
Definition, Characteristics and Determining Parameters of Antennas in Terms of Synthesizing the Interrogation Zone in RFID Systems

Piotr Jankowski-Mihułowicz and Mariusz Węglarski

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Abstract

The radio frequency identification (RFID) systems are gaining in popularity in automated processes of object identification in various socioeconomic areas. However, despite the existing belief, there is no universal RFID system on the commercial market that could be used in all user applications. All components of a developed solution should be carefully selected or designed according to the specification of objects being recognized and characteristics of their environment. In order to determine parameters of propagation or inductively coupled system, especially when it is dedicated to uncommon applications, a multiaspect analysis has to be taken into consideration. Due to complexity, the problem is reduced to analytical or experimental determination of RFID system operation range and a “trial and error” method is mostly used in the industry practice. In order to cope with the barriers existing in the RFID technology, the authors give the review of latest achievements in this field. They focus on the definition, comprehensive characteristics and determination of the antenna parameters. They also pay attention to the 3D interrogation zone (IZ) that is the main parameter in which multitude technical aspects of the RFID systems are gathered simultaneously, as regards the theoretical synthesis as well as market needs.

Keywords: RFID, antenna, interrogation zone, passive/semi-passive transponder, read/write device

1. Introduction

Radio frequency identification (RFID) refers to modern technology applied to the radio identification of objects of any kind [1]. The RFID systems are gaining in popularity because of their multitude advantages, and today they are frequently used in automated processes in

various socioeconomic areas. Usability of this technology is confirmed by a rapidly growing number of innovative practical implementations [2–4]. From an economic point of view, it results from wider availability of RFID devices on the market as well as forecast in terms of their applicability within the next few years [5]. On the other hand, better recognition of the essence pertinent to the operation of these devices as well as methods of determining their parameters constitute the reason in technological terms.

Widely understood processes of automated object identification applied in various areas of life and economy constitute the subject of contemporarily conducted implementation works [1, 6, 7]. RFID devices are, inter alia, increasingly more frequently chosen in security and access control systems, in industrial logistic processes (during shipping of packages, materials or products), and in the course of identification of measurement samples or valuable materials in research processes (in various fields of research, technology or medicine). Significant number of the implementations is carried out in the range of the Internet of Things (IoT) [8]. The RFID system complied with electronic product code (EPC) recommendations is thought to replace barcodes being currently in common use [9]. The development works are conducted to ensure that automatic identification will be effectively and smoothly applied to the fast-moving consumer goods (FMCG) in supply chains [10]. Similar activities are pursued in the areas of reliable and safe identification of moving objects, for example, in the public transport (automatic vehicle identification (AVI)) [7].

It may well be concluded that the observed potential of application use of the radio frequency identification technology justifies the need to conduct intensive research and development works which will constitute a factor of innovative changes in the said framework. The development in this scope is mainly stimulated by highly industrialized countries, but the results obtained by the authors also constitute a contribution to ways of solving many problems in the RFID technology.

Presented works were carried out in many aspects (Chapter 2), including operational effectiveness of single and anti-collision passive and semi-passive RFID systems for perspective frequency bands (HF, UHF). In the course of research, each time it was assumed that it is necessary to achieve essential utility values. Therefore, the majority of published results were positively confirmed experimentally, and then, practical applications were found in the industry, institutions and other places where automated systems were implemented. Considerable part of these works was conducted in the field of definitions, characteristics and determining antenna parameters, which essentially influence the process of synthesis of an interrogation zone (IZ) in RFID systems (Chapter 3).

Overcoming implementation barriers with regard to the RFID technology in various socioeconomic activities constituted the essence of this works. It is worth remarking that determination of RFID system parameters rationally, especially in the aspect of their unusual applications, is only possible by means of a multispect analysis of real problems in an automatic identification process (**Figure 1**). It means that despite the existing belief, there is no universal RFID transponder on the market, which could be used to label any object. Such a transponder should be properly selected or—which is more beneficial—designed for the object, in view of many conditions of its performance. Moreover, there is no system that could be used in any automated process. System configuration should be adjusted to the needs of automatic identification of marked objects.

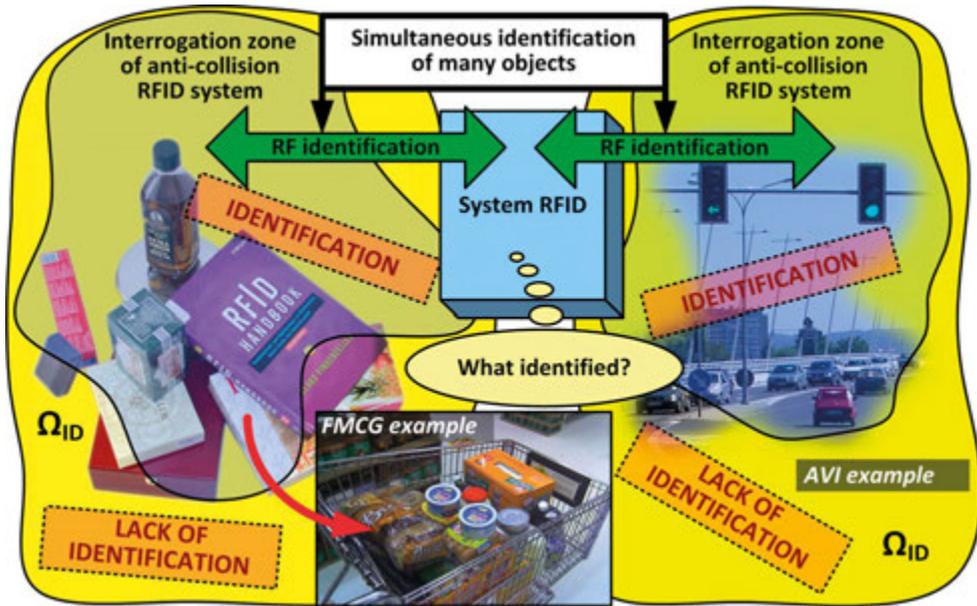


Figure 1. Illustration of RFID automatic identification processes.

The radio communications process in the RFID system can only be conducted in the interrogation zone (Figure 1). If only one electronically marked object is assumed to be in it, then this arrangement is called a single identification system. In the case of an anti-collision system, the communications process is conducted simultaneously with many transponders. In this case, radio channel multiaccess algorithms are used, which enable to simultaneously differentiate between many objects. The mechanisms are included in appropriate communication protocols. In the two said examples of RFID systems, it should be assumed that marked objects are located in a three-dimensional Ω_{ID} space. Then, one cannot be certain that all these objects will be identified during an automated process since it can also be conducted in a static (permanent spatial location and orientation of objects) as well as in a dynamic manner (changing spatial location and/or orientation of objects).

A properly implemented RFID system is a system in which all objects are successfully marked and—irrespective of the location, orientation or operation status—quickly identified in a planned (anticipated) manner. The solution of the problem consists in predictability of a three-dimensional interrogation zone (3D IZ). The essence of this parameter was pointed out by Klaus Finkenzeller in the monograph [1] where the categorization of aspects in the RFID technology was done for the first time. The importance of the publication and thus validity of the proposed assumptions and solutions is confirmed by the number of its citations. Considerable problems with regard to determining the interrogation zone in a three-dimensional space were noticed, for example, by Nemaï C. Karmakar in monograph [11]. Many researchers reduce the IZ synthesis to analytical or only experimental determination of RFID system operation range [12–17]. In industrial conditions, the parameter is usually determined

with a “trial and error” method [18, 19] since by definition it means a maximum distance that is necessary to properly conduct a process of read/write data from/into a transponder’s memory which is located in an axis of symmetry of a read/write device (RWD) antenna. It can be used directly only in the case of static single identification. In accordance with the definition, the range cannot be utilized to describe a static anti-collision identification or all systems where dynamic changes take place, as it constitutes only a selected parameter of the three-dimensional RFID interrogation zone.

In this context, it should be deemed that some additional parameters should be specified in the practice of designing and validating devices and systems of the RFID technology, in order to determine basic conditions for synthesis of the three-dimensional interrogation zone. In particular, it is related with the necessity to define, characterize and measure parameters, which so far have been: (1) omitted in view of lack of comprehensive recognition, (2) determined by means of an ineffective experimental “trial and error” method, or (3) measured with the use of wrong methods. Among others on the basis of documented R&D works conducted by the authors, it may be deemed that the 3D IZ is a parameter in which multitude technical aspects are gathered simultaneously, as regards the operation of RFID devices, as well as market needs to use them effectively in automated systems. Therefore, the title of this chapter includes the word “synthesis” which—in the determined framework—enabled the authors to present the problem in its entirety, including its many aspects. The factors are already noticeable by leading manufacturers who try to fill the gaps in specifications of their devices and systems based on effects of intensive research and development works conducted throughout the world.

2. The scope of scientific issues

2.1. Frequency bands of RFID systems

Although the performance of RFID systems is pertinent to a radio communication process, many parameters and phenomena should be understood in a nonstandard way. It refers to, for example, a zone in which energy is not radiated but stored in an electric and magnetic field, performance of antennas that are unmatched in terms of waves, phenomenon of impedance matching of a transmitter/receiver and its antenna that is adjusted during wireless data transmission and so on. With regard to the RFID technology, it is necessary to apply many new terms which—in order to be understood—require taking into account construction of RFID devices and their performance.

The scientific investigations in the RFID technology have to be considered according to the used frequency bands (**Figure 2**). In terms of electromagnetic field emission, the RFID systems are placed in a group of radio equipment devices. They use bands (typically LF, HF and UHF) and operating frequencies (f_0) that are commonly available for industrial, scientific and medical (ISM) purposes [20]. Therefore, band and frequency constitute basic factors influencing the differentiation between types of RFID systems, which subsequently determines a different approach in terms of considering the essence of their performance.

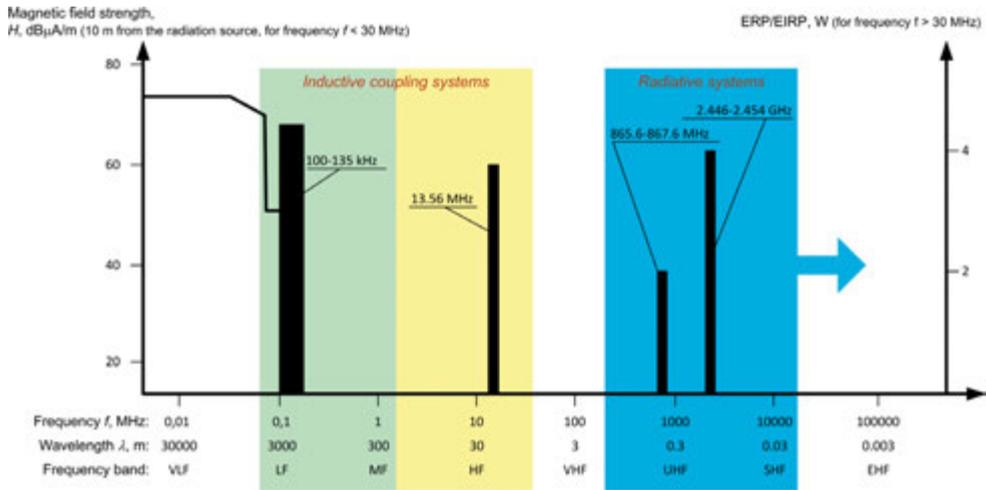


Figure 2. Frequency bands for RFID systems.

2.2. RFID system structure

Irrespective of considered frequency band, a software and hardware component may be distinguished in a radio frequency identification system. The software serves for both direct controlling of individual digital devices and managing the whole system. The second component is composed of two main parts: a read/write device (RWD) with antenna and single or many electronic transponders which are used to mark objects (Figure 3).

With regard to the definitions that are used in the RFID technology, the notion of a “reader” can be frequently encountered in the reference literature. Nonetheless, it is worth noticed that the RWD performs a double function in the system (transmitter/receiver) which enables

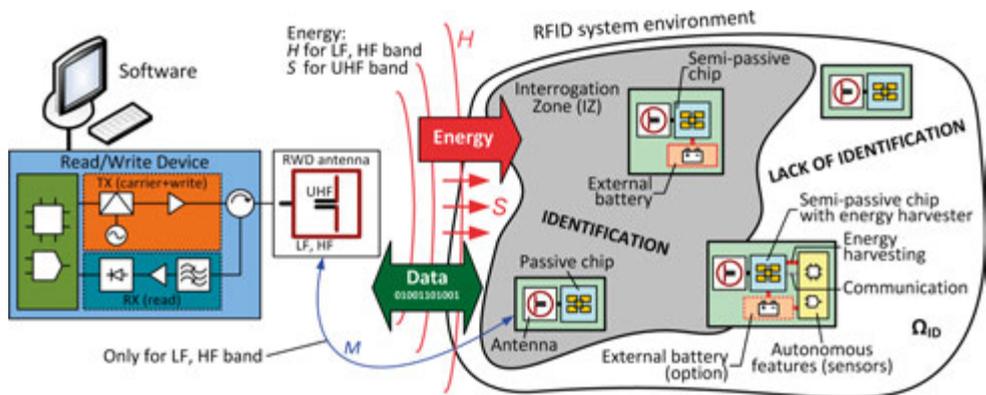


Figure 3. Generalized block diagram of an RFID system.

data transmission in two directions. If in the automated process of object identification, data are not saving into transponders' internal memory, then it may be justified to use the term "reader." In other cases, where information is also written to the transponder memory, a "reader" constitutes an abbreviation which does not reflect the essence of device performance.

The most popular RFID transponder contains only the chip with the connected antenna, so it is called passive transponder, whereas semi-passive type (sometimes called active) has built-in an extra supply source (e.g., lithium disposable battery) which can be exchangeable or not. Generally, the battery is used for enlarging the IZ, which is a very desirable feature for most applications. Moreover, in some new chips integrated with both wired and wireless access ports, the additional energy is used for powering blocks of supplementary autonomous functions, such as measuring physical quantities (humidity [21, 22], temperature [22–24], light intensity [22, 23], pressure [25], acceleration [26], gas [24], etc.), writing gathered data into a built-in memory, managing activity cycles and power distribution in a data acquisition system and so on. These functions are realized without the participation of RWD and give transponders the autonomy. It should be noted that the RWD has to be active in order to conduct the radio communications process, because the extra battery system of transponder is never used for activating the transmission circuit. It means that the transponder antenna does not emit the electromagnetic field as it is in the case of conventional short-range devices (SRDs) [20]. These characteristics help distinguish the semi-passive RFID transponders from the classical active SRDs.

2.3. Inductively coupled systems

According to the main classification of the RFID technology, the first group is composed of inductively coupled systems. The carrier frequency is between 100 and 135 kHz (typically 125 kHz) for the LF band or 13.56 MHz for the HF band. This kind of the systems operates by utilizing zone that is characterized by an inhomogeneous magnetic field (described by the magnetic field strength H) and strong coupling (described by the mutual inductance M) between antennas of the arrangement components. For the typical operating frequency $f_0 = 125$ kHz of the LF band, the wavelength λ is 2400 m, and for the $f_0 = 13.56$ MHz of the HF band, λ is about 22 m. For this reason, the RWD and transponder antennas are made in the form of loop which is small in relation to λ . Hence, the inhomogeneous magnetic field generated into RWD antenna vicinity is the medium for both transferring energy and wireless communications.

A load modulation is the most widespread way of communications with the use of this medium. Thus, in the LF systems, information is transferred by a modulated carrier wave (amplitude shift keying (ASK)). In the range of short waves, inductive coupling between transponder and RWD antenna loops is considerably weaker. Therefore, in the HF band, data are transferred by means of load modulation with subcarrier in order for the energy to be properly transferred to transponders. If a spectrum of a modulated signal is taken into consideration for the LF systems, conveyed information is gathered in sidebands, occurring around the carrier wave, whereas for the load modulation with subcarrier, it has to be regained from precisely defined subcarriers (e.g., 13.56 MHz/16, 32, 64 = 847 kHz, 424 kHz, 212 kHz) [27]. The said communication mechanisms are implemented in appropriate protocols (e.g., ISO/IEC15693, 14443, 18000-3 for an HF band).

The basic parameter that characterizes the interrogation zone and read/write range of the inductively coupled RFID systems is a minimum magnetic field strength H_{min} (or a minimum value of magnetic induction B_{min}) at which the correct data transmission between the RWD and transponder takes place [28]. The minimum value H_{min} that is required in a process of writing data to the transponder's internal memory ($H_{minWrite}$) is bigger by a few percent than a value for readout ($H_{minRead}$). It is the reason why the RFID interrogation zone is depended on the type of operations conducted in communication frame.

The anti-collision systems are even more troublesome in synthesis. Since the several transponders can be simultaneously located in the vicinity of an RWD antenna, it is necessary to provide appropriate power supply for all of them. The influence of their magnetically coupled circuits on the loop impedance of the RWD antenna causes a considerable change of many parameters in the entire system. As a consequence, the phenomenon leads to difficulties in communication with transponders that are located at the zone boundary where the magnetic field strength has a minimum value. In order to assess properly the acceptable borders of spatial distribution for deploying marked objects in a designed system, the correct analysis of the RWD loop impedance with coupled antennas of transponder, and therefore, an analysis of changes in the magnetic field strength has to be performed. The three-directional interrogation zone of an inductively coupled RFID system, independently for a required direction of data transmission, can be determined on the basis of comparison of the H_{min} parameter and a value of magnetic field strength generated in a particular point $P(x, y, z)$. In order to conduct the correct synthesis, apart from fulfilling minimum energy conditions, the efficiency of communication between RFID devices in the anti-collision system with inductive coupling has to be taken into consideration.

