Radio-frequency positioning methods for solving the problem of high precision 2D positioning

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Abstract. The paper describes methods and a corresponding practical approach on designing of a 2D UWB RTLS prototype (RF IPS) from the ground up. It is based on universal high performance SDR-platform able to produce and process HRP UWB pulses. The designed RF IPS prototype hardware part consists of three anchors and one tag. The RF IPS prototype software part implements TDoA multilateration algorithm to calculate local tag coordinates. The paper describes both the hardware and the software parts and their communication protocol as well.

1. Introduction
Radio-frequency positioning currently becomes more and more popular [1,2]. This is due, on the one hand, to the rapidly growing demand for high-precision indoor navigation, where the use of GNSS (global navigation systems) is limited or impossible, and on the other hand, the active development of civil radio frequency communications technologies. Another important factor is the development of standards and legislative framework in this area [3,4]. The first hardware solutions in the field of radio frequency positioning for civilian applications appeared on the market about 10 years ago [2,5,6].

This article discusses the solution to the problem of positioning in two-dimensional space based on radio frequency methods. Testing of the proposed approaches is carried out on the example of a developed experimental model of a hardware-software complex for radio-frequency positioning of objects (RF IPS). The developed RF IPS is designed to solve the problems of 2D positioning of objects in all industries where high accuracy is required and the use of radio-frequency positioning methods is acceptable. These include the tasks of positioning objects both in industrial applications (“smart factory”): in workshops, warehouses, construction sites, in the mining industry, and in consumer segment applications: “smart home”, “smart city” systems, sports analytics, navigation and security in shopping centers, etc.

2. Overview of existing methods and solutions for radio frequency positioning
At the moment, the vast majority of civil radio frequency positioning systems are designed in accordance with the IEEE 802.15.4 standard. This standard describes the principles of building wireless networks with low transmission speeds, the implementation of their physical and data link layer, including their use for high-precision positioning [7,8]. For positioning tasks, the standard
involves the use of ultra-wide band (UWB) technology, and specifically HRP UWB with a high pulse repetition frequency (HRP - High Rate Pulse repetition frequency). The standard for positioning also considers the technology of chirp - linear frequency modulation (CSS - Chirp Spread Spectrum), but this technology did not allow to achieve characteristics comparable to UWB in accuracy of positioning of objects and was less widely used [9].

One of the most striking examples of components for UWB-positioning on the market is the products of DecaWave (Ireland) [10]. Their developers were one of the first to implement the standard and do it so successfully that many manufacturers of turnkey solutions in the field of positioning, abandoned the independent development of components and began to purchase them from DecaWave. DecaWave UWB positioning systems provide accuracy of up to 10 cm and range of up to 300 m (in open areas).

UWB positioning systems (Figure 1) consist of tags (Tags), the position of which you want to determine, and anchors (Anchors), interacting with tags and synchronized with each other [14]. Anchors record the moments of arrival of signals from the tags and send them to the system controller (System Controller / Server), which calculates the coordinates of the tags using the ToA (Time of Arrival) or TDoA (Time Difference of Arrival) algorithm [15]. The first option assumes that the propagation time of the signal between the tag and the anchor is known and based on this information calculates the coordinates of the tag, it requires complete synchronization of the tags with the anchors. The second option uses the difference between the absolute arrival times of the signal from the tag to different anchors and requires that only the anchors are synchronized with each other. The application of the TDoA algorithm requires more computing resources of the system controller, however, it allows to simplify the equipment of tags and increase the accuracy of positioning [16].

![Figure 1. UWB Positioning System.](image)

In the general case, to simplify and reduce the cost of the UWB-positioning system, the synchronization of the anchors is carried out over the radio channel, which imposes restrictions on the accuracy of synchronization, and, consequently, on the accuracy of positioning [7, 9, 17].
3. Requirements for the developed positioning system

The developed RF IPS should ensure centimeter accuracy of positioning of objects on a plane, with a range of hundreds of meters. The developed RF IPS is a platform for implementing and debugging new algorithms and methods for high-precision radio-frequency positioning. Its structure is shown in Figure 2, it consists of three anchors (Anchor A, B, C) and one tag (Tag). Anchors interact with a tag over radio frequency UWB channel. Between themselves, they are synchronized via a fiber optic link (FOL - Fiber Optical Link) using the subnanosecond synchronization protocol. Anchors record the time of arrival of messages from the tag and send information to the server (system controller), via Ethernet for further coordinate calculations.

The interaction between the anchors and the tag over the air is simplex: the tag sends blink messages, and the anchors receive and process them. This approach is sufficient to implement the TDoA positioning algorithm and at the same time significantly simplifies the interaction [21].

The functions of the anchor and the tag are implemented by the unified hardware node of the RF IPS. In order to accelerate and reduce the cost of development, the construction of a universal system unit is carried out on standard components available on the market. The components used must be highly integrated, configurable, well-documented, and supported by development tools. This imposes significant restrictions on the use of HRP UWB technology.

