Application of Monte Carlo Method for Determining the Interrogation Zone in Anticollision Radio Frequency Identification Systems

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1. Introduction

Current problems that occur in the field of anticollision Radio Frequency IDentification (RFID) prototype systems are solved in experimental way (De Blasi et al., 2010; Lehto et al., 2009; Polivka et al., 2009; Brown, 2007; Clarke et al., 2006; Penttilä et al., 2006; Jones & Chung, 2007). The low efficiency coefficient of identification for the multiple objects localized in the space Ω_{ID} doesn't allow to realize practical projects, such as, the identification of Fast Moving Consumer Goods (FMCG) – Fig. 1. In the light of nascent and modified legal communications standards, like for example, Electronic Product Code (EPC) in the area of UHF and HF ISO 18000-6, ISO 15693, ISO 18000-3 normalizations, there is a necessity to continue complex theoretical research and experimental investigations in the range of simultaneous analysis of EM field, communication protocols, and electric aspects of operating conditions of efficiency identification in anticollision RFID systems.

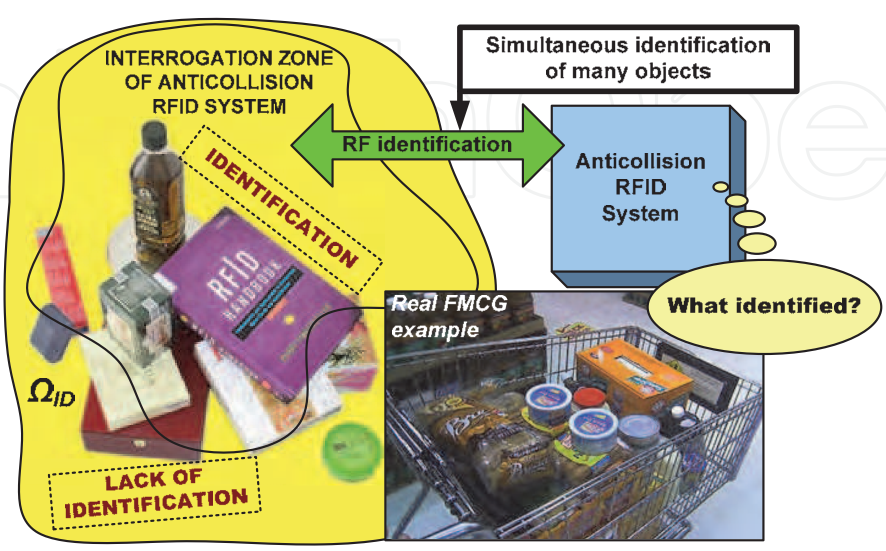

Fig. 1. Illustration of RFID automatic identification process

To generalise, the operation of passive anticollision inductive- (LF, HF), and also propagation (UHF) coupling RFID system is characterized by the interrogation zone (IZ) which is estimated in any direction of 3D space for a group of electronic tags. The elements of algorithm of identification of interrogation zone for anticollision RFID system with the consideration of the energetic (i.e. field and electrical) and communication aspects of operation conditions have been presented in the following chapter. For calculations of the interrogation zone the algorithm based on Monte Carlo (MC) method and a computer program with the use of Mathcad 14 (called *JankoRFIDmc'IZ*) has been utilized.

2. Determining the interrogation zone using MC method

Unequivocal estimation of the interrogation zone for anticollision RFID system depends on automatic identification process. In accordance with the conditions of the correct operation of any RFID system, different locations of many tags strongly change the functioning of an antenna unit array: read/write device (RWD) and individual tags. The problem of determining the interrogation zone is related to two cases. In the first of them, an assumption is made that the location of the n-tags group is determined, whereas in the second case, all possible locations of the group of n-tags in a space around the RWD antenna are going to be analyzed. The problem connected with the first case is realizable by the assumption that the process of determining the interrogation zone in RFID system will be carried out in a few feedback cycles which allow to find the proper location of tags. The statement "few feedback cycles" is related to the time which is accepted for determining the interrogation zone for all n-tags. The mentioned feedback cycles in the carried out simulation include a modification of the tags location which don't fulfil conditions of the correct RFID system operation. The problem from the second case is almost impossible to solve because the prolonged process of calculations would be ineffective. Seemingly, in that case, a method of "trial and error" during the search of the interrogation zone of RFID system might be easier to apply, however, the presented MC method is a well-founded alternative.

The presented premises lean towards the necessity of application of the techniques which make use of random numbers (Kalos & Whitlock, 2008). The result of this is the solution of the problem of the n-tags group location, and testing the functional efficiency of the antenna unit array: read/write device-tags, that is an estimation of anticollision RFID system interrogation zone for given efficiency of identification η_{ID}. The percentage of identification efficiency is given by the equation:

$$\eta_{ID} = \frac{l_{IDOK}}{n} \cdot 100\% \qquad (1)$$

where l_{IDOK} is the number of tags for which the desired read/write operations have been properly done.

The problem contained in the MC method has a probabilistic nature, and it's solution is obtained by simulation of the given object (Rubinstein & Kroese, 2007). The simulation object is represented by the antenna unit array: RWD-tags with the consideration of a synthesis of this antenna unit array and according to all equations which are going to be determined during the synthesis of its electric model in an anticollision RFID system.

For a laboratory process of automatic objects identification the solution of the problem consists in finding the interrogation zone of given RFID system, with its shape, location and

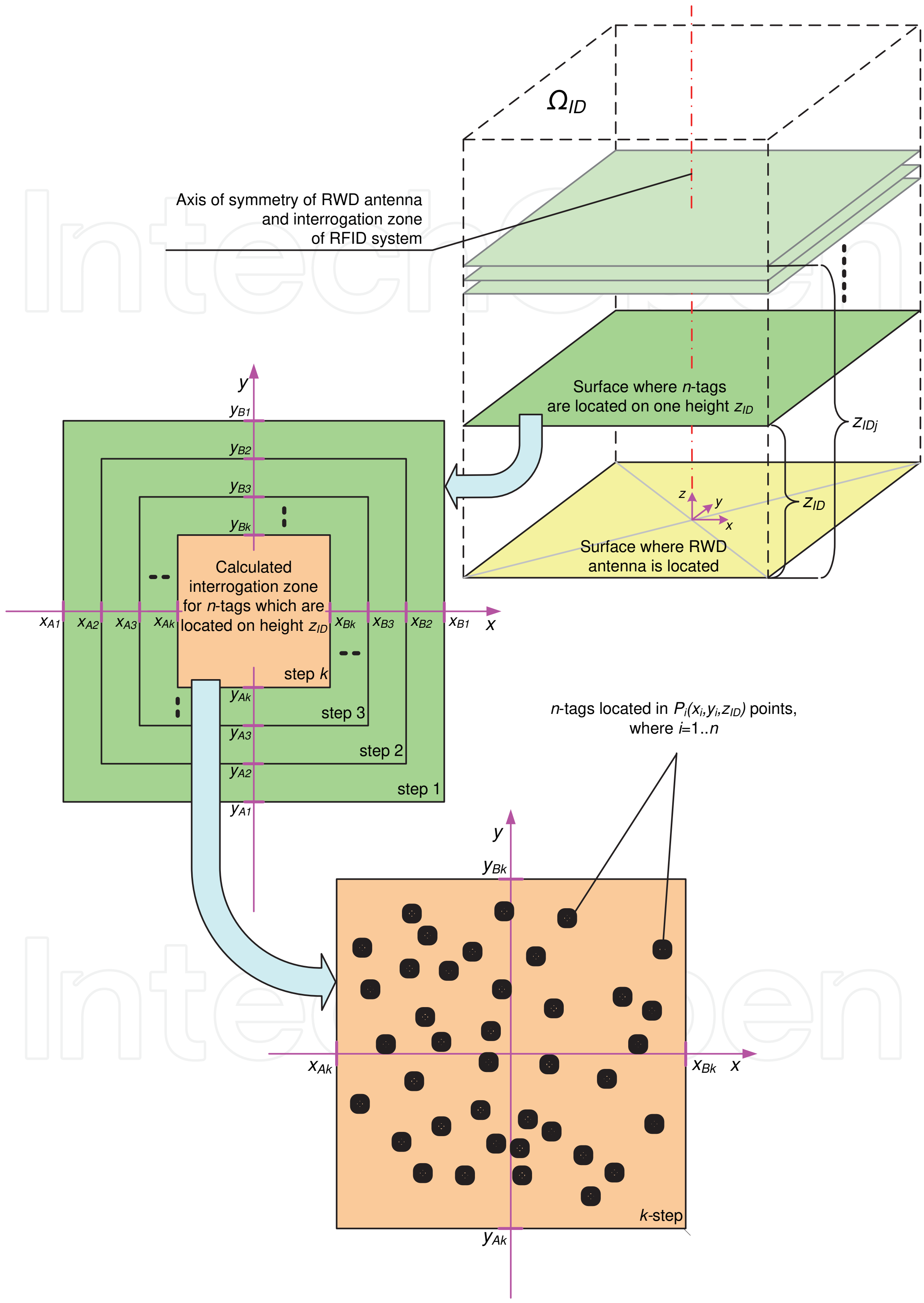

Fig. 2. Graphic representation of the process of determining the interrogation zone in anticollision RFID system using MC method

orientation in 3D space assumed. In the conducted research it was assumed that the demanded area should be square shaped and situated at the z_{ID} height, whereas it's location should be axially - symmetrical and parallel to RWD antenna (Fig. 2). Such an assumption results from the orientation of tags that are parallel to symmetrical RWD antenna which has, for example, circular or square shape in inductive coupling RFID systems.

