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Interrogation zone determination in HF RFID systems with multiplexed antennas*

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Abstract: The operation of an anti-collision RFID system is characterized by the interrogation zone which should be estimated in any direction of 3D space for a group of electronic transponders. The interrogation zone should be as large as possible. However, the many problems in this area are due to the fact that energy can be transferred to transponders only on a limited distance. The greatest flexibility in developing RFID applications and shaping the interrogation zone can be achieved using the system with an antenna multiplexer. Therefore the problem of the interrogation zone determination in HF RFID systems with two orthogonal RWD antennas is presented in the paper. The perceived issues have been effectively dealt with and the solution has been proposed on the basis of the elaborated model. Conducted studies have been used to develop the software tool JankoRFIDmuxHF in the Mathcad environment. The research results are analysed in an example system configuration. The specialized measuring stand has been used for experimental verification of the identification efficiency. The convergence of the measurements and calculations confirms a practical usefulness of the presented concept of interrogation zone determination in anti-collision systems. It also shows the practical utility of the developed model and software tools.

Key words: anti-collision identification, interrogation zone, multiplexed antennas, RFID

1. Introduction

The typical RFID single (or anti-collision) system consists of transponder(s), read/write device (RWD) and its antenna [1]. The RWD connected to a computer and their software form a management centre whereas the electronic transponders are used for marking objects in various areas of people's economical and social activities (e.g. industry, science, medicine, logistics, consumer market and many other fields [2, 3]).

The HF RFID systems (carrier frequency f_0 = 13.56 MHz) operate in the area (Ω_{ID}) that is characterized by an inhomogeneous magnetic field (expressed by the magnetic field strength H) and strong coupling (expressed by the mutual inductance M) between antennas of the

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arrangement components (Fig. 1). The inhomogeneous magnetic field generated in the RWD antenna vicinity is a medium for both energy transfer and wireless communication. The communication mechanisms in the HF band are implemented in adequate protocols, such as ISO/IEC 14443 [4], 15693 [5], 18000-3 [6] and others.

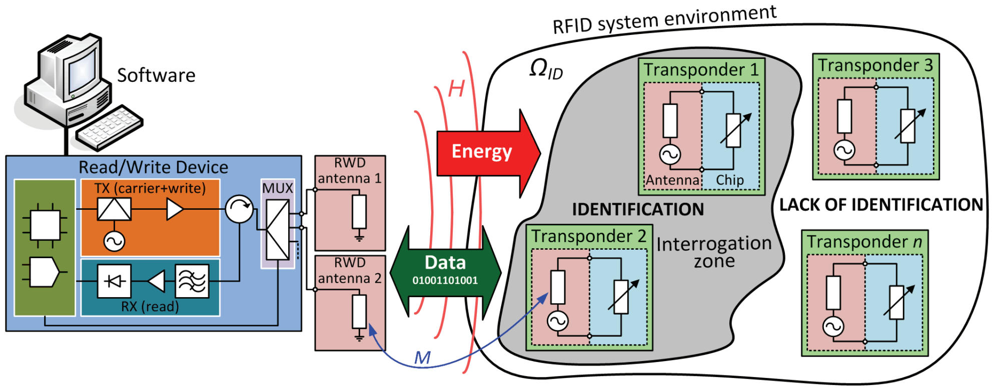

Fig. 1. Anti-collision HF RFID system with multiplexed antennas

The communication process can be activated only when transponders are in the interrogation zone (IZ). It means that the operational capability of RFID systems is characterized by the IZ. This parameter covers problems of energy and communication activity with regards to all parts of a system arrangement. It also determines and comprehensively describes possibilities of an RFID system application in desirable automated processes.