2.4. Propagation systems

Operating principles of the RFID devices dedicated to the UHF band (860–960 MHz depending on world regions) are significantly different. In the UHF RFID systems, a far-field region is utilized and the wave locally can be considered as plane. In this region, vectors of electric and magnetic field strength are perpendicular both to each other and to the direction in which the wave disperses. The radiated electromagnetic wave of power density S is energy medium supplying passive or semi-passive transponders (**Figure 3**). The carrier wave of the frequency f_0 is used to transmit energy between matched antennas, but it should be noticed that the impedance matching of a transmitter and a receiver known from classical theory is valid only for the read/write device and its 50 Ω antenna (not for transponders).

The problem with definition, characterization and determination of parameters which essentially influence the synthesis process of the interrogation zone in the UHF band is presented on the basis of the proposed model of a radio communications system (**Figure 4**). The model represents electrical circuits and antenna of the read/write device as well as a single transponder (passive or semi-passive). For simplicity, only the single identification process is considered. But, the same algorithm can be multiplied for all arrangements (RWD and additional transponders in IZ) when the anti-collision system is synthesized.

The electronic chip of a transponder is designed to be supplied by the minimal voltage U_T that is induced at terminals of the connected antenna. As a consequence, the complex impedance

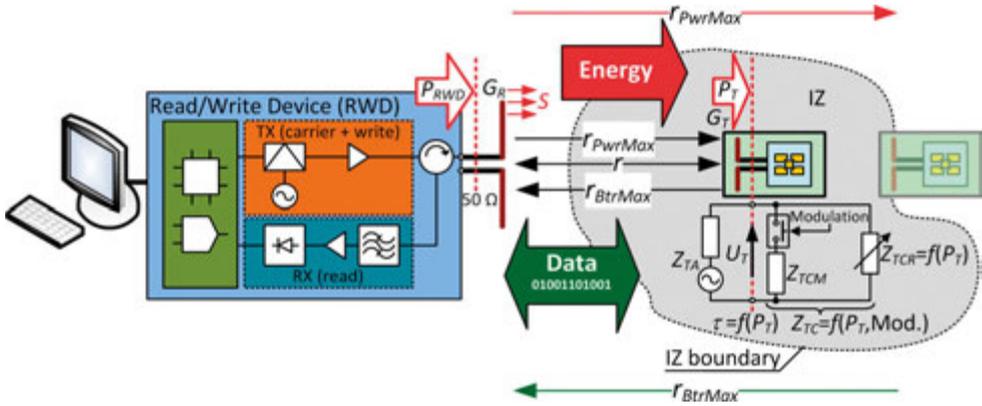


Figure 4. Generalized block diagram of an UHF RFID system.

(Z_{TC}) of the chip front end is continuously changed. The part (Z_{TCR}) of the impedance that represents a rectifier and voltage regulator is strongly influenced by the electromagnetic field. On the other hand, parameters of the electromagnetic field are dependent on the orientation of marked object and its localization in the operating space where both energy and communication conditions have to be established in order to ensure the proper work of the system. The conditions are described by the interrogation zone that constitutes the basic parameter of RFID systems. Since the amount of conveyed energy is very small, the backscatter communications is used for transmitting data in the direction from the transponder to the RWD. In this process, a battery-less device communicates by modulating its reflections of an incident radio frequency (RF) signal. The modulation is realized by step changes of the chip impedance (Z_{TCM} switching). The communication principles are implemented in the protocol of electronic product code (EPC) Class 1 Gen 2 [29], which the latest version is currently standardized in ISO/IEC 18000-63 (formerly ISO/IEC 18000-6).

The Friis transmission equation can be utilized for determining the interrogation zone of a common radio channel [30]:

$$P_T = P_{RWD} \frac{G_R G_T \lambda^2 \tau \chi}{(4\pi r)^2} \quad (1)$$

where P_{RWD} means the power supplied to terminals of the impedance-matched RWD antenna, G_R —the gain of the impedance-matched RWD antenna, P_T —the power received in the transponder antenna, G_T —the gain of the transponder antenna (impedance matching of the antenna and the chip is assumed), χ —the polarization matching factor for a given arrangement of the radio communication antennas, τ —the coefficient of power transfer from the antenna to the chip, λ —the wavelength and r —the distance between the antennas.

The boundary of the interrogation zone, that is, the maximal distance r_{PwrMax} between the axial-symmetrical antennas of a communications system, can be determined by transforming

equation (1). The proper conditions for supplying energy to the passive transponder are established in such a defined space. The conditions are characterized by the minimal power P_{Tmin} (chip sensitivity) which is enough for activating internal circuits of the transponder:

$$r_{PwrMax} = \frac{\lambda}{4\pi} \sqrt{\frac{P_{RWD} G_R G_T \tau \chi}{P_{Tmin}}} \quad (2)$$

The transponder sensitivity is dependent on its type (passive or semi-passive) [31, 32] as well as on parameters of radio communication protocol. There is a relation between the sensitivity of passive transponder chip P_{TminP} and semi-passive one P_{TminSP} :

$$P_{TminP} > P_{TminSP} \quad (3)$$

It yields a larger geometrical space of the interrogation zone in semi-passive systems. It is possible due to an extra battery source connected to the chip. But it should be emphasized that the relation (3) is valid when the voltage of internal source is in the range of minimal U_{BatMin} and maximal U_{BatMax} values (Figure 5). Therefore, the sensitivity of semi-passive chip should be specified for the given voltage value U_{Bat} of internal supply module.

The maximal distance r_{PwrMax} has to be compared with a r_{BtrMax} value in the process of interrogation zone synthesis. The r_{BtrMax} means the maximal distance between the centers of antennas where proper detection of transmitted signal is possible:

$$r_{BtrMax} = \sqrt[4]{\frac{\lambda^2 P_{RWD} G_R^2 \chi \sigma_T}{(4\pi)^3 P_{Rmin}}} \quad (4)$$

where σ_T means the effective reflecting area of the transponder antenna (Radar Cross Section (RCS)) and P_{Rmin} —the minimal power at the RWD input for signal wave reflected off the transponder.

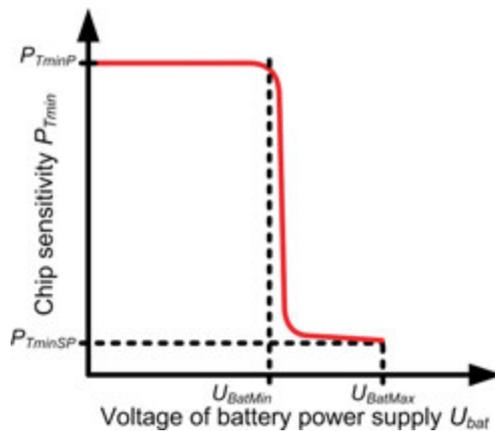


Figure 5. Generalized curve of the sensitivity for a passive and semi-passive chip.

The signal is transmitted by backscatter communications in the direction from the transponder to the read/write device. The process of data exchange can be carried out successfully provided only that the power in antenna circuits of both the RWD and transponder reaches the necessary level. The energy gathered by the transponder located in a point (x, y, z) has to be enough for supplying the chip with a power P_T greater than the minimal value P_{Tmin} . And also the energy of a signal wave reflected back to the RWD antenna has to be sufficient to give a power P_R greater than the P_{Rmin} value:

$$\frac{P_T(x, y, z)}{P_{Tmin}} \geq 1, \quad \frac{P_R(x, y, z)}{P_{Rmin}} \geq 1 \quad (5)$$

Eqs. (1)–(5) can be used to determine the interrogation zone in passive or semi-passive RFID systems of the UHF band. It should be borne in mind, however, that many of the listed parameters depend on electrical and geometrical arrangements of RWD and transponder antennas. This is particularly important in dynamic and anti-collision RFID systems which are dedicated to automated processes of object identification. For example, despite the antenna polar diagrams of $G(\theta)$ and $G(\phi)$, the three-dimensional antenna radiation pattern $G(\theta, \phi)$ has to be taken into consideration when orientation of labeled object is changed in all directions. Moreover, the chip sensitivity (i.e., minimal power P_{Tmin}) is the most important in the IZ synthesis process. It describes supply conditions of a transponder [33]. On the base of this parameter, the impedance of the chip placed at IZ boundary, the construction of transponder antenna and the shape of interrogation zone for a given implementation of RFID system are worked out.

The impedance of transmitters or receivers in conventional radio systems is fixed (e.g., 50, 75 Ω) and matched to the antenna at a given frequency. Another situation is in passive and semi-passive RFID systems. The chip impedance Z_{TC} of a transponder varies, while it is working. The impedance matching of chip and antenna Z_{TA} is characterized by the power transfer coefficient τ (**Figure 4**).

The gain G_T in Eqs. (1) and (2) has to be determined at full impedance matching of antenna and chip ($Z_{TA} = Z_{TC}^*$, $\tau = 1$) in order to carry out the interrogation zone synthesis. Thus, the power transfer coefficient is described by equation:

$$\tau = \frac{4\text{Re}(Z_{TA})\text{Re}(Z_{TC})}{\text{Re}(Z_{TA} + Z_{TC})^2 + \text{Im}(Z_{TA} + Z_{TC})^2} \quad (6)$$

In practice, the antenna impedance Z_{TA} is constant at a given frequency, but the chip impedance Z_{TC} varies while the transponder is working (**Figure 4**). This characteristic is crucial in the IZ synthesis, but producers of RFID components do not specify it.

3. Experimental research

3.1. Determining chip parameters in UHF RFID transponder

An attempt to define, characterize and determine parameters of a transponder chip may be found problematic in relation to the considered systems. In the course of preparing

research works in this field, the authors observed that both the literature and knowledge on the subject in question are incomplete. Above all, this applies to the UHF band and newly implemented chips with semi-passive functions. In this context, the effective methods of determining parameters for passive and semi-passive UHF RFID chips are presented in the chapter [34]. Elaborated measuring procedures were verified experimentally and discussed in detail. The special untypical laboratory stand was prepared for carrying out the research tasks. Furthermore, the importance of the parameters for the interrogation zone synthesis was described methodically. The special software tools that allow researchers to effectively conduct investigations on protocol parameter modifications in both newly developed and approved standards (e.g., ISO/IEC18000-63) were also designed. These facilities can significantly support many theoretical and simulation works that are developed and described in the branch literature and can improve the reliability and efficiency of designed RFID applications.

Values of impedance Z_{TC} are depended on transponder localizations and orientations according to the RWD antenna. It is because this parameter varies with power P_T that is transferred from the antenna to the chip (**Figure 4**). Power level changes are caused by a rectifier and voltage regulator that are main parts of a transponder RF frontend [35, 36]. Operating modes (e.g., reading or writing operation realized on an internal memory of the chip) also affect the chip impedance, because they can be activated at different power levels ($P_{TminWrite} > P_{TminRead}$). Furthermore, parameters of communications protocols, for example, ISO/IEC18000-63 compatible with EPC requirements [29], have an effect on the Z_{TC} . Unfortunately, the variable chip impedance has significant influence on measurements of the minimal power P_{Tmin} what makes a measuring task very difficult. In order to cope with this problem, a special laboratory stand has to be set in which two methods of chip sensitivity determination can be integrated in the proposed research procedure (**Figure 6**).

The essence of both methods is to determine the minimum power P_{min} at the moment when *16b Random or Pseudo-Random Number (RN16)* is identified as a response from the transponder. The number is generated as an answer to the *Query* command according to communication protocols [29] when the condition of $P_T \geq P_{Tmin}$ is met. The power P_{Tmin} is obtained with giving special consideration to the impedance mismatching of chip (Z_{TC}) and 50Ω measuring channel (Z_0).

In the first method, the real frame with the *Query* command is generated by measuring equipment. An arbitrary waveform generator is used as a simulator of modulated signal source, and a vector signal generator is a source of a carrier signal with adjustable output power. The pattern of real communication frame is generated by *JankoRFIDchip'UHF* program which was designed in the Mathcad environment for the research task. A file with the frame prepared according to the specified protocol (**Figure 7**) is written to the arbitrary waveform generator by a LAN interface.

The pattern signal is integrated with the carrier in the vector generator. The power P_C (**Figure 6**) of output signal with modulated amplitude can be adjusted to a desired level. Generally, the power is transferred with nonmodulated carrier, for example, during *Start* or *Stop* sequences. The frame is sent periodically—it begins with the *Reset* sequence of turning off and resetting internal circuits and finishes with the *Stop* sequence of sending back transponder answer and shutting-down internal blocks. The transmission parameters are synchronized during the header sequence [29].

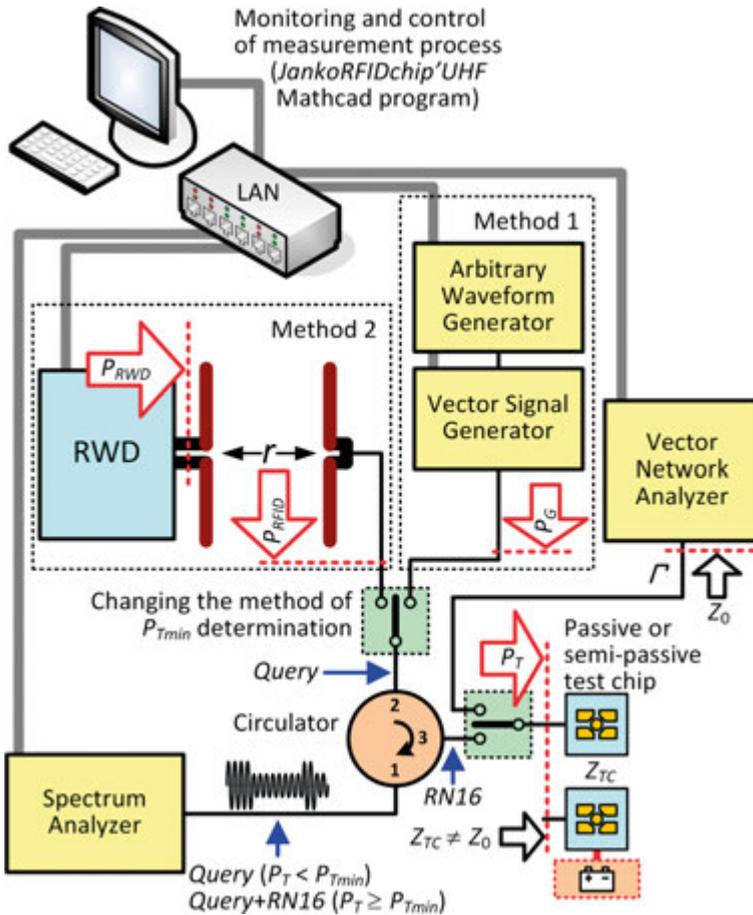


Figure 6. Block diagram of the test stand.

In the second method (Figure 6), a long-range read/write device with an antenna is utilized instead of expensive research apparatus. The main advantage of this equipment is the possibility to set up communication protocol parameters according to investigators' tasks. Also, a level of output power P_{RWD} can be adjusted. In this laboratory stand, the power P_{RFID} transferred in a tested RFID application can be also adjusted in the intrinsic way by changing the distance r between antennas of a real arrangement.

Comparing both methods, it should be noticed that the universal and versatile but very expensive generators are used in the first procedure. Thanks to the elaborated special software, an initial process of protocol pattern preparation is very easy and allows designers to control all communication parameters. So, this method can be utilized to conduct all kinds of typical and untypical measurement tasks, even including investigations connected with a synthesis of analytical model. Also, potential environmental disturbances have limited influence on the

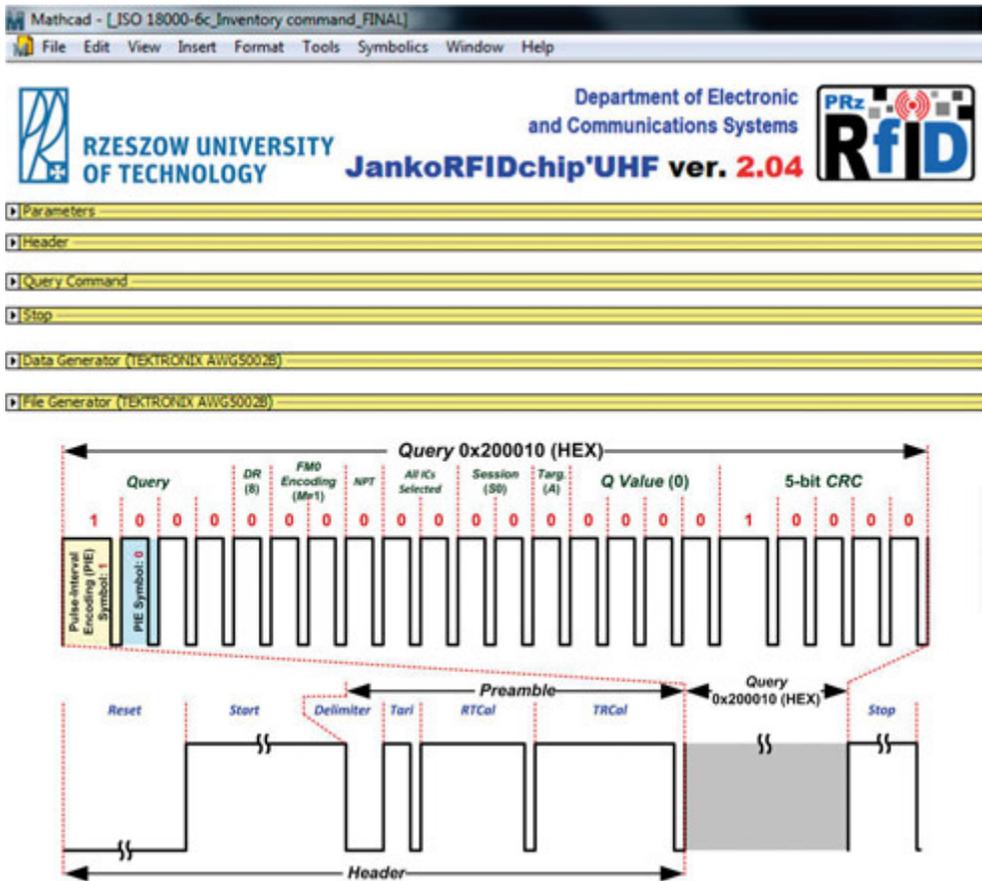


Figure 7. JankoRFIDchip'UHF program (developed in the Mathcad environment).

obtained results. The second method is more time-consuming with regard to the measurement process configuration. Its versatility is restricted by commercial software tools, and it is affected by radio interferences. The main advantage consists in comparatively negligible costs of the laboratory stand.