A random layout of n-tags at P_i points of Cartesian space at (x_i,y_i,z_{ID}) has been assumed in - considered in a sequence - k steps during the search of the RFID system interrogation zone. The random variables x_i and y_i, for i=1..n obtain various values which can't be predicted, but for which the definite distribution is assumed. The electromagnetic field in any point of communication space is heterogeneous. This effect becomes the clearer, the nearer to the surface of RWD antenna, and the farther from its centre a point is situated. This knowledge allows to make a uniform (rectangular) distribution in intervals: $\langle x_{Ak},x_{Bk}\rangle$ for the random variable x_i, and $\langle y_{Ak},y_{Bk}\rangle$ for the random variable y_i, in k-step for the analyzed area. For uniform distribution of the random variables x_i and y_i, and for the definite values of x and y, the distribution functions are given by: $(x-x_{Ak})/(x_{Bk}-x_{Ak})$ and $(y-y_{Ak})/(y_{Bk}-y_{Ak})$. It should be noticed that the random variables x_i and y_i are mutually independent. This means that the random variables x_i and y_i are stochastically independent, since the distribution of the x_i does not depend on the value y_i and vice versa. In this case, the probability density of a pair of random variables (x_i,y_i) is equal to the product of the probability density (x_i) and (y_i) independently.

In order to determine that the RFID system is functioning correctly for given tags locations it is not enough to achieve the efficiency of identification η_{ID}=100% for n-tags and fulfill all conditions for a correct operation of anticollision RFID system. It cannot be predicted whether for k area in which all the conditions mentioned above are fulfilled, the coordinates sampling of tags locations on the surface of their arrangement, allows to fulfill the border case of a correct operation of the whole RFID system. In k-step for the analyzed area in which all the conditions of a correct operation of anticollision RFID system for given efficiency of identification are fulfilled, the practical use of the law of large numbers (Kalos & Whitlock, 2008) is the solution to this problem. For the random variables x_i and y_i independently, the strong law of large numbers for the analyzed case is given by:

$$PP\left(\lim_{m\to\infty} S_m\left(x_i\right) = \lim_{m\to\infty}\sum_{i=1}^{n\cdot m}\frac{x_i}{n\cdot m} = p = \frac{x_{Ak}+x_{Bk}}{2}\right) = 1 \tag{2}$$

$$PP\left(\lim_{m\to\infty} S_m\left(y_i\right) = \lim_{m\to\infty}\sum_{i=1}^{n\cdot m}\frac{y_i}{n\cdot m} = p = \frac{y_{Ak}+y_{Bk}}{2}\right) = 1 \tag{3}$$

where p denotes the expected value of the random variables x_i and y_i (which are equal to zero because the interrogation zone is axially - symmetrical and parallel to RWD antenna), and PP denotes the probability of sampling of variables for m approaching to infinity, but m denotes the number of multiple sampling of tags location (i.e. random variables x_i and y_i) for k analyzed area.

What follows from the equations (2) and (3) is that the sequences of random variables $S_m(x_i)$ and $S_m(y_i)$ converge with probability "1" to the expected value p=0 of the random variables x_i and y_i. It can be found that the m-tuple increase of the number of the random variables x_i and y_i sampling in k-step for the analyzed area lengthens the calculation process during the simulation of an antenna unit array. In accordance with the law of large numbers, the

probability of a correct estimation of the interrogation zone for RFID system increases. First of all, this is connected with the examination of a larger number of localized *n*-tags cases. If the conditions of the correct operation of anticollision RFID system are not fulfilled in any of *m* multiple sampling of tags location for *k* analyzed area, then the next process of multiple sampling should be stopped, and it becomes necessary to examine the next (*k+1*) - smaller area of tags location in the *x-y* plane. The MC solution for the analyzed object completes a procedure which confirms the fulfillment of all conditions for the correct operation of anticollision RFID system. The procedure is correct for the given efficiency of identification, and for the area in which all the *m* multiple sampling of tags location lead to a positive calculation result of the antenna unit array: read/write device-tags.
Correct selection of the *m* number, which will be satisfactory under the experiment, as well as adequate to calculation time and probability of possible tags locations, is a problem. From equations (2) i (3) which describe the strong law of large numbers, the dependence of probability *PP* for the random variables x_i and y_i (which are stochastically independent, and which have a uniform distribution) in function of the $m \cdot n$ has been presented in Fig. 3.

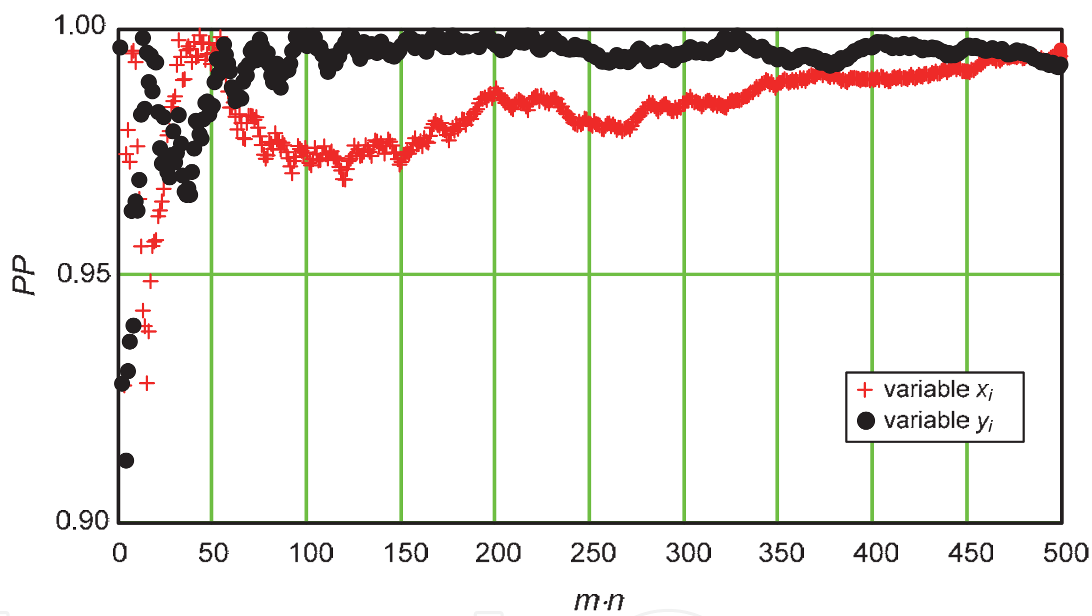

Fig. 3. Example result of probability *PP* of sampling of independent random variables x_i and y_i in function of numbers product: multiple sampling of *m* and *n*-tags location

Assuming that the probability *PP* exceeds the value 0.95 independently for the random variables x_i and y_i, the value $m \cdot n$=250 was determined during the calculation of interrogation zone in automatic identification process. These parameters were determined for 10^6 sampling of 250 independent random variables x_i and y_i which have a uniform distribution. For every sampling, the minimum value of probability *PP* has been searched. The determined value of $m \cdot n$=250 is compatible with a central limit theorem which states that the sum of a sufficiently large number of identically distributed independent random variables, each with finite mean and variance, is going to be approximately normally distributed (Rice, 2006). Uniform distribution of the random variables x_i and y_i is in fact different from a normal distribution, but - for this determined value of $m \cdot n$=250 - random variables x_i and y_i are convergent to a normal distribution. In this case, the obtained compatibility with a central limit theorem confirms the correctness of product $m \cdot n$=250.

The presented idea of n-tags analysis at a specifically determined z_{ID} height, results from a practical demand for realization of automatic identification process with the anticollision RFID systems. The identification of single products which are located inside a container on a pallet can be the practical example of this process. Identification of single objects separately is impossible in this situation, but their location on a pallet is mostly scheduled - because logistic system has to work satisfactorily (Mo & Lorchirachoonkul, 2010; Shaoping Lu et al., 2007; March, 2005; Jones & Chung, 2007). The development of the presented MC solution on an area Ω_{ID} in the x-y-z space requires investigation of every j-surface independently where tags will be located on the whole area Ω_{ID} at points $P_{ij}(x_i,y_i,z_{IDj})$ - (Fig. 2). If all n-tags are in a disordered state in the space Ω_{ID}, then the stochastic independence of all the coordinates x_i, y_i, z_i should be assumed. However, this idea is very complicated because it is not enough to assume that all the pairs of random variables are independent. Taking into consideration the practical requirements of different automatic identification processes, the example presented above is marginal, yet very interesting from a scientific point of view.