From a practical point of view (an effective implementation of an RFID system), the interrogation zone should be as large as possible regardless of the variable location/orientation of activated transponders. However, it is not possible to identify all transponders at any point in the space Ω_{ID}. The most of all these problems are due to the fact that energy can be transferred from the RWD to transponders only on a limited distance [1, 7-17]. Additionally, many parameters and phenomena describing RFID systems have to be considered in a different way than it is in the classical theory valid for typical radio-communication systems. In the HF RFID systems, the energy is not transferred (far-field region) but stored in an inhomogeneous magnetic field (near-field region). At the present stage of knowledge, it is the main reason why the practical implementation of anti-collision identification (many transponders can be present in the IZ and simultaneously communicate with the RWD) is restrained especially in automated systems operating in dynamic conditions.

The IZ maximization is the most effective solution of these problems. It should be noted that a lot of issues in this regard remain unresolved at the current stage of the contemporary knowledge. For example only the maximal distance (RFID system range) between one-transponder and the one-RWD antenna centre is considered in common design processes in practice. Whereas the RFID system range is only the basic parameter describing the interrogation zone. Moreover, the IZ should be estimated in any direction of 3D space Ω_{ID} for a group of electronic transponders. The greatest flexibility in developing RFID applications and shaping the IZ space can be achieved using the RFID system in which a multiplexer (MUX) and more than one RWD antenna is applied (Figure 1). Because of this, the authors paid particular attention to the problem of energy transfer in the RFID systems with multiplexed antennas that is more sophisticated than typical applications (with one RWD antenna). Such a solution is used in order to maximize the IZ, especially in automated systems operating in dynamic conditions.

2. Interrogation zone maximization – review

The problem of IZ maximization consist in increasing the size of space in which the object identification process is realised. This definition is related to the RFID system range that is defined as the maximal distance between the transponder and the RWD antenna centre (assuming that the read/write information to/from transponder's memory is correct). Therefore, this problem should be considered with respect to the range of HF RFID system: the near field communication (NFC – operating up to a several centimetres), the proximity range (PR – operating up to a dozen centimetres), the medium range (MR – operating up to several tens of centimetres) and the long range (LR – operating from few dozen centimetres to several meters).

The HF RWD antennas are made in a form of loop which is small in relation to the wavelength (for the f_0 = 13.56 MHz λ is about 22 m). The antenna loop is typically made as a square [8], a rectangle [9], a circle [10] or other polygon [11]. The primary way to enlarge the size of IZ consists in conveying more energy to transponders that are freely deployed and oriented in the space Ω_{ID}. This can be achieved, for example, by only increasing the power supplied to RWD antenna terminals. However, it should be noted that the magnetic field strength is restricted by ETSI EN 300 330 standard [7] for the HF RFID systems with inductive coupling. So, it is needed to find other methods for solving the considered problem. It could be reached by enlarging the size of RWD antenna loop [12]. However, it causes the necessity to increase the power across antenna terminals in order to achieve the objective pursued. And also a signal-to-noise ratio (S/N) has to be controlled more carefully while data from the transponder are being received. Another method consists in redesigning antenna to an untypical shape [11, 13] or in modifying its position and orientation in the space [14]. More expensive systems are based on multiple RWD devices and their antennas [15]. The costs of such a modification are significant, especially in the case of LR devices. As an alternative, a gate antenna could be used [16, 17], but it is still not a chip approach and additionally, only one space configuration of the inductive loop is usually achievable.

The greatest flexibility in improving the IZ parameter can be achieved using the RWD with an internal/external MUX and more than one RWD antenna that could be freely positioned in the space. Therefore, a practical problem with two interacting square and orthogonal RWD antennas is presented in the paper. The proposed method can be practically used to solve many identification problems e.g. in logistic (forwarding mail, materials, articles) [18], at tracking luggage in airports [19], for ski lift access control [20] and many others RFID processes where only one RWD antenna is used nowadays. Furthermore, it should be noted that the proposed method is optimal for using in anti-collision applications, especially when marked objects dynamically change their locations [21]. In the foreseeable future, the proposed solution will allow a broad replacement of currently used barcodes by RFID transponders that are consistent with the electronic product code (EPC). This author's activity is to provide an efficient realization of RFID identification process with regard to fast moving consumer goods (FMCG) [2, 22].

