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HYBRID NAVIGATION SYSTEM FOR INDOOR USE

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Abstract. *This article describes the design and implementation of a hybrid in-building navigation system. The word hybrid has a twofold meaning in this case. On the one hand, it refers to the use of two tracking methods: demanding (beacons) and not requiring an electronic device (radio tomography imaging). On the other hand, it specifies several commercial wireless communication protocols that make up the presented system. Ultimately, the network created in this way will be designed to provide the user with location and navigation services with increased accuracy and reliability. The text describes both the topology of created networks, methods of communication between devices and their hardware layer, as well as the effects of work resulting from the actual test object.*

Keywords: bluetooth, electromagnetic propagation, indoor radio communication, radiofrequency integrated circuits, radio navigation, tomography

HYBRYDOWY SYSTEM NAWIGACJI DO UŻYTKU WEWNĄTRZ POMIESZCZEŃ

Streszczenie. *Artykuł opisuje projekt i sposób realizacji hybrydowego systemu nawigacji wewnątrzbudynkowej. Słowo hybrydowy ma w tym przypadku dwojakie znaczenie. Z jednej strony odnosi się do zastosowania dwóch metod namierzania: wymagającej (radiolatarnie) i nie wymagającej posiadania urządzenia elektronicznego (obrazowanie radio-tomograficzne). Z drugiej wyszczególnia kilka komercyjnych protokołów komunikacji bezprzewodowej składającej się na przedstawiony system. Docelowo utworzone w ten sposób sieć będzie miała za zadanie świadczyć użytkownikowi usługi lokalizacyjne i nawigacyjne o zwiększonej dokładności i niezawodności. Treść tekstu opisuje zarówno topologię tworzonych sieci, metody komunikacji między urządzeniami oraz ich warstwę sprzętową jak i efekty prac wynikłych na podstawie rzeczywistego obiektu testowego.*

Słowa kluczowe: bluetooth, propagacja fal elektromagnetycznych, systemy radiowe do użytku wewnętrznego, układy scalone o częstotliwości radiowej, nawigacja radiowa, tomografia

Introduction

Hybrid navigation system is a wireless network consisting of a given number of radio measuring sensors and associated monitoring devices. It combines the features of three radio technologies: Bluetooth, Wi-Fi (IEEE 802.11) and IEEE 802.15.4 protocol (e.g. XBee modules). The system covers the ISM 2.4 GHz radio band (Industrial, Scientific, Medical), which works well for the purpose of detecting living beings in closed rooms due to the high percentage of water content in organisms. To a lesser extent, the system can also be used to detect inanimate objects depending on what material they are made of. This is due to the nature of the electromagnetic wave and its tendency to be reflected and absorbed depending on the type of matter it encounters. The basic task of the presented system is to guarantee all users within the range the data necessary to determine their location relative to the monitored object (coarse radio beacon navigation). If the user enters the room, the system can additionally increase its measuring accuracy by means of radio tomography, whose algorithms have been implemented in electronic systems (diminutive navigation).

1. Beacon system structure

The beacon network is a set of highly energy-efficient radio signal transmitters with which the user's device (equipped with proprietary software) is able to determine its own position and plot it on a planar model of the building. The main point of reference here is the calculation performed on RSSIs, which are reference radio signal values expressed in decibels per milliwatt (dBm). The user's device, against a comparison of signal sources from different transmitting stations, becomes capable of providing location services to the user. While this method works well in large-area facilities and is easily scalable, it is unfortunately subject to relatively high inaccuracy. For this reason, it plays the role of navigation along main traffic routes in the system. The RTI system (radio tomographic imaging) was designed and intended for precise tracking.

The radio beacon is a circular PCB with a diameter of 30 mm. This device is designed to work with battery power supply, which in combination with the small size of the laminate allows for installation even in hard to reach places of the building. Due to the intermittent nature of the transmitter's work, the device goes into sleep mode most of the time. Thanks to this procedure, an operating time of several months has been achieved. This statement applies to a CR2077 lithium battery with a capacity of 960 mAh. Together with the basket the overall dimensions of the device increase up to 20 mm in thickness giving approximately a cylindrical shape.

The visualisation of the device can be traced in figure 1, while the block diagram is presented in Figure 4 but reduced from the stationary power supply (power conditioning system and USB port) and the IEEE 802.15.4 communication module section together with the antenna.