3. Conditions of correct operation of anticollision RFID system with inductive coupling

Passive RFID systems with inductive coupling are widespread (ID World, 2009; Wolfram et al., 2008; Jones & Chung, 2007; Paret, 2005). These systems can operate in individual and anticollision regime (Finkenzeller, 2003), and the need to design such systems appears more often nowadays. Functioning of RFID systems with inductive coupling is based on the use of energy which is stored in a magnetic field (Chen & Thomas, 2001; Rautio, 2003; Troyke & Edgington, 2000). The kind of executed operation in individual phases of the exchange of data between units of a system is essential during communication in anticollision identification process (Jankowski-Mihułowicz et al., 2008). The basic condition of effective operation of the system is the proper supply of each tag in a heterogeneous magnetic field created by RWD antenna loop. A minimal value of energy (necessary for proper read/write operation of the tag) is determined by minimal value of magnetic induction B_{min} in each point $P(x,y,z)$ of its location (Fig. 4).

Analysis of the general RFID system schema allows for the determination of the complete impedance of RWD antenna Z_R, taking into account an influence of all coupled tags. Maximal change of the impedance Z_R under the influence of the tags is expressed by the maximum value of difference in impedance arguments $\Delta\varphi_{Rmax}$ without the tags and with them, respectively. The value $\Delta\varphi_{Rmax}$ is limited to assure the correct operation of the system.

A determination of communication conditions for proper operation of RWD-tags antenna set is also possible on the basis of the schema analysis, taking into consideration the properties of data transmission process (transmitted frequency band, data flowability and required time relations in selected communication protocol).

The quality factor Q is a measure of tag antenna unit functioning efficiency in areas of energy transfer and communication conditions in RFID systems with inductive coupling (Newman et al., 1975; Redinger et al., 2003). These conditions are expressed by maximal values of quality factors of RWD and tag antennas: Q_{Rmax} and Q_{Tmax}, respectively. In this case, it is necessary to observe that selection of value Q_{Tmax} is compromised by energy (utilization of magnetic field energy) and communication requirements (Jankowski-Mihułowicz & Kalita, 2009).

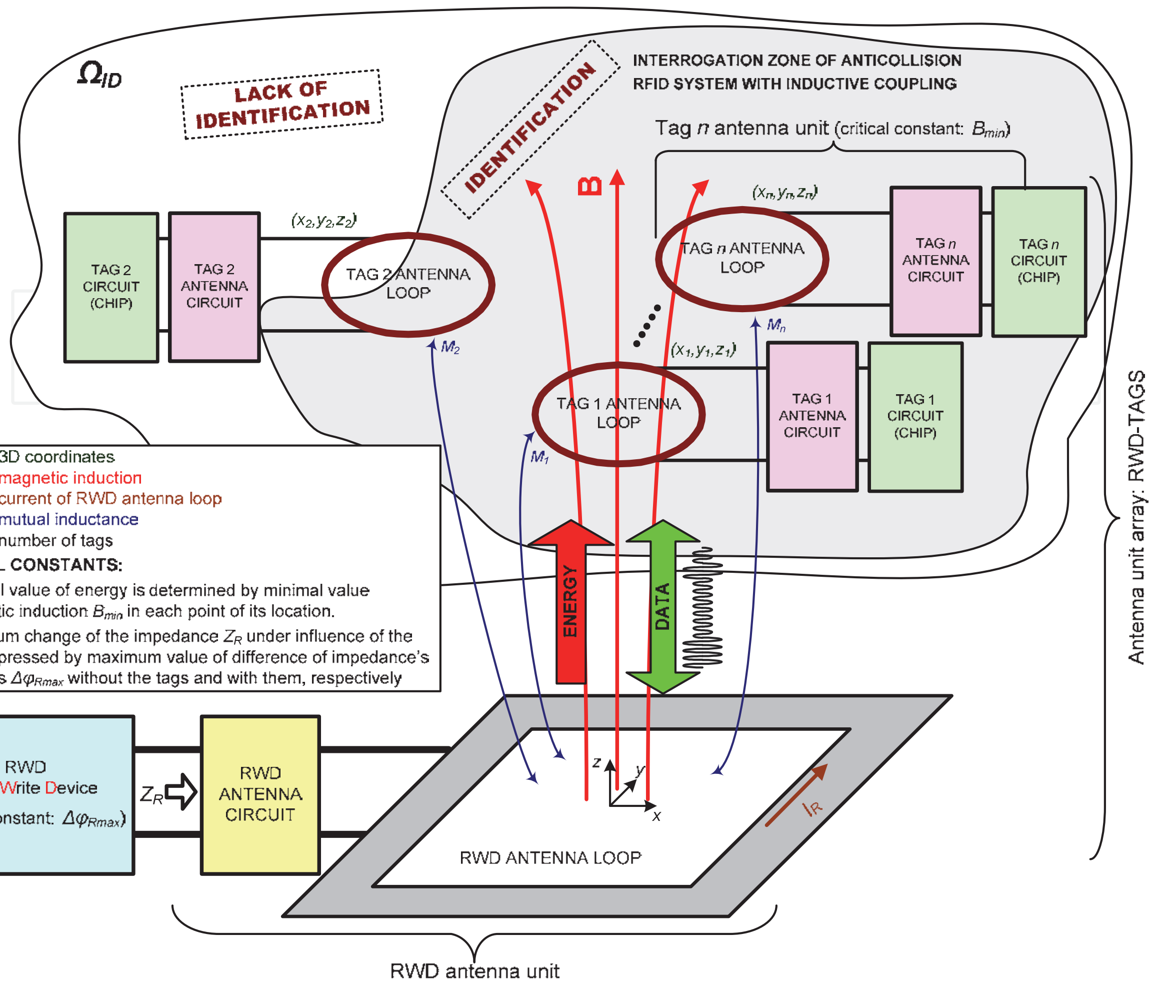

Fig. 4. Block diagram of anticollision RFID system with inductive coupling

During the synthesis of tag antenna, the changes of this parameter can be made by inductance change (indirectly – by changing the effective resistance of antenna loop), adjusted to requirements of the shape and geometrical sizes of an electronic tag. The proper synthesis of interrogation zone of RFID system is closely connected with three aspects which concern the maximum value of Q factor for the operating tag. The first of these aspects is related to the correct operating of the tag supply system, that is, the possibility of radio communication appearing. The second aspect concerns the necessity to obtain the required data transmission bit-rate (and also the bandwidth) in direction: tag-read/write device. The third aspect concerns the impulse and step response of tag circuit in case of reverse data transmission, to provide a correct identification of commands sent from the RWD. The last two aspects should result directly or indirectly from the electronic tag chip specification for which the antenna is going to be projected. The first aspect should be considered at the stage of antenna synthesis, and the value of Q factor should contain all of the mentioned limitations of operating passive tag. It is essential to ensure the homogeneous proper interrogation zone of RFID system that is a mutual overlay of zones that result from conditions of tag supply (by absorbing the energy of magnetic field) and the radio communication carried in the system (realized with the suitable value of signal-to-noise).
Paying attention to the maximum work distance between elements of the RFID system, in particular for systems working in the RFID far field, it is necessary to estimate the simulated

and built antenna set RWD-tags in relation to the obligatory normalizations of communication and EMC (ETSI EN 300 330, 2010; Jankowski-Mihułowicz, 2010).

4. Energy transfer in passive anticollision RFID system with inductive coupling – fundamental equations

4.1 EM field aspects

Analysis of the read/write device antenna unit allows to make an assumption that the antenna loop current (I_R) is constant along the whole flow way (Fig. 5).