This solution has been proposed on the basis of the elaborated model that can be used for passive and semi-passive transponders (manufactured as label, ISO card, disk or coin, glass tube, plastic housing and other forms). The presented method is suitable for the NFC, PR, MR or LR RFID systems. It also can be used for any type of RWD antennas for which the magnetic field strength should be calculated. The developed solution can be extended to the IZ determination by using the Monte Carlo (MC) method described in [23].

3. Model

The problem to solve is the arrangement of two perpendicular antennas connected to the one RWD with the MUX. The antennas have to be switched while marked objects are being identified in the inside of a cube of side b (Fig. 2a). The process of energy transfer from the RWD to RFID transponders is subjected to the analysis in the study to be carried out. The energy is conveyed by the inhomogeneous magnetic field of intensity H (Fig. 2c).

In the HF band, the minimum value of magnetic field strength (H_{min}) is the basic parameter at which the correct data transmission between the RWD and the transponder takes place. The analysis of the magnetic field in the space Ω_{ID} allows designers to estimate the proper boundaries of the space with spatially placed multiple transponders, for the case of designing anti-collision RFID system with inductive coupling.

The components of magnetic field strength in any spatial point $P(x, y, z)$ for a square antenna loop can be calculated from [7]:

$$H_x = \frac{I_R N_R}{4\pi}\left[\int_{\frac{-a}{2}}^{\frac{a}{2}} \frac{z}{\left[\left(x-\frac{a}{2}\right)^2 + (y-y')^2 + z^2\right]^{3/2}} dy' + \int_{\frac{a}{2}}^{\frac{-a}{2}} \frac{z}{\left[\left(x+\frac{a}{2}\right)^2 + (y-y')^2 + z^2\right]^{3/2}} dy'\right] \quad (1)$$

$$H_y = \frac{I_R N_R}{4\pi}\left[\int_{\frac{-a}{2}}^{\frac{a}{2}} \frac{-z}{\left[(x-x')^2 + \left(y+\frac{a}{2}\right)^2 + z^2\right]^{3/2}} dx' + \int_{\frac{a}{2}}^{\frac{-a}{2}} \frac{-z}{\left[(x-x')^2 + \left(y-\frac{a}{2}\right)^2 + z^2\right]^{3/2}} dx'\right] \quad (2)$$

