to inherent limitations in the available internet maps and conversions between coordinates. When considering the measured signal arrival time differences on real data, the system showed an average error of only 40.2 m. The analysis of the results, coupled with the high accuracy of the system, provides strong motivation for further improvements, including extending the functionality to three-dimensional space and exploring new computational methods to enable object localisation during motion. These results highlight the potential of the system for practical applications in various domains.

Acknowledgment

The work was supported by the Ministry of Education and Science, Poland.

References

[1] Chao Lu, Pei Wang, Zhiyuan Dong, Zhihui Ye, "Rocket Recovery Carbin Section Passive location based on whale optimization algorithm," Journal of Physics: Conference Series, vol. 2364, no. 1, IOP Publishing, 2022, doi: 10.1088/1742-6596/2364/1/012068.

[2] Ma G, Huang Z, Wang M, Ji Z, Li X, Shen B, Tian J. "Performance Analysis and Sensor-Target Geometry Optimization for TOA and TDOA-Based Hybrid Source localisation Method", Applied Sciences, 2022, doi: 10.3390/app122412977.

[3] Semtech, "LoRa modulation basics", AN1200.22, 2015.

[4] A. A. Doroshkin, A. M. Zadorozhny, O. N. Kus, V. Y. Prokopyev and Y. M. Prokopyev, "Experimental Study of LoRa Modulation Immunity to Doppler Effect in CubeSat Radio Communications," in IEEE Access, vol. 7, pp. 75721-75731, 2019, doi: 10.1109/ACCESS.2019.2919274.

[5] N. Podevijn et al., "Experimental TDoA localisation in real public LoRa networks," in Short Paper Proceedings of the Tenth International Conference on Indoor Positioning and Indoor Navigation - Work-in-Progress Papers (IPIN-WiP 2019) co-located with the Tenth International Conference on Indoor Positioning and Indoor Navigation (IPIN 2019), Pisa, 2019, vol. 2498, pp. 211–218.

[6] B. C. Fargas and M. N. Petersen, "GPS-free geolocation using LoRa in low-power WANs," 2017 Global Internet of Things Summit (GIoTS), Geneva, Switzerland, 2017, doi: 10.1109/GIOTS.2017.8016251.

[7] D. Plets, N. Podevijn, J. Trogh, L. Martens, W. Joseph, "Experimental Performance Evaluation of Outdoor TDoA and RSS Positioning in a Public LoRa Network," 2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN), Nantes, France, 2018, pp. 1-8, doi: 10.1109/IPIN.2018.8533761.

[8] E. H. Yoshitome, J. V. R. Cruz, M. E. P. Monteiro and J. L. Rebelatto, "LoRa-aided outdoor localisation system: RSSI or TDoA?", Internet Technology Letters, vol. 5, no. 2, pp. 1-6, Mar. 2022, doi: 10.1002/itl2.319.

[9] W. Chen, "Research on Improving Positioning Accuracy of Sensor Networks," 2020 IEEE 20th International Conference on Communication Technology (ICCT), Nanning, China, 2020, pp. 841-845, doi: 10.1109/ICCT50939.2020.9295669.

[10] M. Brzynska, "Projekt transceivera sluzacego do wykrywania lokalizacji obiektu w oparciu o metode multilateracji," Poznan University of Technology, 2023.

[11] A.C. Andersen, "Signal Emitter Positioning Using Multilateration", https://web.archive.org/web/20230322054520/http://blog.andersen.im /2012/07/signal-emitter-positioning-using-multilateration/, (accessed June 2023)

[12] Yu Zhang, Kai Gao, Jiang Zhu, "A TDOA-Based Three-Dimensional Positioning Method for IoT", 2018, doi:10.2991/mecae-18.2018.136.

[13] M. Mihoubi, A. Rahmoun and P. Lorenz, "Node localisation in WSN and IoT Using Harris Hawks Optimization Algorithm," 2021 IEEE Global Communications Conference (GLOBECOM), Madrid, Spain, 2021, pp. 01-06, doi: 10.1109/GLOBECOM46510.2021.9685105.

[14] Heltec automation, "WiFi LoRa 32", heltec.org/project/wifi-lora-32/

[15] T. Jankowski, M. Nikodem, "Synchronization-free TDoA localisation method for large scale wireless networks," 2017 International Conference on Indoor Positioning and Indoor Navigation (IPIN), Sapporo, Japan, 2017, doi: 10.1109/IPIN.2017.8115890.

[16] Mihoubi, M., Rahmoun, A., Lorenz, P. (2019). Moth Flame Optimization Algorithm Range-Based for Node localisation Challenge in Decentralized Wireless Sensor Network. Int. J. Distributed Syst. Technol., 10, 82-109.

[17] R. Muppala, A. Navnit, D. Devendra, E. R. Matera, N. Accettura and A. M. Hussain, "Feasibility of Standalone TDoA-based localisation Using LoRaWAN," 2021 International Conference on localisation and GNSS (ICL-GNSS), Tampere, Finland, 2021, pp. 1-7, doi: 10.1109/ICL-GNSS51451.2021.9452311.

[18] ST microelectronics, "Ultra-low power multi-modulation wireless STM32WL5x microcontrollers", www.st.com/en/microcontrollers-microprocessors/stm32wl5x.html

[19] Skyworks, "400 MHz Transmit/Receive Front-End Module", www.skyworksinc.com/en/Products/Front-end-Modules/SKY65366-21

[20] Quectel, Quectel L96, www.quectel.com/product/gnss-l96

[21] ST microelectronics, "STM32 Nucleo-64 development board with STM32WL55JC MCU, SMPS, supports Arduino and morpho connectivity", www.st.com/en/evaluation-tools/nucleo-wl55jc.html