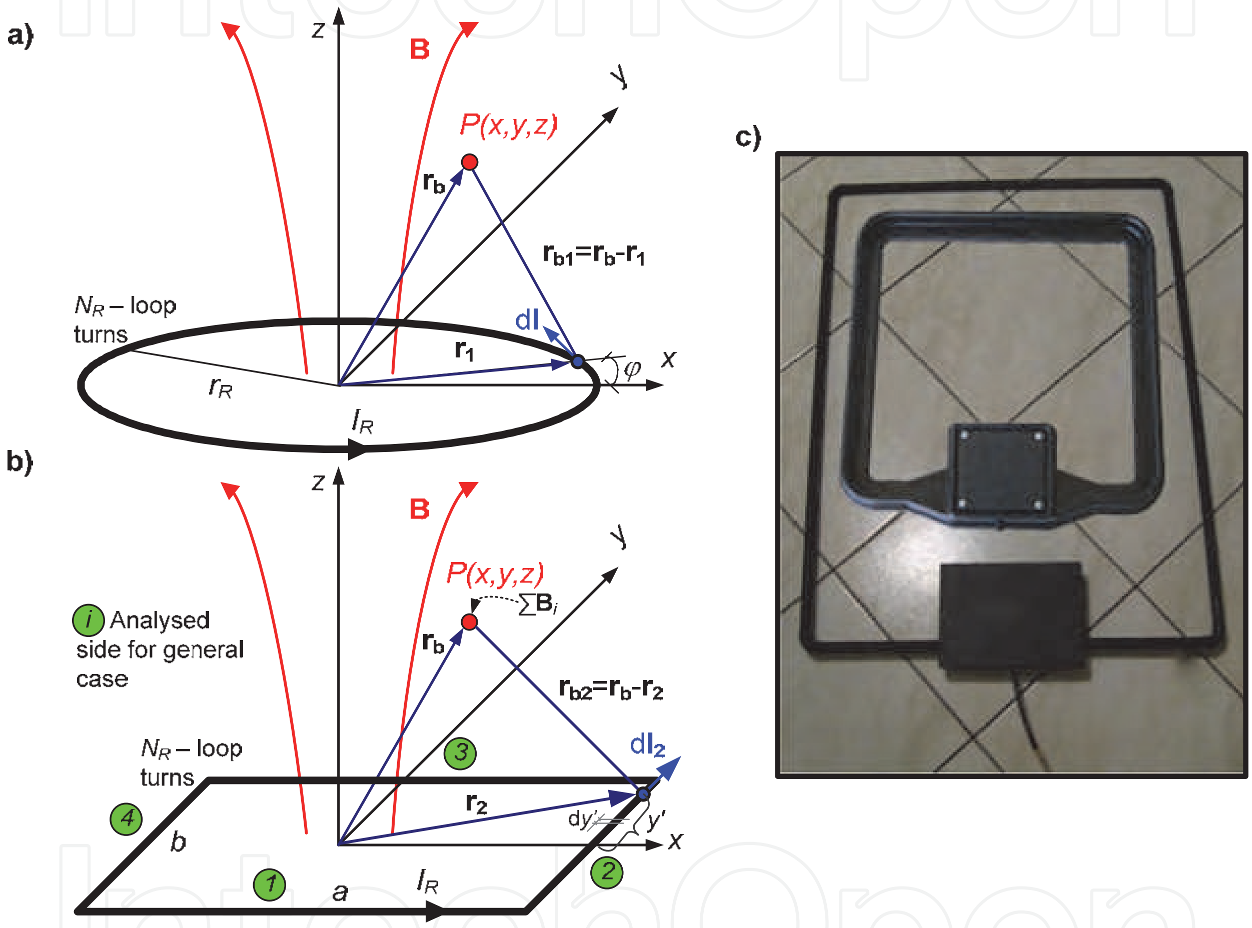

Fig. 5. Analyzed cases of RWD antenna loop: a) circular loop, b) loop of polygon shape, c) some realizations of tested RWD antennas

Change of the electric charge density in time equals zero, so in that case the electric current density divergence equals zero as well. Making these assumptions permits to apply the magnetostatic laws to magnetic field analysis for any RWD shape. In accordance with vector Biot-Savart law, the magnetic induction value of **B** in any space point *P(x,y,z)* is given by the equation:

$$\mathbf{B} = \frac{\mu_0 I_R N_R}{4\pi}\oint \frac{d\mathbf{l} \times \mathbf{r}_{b1}}{\left|\mathbf{r}_{b1}\right|^3} \qquad (4)$$

where: $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m.

Application of the Biot-Savart law for the RWD's antenna loops is possible by the additional assumptions that the wire diameter of RWD's antenna is negligible in relation to the geometrical loop sizes, and also that there is full inductive coupling between the individual loop turns (N_R).

For the circle-shaped loop (Fig. 5-a), the axial symmetry permits convenient change from Cartesian to cylindrical coordinates. The vector describing the d**l** location at P point, in which the value of magnetic induction is calculated, is given by the formula:

$$\mathbf{r_{b1}} = \mathbf{r_b} - \mathbf{r_1} \tag{5}$$

where the vector describing d**l** element location that changes in φ angle function, and the vector describing location of point P, are given as follows:

$$\mathbf{r_1} = \begin{pmatrix} r_R \cdot \cos(\varphi) \\ r_R \cdot \sin(\varphi) \\ 0 \end{pmatrix} \tag{6}$$

$$\mathbf{r_b} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{7}$$

The unit vector connected with $\mathrm{d}\mathbf{l} = r_R \cdot \mathrm{d}\varphi$ is given by the formula:

$$\mathbf{u}_\varphi = \begin{pmatrix} -\sin(\varphi) \\ \cos(\varphi) \\ 0 \end{pmatrix} \tag{8}$$

Changing the coordinate system leads to final equation, which describes the magnetic vector at any space location with *(x,y,z)* coordinates for circle-shaped RWD loop:

$$\mathbf{B} = \frac{\mu_0 I_R N_R}{4\pi} \int_0^{2\pi} \frac{r_R \cdot \mathbf{u}_\varphi \times \mathbf{r_{b1}}}{\left|\mathbf{r_{b1}}\right|^3} \mathrm{d}\varphi \tag{9}$$

In the case of RWD antenna loop, constructed as polygon (Fig. 5-b, c), Biot-Savart law with principle of superposition permits to add at location P vectors, that descend from individual antenna parts. In this case, the total magnetic induction is calculated from the equation:

$$\mathbf{B} = \sum_i \mathbf{B}_i \tag{10}$$

where i denotes analysed side for RWD antenna loop, constructed as polygon.

The obtained vector equations permit numerical calculating of the value of magnetic induction separately for individual components in directions x, y and z (B_x, B_y, B_z). The components of magnetic induction B in any space point $P(x,y,z)$ are given for a circular loop shape (Fig. 5-a) by the following equations:

$$B_x = \frac{\mu_0 I_R N_R}{4\pi} \int_0^{2\pi} \frac{z \cdot r_R \cdot \cos(\varphi)}{\left[\left(x - r_R \cdot \cos(\varphi)\right)^2 + \left(y - r_R \cdot \sin(\varphi)\right)^2 + z^2 \right]^{3/2}} \mathrm{d}\varphi \tag{11}$$

$$B_y = \frac{\mu_0 I_R N_R}{4\pi} \int_0^{2\pi} \frac{z \cdot r_R \cdot \sin(\varphi)}{\left[\left(x - r_R \cdot \cos(\varphi)\right)^2 + \left(y - r_R \cdot \sin(\varphi)\right)^2 + z^2\right]^{3/2}} \mathrm{d}\varphi \tag{12}$$

$$B_z = \frac{\mu_0 I_R N_R}{4\pi} \int_0^{2\pi} \frac{-r_R \cdot \sin(\varphi) \cdot \left(y - r_R \cdot \sin(\varphi)\right) - r_R \cdot \cos(\varphi) \cdot \left(x - r_R \cdot \cos(\varphi)\right)}{\left[\left(x - r_R \cdot \cos(\varphi)\right)^2 + \left(y - r_R \cdot \sin(\varphi)\right)^2 + z^2\right]^{3/2}} \mathrm{d}\varphi \tag{13}$$

and for any polygon (e.g. rectangular; Fig. 5-b) shape:

$$B_x = \frac{\mu_0 I_R N_R}{4\pi} \left[\int_{\frac{-b}{2}}^{\frac{b}{2}} \frac{z}{\left[\left(x - \frac{1}{2}a\right)^2 + \left(y - y'\right)^2 + z^2\right]^{3/2}} \mathrm{d}y' + \int_{\frac{b}{2}}^{\frac{-b}{2}} \frac{z}{\left[\left(x + \frac{1}{2}a\right)^2 + \left(y - y'\right)^2 + z^2\right]^{3/2}} \mathrm{d}y' \right] \tag{14}$$

$$B_y = \frac{\mu_0 I_R N_R}{4\pi} \left[\int_{\frac{-a}{2}}^{\frac{a}{2}} \frac{-z}{\left[\left(x - x'\right)^2 + \left(y + \frac{1}{2}b\right)^2 + z^2\right]^{3/2}} \mathrm{d}x' + \int_{\frac{a}{2}}^{\frac{-a}{2}} \frac{-z}{\left[\left(x - x'\right)^2 + \left(y - \frac{1}{2}b\right)^2 + z^2\right]^{3/2}} \mathrm{d}x' \right] \tag{15}$$

$$\begin{aligned} B_z = \frac{\mu_0 I_R N_R}{4\pi} \cdot \Bigg[& \int_{\frac{-a}{2}}^{\frac{a}{2}} \frac{y + \frac{1}{2}b}{\left[\left(x - x'\right)^2 + \left(y + \frac{1}{2}b\right)^2 + z^2\right]^{3/2}} \mathrm{d}x' + \int_{\frac{-b}{2}}^{\frac{b}{2}} \frac{-x + \frac{1}{2}a}{\left[\left(x - \frac{1}{2}a\right)^2 + \left(y - y'\right)^2 + z^2\right]^{3/2}} \mathrm{d}y' + \\ & + \int_{\frac{a}{2}}^{\frac{-a}{2}} \frac{y - \frac{1}{2}b}{\left[\left(x - x'\right)^2 + \left(y - \frac{1}{2}b\right)^2 + z^2\right]^{3/2}} \mathrm{d}x' + \int_{\frac{b}{2}}^{\frac{-b}{2}} \frac{-x - \frac{1}{2}a}{\left[\left(x + \frac{1}{2}a\right)^2 + \left(y - y'\right)^2 + z^2\right]^{3/2}} \mathrm{d}y' \Bigg] \end{aligned} \tag{16}$$

Many practical solutions for identification are characterized by the parallel location of tag antenna and RWD loop (Fig. 6).