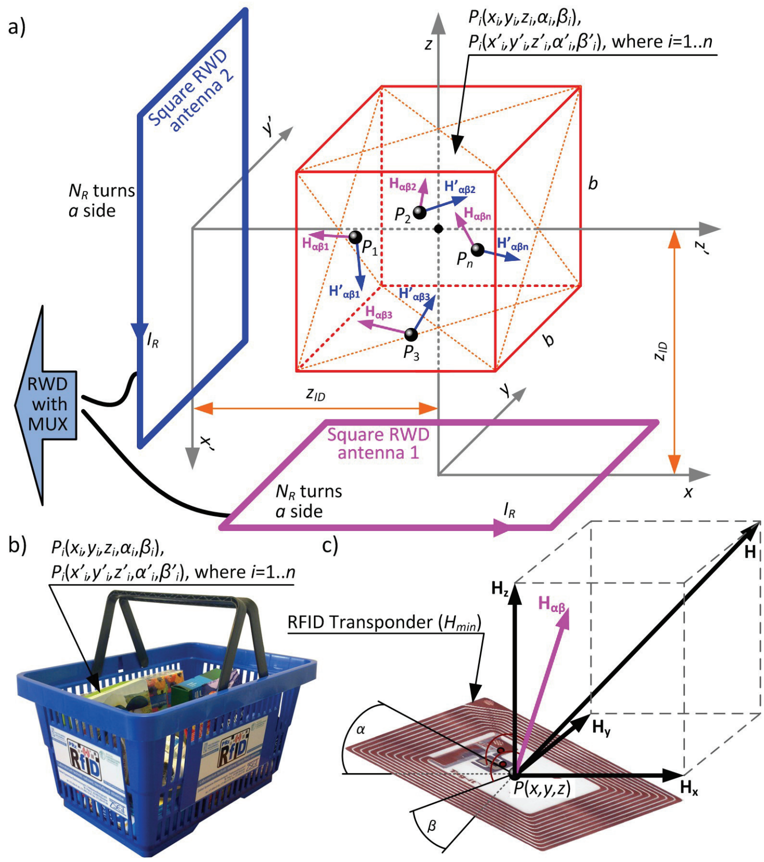

Fig. 2. Problem of objects identification in the HF RFID systems with two orthogonal RWD antennas: a) geometrical model, b) example of a future application - shopping basket with FMCG marked by EPC, c) orientation of transponder which is deviated by α and β angles

$$H_z = \frac{I_R N_R}{4\pi}\left[\int_{\frac{-a}{2}}^{\frac{a}{2}} \frac{y+\frac{a}{2}}{\left[(x-x')^2+\left(y+\frac{a}{2}\right)^2+z^2\right]^{3/2}}dx' + \int_{\frac{-a}{2}}^{\frac{a}{2}} \frac{-x+\frac{a}{2}}{\left[\left(x-\frac{a}{2}\right)^2+(y-y')^2+z^2\right]^{3/2}}dy' + \right.$$

$$\left. + \int_{\frac{a}{2}}^{\frac{-a}{2}} \frac{y-\frac{a}{2}}{\left[(x-x')^2+\left(y-\frac{a}{2}\right)^2+z^2\right]^{3/2}}dx' + \int_{\frac{a}{2}}^{\frac{-a}{2}} \frac{-x-\frac{a}{2}}{\left[\left(x+\frac{a}{2}\right)^2+(y-y')^2+z^2\right]^{3/2}}dy',\right. \quad (3)$$

where: I_R denotes antenna loop current, N_R – number of loop turns and a is side length.

The obtained equations (1)-(3) allow designers to calculate values separately for individual components in x, y and z directions (H_x, H_y, H_z). The case of an object orientation in the space Ω_{ID} can be described as a transponder deviation by α and β angles from parallel planes of the RWD-transponder antenna loops (Fig. 2c). It means that marked objects are in a chaos state, such as in a shopping basket that contains the so-called fast moving consumer goods FMCG (Fig. 2b). In this case, a perpendicular component of magnetic field strength for a deviated transponder is given by [7]:

$$H_{\alpha\beta} = H_z \cos(\alpha)\cos(\beta) + H_x \sin(\alpha)\cos(\beta) + H_y \sin(\beta). \tag{4}$$

If the condition $|H_{\alpha\beta}| \geq H_{\min}$ is met then a transponder is powered correctly and can exchange data with RWD. The value of $H_{\alpha\beta}$ should be considered separately for each multiplexed antenna and individually for each transponder that is located and oriented in the point P_i (where $i = 1 \ldots n$, and n denotes the number of considered transponders). It means that the condition for correct supplying one of the transponders should be analysed in two steps i.e. the $H_{\alpha\beta}$ should be calculated in the point $P_i(x_i, y_i, z_i, \alpha_i, \beta_i)$ for the antenna #1, and in the $P_i(x'_i, y'_i, z'_i, \alpha'_i, \beta'_i)$ for the antenna #2. The coordinates in the system (x', y', z') can be calculated from:

$$\begin{pmatrix} x' \\ y' \\ z' \\ \alpha' \\ \beta' \end{pmatrix} = \begin{pmatrix} z_{ID} - z \\ y \\ z_{ID} + x \\ 90° + \alpha \\ \beta \end{pmatrix}. \tag{5}$$

It should be emphasized that more antennas and their hypothetic localisations in a space can be considered by using the elaborated model.