The heart of the device is the nRF52832 microcontroller, which, due to its internal architecture and the presence of a radio layer capable of transmitting in the 2.4 GHz ISM band (modulation with phase keying and approximation using a Gauss curve), enables the implementation of such wireless communication technologies as Bluetooth LE or ZigBee. The rest of the electronic structure consists of the components necessary for the radio layer and the CPU (central processing unit) to function properly. These include two quartz resonators: 32 MHz (performance) and 32.768 kHz (power saving), signalling, interference filters, antenna path, programmer port and RGB LED signalling.

It should be emphasized that due to the nature of communication between the beacons and the user's device (one-to-many communication), no permanent connections are created between them, as e.g. in the case of Bluetooth Classic and streaming. Beacons will use the advertising offered by the fifth version of Bluetooth LE technology. It causes that each of the radio transmitters behaves like an individual, miniature broadcasting station that uses only cyclic transmissions of data packets without the need to acknowledge their receipt.

Fig. 1. Graphical presentation of the concept of beacon navigation

2. Structure of the radio tomography system

The presented RTI system consists of a set of sixteen hybrid measurement probes, data acquisition device, Apache Kafka data bus and a computational unit performing reconstruction for the needs of radio tomography. The dependencies exist between the radio probes are presented in figure 2.

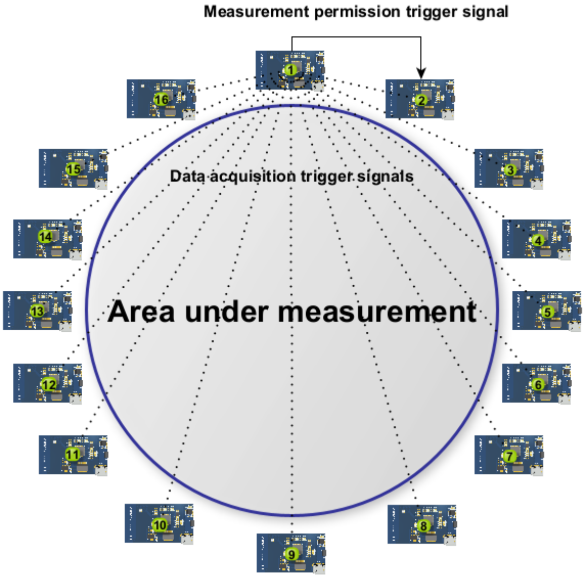

Fig. 2. The structure of the hybrid radio tomography system inside the single test room with a resolution of 16×16 (measuring sequence for probe number 1)

The structure of RTI navigation system also does not maintain permanent network connections between devices (in particular by means of probes), and its operation is based on Bluetooth technology (in one-to-many radio transmission variant) and the IEEE 802.15.4 (in one-to-one radio transmission variant) [3]. In practice, this means that the hybrid radio sensor is able to act independently and engage in various tracking processes without having to cooperate with other elements of the system. However, despite the relative independence of the units and the abandonment of the coordination of transmitters by means of a central unit, the synchronisation burden was transferred to the radio probes [1].

After the exchange of information between probes on RSSIs, the trigger signal is sent to the next probe by sequence number. The resulting data (contained in a Bluetooth LE version 5 compatible communication package) is acquired by the central control unit and treated as a single row of the measurement matrix needed to perform the reconstruction. After completing all rows of the matrix (one from each radio probe), they are properly segregated and sent via the Apache Kafka data bus to the reconstruction server (network connection – via twisted-pair Ethernet or Wi-Fi wireless connection), and then returned via the network in the form of reconstruction to a designated device equipped with a display [5].

In order to better understand the processes taking place between devices, one should start with the structure of the communication frame and the types of data carried by the devices.

As mentioned, the RSSI indicator was used for determining the user's position in both radio beacons and RTI, but it is processed and compiled differently. In communication by beacons, only the signal value at a given time and at least three beacons are enough. To enable human detection in radio tomography, differential analysis of two arrays was used. The first matrix is a set of projection angles (i.e. mutual relations of signal strengths received alternately by all RTI probes) of the monitored area in a rest state (devoid of a living factor). Such a matrix is called a background matrix. Then, measurements of a normally used room are made and the obtained measurement matrix is compared with the background matrix using appropriate algorithms [2].

The source of the signals can be both the Bluetooth 5 (speed) and IEEE 802.15.4 transmitter (smaller standard deviations of the RSSI results in the system equilibrium). In the presented solution, IEEE 802.15.4 was used as a reference signal source, and Bluetooth 5 as a wireless transport layer.