This location of individual tags allows the magnetic induction B_{min} to reach its minimum value only in relation to z-magnetic induction components (vectors $\mathbf{B_{z1}} \div \mathbf{B_{zn}}$ for 1 to n tags). This case applies to places in which tags working in anticollision process has been located ($P_1(x_1,y_1,z_1) \div P_n(x_n,y_n,z_n)$).

The presented approach creates numerous limitations connected with the decrease of the interrogation zone in RFID system. This results from too low value of the perpendicular magnetic induction component in relation to tag antenna loop plane. The efficient use of communication space in which anticollision process is going to take place, and also specification of the object marked by passive RFID tag, requires consideration of any tag orientation with regard to the individual components of magnetic induction vector.

The issue of any tag orientation in three dimensions *x*-*y*-*z* comes down to the tag deviation of α and β angles from parallel location of RWD-tag antenna loops (Fig. 7-a). In accordance with presented model (Fig. 7-b and Fig. 7-c), deviation of α angle occurs in *z*-*x* plane, however deviation of β angle occurs in α-*y* plane. Calculating the value of perpendicular magnetic induction component for tag, which is deviated of α and β angles ($B_{\alpha\beta}$) has been divided in two parts. By application of the superposition theorem in the first part, after tag deviation of α angle, the perpendicular magnetic induction component is given by:

$$B_{xz\alpha} = B_{x\alpha} + B_{z\alpha} \tag{17}$$

where the values of vector components are given by:

$$B_{x\alpha} = B_x \cdot \sin(\alpha) \tag{18}$$

$$B_{z\alpha} = B_z \cdot \cos(\alpha) \tag{19}$$

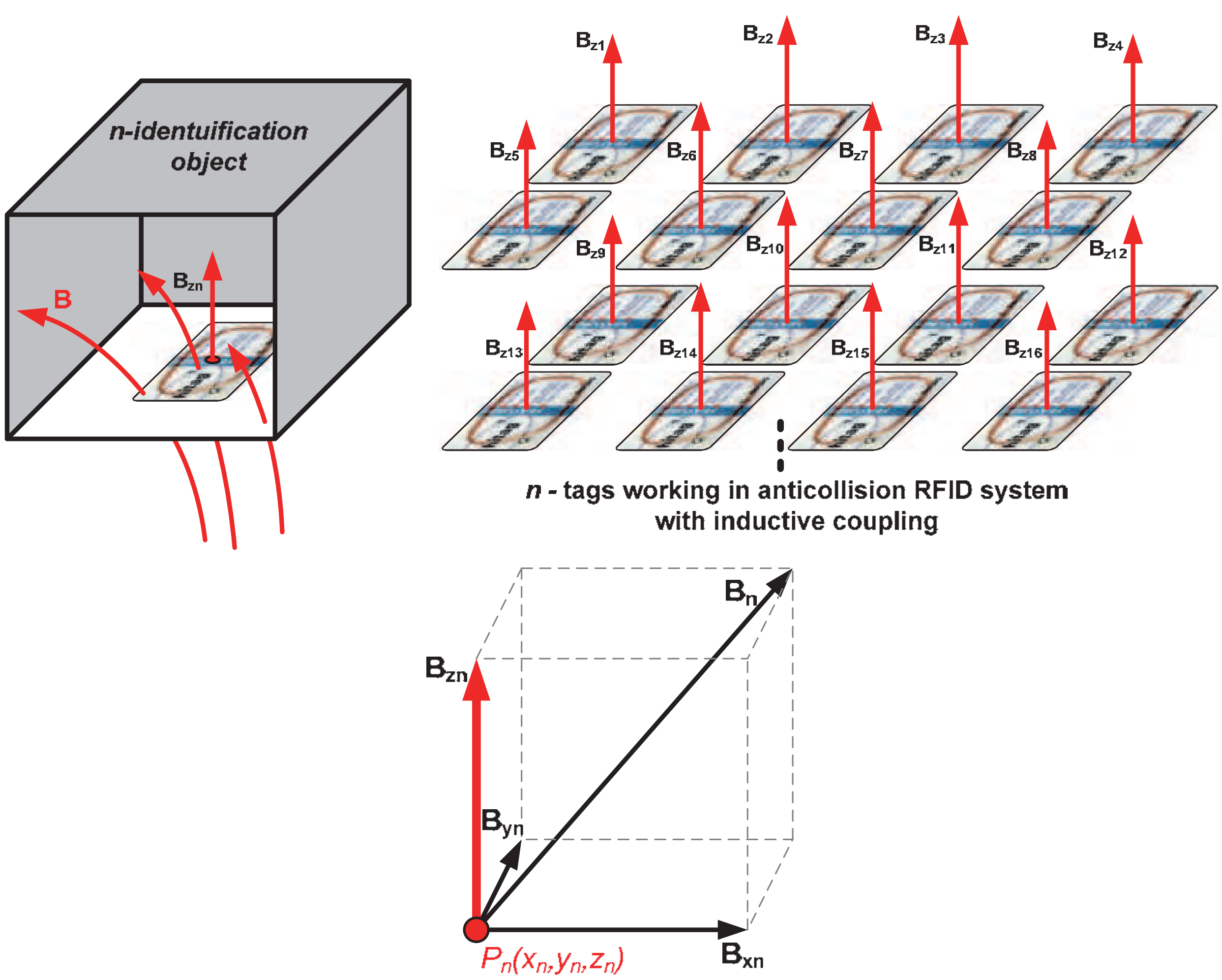

Fig. 6. Typical orientation of tags working in anticollision RFID system in relation to components of magnetic induction vector

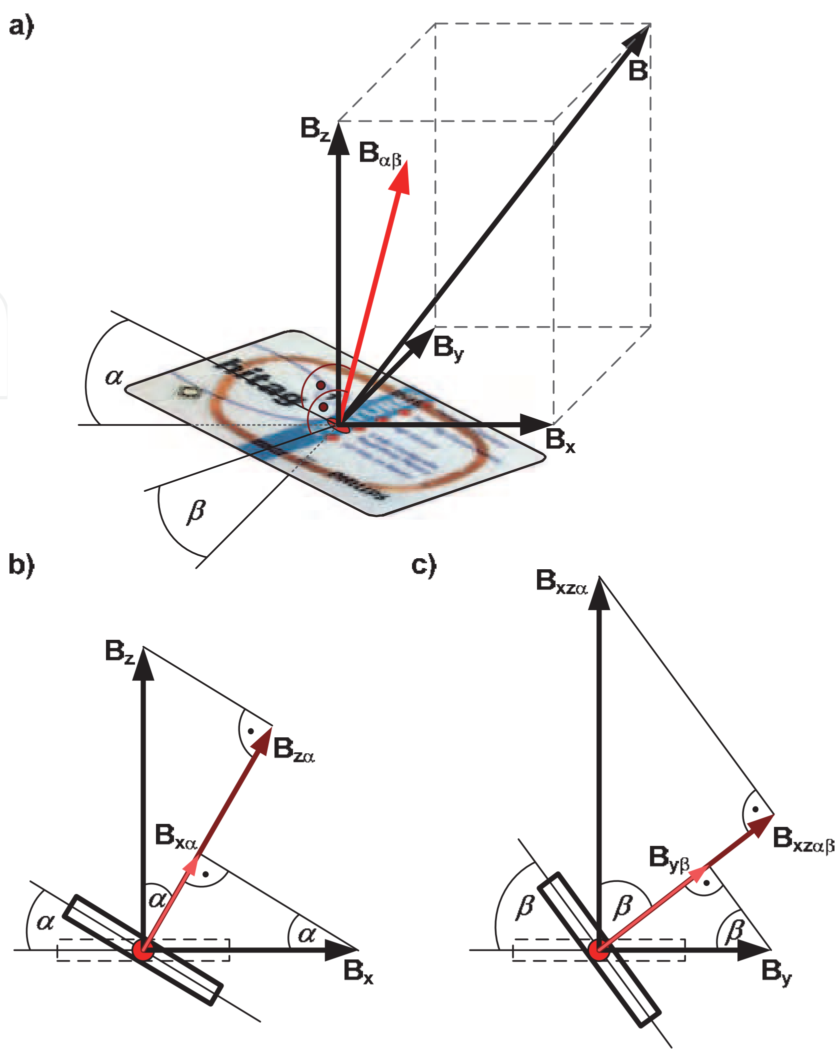

Fig. 7. Orientation of a tag, which is deviated of α and β angles from components of magnetic induction vector: a) deviation in 3D coordinate, b) deviation of α angle on z-x plane, c) deviation of β angle on α-y plane

By application of the superposition theorem in the second part again, after tag deviation of β angle, the perpendicular magnetic induction component is given as follows:

$$B_{\alpha\beta} = B_{y\beta} + B_{xz\alpha\beta} \tag{20}$$

where the values of vector components are given by:

$$B_{y\beta} = B_y \cdot \sin(\beta) \tag{21}$$

$$B_{z\alpha} = B_z \cdot \cos(\alpha) \tag{22}$$

From the equations (17)÷(22) comes, that the perpendicular magnetic induction component for passive tag, which is deviated of α and β angles, is given by:

$$B_{\alpha\beta} = B_z \cdot \cos(\alpha) \cdot \cos(\beta) + B_x \cdot \sin(\alpha) \cdot \cos(\beta) + B_y \cdot \sin(\beta) \tag{23}$$

Knowing the magnetic induction separately for individual components in directions x, y and z (B_x, B_y, B_z), the obtained equation (23) permits calculation of the perpendicular magnetic induction component. The aforementioned necessity of changing the tag orientation should be carried out for assurance of correct tag work in the individual space point $P(x,y,z)$. In this way it is possible to calculate the system interrogation zone, which is forced by the specification of identified object, that is the necessity of individual tag location on marked object.