The exemplary location and orientation of n-transponders is analysed in Figure 2a. It is difficult to accurately predict the coordinates of the points P_i in a chaos state. In fact, it isn't possible to analyse all potential locations and orientations of a group of n-transponders in the inside of a cube of side b. The described problem has a probabilistic nature, and proposed solution is obtained by simulating the group of given objects by using the MC method [23, 24]. Therefore, in this case, the IZ is determined for a given efficiency of identification η:

$$\eta = \frac{k}{n \cdot m} \cdot 100\%, \tag{6}$$

where: k is the number of transponders for which desired read/write operations have been properly executed, and m is the number of sampling points P_i of n-transponders.

The correct identification of one transponder and for one cycle of multiplexed antennas occurs when one of the two conditions is met: a) $|H_{\alpha\beta}| \geq H_{min}$ or b) $|H'_{\alpha\beta}| \geq H_{min}$. If the conditions are not met, the transponder cannot be recognized by the RFID system (lack of identification).

4. Results

A key aim of the study has been to elaborate the numerical model. The utility program called *JankoRFIDmuxHF* has been developed on the basis of this model (Fig. 3).

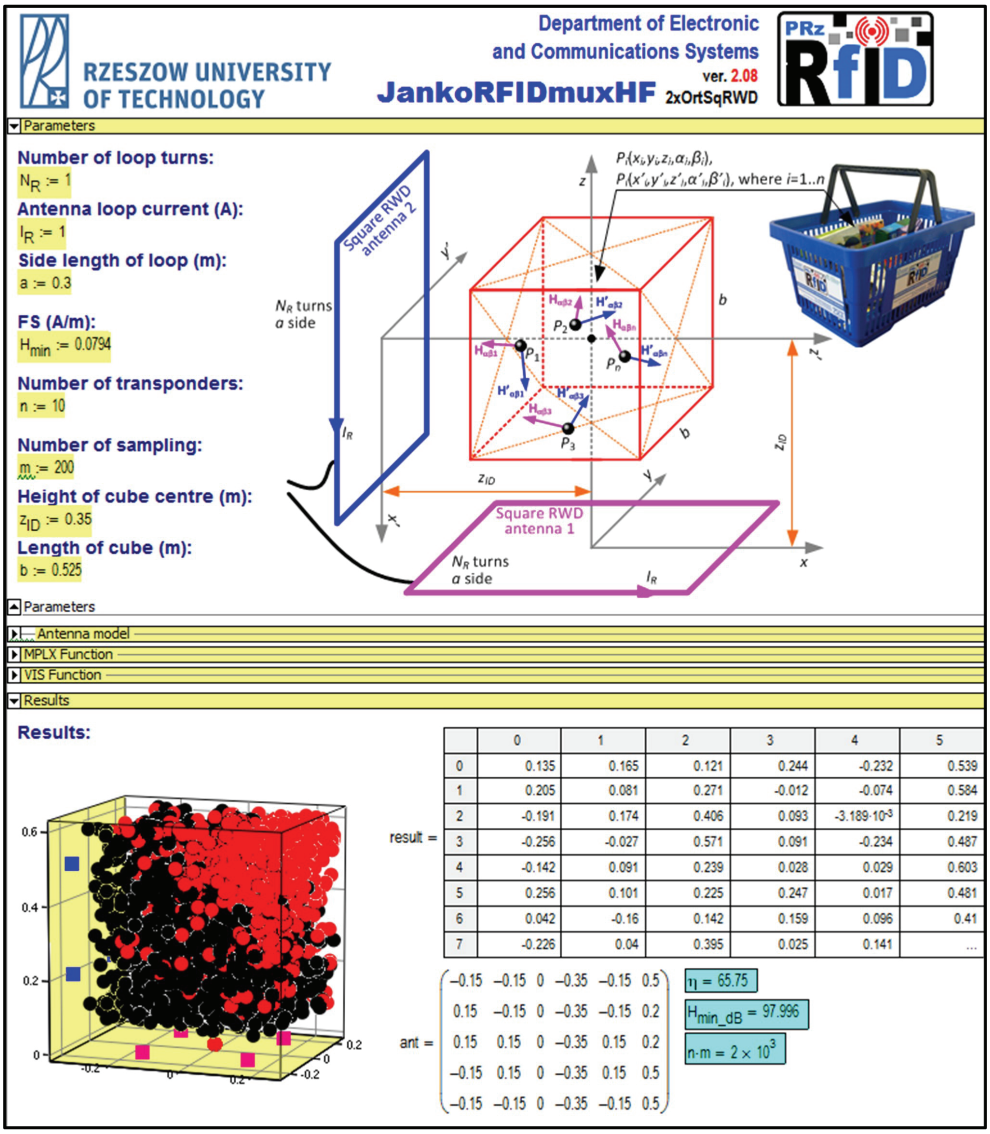

Fig. 3. *JankoRFIDmuxHF* program

The essence of the model is represented by the *MPLX* function (Fig. 4). Input arguments for this function are determined on the basis of primary parameters of the HF RFID system with two orthogonal and multiplexed RWD antennas.

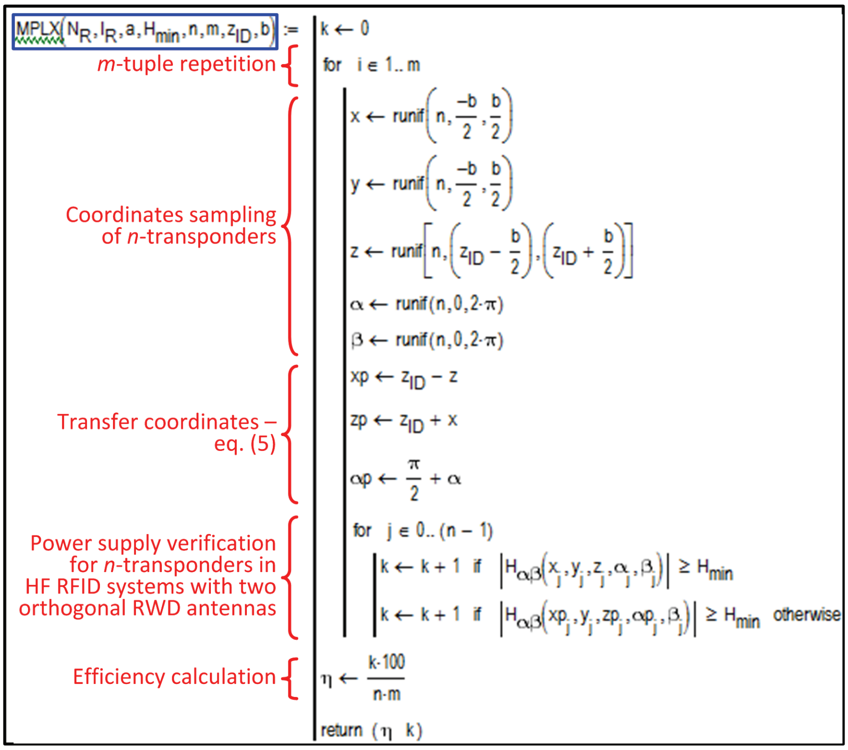

Fig. 4. *MPLX* procedure with comments

The *JankoRFIDmuxHF* program can be used for calculating the identification efficiency and the RWD antenna localisations for the given input data. The results of identification process are presented graphically along with efficiency effects (correct/incorrect identification). A user may select any format of output data for further analysis during preparation of graph visualisation e.g. in the OriginPro software. An example of output results is presented in Figure 5.