The command *Query* which is sent in both the procedures is transmitted to the chip by using a ferrite circulator. Since $Z_{TC} \neq Z_0$ the transferred data can be decoded by the spectrum analyzer according to the requirements of [29]. The analyzer can be also utilized to measure the minimal power P_{min} , but losses of measuring channel on the way between the analyzer input and the chip gate have to be taken into account. The sensitivity of tested chip is determined by the relationship:

$$P_{Tmin} = P_{min}(1 - |\Gamma|^2) \quad (7)$$

where Γ means the reflection coefficient which is measured by the vector network analyzer (VNA).

The reflection coefficient is specified at the previously determined value of power P_{min} . Prior to the measuring procedure, the VNA input has to be calibrated with the impedance $Z_0 = 50 \Omega$. Also the reference plane has to be moved to the junction of chip and its antenna—the method of port extension can be used [37, 38]. The testing stand and all time-consuming measuring procedures can be controlled remotely by the LAN network on the base of TCP/IP protocol.

Selected chip groups were tested in the measurement stand (**Figure 8**). Obtained results [34] are convergent for the methods presented in **Figure 6**. The measured P_{Tmin} values are very close to the information given in producer's documentations. However, it should be noted that the information specified by manufacturers is too perfunctory from the RFID system designer point of view.

The chip sensitivity varies with frequency, communication protocol parameters, etc., but these characteristics are very often suppressed in specifications. Moreover, the conditions of this parameter determination (e.g., what frequency or band was it determined for?) are not described by producers. Also, the same problems are valid for the difference between sensitivity values for the chip working in passive ($U_{bat} = 0 \text{ V}$) and semi-passive ($U_{bat} > 0 \text{ V}$) modes (**Figure 9**). So, it is necessary to determine the sensitivity P_{Tmin} of semi-passive transponders with regard to voltage levels of the auxiliary battery supply unit (**Figure 9a**). It has to be taken into consideration by designers on the stage of RFID equipment preparation.

If the chip sensitivity is determined correctly, it is possible to measure the chip impedance by the means of VNA. The results of impedance measurement can be obtained at the sensitivity P_{Tmin} (**Figure 9b**) [34]. Significant differences in the gathered data can be observed for the higher value of the power P_T . It is caused by an internal stabilizer of chip which has to adjust voltage in the input circuits. This effect does not have significant impact on the measuring

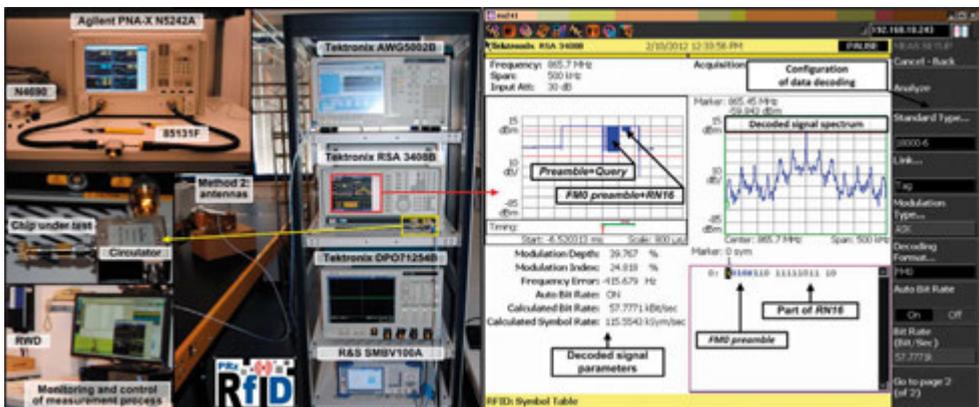


Figure 8. Test stand in the authors' RFID laboratory at the Department of Electronic and Telecommunications Systems (DETS) in Rzeszow University of Technology (RUT).

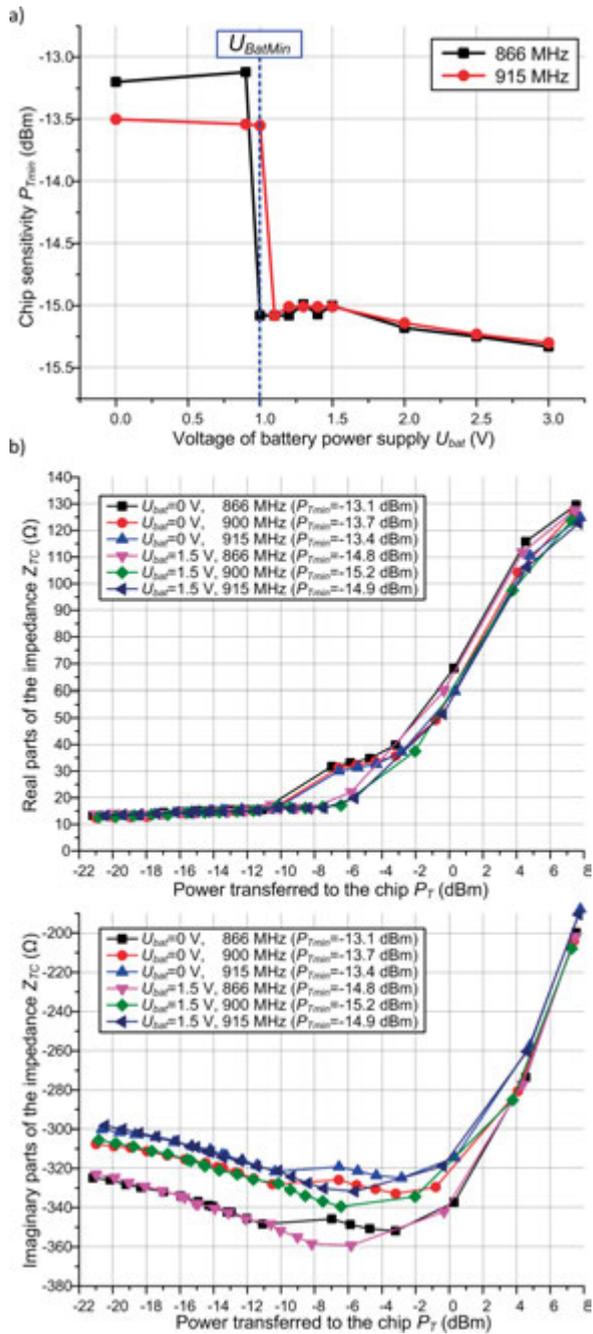


Figure 9. Example results for a passive/semi-passive chip: (a) the sensitivity vs. battery voltage and (b) the impedance vs. power transferred to the chip.

procedure of interrogation zone. It is because the amount of energy which is harvested from the electromagnetic field generated by the RWD antenna is enough for proper operation of the chip. However, it should be noted that the impedance value at the power P_{Tmin} for the semi-passive chip is independent of the supplementary battery source. This fact has essential practical meaning because it allows designers to construct only one type of transponder antenna for both the operating modes (passive and semi-passive).

3.2. Antenna synthesis for UHF RFID transponder

Since the huge progress observed in the RFID technology covered also aspect of antenna constructions, the complement of the knowledge in the field of literature and verification of well-known methods used in synthesis of transponder antennas for various frequency bands is compulsory.

An example problem for the UHF band was discussed in [39]. A novel microstrip antenna dedicated to UHF semi-passive RFID transponders with an energy harvester was presented in this paper. The antenna structure designed and simulated by using Mentor Graphics HyperLynx 3D EM (HL3DEM) software was described in detail. The modeling and simulation results along with comparison with experimental data were analyzed and concluded. The need to eliminate a traditional battery form a transponder structure was the main goal of the project. The energy-harvesting block, which was used instead, converts ambient energy (electromagnetic energy of common radio communication systems) into electrical power for internal circuitry. In order to benefit from the additional function of gathering extra energy, it was necessary to create new designs of antennas.

Typical values of a UHF semi-passive chip resistance R_{TC} equal from a few to tens Ω at the chip sensitivity P_{Tmin} . A value of a chip reactance X_{TC} (typically a few of hundreds Ω) depends mainly on an internal capacitance that accumulates energy which is necessary for supplying the transponder [34]. Impedance matching means that the chip resistance R_{TC} is equal to an antenna resistance $R_{TA'}$ and also an antenna reactance X_{TA} has inductive character; then, the equation $Z_{TA} = Z_{TC}^*$ is met.

In the classical passive UHF chip, there are several ways to obtain highly inductive character of the antenna impedance [40]. The first group of methods consists in modification of a microstrip antenna construction. It can be achieved by adjusting the coupling effect between the antenna and the transponder environment [41] or by modifying chip circuit by utilizing T-matching (**Figure 10a**) [42] or a parasitic induction loop (**Figure 10b**) and others. These methods cannot be applied to same solutions of chips due to their specific internal circuit design [34]. Then, it is necessary to use symmetrical/asymmetrical open-antenna arms (open dipole) which are adjusted by a microstrip and/or SMD elements (**Figure 10c**).

Type of chips considered in [39] has an RF rectifier output for gathering energy from the electromagnetic field of RFID system (**Figure 11**). This output, together with an external battery, is used for powering blocks of supplementary autonomous functions in a semi-passive transponder. The classical passive RFID antennas (utilizing, e.g., T-matching or parasitic induction loop for matching impedance) negatively influence the harvester, and lack of energy blocks the

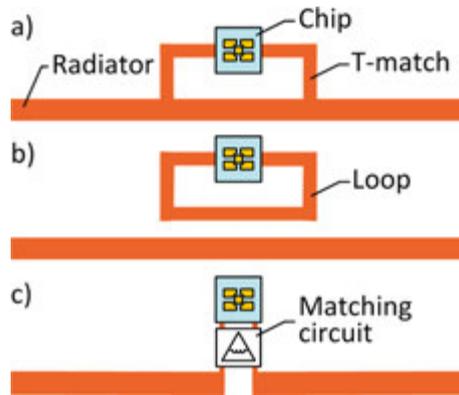


Figure 10. Means of impedance matching in the UHF RFID transponder: (a) T-match, (b) parasitic loop, and (c) other antenna circuit.

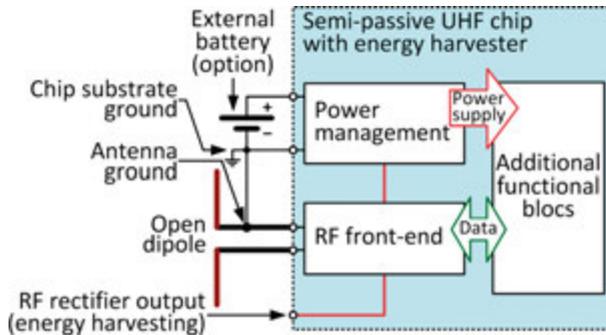


Figure 11. RF frontend in a semi-passive UHF chip with the energy harvester.

whole transmission between the transponder and RWD. It is due to the fact that the antenna and chip have a common ground. So, it is necessary to use the symmetrical/asymmetrical open dipole for the semi-passive UHF RFID transponder with the energy harvester (**Figure 10c**).

The process of antenna designing for the semi-passive UHF RFID transponder with the energy harvester is discussed on the basis of numerical calculations (model HL3DEM) and practical implementations in the PCB technology (**Figure 12**). The investigation is applied to the real RFID passive/semi-passive chip (AMS SL900A in QFN16 package [43]). Additionally, it is assumed that the designed antenna should be resistant to the proximity of metal objects. This assumption stems directly from the fact that the construction of this kind of chips is the most advanced and the most expensive among the currently available solutions on the market. For this reason, only those objects of significant value are marked with such transponders—during freight forwarding processes, it is necessary to guarantee that the valuable products will get to a proper destination by an agreed upon date, and in good condition. Hence, it is a good idea but expensive in practice to control parameters of the surrounding environment

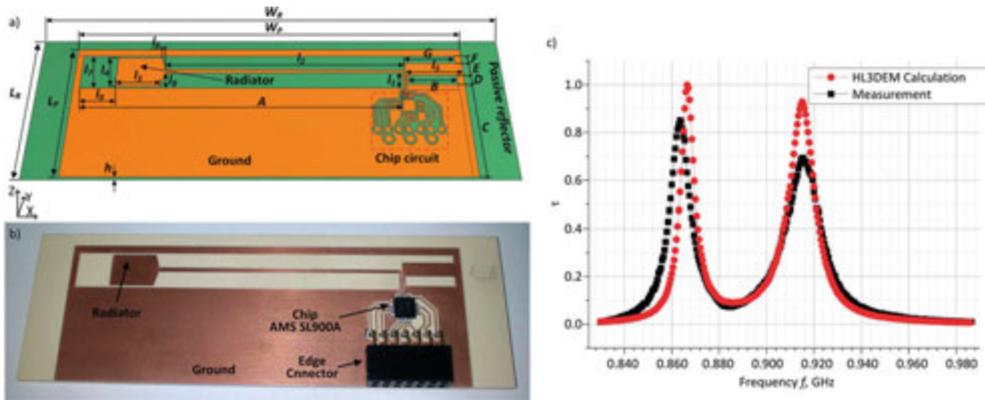


Figure 12. Proposed antenna for a semi-passive UHF RFID transponder with the energy harvester: (a) HL3DEM model, (b) practical implementation and (c) results of the power transfer coefficient.

by means of sensors, for example, embedded in the high-performance transponders [44–46]. On the other hand, it is impossible to use typical low-cost transponders made in a form of pressure-sensitive labels in a disturbing environment (metal or any other object made of electrically conductive materials).

Additionally, it is assumed that the designed antenna should have a directional radiation pattern, a small geometrical size and a power transfer coefficient $\tau = 0.7:1$ in the band: 865–867.6 and 902–928 MHz. The choice of the frequency band meets the requirement of proper operation in various regions of the world. It is especially important for long-range RFID systems which work complying with the requirements of electronic product code in the UHF band (protocol ISO 18000-63, RWD compatibility: (a) European version of ETSI EN 302 208 – 2W ERP, frequency band 865.6–867.6 MHz, or (b) American version of FCC Part 15.247 – 1 W of transmitter output power with maximal gain of 6 dBi – 4 W EIRP, frequency band 902–928 MHz).

In order to justify the elaborated numerical model (**Figure 12a**), the test samples (**Figure 12b**) were made on low-loss double-sided laminates (ISOLA IS-680-300: thickness of dielectric layer $h = 1.547$ mm, thickness of copper layer $18 \mu\text{m}$, $\epsilon_r = 3$, $\text{tg}\delta = 0.003$ at $f_0 = 2$ GHz). The convergence of measurements and calculations is confirmed in **Figure 12c** [39]. It should be mentioned that due to the lack of reliable information about parameters of the dielectric layer for the presumed resonance frequency (866 and 915 MHz), additional tests had to be carried out. The proper value of $\epsilon_r = 3.08$ necessary in the model calculation is determined on the basis of ring resonators [47]. The proposed solution had provided basis for further development work (e.g., Grant No. PBS1/A3/3/2012) conducted in the scope of the RFID technique.

3.3. Antenna synthesis for HF RFID transponder

The progress in the RFID technology is also pertinent to changes of technological materials that are used in transponder constructions. It substantially influences the process of antenna synthesis and determining operation parameters. In the context of problems described in

Section 3.2, the synthesis of flexible antenna dedicated to semi-passive transponders of a HF RFID system with inductive coupling is presented in the paper [48]. It can be found in this work that the considered matching of an antenna to a chip is completely different than in the UHF band case. Moreover, the possibility of manufacturing the antenna in the inkjet technology is emphasized in it. Impact of the technology on antenna parameters is also discussed as it is important for transponder operation in a target application. The validation study of the synthesis method and sample behavior in the inhomogeneous magnetic field is carried out by the authors of the chapter.

It should be mentioned that planar structures on elastic substrates and their diverse modifications are currently the subject of intensive research in the world's laboratories. The permanent progress is possible due to availability of new materials, technologies and also software tools that significantly support antenna designers. It allows researchers to develop, for example, 3D antennas of RFID transponders [49, 50] or transponder antennas operating in two frequency bands [51] and following to integrate these antennas with very thin objects such as tickets, banknotes, valuable and identity documents and so on [52].