4.2 Electric aspects

The second essential stage of energy transfer from RWD to tags includes an elaboration of electrical model of the whole anticollision RFID system with inductive coupling for the full frequency range (LF – typically 125 kHz, 138 kHz and HF – typically 13.56 MHz). The basic part of the system is circuitry of RWD - tag antenna set in which an adequate operation states should be taken into consideration. The idea of electrical model of analyzed RFID system is based on the circuitry of RWD - tag antenna units (Fig. 8).

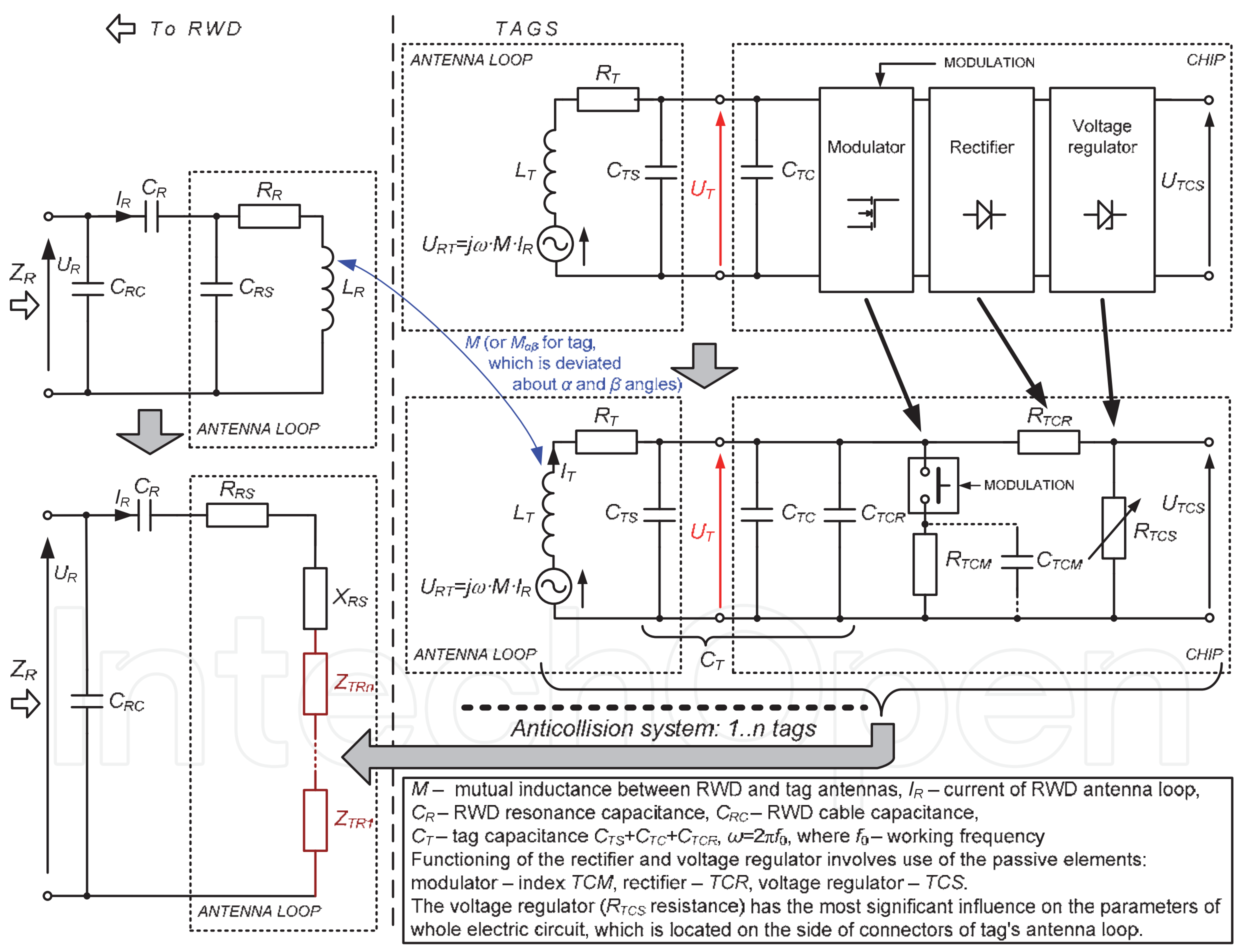

Fig. 8. Equivalent schematic diagram of anticollision RFID system with inductive coupling

The correct operation of tag internal integrated circuit in communication process phases is conditioned by the voltage U_T which is inducted on the trimming tag antenna. Functioning of the memory and microprocessor of passive tag circuit is connected with the occurrence of the stabilization voltage U_{TCS} inside its chip (Villard, 2002; Friedman et al., 1997).

Taking into consideration the fact that the stabilizer is on input to the part of the tag chip and it influences tag's antenna unit, it is necessary to make the synthesis of a module which was divided into two parts: rectifier and voltage regulator. Rectification of the voltage induced in the tag antenna loop, takes place in half-wave and full-wave rectifier (Jamali, 2006), however, it is controlled by a voltage regulator (Friedman et al., 1997). Functioning of the rectifier and voltage regulator involves the use of other passive elements to the tag's schematic diagram (modulator - index *TCM*, rectifier - *TCR*, voltage regulator - *TCS*). The voltage regulator (represented by the R_{TCS} resistance) has the most significant influence on the parameters of the whole electric circuit which is located on the side of connectors of the tag's antenna loop.

The inductive coupling between the antenna loops is expressed by mutual inductance M determined in relation to field conditions at the given system efficiency for arbitrary location and orientation of the tags:

$$M = \frac{N_T}{I_R} \int_0^{r_T} \int_0^{2\pi} B_z \left(r\cos(\varphi) + x,\, r\sin(\varphi) + y,\, z \right) r \,\mathrm{d}\varphi \,\mathrm{d}r \tag{24}$$

and:

$$M_{\alpha\beta} = \frac{N_T}{I_R} \int_0^{r_T} \int_0^{2\pi} B_{\alpha\beta} \left(r\cos(\varphi) + x,\, r\sin(\varphi) + y,\, z \right) r \,\mathrm{d}\varphi \,\mathrm{d}r \tag{25}$$

where N_T is number of tag antenna turns of wire.

In tag antenna loop is induced the voltage U_T (as effect of the coupling):

$$U_T = \frac{j\omega \cdot M \cdot I_R}{1 + \left(\dfrac{1}{\left(R_{TCR} + R_{TCS}\right) \| R_{TCM}} + j\omega C_T \right) \cdot \left(j\omega L_T + R_T \right)} \tag{26}$$

where the symbol || denotes the parallel connection of resistances representing the generalized circuit of rectifier and voltage regulator (R_{TCR}, R_{TCS}) and the modulator (R_{TCM}) inside the chip structure.

Assuming that the module of U_{TCS} is constant, the variable resistance of voltage regulator is given by (27). This equation is true when $U_T > U_{TCS}$:

$$R_{TCS} = \left| \frac{U_{TCS} \left(\omega^2 L_T C_T R_{TCR} - R_{TCR} - j\omega L_T - j\omega C_T R_T R_{TCR} - R_T \right)}{U_{TCS} \left(1 + j\omega C_T R_T - \omega^2 L_T C_T \right) - j\omega M I_R} \right| \tag{27}$$

The minimum value of U_T (U_{Tmin}) is the base for determining the interrogation zone for the anticollision system. The value of voltage U_{Tmin} clearly impacts the analytical relation, which allows for expression of the minimum value of magnetic induction B_{min} – the elementary parameter defining the interrogation zone:

$$B_{min} = \left| U_{Tmin} \right| \cdot \left| \frac{\left[1 + \left(\dfrac{1}{R_{TCR} + R_{TCS}} + j\omega C_T \right) \cdot \left(j\omega L_T + R_T \right) \right]}{j\omega \cdot N_T \cdot S_T} \right| \tag{28}$$

The induction B_{min} is differentiated on the basis of value U_{Tmin}, for the direction of data transmission and the kind of operations in internal tag memory. For experimental verification of calculated value B_{min} the special laboratory stand has been made. The stand allows to measure the maximum distance between the RWD and tag antennas, for which the correct operation of the RFID system is ensured.