The example calculations ($m = 200$, $z_{ID} = 0.35$ m, $b = 0.525$ m) are performed for 10-transponders ($H_{min} = 0.0794$ A/m that means 98 dBμA/m) and two square antennas ($a = 0.3$ m, $I_R = 1$ A, $N_R = 1$) supplied from the RWD with MUX (two antenna inputs). The determined 3D IZ is characterized by the cube in which the efficiency η has been calculated.

The measured part of the example has been carried out in the laboratory stand that had been especially prepared for this aim by the authors (Fig. 6). The two-axis (azimuth/elevation) positioner is the main component of the stand and allows any change of spatial orientation according to the elements of RFID system [25]. Furthermore, an impact of its parts on the magnetic field generated by the antenna of RWD is negligible (plexiglass construction). Its spatial and time parameters are fully controlled by the dedicated software application. An integration of the positioner with specialized equipment of the author's RFID laboratory allows to measure the impact of dynamic changes in the position of transponders on the parameters of the anti-collision identification process for labelled objects.

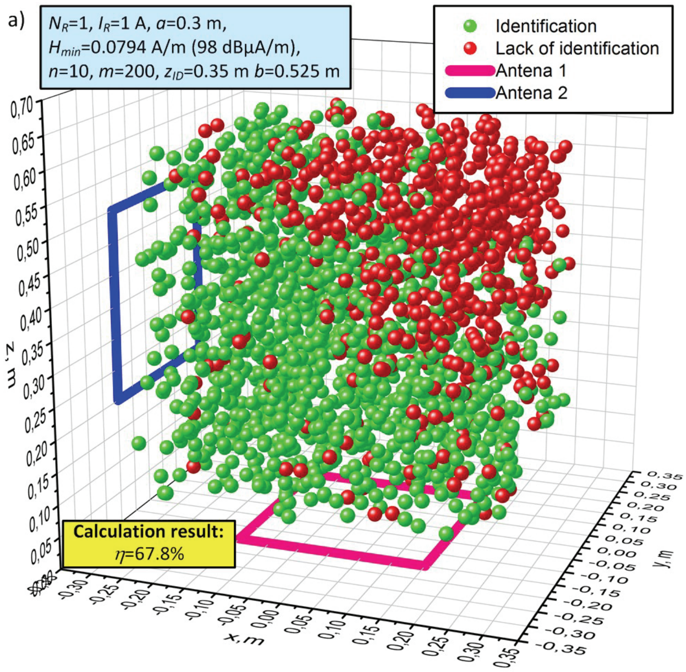

Fig. 5. Example results of interrogation zone determination in calculation process

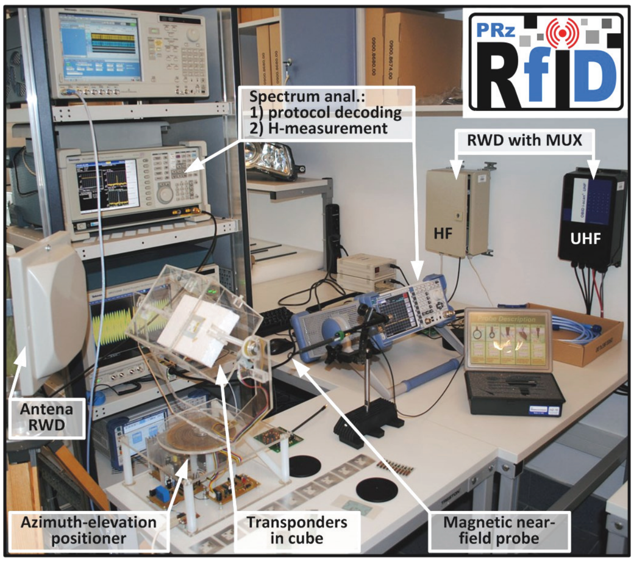

Fig. 6. Test stand in RFID laboratory

The detailed parameters of the models used in the calculations as an equivalent of RFID system components correspond to the parameters of real devices available in the laboratory.