The antenna loop (Figure 13a) is represented by a parallel circuit where L_T is the self-inductance and R_T characterizes the resistance of wires that are used for creating the winding and it also includes the ohmic losses (C_{TS} denotes the inter-turn capacitance). R_{TS} and L_{TS} quantities denote respectively the resistance and the inductance of series antenna circuit. The source U_{RT} represents the voltage induced in the antenna loop when the transponder is in the magnetic field of RWD antenna. The maximum value U_T across loop antenna terminals is obtained for the parallel resonance between the inductance L_{TS} and the capacitance C_{TC} of an active chip. This phenomenon is used to supply the chip and also to harvest additional energy from RFID system

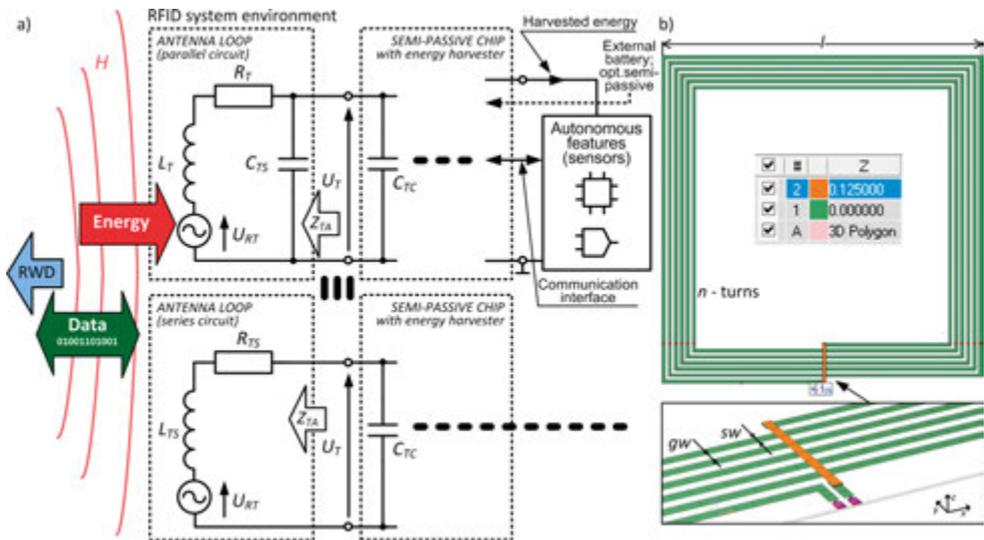


Figure 13. HF RFID semi-passive transponder: (a) diagram of antenna circuit and (b) HL3DEM design model.

environment. These operating principles concern the semi-passive transponders with the extra harvester that recovers energy from the magnetic field of RWD antenna. The harvested energy can be accumulated and used for powering blocks of additional autonomous functions.

The flexible square antenna synthesized in the research is dedicated to the STM M24LR16E-R transponder chip [53]. The selected chip operates according to the communication protocol ISO/IEC15693. The presented design is a development base for flexible construction of autonomous semi-passive transponders dedicated to operation in anti-collision dynamic RFID systems (works conducted as a part of the grant PBS1/A3/3/2012).

The numerical model of loop antenna (**Figure 13b**) was developed in the HL3DEM. The project was prepared for the selected DuPont Kapton HN-500 substrate (thickness 125 μm , relative permittivity 3.5, loss tangent 0.0026) and the Harima NPS-J silver nanoparticle ink (thickness for three layers: 3 μm , resistance: 3 $\mu\Omega\text{-cm}$). The calculation of model parameters were carried out to obtain the parallel resonance between the L_{TS} and the C_{TC} at the $f_0 = 13.56$ MHz.

The test antenna (**Figure 14a**) was realized practically by using PixDro LP50 inkjet printing system (**Figure 14b**). The results of measurements and calculations were compared, and usefulness of the developed antennas in flexible RFID transponders was confirmed (**Table 1**). The prefabricated samples of antennas can operate correctly in the inhomogeneous magnetic field of RFID system and can be matched to any HF RFID chip in both communication and energy aspects.

3.4. Determining impedance parameters for RFID antennas

Measurements of antenna parameters pose a considerable problem in the RFID technology [39, 45, 46, 48, 54]. For this reason, in the paper [55], the authors were paid particular attention



Figure 14. HF RFID semi-passive transponder: (a) sample and (b) inkjet printing stand in the authors' HYBRID laboratory at DETS in RUT.

Calculation/measurement	R_{TS} , Ω	L_{TS} , μH	sw , mm	gw , mm
HL3DEM model (calculation)	39.3	5.04	0.60	0.60
Sample #1 (measurement)	46.5	5.50	0.69	0.65
Sample #2 (measurement)	39.5	5.52	0.73	0.58
Sample #3 (measurement)	35.8	5.48	0.73	0.61
Sample #4 (measurement)	35.3	5.46	0.70	0.63
Sample #5 (measurement)	35.5	5.49	0.75	0.58
Sample #6 (measurement)	41.0	5.48	0.73	0.61
Sample #7 (measurement)	51.1	5.51	0.81	0.52

Table 1. Example results.

to this subject. Such kinds of investigations have to be realized by using two ports of VNA and dedicated passive differential probe (PDP). Since the measuring procedures and estimated parameters are strongly depended on the frequency band (LF/HF/UHF), operating conditions, type of the element (transponder or RWD) and its antenna designs, the appropriate verification on the base of properly conducted experiments is a crucial stage. Accordingly, a systematized procedure of impedance measurements is proposed in [55]. It can be easily implemented by designers preparing antennas for different kinds of RFID applications. It should be emphasized that precise values of antenna parameters are essential for estimating the interrogation zone which is the main parameter that describes an RFID system in its target application and also which is very sensitive to errors made in the design stage.

The RWD antenna together with transponder antennas comprises a radio communication arrangement that has to be wave- and impedance-matched. It should be emphasized that the classical impedance matching of a transmitter and receiver is established only between the RWD output and connected antenna (**Figure 15**).

During antenna synthesis (for both components: transponders and RWDs) in the inductively coupled systems, the measurement problem is mainly related to determining parameters of a symmetrical (with respect to ground) antenna loop with an impedance Z_L which is different from the typical value of 50 Ω . This impedance can be expressed by formula:

$$Z_L = R_s + j\omega L_s \tag{8}$$

where R_s and L_s denote the serial resistance and the inductance of the loop antenna and $\omega = 2\pi f_0$ describes the pulsation.

Correct specification of the loop parameters has significant influence on next stages of the synthesis. In the RWD, the results are necessary for designing a construction of impedance matching circuit [56–60] whereas in the transponders for determining a parallel resonance between an antenna and a chip [45, 61–64].

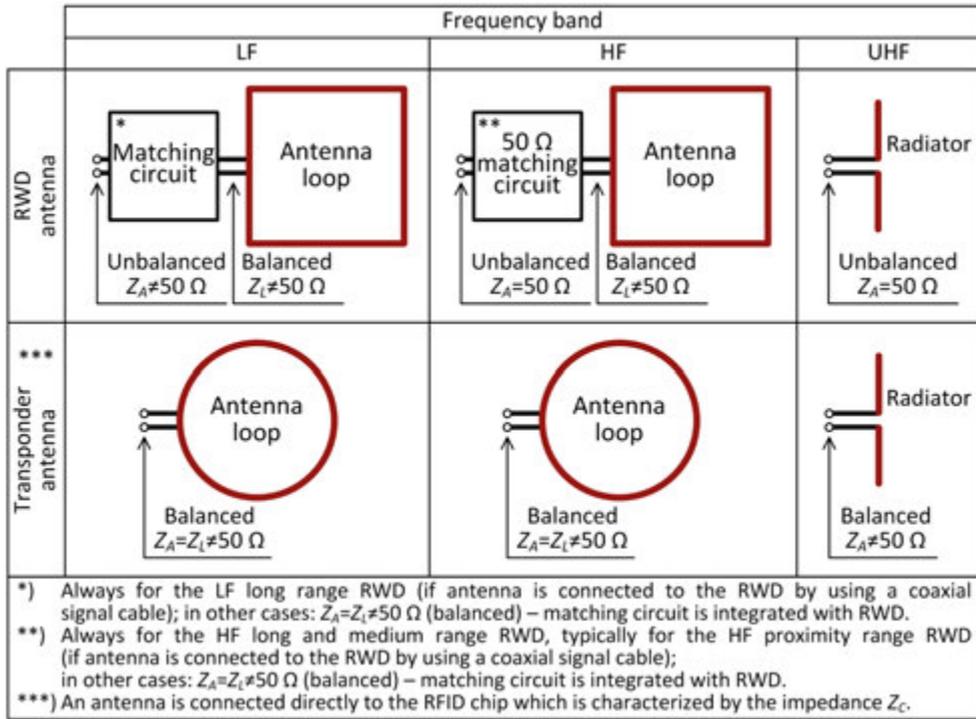


Figure 15. Antenna constructions for RFID devices.

In the RFID systems of the UHF band, the measurement problem concerns transponders and consists in the necessity of determining impedance that is different from the common value of 50 Ω. This impedance can be described as:

$$Z_A = R_A + jX_A \tag{9}$$

where R_A i X_A denote the resistance and the reactance of the transponder antenna.

The impedance parameters mentioned in [55] that are determined in each of described frequency bands (LF, HF and UHF) are essential for estimating energy and communication conditions of RFID systems. The energy conditions influence the amount of energy conveyed from the RWD to transponders. The communications conditions have an effect on efficiency of data transmission by wireless medium.

In LF systems, the typical RLC bridge working at the given frequency band can be used for measuring parameters of antenna loops. The measurement problem is more complicated in the HF and UHF bands. Two nonsymmetrical 50 Ω ports (P1, P2) of a vector network analyzer and PDP probes (Figure 16) have to be used in the experimental procedure. The procedure consists in realization of indirect differential measurement of impedance parameters: balanced

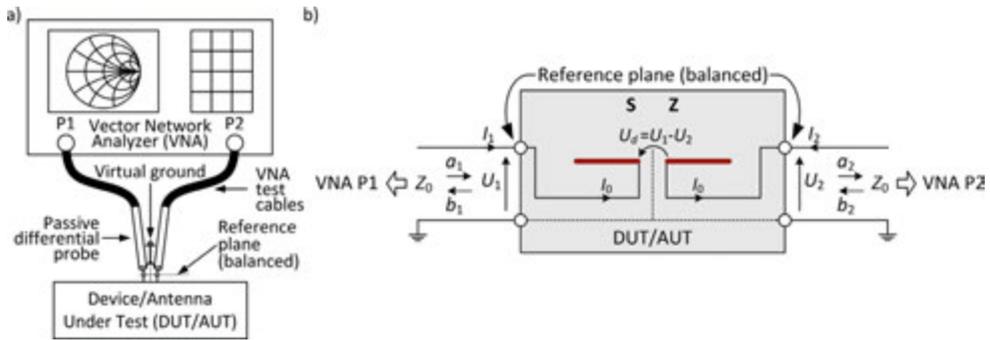


Figure 16. Test stand: (a) block diagram and (b) measurement model.

Device Under Test (DUT) or Antenna Under Test (AUT)—with respect to a kind of device under the test: antenna or its part. The differential measuring technique cannot be applied to RWD antennas of the UHF band because their impedance is matched to the typical value of 50Ω . In such a case, the tests are realized by using just the one nonsymmetrical port of VNA.

The ports of VNA play function of a signal transmitter or receiver. The function can be distinguished on the basis of estimated scattering matrix S . The DUT/AUT separation from connection wires is provided by the differential probe. It makes possible to connect test samples to the measurement equipment. The probes should be matched to tested samples individually because of the diversity types and designs of antennas [39, 46–48, 54].

Measurements of the scattering matrix S does not provide immediate readout of the impedance parameters (8) or (9) in DUT/AUT cases. The dependence of the differential impedance Z_d has to be used, and it is discussed in [55]:

$$Z_d = 2 Z_0 \frac{S_{12} S_{21} - S_{11} S_{22} - S_{12} - S_{21} + 1}{(1 - S_{11})(1 - S_{22}) - S_{12} S_{21}} \quad (10)$$

The problem is crucial in the context of measuring various antenna structures since they work in both transponders and RWD devices and in the LF, HF and UHF bands.

The impedance measurement problem in the RFID technique can be discussed on the basis of practical implementations of various antenna constructions which are made in the PCB technology (Figure 17). The investigation can be done for example on the test stand presented in Figure 18. The measurement results are compared with numerical data obtained for models in the HL3DEM software. They show a satisfactory convergence, so the presented procedures can be easily implemented during designing new RFID systems.

3.5. Determining the radiation pattern of UHF RFID transponder

The antenna radiation pattern is one of the basic parameters that are required to evaluate the usefulness of a given radio communications system. The typical hardware and software

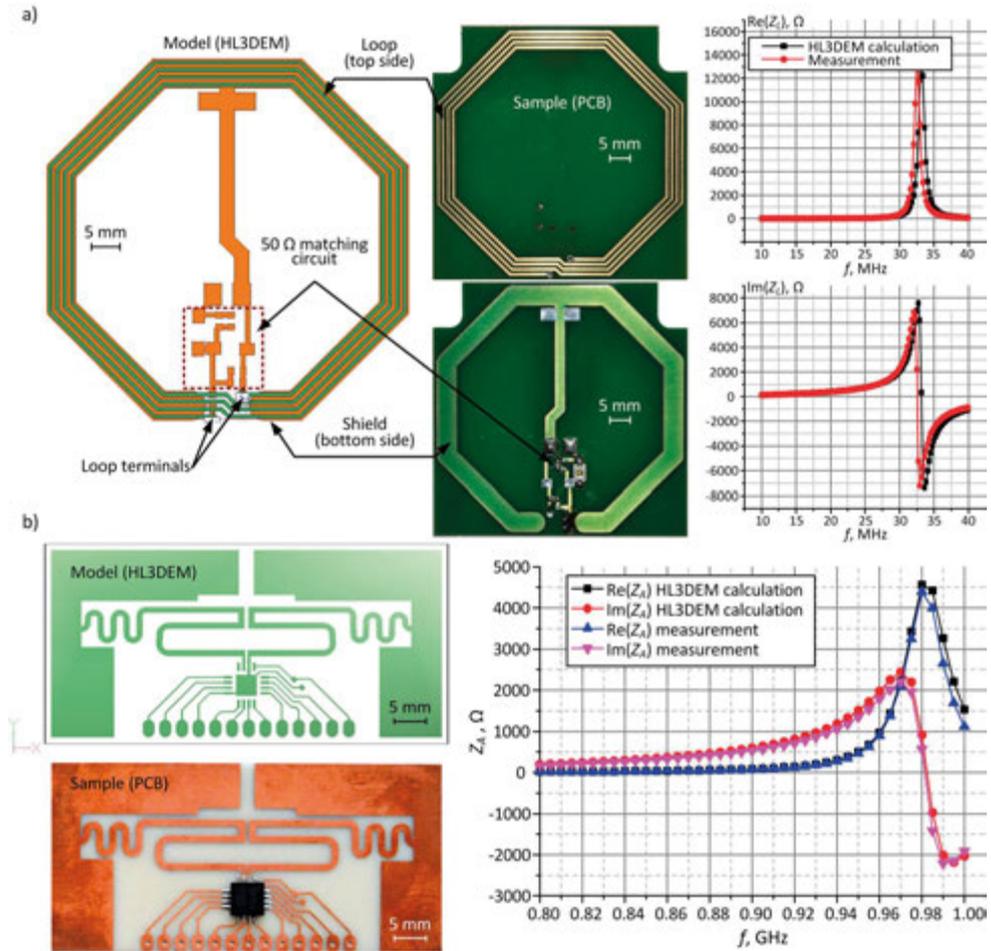


Figure 17. Examples: (a) HF RWD antenna and (b) UHF transponder antenna.

configuration of measurement systems can be applied to determine the radiation pattern of most antennas that are commonly used in DVB-T, GSM, UMTS, LTE or WiFi and others [65]. They can also be adapted to new antenna constructions [66] as well as to new implementations of common antennas in wireless communications [67]. But there is a problem in the case of RFID systems operating in the UHF band. It is impossible to determine the radiation pattern of RFID transponders by using the standard laboratory stands and measurement methods. The problem consists in impedance matching of an antenna and a chip. A complex impedance of RF front end varies, while the transponder chip is working and its value is dependent on the electromagnetic field parameters (the electromagnetic field in RFID systems is influenced by environmental conditions around marked objects).

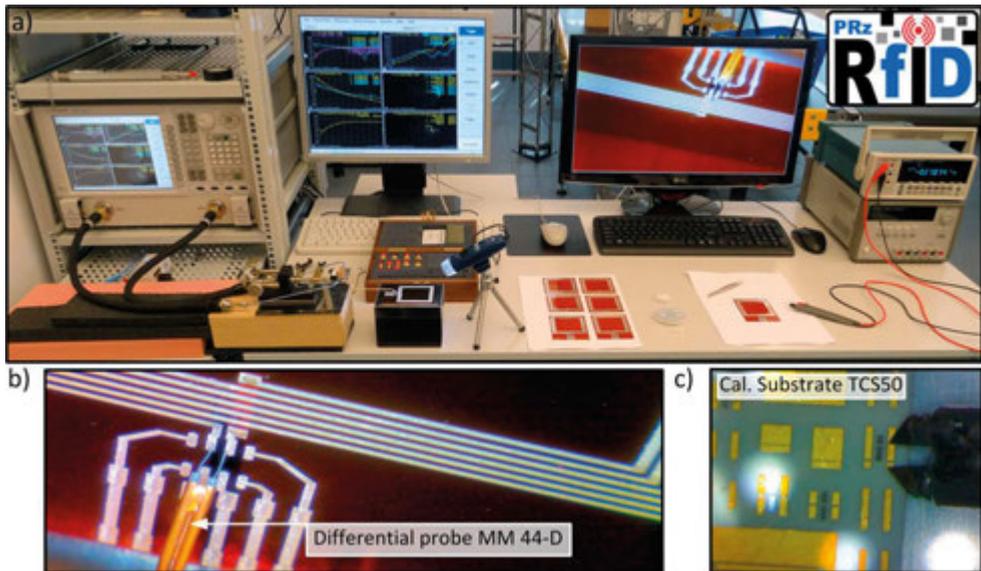


Figure 18. Measurement process: (a) antenna measurement stand in the authors' RFID laboratory at DETS in RUT, (b) differential probe fixed to terminals, and (c) calibration set of test stand.