Microcontrollers of radio probes, by means of a serial port connection with a radio module compatible with the IEEE 802.15.4 standard, issue cyclical commands to him to obtain information on RSSI. A single measurement cycle is presented in figure 2 for the probe case number one. After the values are obtained, they go to the serial bus buffer, which is the same route as the commands are issued. Based on the unique addresses, the values are recognized and sorted in such a way as to form a matrix row. The matrix row (depending on its length) is placed in the data frame shown in figure 3.

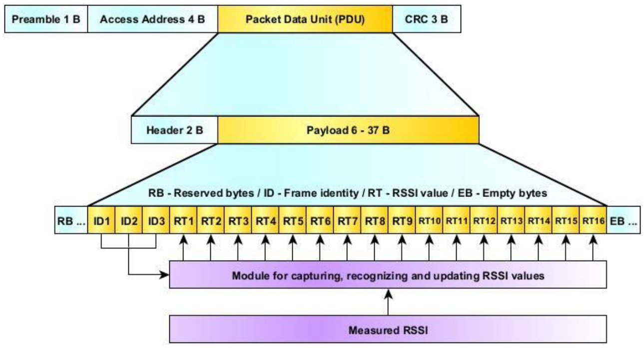

Fig. 3. Communication package created for the transport of RSSI indicators to the central control unit

The RSSI indicators in number depending on the system size are sequentially folded together with the identification bytes in the container for user data (Bluetooth LE advertising mode). The ID bytes allow the CPU to recognize which probe the row of the matrix comes from and where it should place it in relation to the others. The number of ID bytes may vary depending on the need (to reduce the probability of transmission errors or system size changes).

The data frame prepared in this way is cyclically broadcast every 100 milliseconds. The BLE scanner implemented in the central unit scans the environment in search of packets compatible with the conditions written in the code and only identical to the content offered by RTI probes. This process occurs every 50 milliseconds and lasts 50 milliseconds (measurement window) [3].

The RSSIs inserted in the data frame are calculated according to the algorithm implemented in the IEEE 802.15.4 protocol and are sent in a ready-to-use form via the serial port from the XBee radio module to the microcontroller. These are values stored on a single byte in U2 code (with sign). This is due to the fact that an electromagnetic wave is not able to pass through a medium such as air, water or building materials without loss. This makes the real values oscillate between -20 dBm down to about -100 dBm, which is the so-called sensitivity, characteristic for modern commercial radio systems. Further development of data structures was therefore not logically justified. The only exception is the desire to increase the number of identification bytes or to increase the number of transmitters. Then it is possible to expand a single frame to 20 bytes of RSSI value. Further scaling of the system required the use of the Bluetooth LE scan response mode (allows a second, additional data frame to be transmitted in response to a scanner request), splitting the matrix row into an older and a younger part and transferring them alternately, or using extended Bluetooth LE data packets.

The data collected by the CPU is collected using a proprietary adapter connected to the peripherals of the single chip computer via a serial port. The adapter is a technical variation of the radio beacon adapted primarily for scanning, pre-formatting data and continuous transfer to the system. Before this can happen, however, they must be received by the Jetson Nano or Raspberry

Pi computer, then formatted and nested in JSON. Only then are they ready to be put into the network and via the Apache Kafka data bus to the so-called cloud. From there, the reconstruction server retrieves them and starts computational sequences aimed at synthesising a heat map of the room under study.

3. RTI hardware solutions

According to the description of the system structure, each of the two parts of the hybrid navigation system comprises a certain pool of equipment necessary for operation. While in the case of the radio beacon it is one type of device, in the case of the developed RTI system it is a radio probe and a central unit, which consists of several components. In addition, all the communication devices that are not original technical solutions, but mediate in the transmission of data after entering the Internet network, should be specified.

3.1. Radio probes

The radio probe is a development of the radio beacon base design. The core of the device is still the nRF52832 microcontroller. The block diagram of the device is shown in figure 4, while the PCB appearance is presented in figure 5. It is distinguished from the radio beacon by the presence of a stationary power supply system realised in the form of a USB port and a voltage stabilizer. The stabilizer reduces the voltage of 5 V to the level required for proper operation of the nRF52832 microcontroller system, i.e. 3.3 V. This makes it possible to realise an RTI network using a regular cable for mobile device chargers. This procedure was intended to simplify the testing process. At the same time, for the purposes of building installations, two types of proprietary power supplies have been designed to work with 230 VAC electrical installation and PoE (Power over Ethernet), respectively. The power supplies not exceeding the dimensions of a matchbox in combination with a 30 mm radio transmitter make it possible to install it in building junction boxes or lighting fixtures. During the commissioning tests in the lighting fixture, the operating conditions of the electronics were also examined in terms of temperature. Based on the readings from the thermal imaging camera, the maximum was recorded on the body of the voltage converter, but it did not exceed 32°C due to the high efficiency reaching 90% and very low load energy consumption [4].