Operating of the anticollision RFID system with inductive coupling means that working tags, which are located in the system interrogation zone, are going to have an influence on the parameters of RWD antenna unit. The synthesis of the electrical model of an anticollision RFID system includes the replacement of all tag electric circuits by the impedance Z_{TR} (Fig. 8). Those circuits are coupled by the mutual inductance M. Location of a specific number of n-tags in the interrogation zone of RFID system means that the working tags' quantitative participation in the influence on the RWD is going to be represented by the sum of all impedances Z_{TR} (from Z_{TR1} to Z_{TRn}). Such an influence of impedances Z_{TR} on the read/write device leads to the adverse effect of detuning the RWD antenna. Additionally, the value of antenna loop current I_R decreases in a read/write devices without output current stabilization. In a read/write device with current stabilization, the antenna voltage U_R increases to the limit, and after an overflow, the value of antenna loop current I_R also decreases as in the previous case. The consequence of the influence of operating tags on the RWD in each case is the reduction of the system interrogation zone which is caused by the energetic conditions of devices' operation. Changes are the stronger the larger is the value of the mutual inductance between tags antenna loop and RWD.

This problem can be illustrated by the total impedance of RWD antenna Z_R, taking into account the influence of all coupled tags. For an equivalent schematic diagram from Fig. 8, this impedance is given by the following equation:

$$Z_R = \left[\frac{\left(j\omega L_R + R_R\right)\cdot \dfrac{1}{j\omega C_{RS}}}{j\omega L_R + R_R + \dfrac{1}{j\omega C_{RS}}} + \frac{1}{j\omega C_R} \right] \left\| \frac{1}{j\omega C_{RC}} + \sum_n Z_{TRn} \right. \tag{29}$$

where the equation describes the impedance Z_{TR}, and also quantitative influence of working tags on the RWD, that is given by:

$$Z_{TR} = \frac{\omega^2 M^2}{R_T + j\omega L_T + \dfrac{\left(R_{TCR} + R_{TCS}\right)\| R_{TCM}}{1 + j\omega C_T\left[\left(R_{TCR} + R_{TCS}\right)\| R_{TCM}\right]}} \tag{30}$$

An influence of working tags causes the RWD antenna unit to detune of the value Δf_R from the frequency f_0. This detuning is revealed by the change of impedance's argument $\Delta\varphi_R$ for the working frequency of RFID system. The border values of these parameters determine the last directive to the efficiency of antenna unit array research for given read/write device. There is a necessity to maintain $\Delta\varphi_R$ within the limits in order to provide correct functioning of the RWD and of the whole anticollision RFID system. Such an assumption is practically used in external antenna tuning devices dedicated to tuning the long-range antennas working in LF and HF inductive coupling RFID systems (Feig, 2005, 2006; Philips, 1996; Texas Instruments, 2002).

5. Results

The experimental research have been carried out for different RFID elements using the laboratory system which allows to determine single and anticollision identification process for all frequencies in RFID systems with inductive coupling (Fig. 9).

Fig. 9. RFID laboratory in the Rzeszów University of Technology: a) dynamic test stand, b) static test stand, c) example of long range read/write devices, d) example of measuring equipment

During the search of the interrogation zone of RFID system for a given efficiency of identification η_{ID} (1), the appearance of condition $\Delta\varphi_R > \Delta\varphi_{Rmax}$ makes a correct identification impossible. In MC calculation the parameter $\Delta\varphi_R$ is calculated on the basis of the total impedance Z_R of RWD antennas arrangement (29), taking into consideration influence of functioning tags on this antenna - $Z_{TR1...n}$ calculated from the equation (30). For example, the limit phase value was $\Delta\varphi_{Rmax}=\pm 15^o$ for the Philips HITAG RM 800 read/write device, working at frequency f_0=125 kHz. The technical documentation available on the basis of an agreement reached between the Department and the Philips Semiconductors has been used in the investigations.
For the correct energy transfer in the anticollision RFID system with inductive coupling, assuming the possibility of using identical tags in automatic identification process, the specified value of minimum magnetic induction B_{min} will be the parameter that limits tags' correct operation area. This parameter should be calculated from the equation (28) for the

individual single tag construction and the kind of operations executed in its internal memory (read/write of tags memory). If the value of perpendicular component of magnetic induction vector at point of the location of tag is smaller than his parameter $B_{\min}$, then the correct functioning of this tag in anticollision system is impossible. This denotes that the tag is in the area where communication with RWD is impossible, and efficiency of identification η_{ID} is lowered.

Process of determining the interrogation zone using MC method has been preceded by measurement and calculation of B_{min} conducted during the process of reading information from the internal memory of tag. The results of these measurements and calculations were presented in the table 1.

In the simulation and measuring part of the experiment respectively, the calculated and measured values $B_{\min}$ were the minimum limit of the correct operation of a single tag located in the area of field conditions of functioning of the whole RFID system. In both parts of the experiment locations (in points P_i of cartesian space at (x_i,y_i,z_{ID}) coordinates) of ten tags of a chosen type were selected randomly 25 times (from chapter 2: $n \cdot m$=250).

Tag	Measuded z_{max} 1)	Measured B_{min} 2)	Calculated B_{min} 3)
-	m	µT	µT
HITAG 1 ISO CARD	0.52	0.74	0.74
HITAG 1 WORLD TAG 50	0.44	1.16	1.16
HITAG 1 WORLD TAG 30	0.27	3.72	3.73
HITAG 1 WORLD TAG 20	0.22	5.63	5.62

1) The measurement of the maximum working distance z_{max} from the center on axis of symmetry of RWD antenna loop for square read/write device antenna (where a=0.3 m, N_R=32, I_R=0.213 A) – this is the result of the positive identification of the tag serial number.
2) The measurement by means of analyser Advantest R3132 and Rohde & Schwarz HZ-14 near field probe (Rohde & Schwarz, 2003).
3) The values calculated in the *JankoRFIDmc'IZ v. 4.08* application (Jankowski-Mihułowicz, 2007) - on basis of electrical model - equation (28).

Table 1. Measured and calculated values $B_{\min}$ for tags selected to investigations

The example results of the calculated and measured interrogation zone (Fig. 10), were placed on the plane at (x, y, z_{ID}) coordinates. The measured interrogation zone is the result of the positive identification of all n=10 tags serial numbers, during conducted experiment, all m=25 multiple sampling of their location. For every multiple sampling of the location of tags in measuring chamber, spatial measurements of z component of magnetic induction **B** vector were made. On the basis of (Rohde & Schwarz, 2003), the measurement of the component of the vector **B** perpendicular to the area of the antenna loops of tags was conducted in the 625 points (the resolution of 2 cm on 0.5 m x 0.5 m x-y surface – the movable platform in the measuring chamber – Fig. 9-b).

All of the calculations and measurements were performed for square antenna of the RWD unit which was tuned in the measuring chamber without the influence of tags, and the achieved value was $\Delta\varphi_R$=2.5°. In all studied cases, the border value of $\Delta\varphi_{R\max}$, wasn't crossed. Thanks to this, the efficiency of identification for the height z_{ID} was 100 % in the

area of fulfillment of the condition of the magnetic induction minimum value. Difference between the calculated and measured interrogation zone (in the worst case, for the smallest heights z_{ID}, on the level ±1.5 cm), is caused mainly by applying an approximate geometrical model of the antenna loop of the RWD. These differences are caused by the fact that the RWD antenna loop was build as loose turns of wire, and that was assumed during synthesis of the geometrical model of the RWD antenna loop.
The measurements in the RWD - tags antennas arrangement required applying many direct and indirect measuring methods. The obtained results always contained certain dispersion of the values, which can always be - in a justified way - ascribed to measured sizes. The multiple results were obtained from many measuring sets.
Generally, the problem of the uncertainty of determining the interrogation zone of the anticollision RFID system with the inductive coupling, has two aspects: simulations and measures. In the process of evaluation of the uncertainty of determining the interrogation zone in the measuring part of the experiment, essential factors are uncertainties of the magnetic induction components *u(B)* measurements:

$$u(B)=\sqrt{\left(\left|\frac{\partial B}{\partial H}\right|\cdot u(H)\right)^2+\left(\left|\frac{\partial B}{\partial \mu}\right|\cdot u(\mu)\right)^2} \tag{31}$$

where:

$$u(H)=\sqrt{\left(\left|\frac{\partial H}{\partial V_0}\right|\cdot u(V_0)\right)^2+\left(\left|\frac{\partial H}{\partial AF}\right|\cdot u(AF)\right)^2} \tag{32}$$