It is the reason why the classical theory of antennas cannot be applied to solve the matching problem and new measurement methods have to be developed in order to determine the parameters of RFID antennas. A measurement process in which the nature of a UHF RFID transponder (the variable impedance of the chip) is taken into consideration is seldom described in the branch literature. In one of the encountered solutions, authors use very expensive apparatus dedicated only to the intended aim [68]. In another proposal, supplementary (e.g., movable) antennas are implemented [69], but the described experiment is highly complicated and additional measurement uncertainties have to be taken into consideration. With regard to the endeavors made to solve the abovementioned problems, the authors worked out a universal method of the radiation pattern determination and described it in detail in the paper [70]. The elaborated measurement stands are supplemented with cheap and commercially available RFID devices, and some own control and data-acquisition software procedures. The additional benefit of the proposed method is that the radiation pattern can be determined just for a transponder as well as for a whole electronically marked object. The second option is particularly useful when the efficiency of identification process in automated systems and implementation or maintenance costs are considered.

The main requirement for measurements to be carried out in a proper way is to maintain the constant value of the impedance Z_{TC} (Z_{TCR} without modulation), while polar diagrams of the radiation pattern (according to θ and φ angles of the spherical coordinate system) are being determined (Figure 4). The measuring procedure has to be conducted when the transponder is placed inside the interrogation zone of an RFID system (when the energy and communication

conditions of transponder operation are met). The test conditions can be controlled only at the IZ boundary. In the developed method, the authors propose to perform it by changing the power P_{RWD} supplied to the terminals of the impedance-matched RWD antenna.

Power received in the transponder antenna equals the minimal value P_{Tmin} if the terminals of the impedance-matched RWD antenna are supplied with the minimal energy P_{RWDmin} . It allows the transponder to be properly supplied (in given environmental conditions) according to the relation:

$$P_{Tmin} = P_{RWDmin} \frac{G_R G_T \lambda^2 \tau \chi}{(4\pi r)^2} \tag{11}$$

The (11) dependency is crucial for the IZ boundary determination where the impedance Z_{TC} is equal to $Z_{TCR} = f(P_{Tmin})$ [34]. This impedance is obtained on the basis of communication protocol in the task process where the transponder sends its unique identification number (Unique Identifier (UID)) as an answer to a *Query* command from the RWD [29]. The requirement of maintaining the constant value of the chip impedance that is met when the condition $P_T = P_{Tmin}$ is true for any variation of θ and φ angles at constant distance r is fundamental for the authors' method of measuring the radiation pattern (**Figure 19**).

Since the chip impedance is complex ($\neq 50 \Omega$), the radiation pattern is determined wirelessly. It means that signal paths of measuring devices do not have to be connected to the transponder chip by wires and the radiation plots can also be drawn for electronically marked objects. The test procedure is performed in an anechoic chamber equipped with an AUT positioner, linear polarized RWD antenna with mast and digital controller. A small anechoic chamber can be chosen for the test purposes [71] according to the dimensions of transponders and their operating frequency band. The amount of power conveyed to the tested transponders can be controlled by the RWD and an output attenuator. The normalized radiation pattern (in dB) is determined on the basis of the following dependency:

$$F_{Th \text{ dB}}(\theta, \phi) = [P_{RWD \text{ dBm}}(\theta, \phi)]_{\min} - P_{RWD \text{ dBm}}(\theta, \phi) \tag{12}$$

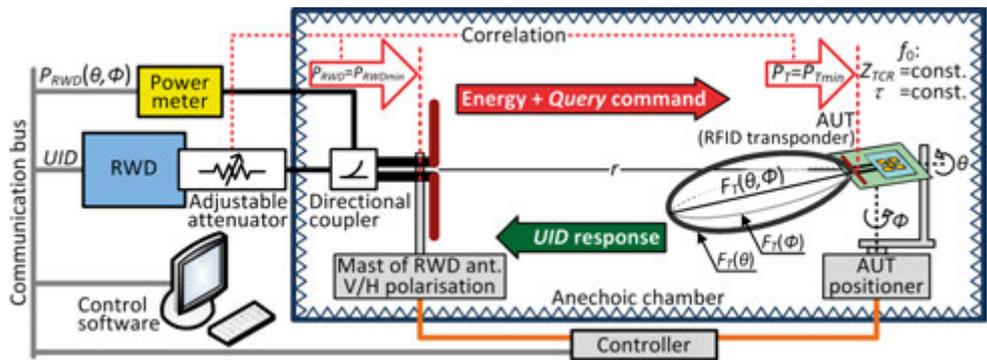


Figure 19. Block diagram of the proposed method for measuring the radiation pattern.

where P_{RWDdBm} means the measured power in dBm (by using a scope probe, spectrum analyzer, etc.), whereas index “min” refers to the minimal value of this parameter.

The elaborated conception can be verified and developed in a typical RFID laboratory (**Figure 20**). The common components of radio communication test sets (anechoic chambers, positioners, etc.) that are typically dedicated to measure radiation patterns of standard antennas can be used to build up the new stands for the method proposed by the authors. In addition, commercially available and relatively cheap RFID devices (in relation to the equipment for common antenna tests) can be implemented in the stand with the aim of adjusting the RF laboratory to the proposed research. Nevertheless, research investigators have to design control procedures in order to adapt the apparatus to the scheduled tests (the special LabView program entitled *RFID(UHF)SysAntPat* was prepared by the authors in their RFID laboratory).

The elaborated conception was verified and developed by the authors in experimental tests on two examples: omnidirectional and directorial antenna, designed especially for commercial RFID chips. In order to evaluate the obtained results, the radiation pattern was measured twice: using the authors’ conception and the classical method (**Figure 21**), in the same experimental conditions. The results of measurements and calculations obtained in both the experiments are convergent for the V as well as H planes of the radiation pattern. It confirms the usefulness of the developed method.

3.6. Synthesis of RWD antennas

The synthesis process of the three-dimensional interrogation zone is to a large extent determined by an RWD antenna, since the device generates the electromagnetic field, which constitutes a source of energy and a medium for two-directional data transmission in an RFID system. The authors conducted a synthesis of RWD antennas for the HF [54] and UHF [72] band. The issue was considered in a view of: (1) proximity range (means the transmission distance up to about a dozen centimeters with a separation of the near-field communication scope in the HF band, where the transmission distance is up to about few centimeters), (2) medium range (means the distance of several dozen) and (3) long range (means the distance to a few meters).

The effective synthesis process of a complete RF output circuit in a proximity-range single RFID system with inductive coupling is presented in [54]. The paper also incorporates problems connected with designing read/write devices that are constructed on the basis of integrated circuits (ICs) from different manufacturers. The presented method can be applied to any process of automatic identification requiring the proximity-range RFID system operating at the frequency of 13.56 MHz and using one of the suitable communication protocols (e.g., ISO/IEC 14443, 15693).

In generalized form, the antenna unit can be represented by a combination of: loop- and impedance-matching components as well as an EMC filter and a signal detection circuit for data transmission in transponder—RWD direction (**Figure 22**). This diagram is adequate for any antenna system design solution in which there is a necessity to separate its individual modules by using wire connectors. On its basis, it is possible to synthesize the effective antenna that can work with the integrated circuit such as: TRF7960, CLRC632, EM4094, AT88RF1354, AS3910 and many others.

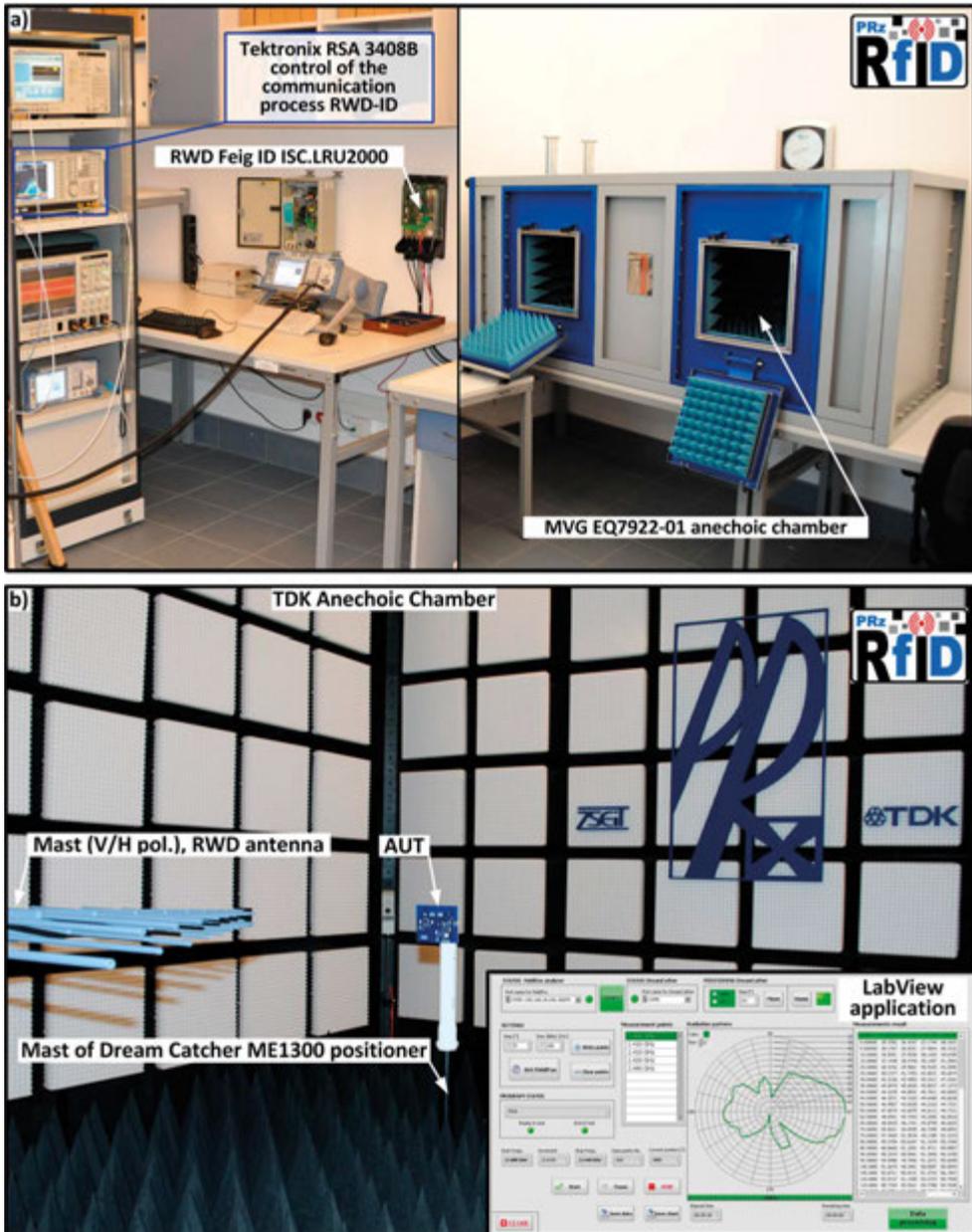


Figure 20. Test stands in the authors' RFID laboratory at DETS in RUT: (a) laboratory room with MVG anechoic chamber and (b) laboratory room with TDK anechoic chamber.

The proper use of the RWD antenna requires a connection of unmatched (in impedance and wave conditions) antenna loop to a symmetric (with respect to ground) input with mismatched impedance in the read/write device (TX1-TVSS-TX2). It is realized by using a coaxial

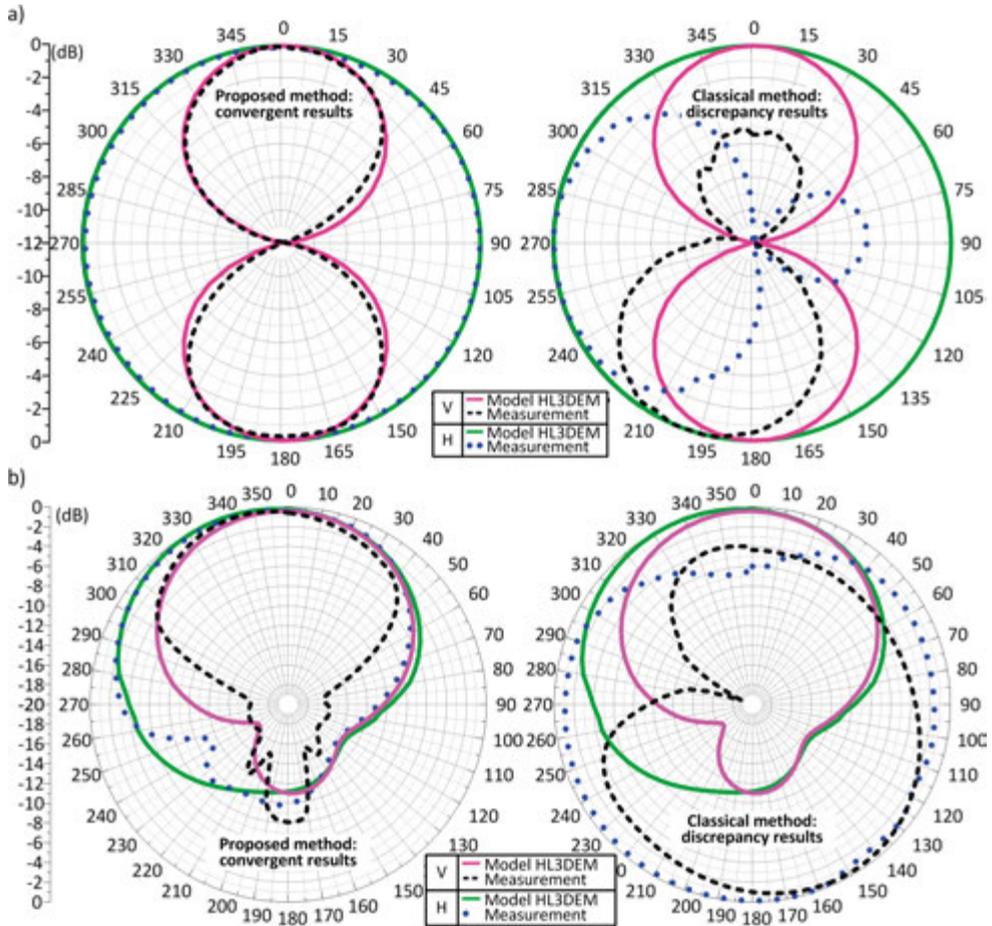


Figure 21. Experimental verification: (a) measurements by using system located in the MVG chamber—Sample #1 and (b) measurements by using system located in the TDK chamber—Sample #2.

signal cable with the wave impedance of $Z_c = 50 \Omega$ as well as by a symmetric EMC filter on the RWD side and an asymmetric matching circuit on the side of the antenna loop. The both systems can be connected by a balancing transformer with configuration 4:1 ($200 \Omega / 50 \Omega$), where a turns ratio is equal $n = 2$.

The impedance matching circuit of the antenna loop consists of a capacitive divider C_{R1}, C_{R2} . It is integrated with a resistance R_{RA} which lowers a Q_R factor of the RWD antenna. The Q factor cannot exceed the maximum value Q_{Rmax} which directly results from the data rate required by a communication protocol. If values of the Q factor are smaller than the maximum Q_{Rmax} the RWD device is more resistance to detuning due to, for example, environmental influences. However, it reduces the size of the interrogation zone and thus limits the usefulness of the designed RFID system in which there is usual tendency to obtain the maximum distance for recording or reading information to or from a transponder memory.

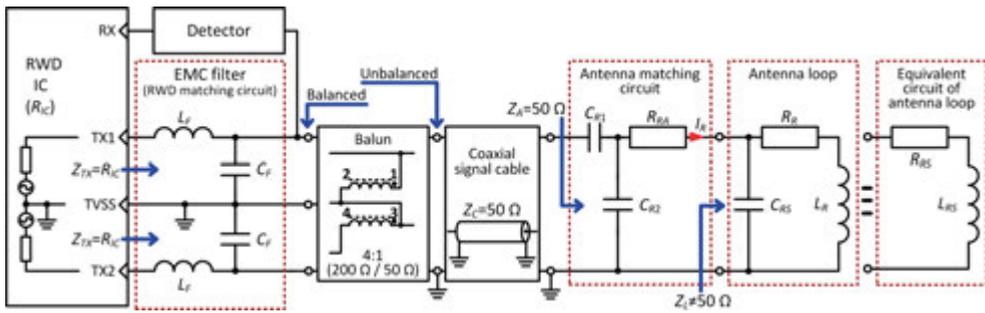


Figure 22. Generalized block diagram of an antenna unit connected to an HF RWD.