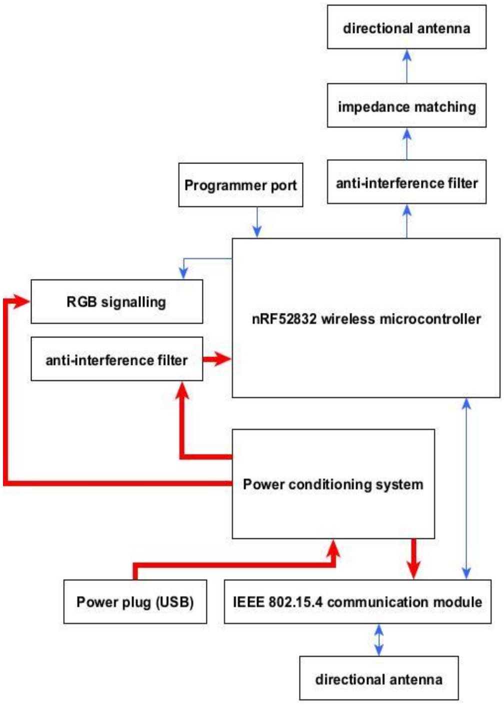

Fig. 4. Block diagram of the radio probe, where bold arrows denote power supply lines and thin arrows denote signal lines

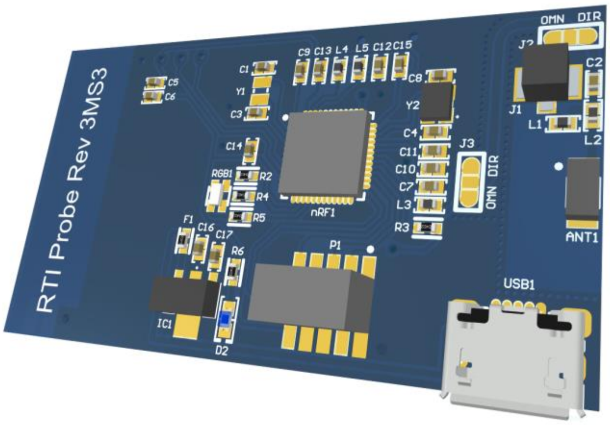

Fig. 5. Three-dimensional visualization of a complex radio probe PCB

Another significant difference is the presence of two radio modules, one of which (Bluetooth) acts as a transmitter, and the other (IEEE 802.15.4) as a transmitter and a receiver. It required a collision-free installation of two antennas in one housing. that is why the Bluetooth transmitter has a ceramic antenna located on one edge of the PCB, and the antenna lines of the XBee module were pulled away from the board using the u.FL connector and the antenna equipped with a 10 cm shielded cable. This gives a greater possibility of avoiding electromagnetic wave interference from both sources. It should be emphasized that both transmitters use the same band and modulation. The differences result from the division of the band into channels, of which in the case of Bluetooth LE, the channel number 37 (2402 MHz), 38 (2426 MHz) and 39 (2480 MHz) should be specified, which are used alternately before the broadcast mode. The BLE channels used by the RTI system are shown on the RSSI monitor in figure 6. In the case of IEEE 802.15.4 and XBee modules, the channel number is automatically determined by the pair of data exchange devices. It is possible to manually change the communication channel, but it has no performance justification. Efficiency of the XBee module buffer and the measured query and response time at the level from 50 milliseconds to 80 milliseconds (time measured in the system connected to the manufacturer's software used for testing and updating the software) [1].