where $u(V_0)$ - standard uncertainty of voltage measured by means of Advantest R3132 spectrum analyzer and the R&S HZ-14 near magnetic field probe.
This uncertainty includes the systematic influences which cannot be removed during the conducted experiment. They are represented by the set of coefficients read from prepared tables and graphs in the Advantest R3132 spectrum analyzer user manual. *u(AF)* denotes the uncertainty of antenna coefficient read for measuring frequency (f_0). For the spatial, multipoint measurements which were made in the measuring chamber of the investigative set, the standard relative uncertainty for the magnetic induction $u_{\%}(B)$ was on the level 1-2 %.
In the process of evaluation of uncertainty of the interrogation zone estimation in the simulating part of the experiment, the component factors of the complex uncertainty of the entrance data measurements and output data calculations were considered. They were taken into account in the process of estimating the efficiency of the system antennas arrangement with the MC method, which is made by the *JankoRFIDmc'IZ* application (Jankowski-Mihułowicz, 2007).
Explaining this problem, function f which represents the interrogation zone exhibits significant nonlinearity. Therefore, regarding the error propagation, the higher terms in the Taylor's expansion should be taken into account. Their form is as follows:

$$\sum_{i=1}^{n}\sum_{j=1}^{n}\left[\frac{1}{2}\cdot\frac{\partial f}{\partial x_i}\cdot\frac{\partial^2 f}{\partial x_i \partial x_j}+\frac{\partial f}{\partial x_i}\cdot\frac{\partial^3 f}{\partial x_i \partial^2 x_j}\right]\cdot u^2(x_i)\cdot u^2(x_j) \tag{33}$$

where: i,j=1..n.

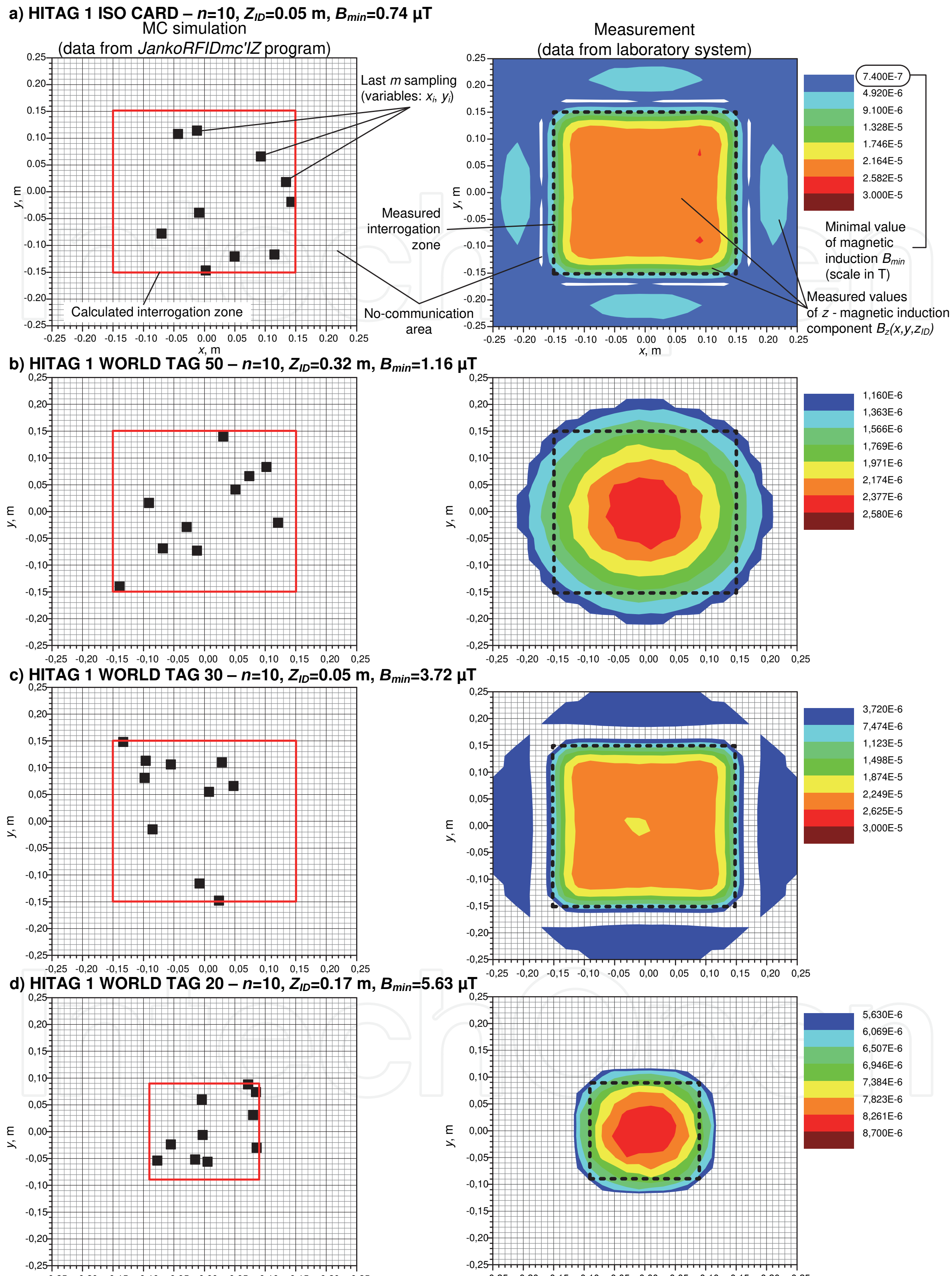

Fig. 10. Description of example elements of calculated and measured characteristics of interrogation zone for HITAG 1: a) ISO CARD (Z_{ID}=0.05 m, B_{min}=0.74 μT), b) WORLD TAG 20 (Z_{ID}=0.32 m, B_{min}=1.16 μT), c) WORLD TAG 30 (Z_{ID}=0.05 m, B_{min}=3.72 μT) and d) WORLD TAG 30 (Z_{ID}=0.17 m, B_{min}=5.63 μT)

In indirect measurements every size, calculated or measured directly, brings the different contribution to the uncertainty *u(f)*. The determination of suitable weighting factors resulting from the uncertainty propagation law for the considerably nonlinear function *f*, according to the higher terms in the Taylor's expansion, is a complicated mathematical question. This is a complicated problem at the present stage of works.

6. Conclusion

The efficient leading of the automatic identification processes, such as: forwarding mail, materials, articles (in industry); identification of valuable minerals, samples for analysis (in science and medicine), requires the use of a modern radio methods of the simultaneous identification of many objects. The mentioned processes generally belong to the automatic identification group, in which RFID electronic tags are replacing, for example, barcodes. This is caused by the well-known technical limitations of the objects identification methods used nowadays. The accessibility of electronic tags, the continuous reduction of their production costs and the standardization of work conditions of RFID technology, allows to make a decision about the implementation of quite a new method in the process of automatic identification.

The laboratory research and tests fully confirm the correctness and usefulness of the elaborated (in Department of Electronic and Communication Systems at Rzeszów University of Technology), method of synthesis of anticollision RFID system, where the essential component, based on Monte Carlo method, is the determination of interrogation zone for the system with suitably located tags. It should be noted that the synthesis procedure includes the simultaneous analysis of electromagnetic field, communication protocols and electric aspects of operation conditions in the process of system efficiency identification. Presented part of the problem of interrogation zone synthesis is the base for practical use of projected identification systems, required for specific anticollision RFID applications. The future investigations will be focused on the analysis of efficiency and interrogation zone of the anticollision RFID systems operated in dynamic conditions (speed changes of orientation of suitably located tags). Additionally, the extension of *JankoRFIDmc'IZ* program on a propagation coupling RFID system is planned. The elements of algorithm of interrogation zone identification for anticollision RFID system taking into consideration the energetic (i.e. field and electrical) and communicational aspects of operation conditions are going to be supplemented by elements of antennas and wave propagation in UHF.

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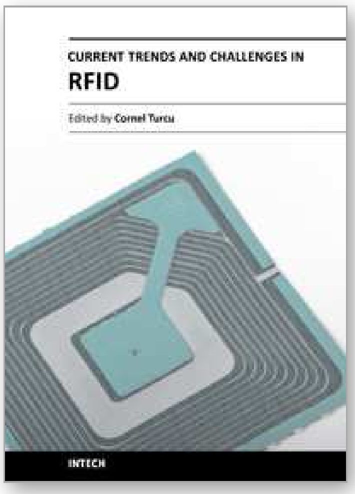

Current Trends and Challenges in RFID

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With the increased adoption of RFID (Radio Frequency Identification) across multiple industries, new research opportunities have arisen among many academic and engineering communities who are currently interested in maximizing the practice potential of this technology and in minimizing all its potential risks. Aiming at providing an outstanding survey of recent advances in RFID technology, this book brings together interesting research results and innovative ideas from scholars and researchers worldwide. Current Trends and Challenges in RFID offers important insights into: RF/RFID Background, RFID Tag/Antennas, RFID Readers, RFID Protocols and Algorithms, RFID Applications and Solutions. Comprehensive enough, the present book is invaluable to engineers, scholars, graduate students, industrial and technology insiders, as well as engineering and technology aficionados.

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