A circuit of the symmetric low-pass EMC filter (L_p , C_f) serves an additional function of impedance matching Z_{TX} to an IC input. The impedance value depends on the type of chip and should be only the real part (close to the required value of R_{IC}). It ensures the effective transfer of power from the circuit of RWD to its antenna. Besides the impedance matching, the EMC filter has to ensure an elimination of higher harmonics during energy transmission, improve signal-to-noise ratio for transmission between a transponder and a read/write device and also improve conditions for transferring data to a transponder. The resonant frequency f_{EMC} should be also taken into consideration in design process. The required value of the frequency f_{EMC} results from the signal spectrum for subcarrier modulation. In this process, the transmitted information should be recovered from the side bands. The frequencies of the side bands are strictly defined according to the used communication protocol (e.g., $f_0/16$, 32 , 64 gives approximately 847, 424, 212 kHz, and so on). For example, if the bit rate equals 106 kb/s, the frequency of the filter is $f_{EMC} = 14.4$ MHz (13.6 MHz + 847.5 kHz).

The circuit of signal detection is the last module presented in the **Figure 22**. It is used for detecting data received from a transponder. This module is characteristic for the IC, and therefore, the detailed electronic diagram is not specified. It must be emphasized that the proper design of the whole circuit connected with energy transfer from the RWD to the transponder is very important in determination of the interrogation zone of a read/write device especially that works in the near field of the HF band. If the specificities of each discussed element are correctly taken into consideration, the proper synthesis of the magnetic field is possible. Then, any implementation process of identifying any object at a distance of several centimeters from the antenna system of RWD is feasible.

The octagonal antenna was synthesized in order to verify the presented experimental method (**Figure 17a**). The antenna is dedicated to a multiprotocol circuit of a read/write device of the proximity-range RFID system in the HF band. The typical two-sided FR-4 laminate is used to prepare the model and test antenna. The shield connected to ground is placed on the bottom layer. The antenna has four terms that are located on the opposite side of the laminate. The shield covers the area of the antenna loop, and its main function is to separate the electronic system from the magnetic field supplying a passive RFID transponder. The distribution of current values that confirms this function is presented in **Figure 23a**. The obtained value of the return loss (**Figure 23b**) confirms the full antenna impedance matching to the designed circuit of RWD.

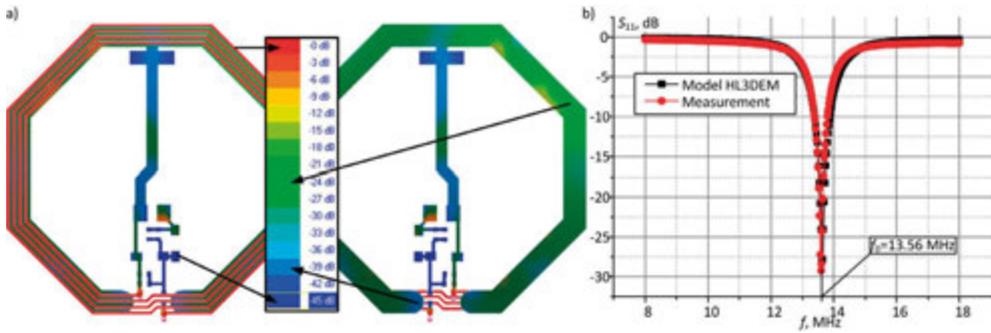


Figure 23. Experimental results: (a) 3D current distribution and (b) return loss.

3.7. Model of antenna radiation pattern

Possibly the best choice of appropriate devices which enable efficient realization of an automated process constitutes an essential stage with regard to implementing an RFID system. However, the devices are selected to the applications with respect to availability in the market and economic aspects. Then, predictability of the three-dimensional interrogation zone comes down to basic analytical or numerical calculations, or sophisticated computer simulations since it is conducted by using a few elementary parameters that are described in product specifications. With regard to selection of UHF transponders or RWD antennas, a radiation pattern constitutes the crucial parameter. From a practical point of view, there is a problem to transform—in easy way—available plots of the radiation patterns (e.g., presented in an antenna datasheet) to analytical dependences or discrete data required for numerical calculations of radio wave propagation.

On the basis of available subject literature, it can be stated that there is the need for developing simple tools by means of which it would be possible to generate a numerical representation of the radiation pattern for a real antenna. For this reason, a numerical model of the directional radiation pattern in which part of energy emitted in side and back lobes is taken into consideration is discussed in the chapter [64]. The authors present the useful software tools (*NmAntPat*) that generate the numerical data on the basis of parameters that can be read from the antenna datasheets. The output file can be easily implemented into an analysis of radio wave propagation phenomenon in any algorithms and numerical calculations. The results of the work are confirmed on the example of real antenna that can be applied in read/write devices working in the UHF band of RFID system.

The essence of the model of directional radiation pattern consists in the power gain diagram G calculation conducted in vertical (θ) or horizontal (ϕ) plane. It is represented by the function *NmAntPat*:

$$G(\theta, \phi) = NmAntPat \left(\begin{matrix} G_0, HPBW, HPBW_{back'} \\ FS, FB, FB_{rest}, n_{side}, n_{back'} \\ ANG, TILT \end{matrix} \right) \quad (13)$$

Basic parameters of the modeled antenna are input arguments of the function $NmAntPat$: G_0 —maximum value of the gain (dBi), $HPBW$ —half-power beam width of the main lobe ($^\circ$), $HPBW_{back}$ —half-power beam width of the main back lobe ($^\circ$), FS —front-to-side ratio (dB), FB —front-to-back ratio (dB), FB_{rest} —front-to-back ratio of the back lobes (dB), n_{side} —number of the side lobes (equal distribution in the range from 0° to 180°), n_{back} —number of the back lobes (equal distribution in the range from 180° to 360°), ANG —variable θ in vertical or φ in horizontal plane (from 0° to 360°) and $TILT$ —tilting of the pattern ($^\circ$).

The $NmAntPat$ program implemented in the Mathcad environment not only visualizes the radiation patterns but also generates files for subsequent data processing (Figure 24). A user may select any format that is typical for data of this kind. It is useful during further analysis of radio wave propagation phenomena. So, it can be utilized in any user algorithm, freeware or commercial platform. The main software procedure $NmAntPat$ comprises the derived dependences (13). An additional procedure is used for calculating and visualizing values of every lobe levels. It simplifies the approximation of modeled radiation pattern.

A real antenna of read/write device (Feig ID ISC.ANTU250/250 in EU version [73]) working in the UHF band of RFID system can be used to present the problem of radiation pattern

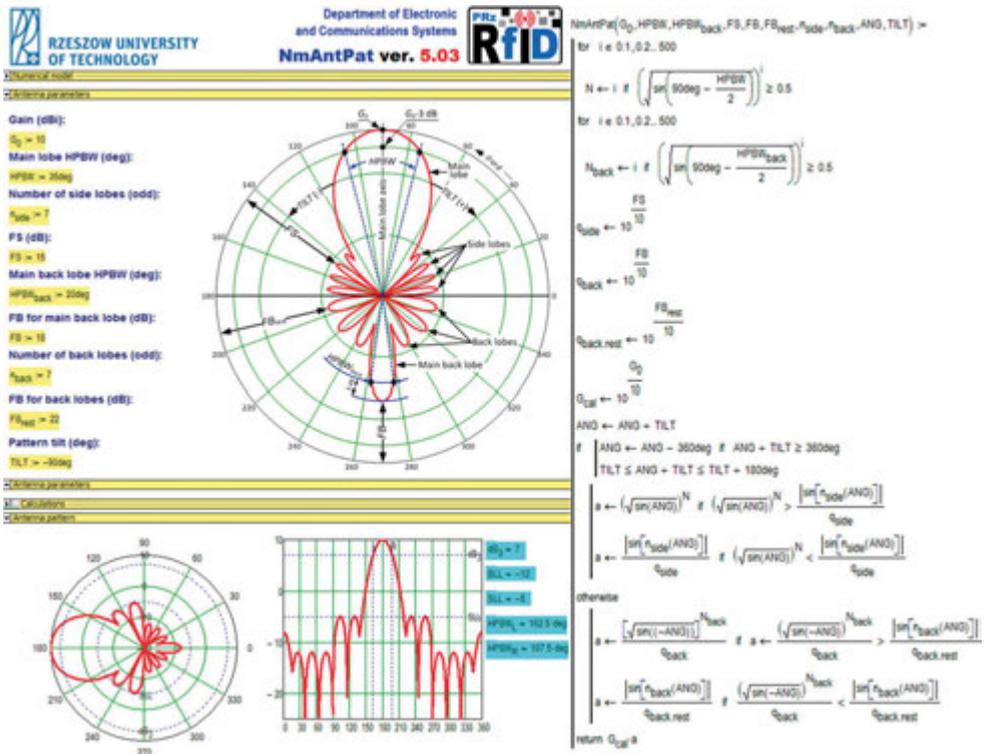


Figure 24. NmAntPat program and its numerical procedure.

synthesis. The comparing chart of directional radiation patterns is presented in **Figure 25**: the first diagram is calculated from producer's datasheet, and the second one—on the basis of measured data. The measurements were carried out in the TDK anechoic chamber by using the MI Technologies antenna system.

The both presented cases give satisfactory results and convergence of the determined radiation pattern. It shows the practical utility of the developed model and software tools. The preparatory studies revealed vagueness of data specification notes published by manufacturers for their products. The lack of important parameter values makes a radio communication system synthesis (e.g., interrogation zone in RFID system) very difficult, and shared information is not sufficient to reproduce the characteristics of the antenna. But an accurate analysis of the specified radiation pattern can lead to determine missing input data for proper implementation of antennas in a real environment.

3.8. Autonomous semi-passive RFID transponder

The problems discussed so far constituted a base for a conception and implementation of a new idea in the field of RFID technology that is presented in publication [44] and partially in [45, 46] (most of this work was supported by the Polish National Centre for Research and Development (NCBR) under Grant No. PBS1/A3/3/2012 entitled "*Synthesis of autonomous semi-passive transponder dedicated to operation in antic-collision dynamic RFID systems*").

A small application area of commercial semi-passive transponders compared to the passive constructions is due to disadvantages of the electrochemical cells. The commonly used batteries have a limited lifetime decreasing in harsh environmental conditions (e.g., in low temperature ambient), restricted ability to supply a load with short high-power pulses, or they have to be replaced after discharge or protected against theft and so on. Because of these drawbacks, the rare semi-passive RFID systems are expensive in production and maintenance, not stable

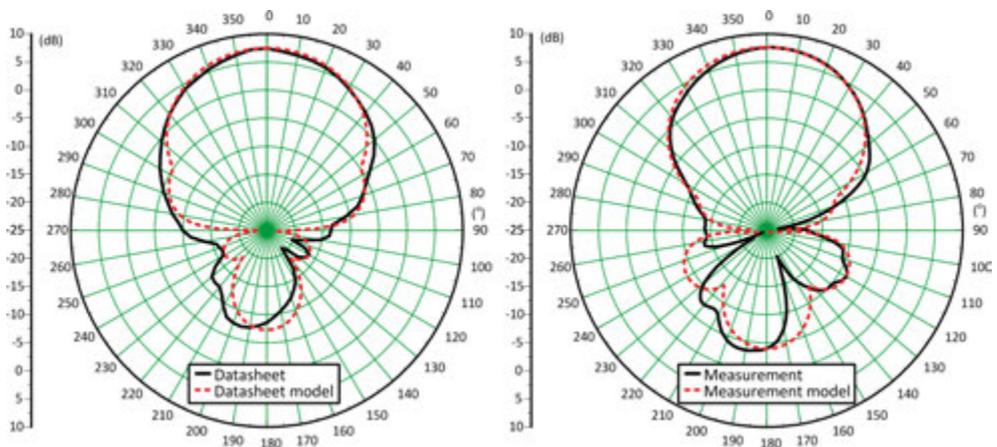


Figure 25. Comparing chart of the directional radiation patterns.

and do not provide a high level of identification efficiency. To cope with these inconveniences, the authors work out the multiband development board dedicated to battery-less autonomous semi-passive RFID transponders in which extra functions of energy harvesting from the electromagnetic field of different radio communication systems as well as a dedicated power conditioner and an energy storage block are implemented. The proposed idea contributes significantly to the development of automatic identification (**Figure 26**).

The beginning stage of the progress in the identification system—optical machine-readable barcodes—provides only basic and unchangeable information about marked objects (**Figure 26**). The recognition process can be realized only with a single object simultaneously, and the barcode has to be visible to a reader. Currently, passive and semi-passive (but not autonomous) RFID transponders are beginning more and more popular and they mark a new stage in the advancement of object identification. They can be not only read, but also it is possible to change stored data during operational use of the systems as well as their configuration or maintenance and so on. Moreover, some user’s extension information is written into a tag memory and a read/write process can be realized simultaneously with several transponders (anti-collision identification) without optical visibility.

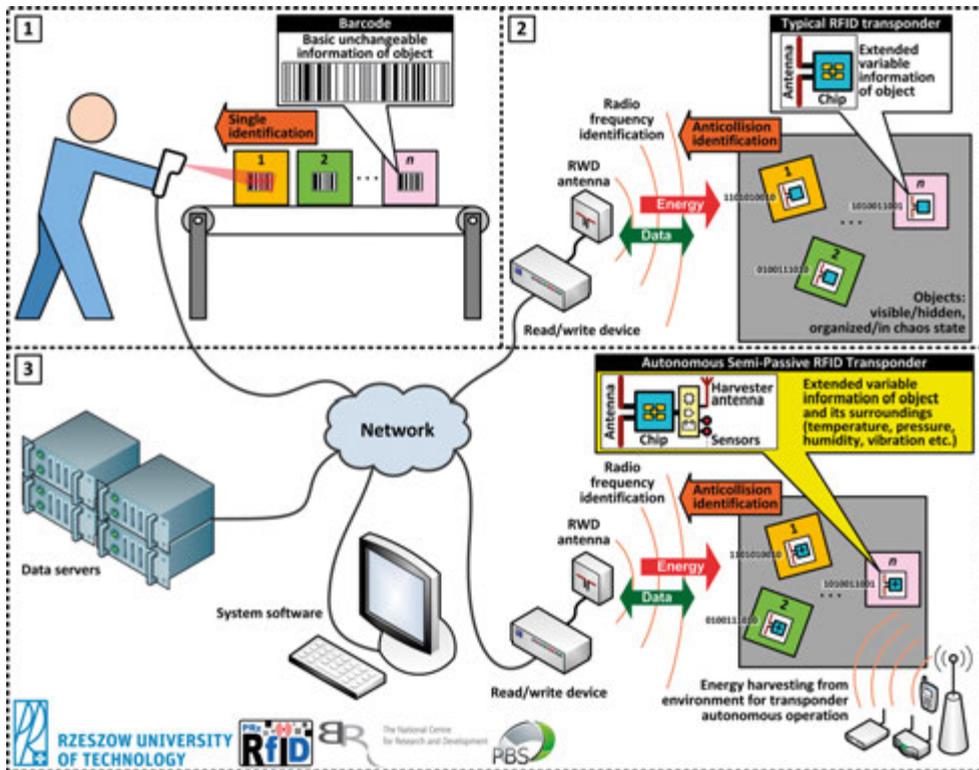


Figure 26. Development stages of automatic object identification systems.

The author's developed idea [44] helps to open a new chapter in the automatic object identification. In the third stage, the RFID transponders provide not only details about marked objects but also extended variable data gathered from surrounding by built-in sensors of different physical quantities. Moreover, the transponders are developed toward the capability of being powered from the electromagnetic field of common radio communication systems. In this case, an internal supply block consists of an energy harvester integrated with an RF frontend and an advanced low-voltage regulator supported by a super-capacitor. The element that stores environmental energy is free of drawbacks and limitations that are inherent for the traditional galvanic cells [74, 75]. The super-capacitors are maintenance free, with low degree of wear. Their high capacity at their small dimensions bridges the gap between possibilities of electrolytic capacitors and rechargeable batteries—significant amount of energy can be released with high volume power [76].

Another important problem is to provide suitable conditions for charging the untypical power source of the autonomous semi-passive transponders. There are examples of effective using electromechanical, thermal or photovoltaic transducers [77, 78] for obtaining energy from the environment. But in the view of RFID system operation principles, the electromagnetic field generated by radio communication systems (e.g., base transceiver stations of the wireless communication technologies like GSM, wireless local loop, Wi-Fi, WiMAX or other wide area networks) that are present almost in every place on the Earth is a more natural source. The choice of electromagnetic waves as the medium of conveying power in the proposed autonomous development board follows the new solutions that appear in RFID chips of semi-passive transponders—a few producers offer the possibility to split energy supplied by the RWD to the chip between the internal communication transceiver and additional blocks, for example, sensors, analog-to-digital converters, external outputs, and so on [34, 46].

The proposed research conception will hopefully make a real contribution toward easing integration of low-power devices in the transponder structure, and it allows the semi-passive transponders to be fully autonomous. In fact, it should be stated that commercial potential of such possibilities is described in the literature, but its practical usefulness in RFID system applications is significantly restricted by the described drawbacks of galvanic cells that are presently in use.

In initially pursued conceptual and designing works, the authors started research that was pertinent to modification and extension of a well-known structure of passive RFID transponders (III stage of a cycle in the advancement of object identification—**Figure 26**) [79]. A particular attention was drawn to characteristics and determining parameters that influence an interrogation zone in RFID systems modified in this way. In this context, in publication [46], a model and practical construction of an HF RFID transponder was put forward, in which new utility functions were implemented (**Figure 27**).