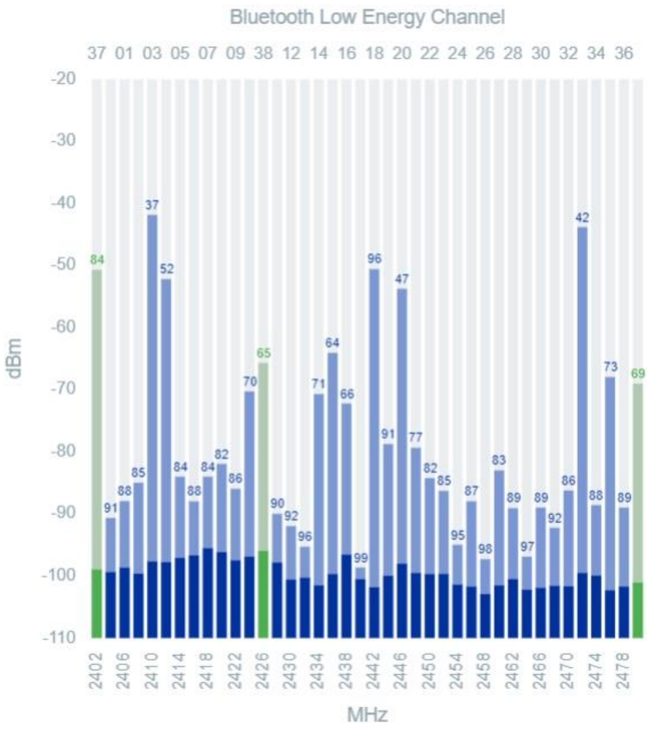

Fig. 6. BLE channels used for data transmission from radio probes to the central unit (specified in a different color with the frequencies 2402 MHz, 2426 MHz and 2480 MHz)

Due to the high sensitivity of radio systems, appropriate filtration of the supply voltage and unnecessary noise from the antenna system was taken care of. To communicate with the user, the probe uses a programmable RGB diode, which marks the processes it carries out (stimulation, measurement and triggering another probe) with an appropriate colour. Thanks to this, it is possible to estimate the speed of the matrix acquisition by visual observation of the activation of successive radio transmitters (e.g. with the help of a stopwatch). Typically, data acquisition and transfer over the PAN does not take more than a few seconds. The measurement time is strictly dependent on the software parameters of the broadcast frequency, scanning frequency, measurement window width, and also within a certain range of the power level. Insufficient power can result in more frequent transmission errors and an increase in retransmission requests. Too high power of the transmitter, in turn, increases the reflection of EM waves in the room, which translates into the level of interference and noise in the image. Noises are manifested in the form of hard to justify, the so-called artifacts in the heat map. The above-mentioned facts make the RTI system implementation for each room different and it is necessary to properly calibrate it (including the appropriate arrangement of the probes so as to maintain the maximum density of the grid made of projection angles) [7].

3.2. Control unit

While the radio probes are responsible for data acquisition, mutual coordination and data transport through the PAN (Personal Area Network) network, the first hardware unit that can be considered as a kind of "operator panel" is the central unit. This unit is entrusted with the operations related to the acquisition and formatting of the entire array, as well as the processes of data transfer and maintaining the connection with the reconstruction server. A Jetson Nano single-board computer was selected to provide the appropriate programming tools and performance (included). The block structure of the device built on the basis of this computer is presented in figure 7.

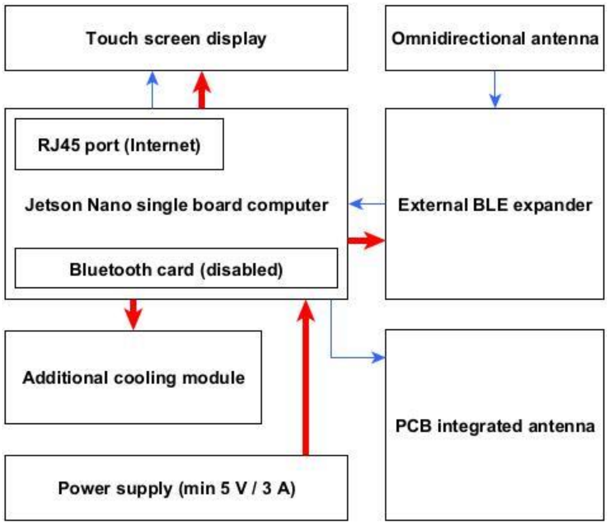

Fig. 7. Block diagram of the central unit, where bold arrows denote power supply lines and thin arrows denote signal lines

The CU consists of components such as a 7 inch TFT touchscreen display for convenient presentation of created arrays. It is connected via a dedicated video connector on the Jetson Nano computer. Although the selected platform already has an integrated 2.4 GHz antenna and the ability to communicate with the world using BLE and Wi-Fi, after performance and stability tests it was decided to introduce modifications. Tests were carried out on a real zone and measurement facility and found frequent hang-ups and connection drops with the built-in Bluetooth hardware layer. This necessitated the need to design and test a custom expander that would be more susceptible to modification and allow more interference with the software layer. It was connected to the computer via a serial port. The external BLE expander is actually a miniature 2.4 GHz receiver (built using an nRF series microcontroller). It offers the possibility of connecting both a directional ceramic antenna and an omnidirectional antenna (this is another advantage of not using the built-in BLE module).