HRP UWB technology uses three frequency ranges: sub-gigahertz (1 channel), low-frequency (4 channels), high-frequency (11 channels) [11]. To work on all 16 channels, the receiver and transmitter must have the widest frequency range from 0.25 GHz to 10.25 GHz. Such devices are not freely available, in connection with which it was decided to exclude support for the HRP UWB high-frequency range, respectively, the required frequency range of the transceiver is reduced to 0.25-4.75 GHz. The standard defines frequency channels HRP UWB as a width of 500 MHz, and a width of more than 1 GHz. Unfortunately, there are no integrated receivers and transmitters on the market that have a wide enough band to implement the latter. Given all the above limitations, the final set of supported HRP UWB channels contains 4 channels (Table 1): sub-gigahertz and three low-frequency.
Table 1. Part of HRP UWB frequency channel supported by RF IPS [11].

| Band group | Channel number | Center frequency, (MHz) | Band width (MHz) | Mandatory/Optional               |
|------------|----------------|-------------------------|------------------|----------------------------------|
| 0          | 0              | 499.2                   | 499.2            | Mandatory below 1 GHz           |
| 1          | 1              | 3494.4                  | 499.2            | Optional                         |
|            | 2              | 3993.6                  | 499.2            | Optional                         |
| 3          | 3              | 4492.8                  | 499.2            | Mandatory in low band            |

RF IPS is based on the IEEE 802.15.4 standard, however, the task of full compliance with the standard was not set, interaction with third-party UWB devices is not expected. Only some algorithms and operating modes are implemented that provide the required characteristics.

4. Development of RF IPS hardware

The maximum bandwidth for radio frequency integrated devices available on the market is 450 MHz. It is provided by transmitters and observation receivers (Eng. Observation receiver) included in the highly integrated RF transceiver ADRV9008-2 manufactured by Analog Devices.

The ADRV9008-2 chip is by far the most broadband all-inclusive solution, it operates in the range from 75 MHz to 6000 MHz, which determines the supported HRP UWB channels.

It should be noted that the most important parameter of HRP UWB systems is the maximum Pulse Repetition Frequency (PRF), which corresponds to the maximum sampling frequency of the DAC transmitter and the ADC of the receiver [19]. According to the standard, it is 499.2 MHz. The ADRV9008-2 provides a maximum NCI of 491.52 MHz, which is not significantly different from what is required. Another important factor is the use of JESD204B high-speed digital interface with deterministic delays in the ADRV9008-2 [20]. A high exchange rate is required to ensure high PRF, and the presence of deterministic delays in the transmission path will ensure high accuracy in calculating the signal travel time required for accurate positioning.

A signal processor (BBP - BaseBand Processor) is connected to the ADRV9008-2 via the JESD204B interface, the functions of which are performed by a programmable logic chip (FPGA). The task of BBP is the generation and output of data to the DAC of the transmitter, the receipt and processing of data from the ADC of the receiver, as well as the initialization and configuration of the RF path. The FPGA of the Intel Cyclone 10 GX family of maximum logical capacity (220 KLEs) was chosen as BBP. These relatively inexpensive FPGAs (low-cost segment) incorporate high-speed transceivers operating at speeds up to 12.5 Gbit/s, which provides sufficient bandwidth and the required PRF. When choosing a platform for implementing a universal unit, the price criterion played an important role, and therefore the choice fell on the Cyclone 10 GX family, and not on the Arria 10, traditionally used together with high-performance Analog Devices RF transceivers.

The universal RF IPS hardware node consists of ADRV9008-2 RF transceiver and Cyclone 10 GX FPGA boards.

Figure 3. The structure of the RF IPS universal node.
The Cyclone 10 GX and ADRV9008-2 communicate with each other through the standard FMC (FPGA Mezzanine Connector) connector. In addition to them, the universal hardware unit includes a clock generator board with an ultra-low jitter required for an RF board. The universal hardware node implements the functionality of both tags and anchors, the difference is in the project loaded into the Cyclone 10 GX FPGA.

The FPGA project for the tag performs the following functions:

- formation of data packets for sending over the air and transferring them to an RF board;
- RF board management;
- low jitter generator board control.

![Figure 4. The structure of the FPGA project for tag.](image)

The FPGA project for anchor performs the following functions:

- receiving data packets from an RF board received over the air and analyzing them;
- calculation of the time of arrival of packets from the tag;
- synchronization with other anchors, interaction with them via optical network;
- interaction with the server via Gigabit Ethernet;
- RF board management;
- low jitter generator board control.

![Figure 5. The structure of the FPGA project for anchor.](image)
The developed universal hardware node of the RF IPS is essentially a high-performance SDR (Software Defined Radio) platform and can be used not only as an element of the radio frequency positioning system, but also as an independent radio device capable of implementing most communication protocols, both standard and specialized.