The efficiency estimation of energy transmission from RWD to passive transponder is very complicated for wireless medium—magnetic field in the HF band, especially in proposed solution with autonomous features (e.g., module for measuring physical quantities). Since the extra electronic circuits disturb the proper operation of transponder, the careful study of its impact on main parameters is compulsory. This problem is explained in detail on the elaborated model

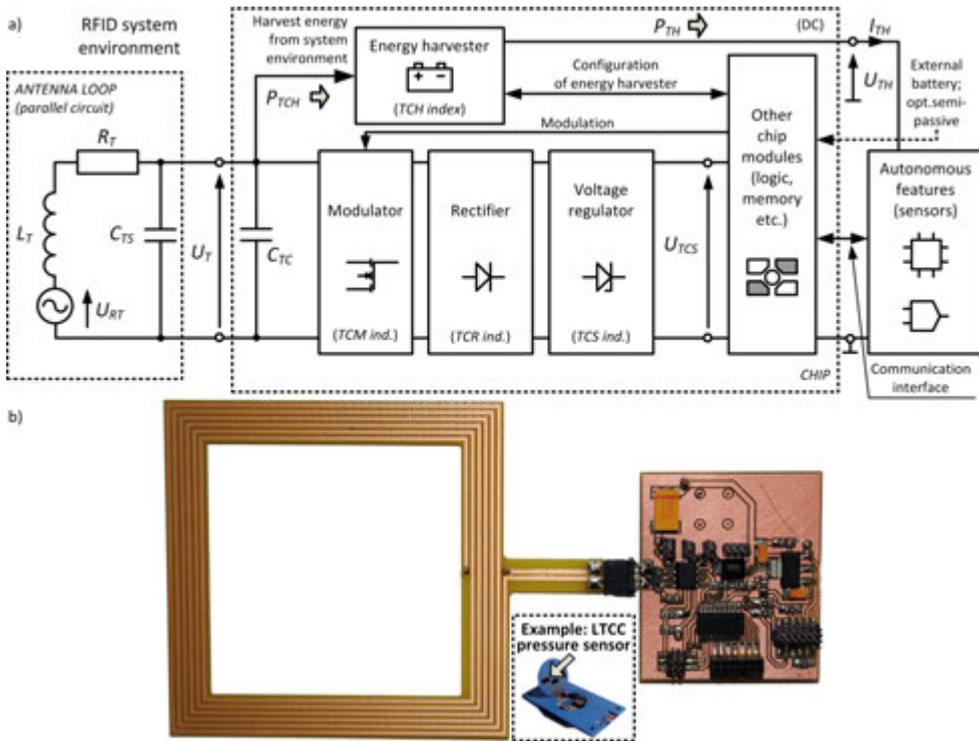


Figure 27. HF RFID transponder with autonomous features: (a) model and (b) practical realization.

of a passive transponder with the active build-in block for harvesting energy from the RFID system environment. It includes all blocks of real solution: loop antenna, chip with extra energy harvester and in addition microprocessor for controlling autonomous features. Since an antenna set of a proximity or long-range RWD device is assumed as an element of the model, the considerations are suitable for the active transponder located in a $P(x, y, z)$ point of the Cartesian coordinate system. System performance and all parameters can be described with appropriate analytical relationships. The correctness of the developed model was confirmed on the basis of calculated and measured (in practical HF RFID application, by control and measurement instruments of RFID laboratory at DETS in RUT) results and presented in [46]. The developed methodology for testing passive and semi-passive transponders with harvester that derives energy from RFID system environment is the key approach to determine the tree-dimensional interrogation zone for both single and anti-collision RFID systems.

A practical flexible construction of an HF RFID transponder in which new usage functions were implemented (Figure 28) was proposed in publication [45]. Temperature change is one of the key factors which should be taken into account in logistics during transportation or storage of many types of goods. In this study, a passive UHF RFID-enabled sensor system for elevated temperature (above 58°C) detection was demonstrated. This system consisted

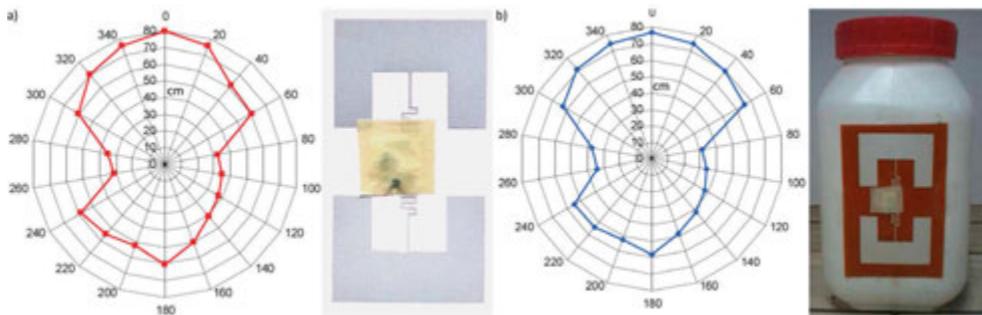


Figure 28. Transponder-sensor with the UHF RFID interface and example results of IZ border: (a) paper substrate and (b) Kapton substrate.

of an RWD and disposable temperature sensor comprising an UHF antenna, RFID chip and temperature-sensitive unit. The UHF antenna was designed and simulated in the HL3DEM software. The properties of the system were examined depending on the temperature level, kind of object package and type of substrate, on which the flexible structure of an UHF RFID transponder-sensor has been prepared.

Finally, the proposed conception was realized under the Polish government project of the PBS1/A3/3/2012 number. The multiband development board of battery-less autonomous semi-passive RFID transponder was elaborated on the basis of worked-out assumptions. The electrical harvester from the electromagnetic field of different radio communications systems, sophisticated low voltage converter and low leakage energy storage were designed especially for the demonstrator (**Figure 29**).

The development board is equipped with two independent RFID interfaces—one of them operates in the HF band (ISOIEC15693 protocol) and the second in the UHF band (EPC Class 1 Gen 2 protocol consistent with ISOIEC18000-63). These blocks are designed on the basis of semi-passive chips that have additional wire serial peripheral buses for communications with a supervising controller (HF band: STM24LR64E chip with I2C bus; UHF band: AMSSL900A chip with SPI bus). Moreover, the both ICs can gather energy from the electromagnetic field generated by antennas of RWD, in their operating frequency bands. It means that the super-capacitor of the supply unit is charged whenever the demonstrator appears in the IZ. Of course, the communications in RFID system can be realized without regard to activities of the extra blocks.

The autonomy of the semi-passive transponder is achieved by applying a harvester that gathers environmental energy derived from radio communications system present in its current location. The antenna of special construction is designed for the presented demonstration board. It operates in the frequency band of 930–975 MHz and is matched to the input circuit of the Powercast P2110B harvester. The block provides the RF harvesting from GSM900, converts RF energy to DC and stores it in a capacitor. Also the power management for battery-free micropower devices is implemented. It is possible to measure the value of power at the input and to adjust how frequently the module is woken up depending on the existing energy

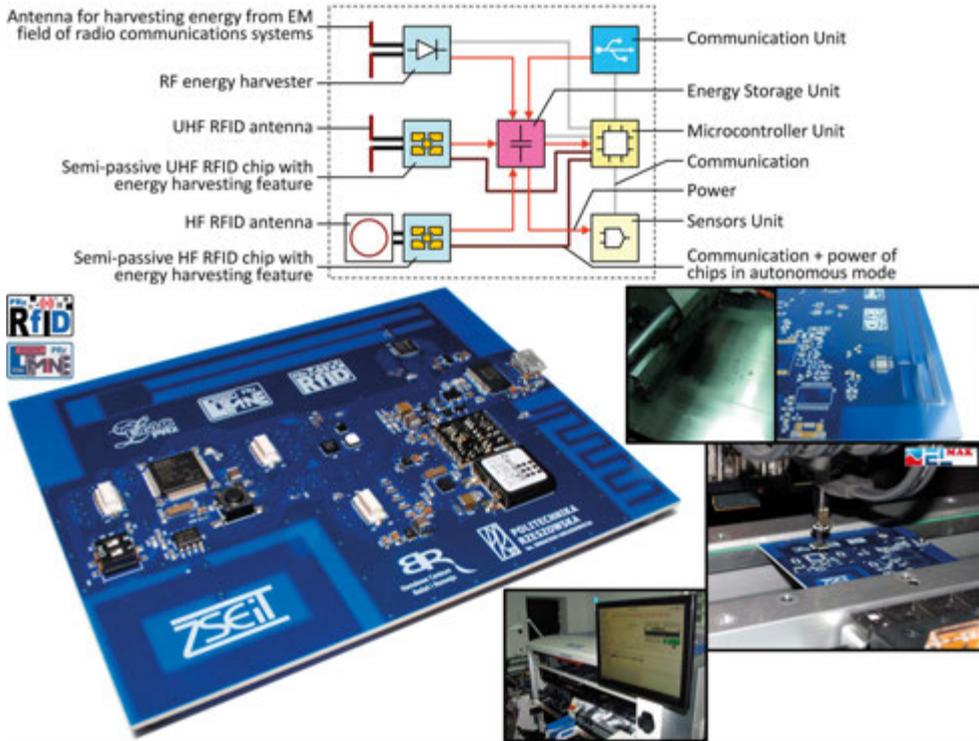


Figure 29. Elaborated development board (Polish government project no. PBS1/A3/3/2012).

conditions. The research and development cooperation with Powercast Company allows the authors to redesign the development board to another radio communication system (e.g., UMTS, LTE and WiFi).

The typical environmental RF energy source is characterized by low capacity, and it causes the necessity to design an ultra-efficient energy storage unit. Stored energy allows the demonstrator to work autonomously, and it is utilized to acquire information about surroundings of electronically market objects. It is achieved by measuring periodically physical quantities and storing results in the data memories of the RFID chips. The block of signal transducers and conditioning circuits is integrated in the module and consists of three-axis MEMS accelerometer (Analog Devices ADXL362), humidity and temperature sensor (Silicon Labs Si7020) and ambient light sensor (Maxim Integrated MAX44009). There is also possibility to connect external intelligent sensors by I2C bus, and it could be useful when the demonstrator is adjusted to future user's applications.

The demonstrator activity is controlled by the digital block that is designed on a basis of 32-bit microcontroller (STM32L151RBT6). The demonstration software is elaborated to support a future user in development works with the presented autonomous semi-passive transponder, and it can be adapted to target application requirements by USB interface.

The worked out development board allows potential users to start investigations and different application projects in the scope of both the object identification and the monitoring of environmental conditions. The undertaken enterprises should quickly lead the users to the product commercialization. In this context, the first preproduction batch was assembled in the production line of ELMAK Company. Also, the project concerning product potential in the market and the possibility of its commercialization as well as the estimation of decision-making determinants in the process of the transponder implementation in the Polish industry was realized [80, 81].

3.9. Synthesis of interrogation zone in RFID systems

The research on definition, characterization and determination of parameters for RFID devices available on the market or new developed designs that are continuously conducted by the authors led to prepare appropriate procedures and synthesis methods useful in the RFID technique. In this context, elements of algorithm for determining the 3D interrogation zone in an inductively coupled anti-collision RFID system are presented in the chapter [60]. The algorithm based on the Monte Carlo (MC) method and the computer program implemented in the Mathcad engineering calculation software is utilized in order to achieve the posed aims.

From a practical point of view of a planned implementation of anti-collision RFID systems, the most useful solution is to look for the interrogation zone with a given shape, position and orientation in space. The essence of its determination by the proposed method is presented in **Figure 30a**. In the conducted research, it is assumed that the demanded volume should be cube-shaped (of side b) and situated at the z_{ID} height, whereas its location should

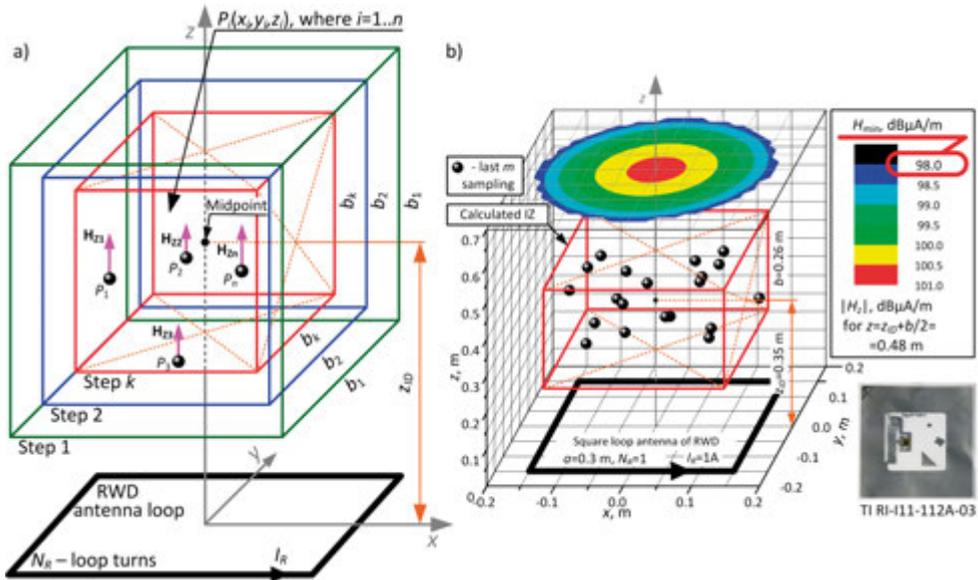


Figure 30. IZ determination by using the MC method: (a) graphic representation and (b) example of measured and calculated results.

be axially symmetrical and parallel to an RWD antenna loop. Such an assumption results from orientation of transponders that are parallel to the symmetrical RWD antenna which has, for example, a circular, square or different polygon shape in inductive coupling RFID systems. The process of the interrogation zone determination is realized according to a proposed algorithm.

A random deployment of n -transponders at P_i points of Cartesian space at (x_i, y_i, z_i) is assumed in steps k considered in a sequence during the search of the RFID system interrogation zone. The random variables x_i, y_i and z_i for $i = 1 \dots n$ have a uniform distribution. It results from the fact that the electromagnetic field in any point of the communications space is heterogeneous. The random variables x_i, y_i and z_i are mutually independent. The interrogation zone is determined for a given efficiency of identification η_{ID} :

$$\eta_{ID} = \frac{l_{IDOK}}{n} \cdot 100\% \quad (14)$$

where l_{IDOK} is the number of transponders for which desired read/write operations are properly done.

In order to determine that the RFID system is operating correctly for given locations of transponders, it is not enough to achieve the $\eta_{ID} = 100\%$ for n -transponders and fulfil all energy conditions (absolute value of the z -component of magnetic field strength H_z is greater than H_{min}) in an anti-collision application. It cannot be predicted whether the sampling of coordinates of transponders placed in k area in which all the conditions mentioned above are fulfilled meets the boundary requirements necessary for correct operation of the whole RFID system. The practical use of the law of large numbers for a k -step (in which all conditions of RFID system proper operation are met with a given efficiency) is a solution to this problem. Nevertheless, it can be found that the m -tuple increase of the number of the random variables x_i, y_i and z_i sampling in k -step lengthens the calculation process during the simulation of an antenna unit arrangement. But in accordance with the law of large numbers, the probability of a correct estimation of the interrogation zone increases. This is mainly connected with the examining a larger number of deployed n -transponder cases. If the conditions of correct operation are not fulfilled in any of m multiple sampling of transponders' 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 cube ($b_k = b_{k-1} - b_{step}$). The MC solution for the analyzed object completes a procedure which confirms the fulfilment of all conditions for the correct operation of anti-collision RFID system. The procedure is completed for a given efficiency of identification and for the area in which all the m multiple sampling of transponders location leads to a positive calculation result of the antenna unit arrangement consisting of a read/write device and transponders.

The experimental determination of the interrogation zone is divided into two parts: calculation and measurement. In the both parts of the experiment, a laboratory process of anti-collision RFID identification is subjected to verification. For the computational part, a program called *JankoRFIDmc'3D-IZ* is developed in the Mathcad environment by the authors. This program enables a random deployment of n -transponders and to study the effectiveness of an antenna set. The interrogation zone for a given efficiency of identification is the solution of

this calculation. The example results of numerical calculations by *JankoRFIDmc'3D-IZ* and the importance of its individual elements are presented in **Figure 30b**.

The convergence of the measurements and calculations confirms a practical usefulness of the presented concept of determining the three-dimensional interrogation zone by using the Monte Carlo method in inductively coupled anti-collision RFID systems. The program *JankoRFIDmc'3D-IZ* developed on the basis of this method is practically used to solve many problems—reported by industry representatives—connected with implementation of RFID systems.