The entire design is powered by a dedicated 5 V / 3 A power supply. Due to the increased temperature of the processor system and during intensive work, the PCB was enriched with an aluminum heatsink with a fan. The reasonableness of the cooling assembly is also supported by the intended use of the CU to work in a sealed enclosure. The first test case was made with the help of a 3D printer and plastic. It included holes for the screen and a thread for mounting an omnidirectional antenna of any length. The device with its surface area does not exceed the size of an A4 sheet of paper and, depending on the needs, can be quadrupled in size provided that the headless version (i.e. screenless, without GUI) is used. A version with a panel was created for the tests. The system managing the CU was Linux OS, while Qt Creator and C++ language was used as a programming environment. The complete prototype is shown in figure 8.

Fig. 8. Complete prototype of central processing unit during RSSI matrix acquisition

4. Research

In order to carry out the image reconstruction process, it is necessary to start with the so-called influence matrix. It is obtained using the Fresnel zone model (a model describing the relationship between the radio signal transmitter and receiver) in calculations. Then the inverse problem must be solved using Tychonoff's regularisation with a lambda of 19 thousand. This parameter was set arbitrarily. The mentioned processes lead to an inverse matrix that can be used to determine the vector image. In order for the RTI system to cover areas of any solid shape, the computational algorithm had to be enhanced with a convolution filter based on the Marr wavelet. After the image matrix is created, this filter takes it to itself to configure its value to 60 per cent of the maximum.

The tests were carried out in a gradual and successive manner. After combining the hardware and software layers, a test area was created in the form of an office room (which was in normal use) and then 4, then 8 and finally 16 radio probes were distributed around its perimeter. The central unit was positioned close to the centre of the room as intended. The shape of the measurement zone and the distribution of transmitters are presented in figure 9. The system reactions to the introduced disturbances were observed on the basis of changes in the heat map obtained by reconstruction. Example maps are also presented within figure 9. The test scenarios included different types of disturbance configurations. These ranged from a single stationary user to a moving group of people. It can therefore be concluded that the calibration of the RTI system was carried out experimentally, however, based on the research carried out, it was possible to formulate several assumptions according to which the system should be scaled.

By correctly defining the room model and accurately marking the positions of the transmitters on it, it was possible to conclude that the response of the heat map to disturbances occurring in the measurement zone was adequate as far as space was concerned. The only limitation in this respect was the density of the grid created from the available projection angles. In some areas of the zone it was simply too small, which could cause slight shifts of maximum disturbance in the planar heat map in relation to the area in reality. This could have been counteracted by increasing the number of transmitters or by modelling the grid (changing the position of the transmitters).

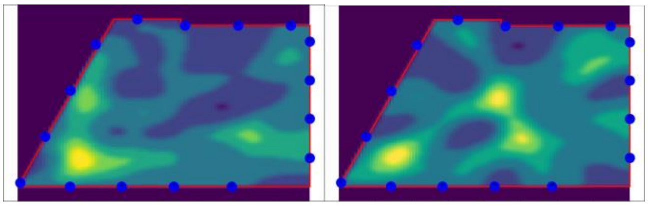

Fig. 9. Reconstructions of the room and the presence registered in it combined with the heat map (bright yellow spots indicate persons): one person in the bottom left corner of the room (on the left) and a total of three people in the corner and in the middle of the room (on the right)

To reconstruct an image like the one in figure 9 the equation must be solved:

$$J*e = m \quad (1)$$

where J represents the sensitivity matrix and the parameter m denotes the vector of measurements. All the resulting finite elements of the computational grid are denoted as e and treated as a vector.