The example measurements are performed for 10-transponders Texas Instruments RI-I11-112A-03 (H_{min} = 0.0794 A/m that means 98 dBµA/m) [26], two square antennas Feig ID ISC.ANT300/300-A (a = 0.3 m, N_R = 1) [27] supplied from RWD Feig ID ISC.LR200 with MUX (2 antenna inputs) [28]. A full control over an automatic identification process in the field of energy and communication conditions is possible thanks to the rich measuring equipment. The output power of RWD can be adjusted according to the proper RMS value of current I_R = 1 A (measured by oscilloscope Tektronix DPO71254B with High Frequency Current Probe CT1 [29]). The magnetic field is controlled by using the spectrum analyser R&S FSL18 with near-field probes HZ-11 [30]. The communication process is controlled in the RWD software Feig ID ISOStart 2014 version: 09.08.02 and also by using the spectrum analyser Tektronix RSA 3408B (frame decoding of the anti-collision sequence – ISO/IEC 15693 protocol [5]).

The marked objects (different-size styrofoam blocks with TI RI-I11-112A-03 transponders) are placed inside the removable-cube (b = 0.525 m). Similarly as in the calculation process, the determined 3D IZ is characterized by the cube of side b in which the efficiency η is calculated. However, this measurement process is extremely time-consuming. At the beginning, random settings are drawn for positions of the both axis in the positioner. In the next step, the number of recognized transponders k (transponders for which unique identifier UID is properly read) is assigned. It is realized in ISOStart software, for a full cycle of multiplexing two-antennas. These steps are repeated m-times (m = 200).

Table 1. Example results of identification efficiency

η, %			
calculation			Measurement (Antenna 1 & 2)
Antenna 1	Antenna 2	Antenna 1 & 2	
44.6	23.2	67.9	65.4

The results for the identification efficiency of the tested system are compared in Table 1. The calculated and measured values (for Antenna 1 & 2 set) are convergent. Additionally, it can be noticed that the arrangement of two perpendicular antennas connected to the one RWD with the MUX significant improves the identification efficiency (Antenna 1&2 vs. Antenna 1, Antenna 2). The points where transponders are not recognized by the considered RFID system are well visible in Figure 5. Utilizing obtained results, RFID system designers can seek to designate the IZ for a given application. The MC method can be utilized in this process [23]. It can be carried out to obtain 100% identification efficiency. The marked objects can both be placed in one steady point or their localisation and orientation can be changed dynamically.

5. Conclusions

An effective implementation of an RFID system can be ensured only on the basis of accurate study of operation conditions that can be established in the automatic identification process. In the case of RFID system, it is crucial to determine the IZ parameter that should be estimated in any direction of 3D space. This is difficult in anti-collision applications, especially when marked objects dynamically change their location and orientation in the space. A practical example is when marked objects are in a chaos state, just as in a shopping basket that contains fast moving consumer goods. In the future, the solution of this problem will allow designers a broad replacement of currently used barcodes by RFID transponders that are consistent with the electronic product code.

The antenna multiplexing is the most flexible method that can be used in order to enlarge the IZ of an RFID system. It is also suitable for shaping boundaries of this space. For this reason, the problem of the interrogation zone determination in HF RFID systems with two orthogonal and multiplexed RWD antennas is presented in the paper. The perceived issues have been effectively dealt with and the solution has been proposed on the basis of the elaborated model. It should be emphasised that elaborated model can be easily supplemented by additional RWD antennas and their localisation in the space can be changed. It can be also efficiently adapted to the UHF band and EPC Class 1 Generation 2 protocol. The conducted studies have been used to develop the numerical algorithm and the software tool *JankoRFIDmuxHF*. The research results (exemplary calculations and measurements) are analysed in details in a one system configuration. Based on the extended results of this research, the practical projects are developed in cooperation with industrial companies. The convergence of the measurements and calculations confirms a practical usefulness of the presented concept of interrogation zone determination in anti-collision HF RFID systems with multiplexed antennas. It shows the practical utility of the developed model and software tools.

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