The implemented SDR platform was tested for HRP UWB pulse generation/processing capability. Figure 6 represents HRP UWB pulse on the oscilloscope screen generated by the developed universal RF IPS hardware node.

![General view of the universal RF IPS hardware node.](image)

**Figure 6.** General view of the universal RF IPS hardware node.

5. **Interaction of hardware and software of the RF IPS**

Software implementing the TDoA algorithm runs on a server that communicates with anchors over Gigabit Ethernet. In this case, no special requirements are imposed on the communication channel (high throughput, deterministic latency), since the arrival time of the blink-packet from the tag (Anchor timestamp), its identifier (Tag message ID), as well as the identifier of the tag that sent the blink-packet (Tag ID) are fixed at anchor and added to the message queue.

All messages in the system consist of two parts (Figure 7):

- **Header** - contains information about the device, the sender and the type of payload;
- **Payload** - contains the required fields necessary for the implementation of the TDoA algorithm, as well as optional fields with additional information.

The message from the tag to the anchor in the header has a tag identifier and a blink-packet identifier, and as a payload carries a tag message - auxiliary information not used directly by the TDoA algorithm. In particular, this can be information from inertial sensors, as well as from a GNSS receiver, which can improve positioning accuracy.

The message from the anchor to the server in the payload (anchor message) fully encapsulates the packet received from the tag and supplements it with its header and 64-bit field containing the absolute time of the arrival of the blink sending to the anchor in picoseconds.

When parsing the message queue on the server, if there are several messages in the queue from the same tag, then only the last message is analyzed, and all earlier ones are deleted, as well. This requires preliminary processing of all messages in the queue, but eliminates the lag in processing and
unnecessary calculations, which require resources, but do not bear practical sense in view of the availability of more relevant data.

Figure 7. The format of the UWB packet for RF IPS.

6. Software development for RF IPS
The hardware part of the RF IPS at this stage consists of only one tag and three anchors in the system, while the software being developed is capable of processing any number of tags and anchors.

The software part uses third-party libraries:

- Eigen (math);
- Libevent (for asynchronous non-blocking I/O);
- Spdlog (logging);
- CLI11 (console interface, command line parsing).

The software part of the complex has a modular structure to provide architecture flexibility. System Modules:

- Server;
- Calculation module;
- Network interface module;
- Simulator;
- Network Interface;
- User Interface Module.

Each of these modules can be replaced by a different implementation of this module. So, for example, the network interface in the current version of the program implements the TCP/IP protocol stack, but TCP is easy to replace with UDP.

This flexibility is provided by standard OOP solutions. All modules have a unified external interface, through which information is exchanged between the modules, and the implementation of each specific module does not affect its interface.

The network interface module operates in a separate thread, and is responsible for receiving messages over the network. This module deals with primary packet parsing, checksum checking, and connection control logic. Data from this module is transmitted to the server.

The server module is responsible for processing data and obtaining calculation results.

Through the module of interaction with the network interface, the server that is working in one thread communicates with the network interface that works in another thread. This communication is implemented by the SPSC (Single producer single consumer) queue, which is used to transmit
commands from the server to the interface in the form of lambda functions that are executed in the interface thread.

The calculation module accepts the generated data packet as input, performs the calculations and returns the result. The TDOA algorithm is used to calculate the position of the RFID tag. The server through the external interface transfers the received data to the user interface module.

The simulator module is used for debugging. Responsible for simulating the behavior of devices connecting to the server. It also has an external interface for setting simulation parameters (number of anchors, tags, their coordinates, frequency of sending messages).

The user interface module is responsible for visualizing the results of the program, and also provides the user with an interface to interact with the program. Allows you to change program settings, control the simulator, visualize the results of calculations.

At the moment, two versions of the user interface are implemented: graphical and console. Both options are currently prototypes and are subject to change, they are represented on Figure 8. Console view demonstrates network communication between RF IPS universal nodes and the sever, graphical view demonstrates tag localization using TDoA algorithm.

![General view of the RF IPS software main GUI window and console interface.](image)

**Figure 8.** General view of the RF IPS software main GUI window and console interface.
7. Conclusion

The developed RF IPS confirms the possibility of 2D positioning due to the independent implementation of the full-stack UWB positioning system using standard components. The implementation of such a system has become possible primarily due to the development and accessibility of Software Defined Radio technologies.

Project development directions:

- Debugging and improving the positioning algorithms used to improve the accuracy and range of positioning.
- Expanding the capabilities of the positioning system by adding alternative geodata sources: GNSS receivers, inertial sensors. Thus, the radio-frequency positioning system will be transformed into a seamless positioning system and will reach a new level: a combination of several geodata sources will increase the accuracy and reliability of the positioning system, ensuring the principle of seamless positioning [12, 13].
- Further development of the designed universal hardware node as an independent SDR platform, in particular, the development of tools for convenient work with it.

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