In the case of the sensitivity matrix, it is built up by rows and columns, where each value contained in them corresponds to the sensitivity achieved by a selected reconstruction pixel per measurement for a given transmitter-receiver pair (in the case of the presented system, sixteen radio devices will form a 256-element matrix). The indexing of the fields of the sensitivity matrix J follows each possible combination of radio devices (transmitter and receiver).

$$J^{-1}*m = e \quad (2)$$

The study encountered a significant computational problem arising from the non-squaring of the sensitivity matrix J. This was true for almost all observed cases. This forced a search for a solution and eventually led to the identification of the reason as a bad conditioning of Tychonoff's regularization (Tychonoff's 1998). As mentioned, a configuration of sixteen transmitters should result in a vector of length equal to 256 elements. Nevertheless, there have been incidents where the number of values was able to exceed 1000. However, this did not trigger the abandonment of the search for inverse matrices with the help of Tychonoff's regularization. As far as the sensitivity matrix is concerned, it is determined assuming that the zone formed by the flow of electromagnetic waves between the transmitter and the receiver assumes an ellipsoidal shape (according to Fresnel's theorem). Of course, it is also assumed that inside the determined zone fluctuations of the RSSI value may occur [3, 6].

Entails huge computational resources. This is especially true when the sensitivity matrix J has not yet been determined because it is a reusable element. Once determined, it provides a benchmark for the room but under the condition that the hardware layer associated with the radio probes is not displaced. It is therefore necessary to keep this matrix in permanent memory in case the calculation is resumed. Once all computational processes have been established, the method achieves performance in terms of reconstruction speed in the order of 1 millisecond to 2 milliseconds per process.

5. Summary

Research on the system has shown that commercial radio technologies used in the construction of the assumed navigation system present the potential for expansion of this type of structure in the future. The efficiency of the system increased as the weaknesses of individual technologies were eliminated by the advantages of others (BLE, 802.15.4 – XBee, 802.11 – Wi-Fi) An office building was used as the object of research of the navigation system, and one of its rooms as a test area for a radio tomography. Beacons and probes have been located in characteristic floor points throughout their area. In the case of probes due to irregularities in the room, the devices were placed on special rotary hooks, which allowed correction of the antenna radiation angles. Thanks to the appropriate calibration of the transmitters and their placement at the appropriate height, at some moments it was possible to determine the circumference in the belt of the individual violating the test area with an accuracy of several cm.

However, it should be noted that the potential for ambiguity increased as the disturbance moved from the edge of the test area towards the centre of the room. It is also worth noting that continually increasing the number of transmitters in the same working area brings the system to a point where too close proximity of antennas will lead to a sharp increase in the level of wave interference, i.e. mutual interference. While in the case of radio beacons this is not so critical, in the case of radio probes moderation must be exercised. However, it is necessary to eliminate the so-called dead zones resulting from locally occurring too low grid densities. This type of event occurs when objects are crossed by only 1-2 angles of projection / beam. From a mathematical point of view, too few measurement points result in low spatial resolution.

References

[1] Bluetooth SIG. Bluetooth Core Specification, version 4.0. Bluetooth SIG: Kirkland, WA, USA, 2010.

[2] Kaltiokallio O., Bocca M.: Real-time intrusion detection and tracking in indoor environment through distributed RSSI processing. Proceedings of the 2011 IEEE 17th International Conference on Embedded and Real-Time Computing Systems and Applications, 2011, 61–70.

[3] Maj M., Rymarczyk T., Kania K., Niderla K., Styła M., Adamkiewicz P.: Application of the Fresnel zone and Free-space Path for image reconstruction in radio tomography. International Interdisciplinary PhD Workshop 2019 – IIPhDW 2019, Wismar, Germany.

[4] Rymarczyk T., Styła M., Oleszek M., Maj M., Kania K., Adamkiewicz P.: Object detection using radio imaging tomography and tomographic sensors, Przegląd Elektrotechniczny 96(1), 2020, 182–185.

[5] Styła M., Oleszek M., Rymarczyk T., Maj M., Adamkiewicz P.: Hybrid sensor for detection of objects using radio tomography. Proc. Applications of Electromagnetics in Modern Engineering and Medicine – PTZE 2019, 219–223.

[6] Vauhkonen M., Vadasz D., Karjalainen P. A., Somersalo E., Kaipio J. P.: Tikhonov regularization and prior information in electrical impedance tomography. IEEE Trans. Med. Imaging 17, 1998, 285–293.

[7] Wilson J., Patwari N.: See-through walls: Motion tracking using variance-based radio tomography networks. IEEE Trans. Mob. Comput. 10, 2010, 612–621.

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