The problem of object identification that changes their location and/or orientation (**Figure 31a**) is encountered by the authors in their research works. It also resulted from the demanded needs of industry partners. In this context, a model of automated identification in the RFID anti-collision system in which communication with groups of transponders entering and leaving interrogation zone (**Figure 31b**) takes place is presented in the chapter [82] as an example. Dynamic location changes of transponders influence RFID system reliability, which is characterized by the efficiency coefficient and the identification probability of objects in the specific interrogation zone. The communication conditions are crucial for efficient exchanging data with all transponders during dynamic process. Presented problem is the base to specify

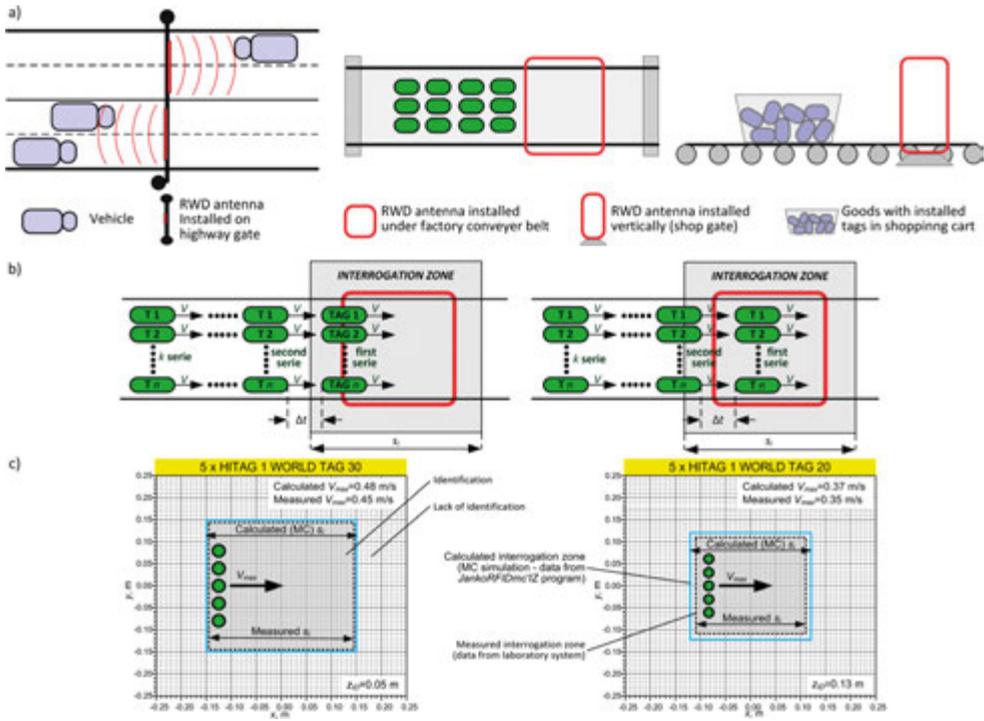


Figure 31. Anti-collision identification with dynamic location change of transponders: (a) selected processes, (b) illustration of considered problem, and (c) example of experimental results.

new application transponder parameters (such as maximum speed of transponder motion) and to synthesize the IZ required for all dynamic anti-collision RFID applications.

The maximum speed of transponders motion V_{max} is the practical parameter that is obviously related to the problem of identified objects that dynamically change their location in anti-collision RFID systems. The maximal value is determined for the speed at which the correct executions of the operations in transponder's internal memories are still allowed. In general case, this parameter can be expressed by the dependence:

$$V_{max} = \frac{s_i}{t_{i\ min}} = \frac{F_s\{IZ\}}{F_t\{D_{UDV}, BR, n_{max}\}} \quad (15)$$

The length of the track s_i that is travelled by transponders crossing the interrogation zone has to be known in order to evaluate V_{max} . For the case of anti-collision object identification, the s_i is the function F_s of the IZ and it has to be determined with regard to the maximum number of correctly operating transponders n_{max} , which—in critical period of time—may be inside the interrogation zone. The minimum time $t_{i\ min}$ is necessary to identify all serial numbers of transponders inside of the IZ. This time is the function F_t , which results from a used communication protocol and takes into account the data quantity D_{UDV} , required for transmission with a proper bit rate (BR).

The example results of calculated (data from the *JankoRFIDmc'IZ* program based on the MC method) and measured (data from the test stand) charts of IZ and V_{max} parameter are presented in **Figure 31c**. The convergence of the curves confirms a practical usefulness of the presented conception of determining the interrogation zone by using the Monte Carlo method in anti-collision RFID systems with dynamic location change of transponders.

3.10. Methods to increase geometric size of the interrogation zone

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 and orientation of objects. This parameter also should be appropriate to requirements established for an application of automated identification. With regard to problems of dynamic anti-collision systems, selected issues pertinent to increasing geometric size of the IZ are presented in the publications [83, 84].

The greatest flexibility in developing RFID implementations and shaping the interrogation zone can be achieved using a system with an antenna multiplexer (MUX). In this context, the problem of the IZ determination in HF RFID application with two orthogonal RWD antennas is presented in the chapter [83]. In the paper, the research results are obtained on the basis of theoretical model as well as investigations in an example system configuration. The specialized measuring stand in the common RFID laboratory is used for experimental verification of the identification efficiency. Finally, the authors propose a software tool *JankoRFIDmuxHF* elaborated in the Mathcad environment (**Figure 32**).

The arrangement of two perpendicular antennas connected to the one RWD with the MUX is the problem to solve. The antennas have to be switched, while marked objects are being

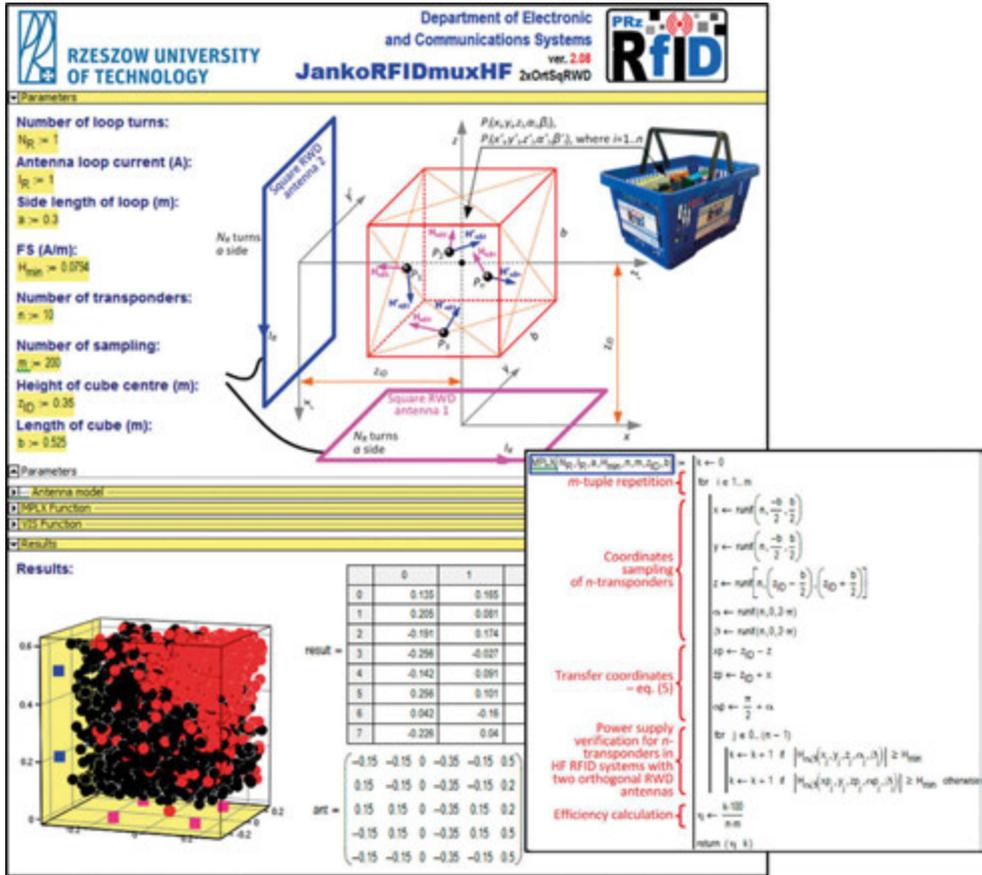


Figure 32. JankoRFIDmuxHF program.

identified in the inside of a cube of side b . 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 .

The obtained equations 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. 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) (Figure 1). In this case, a perpendicular component of the magnetic field strength for a deviated transponder is given by:

$$H_{\alpha\beta} = H_z \cos(\alpha) \cos(\beta) + H_x \sin(\alpha) \cos(\beta) + H_y \sin(\beta) \quad (16)$$

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 the each transponder that is located and oriented in the point P_i (where $i = 1 \dots n$, and n denotes the number of considered transponders). It means that the condition for correct supplying one of the transponders should be analyzed in two steps, that is, the $H_{\alpha\beta}$ should be calculated in the point $P_i(x_r, y_r, z_r, \alpha_r, \beta_r)$ for the antenna #1, and in the $P_i(x'_r, y'_r, z'_r, \alpha'_r, \beta'_r)$ for the antenna #2. The coordinates in the system (x', y', z') can be calculated from:

$$(x', y', z', \alpha', \beta') = (z_{ID} - z, y, z_{ID} + x, 90^\circ + \alpha, \beta) \tag{17}$$

It should be emphasized that more antennas and their hypothetic localizations in a space can be considered by using the elaborated model. It is difficult to accurately predict the coordinates of the points P_i in a chaos state. In fact, it is not possible to analyze all potential locations and orientations of a group of n -transponders in the inside of the cube of side b . The described problem has a probabilistic nature, and proposed solution is obtained by simulating a group of given objects by using the MC method [46].

The essence of the model is represented by the *MPLX* function for which input arguments are determined on the basis of primary parameters of the HF RFID system with the two orthogonal and multiplexed RWD antennas. The *JankoRFIDmuxHF* program can be used for calculating the identification efficiency and the RWD antenna localizations for the given input data. Results of identification process are presented graphically along with efficiency effects (correct/incorrect identification). The convergence of measurements and calculations (**Figure 33**) 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.

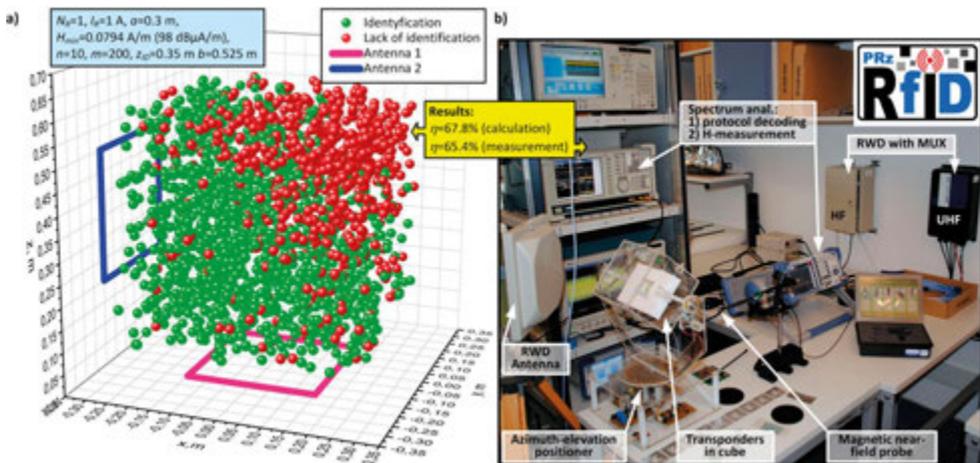


Figure 33. Interrogation zone: (a) example of calculated and measured results and (b) prepared test stand.

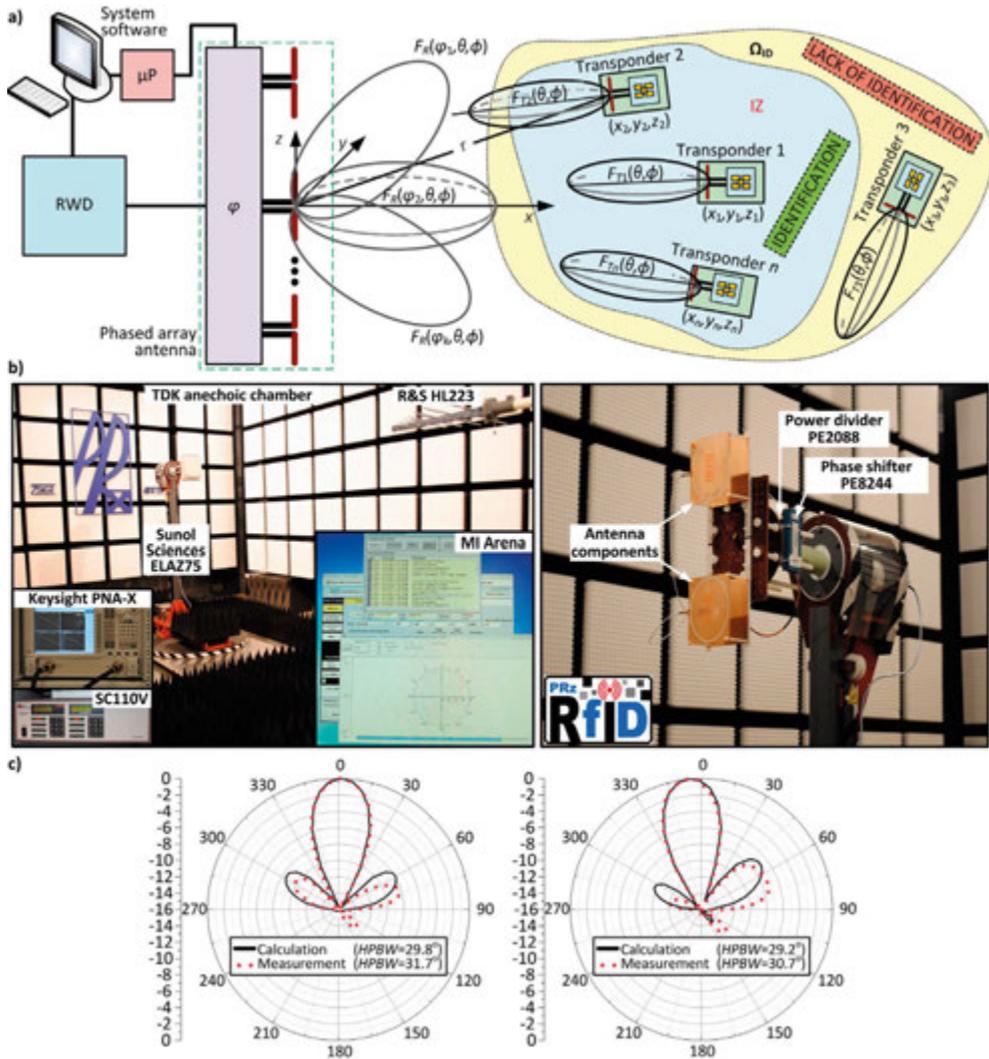


Figure 34. Anti-collision UHF RFID system with the array of phased antennas: (a) idea, (b) test stand and (c) example results.

In the phased antenna array, an interesting solution is an electronic control of the main beam of radiation pattern. Despite the fact that for a long time this function was used only in military applications, now increasingly, its implementations can also be observed in the civilian areas when object identification is based on the shapes of their echoes, for example, in the radio astronomy or weather forecasting [85]. In this context, new opportunities may be sought for the use of the array of phased antennas [86].

Bearing in mind the European (ETSIEN302208) and American (FCCPart15.247) limitations of available energy, the idea and practical solution of the phased antenna array dedicated to UHF read/write devices are presented in the chapter [84]. On the basis of tests carried out, the authors point out the possibility of using developed devices for the synthesis of a determined IZ in anti-collision RFID system.

In analogy to, for example, military radiolocation systems, it is possible to focus energy of the electromagnetic field to variously localized and oriented RFID transponders. It can be obtained by changing/shaping the main beam of the radiation pattern of RWD phased antenna array (**Figure 34a**). The proposed concept of maximizing IZ can be described by a function which includes a k th position of the main beam in relation to n th transponder in a space Ω_{ID} :

$$IZ(\Omega_{ID}) = f(F_R(\phi_k, \theta, \phi), F_{Tn}(\theta, \phi), \tau_n, \chi_n, P_{RWD}, P_{Tmin}) \quad (18)$$

where $F_R(\phi_k, \theta, \phi)$ means the radiation pattern of RWD phased antenna array, $F_{Tn}(\theta, \phi)$ —transponder radiation pattern and ϕ —angle of phase shift for a signal feeding the individual antenna of the array.

Assuming constant location and orientation of transponders in an automated process, a key influence on the IZ can be obtained by shaping the radiation pattern $F_R(\phi_k, \theta, \phi)$. The system with possibility of shifting the main beam can be made even with the simplest set consisting of: power divider, phase shifter, microprocessor system and two antennas (**Figure 34b**). In the read/write device of the proposed solution, the power of the feeding signal is evenly divided on the antennas, but one of them is powered with a phase shift by the angle ϕ . Equal strength of output signal and phase shifting gives the possibility of shaping the radiation pattern without any mechanical changes in the position of the whole antenna arrangement.

On the basis of conducted calculations and measurements (**Figure 34c**), it can be concluded that the effective possibility of changing direction of the main beam energy in the range of 14° is feasible in stable phased antenna array system. Results of this work will provide introduction to comprehensive assessment of the interrogation zone in anti-collision UHF band of RFID systems on the basis of the proposed functions (18).

4. Conclusions

An RFID system is properly implemented only when all marked objects are successfully recognized irrespective of their dynamics, location and orientation or operation status. Possibly the best choice of appropriate devices that enable efficient realization of the automated process constitutes the essential stage when new implementations are designed. Usually, the elements of RFID system are selected mainly with respect to availability in the market and economic aspects. An attempt to define, characterize or determine parameters of RFID devices may be found problematic in many practical or theoretical cases, and predictability of the 3D interrogation zone is often reduced to basic analytical or numerical calculations or computer simulations. Since complete characteristics of the devices are not available, the lack

of important parameter values makes a radio communication system synthesis (e.g., interrogation zone in RFID system) very difficult. The presented studies revealed vagueness of data specification notes published by manufacturers for their products. Since the literature and knowledge in this field are incomplete, the time-consuming and expensive “trial and error” method is most commonly used especially in the industry practice when new applications are designed. Therefore, the authors prepared the comprehensive review on their efforts to change this state of affairs. These facilities can significantly support many theoretical and simulation works that are developed and described in the branch literature and can improve the reliability and efficiency of designed RFID applications.

The presented works were carried out in many aspects connected with single and anti-collision, passive and semi-passive, static and dynamic RFID systems for perspective frequency of the HF and UHF bands. The authors especially focused on the definition, characteristics and determination of the antenna parameters in propagation and inductively coupled systems, and they proved that the 3D interrogation zone is the most important and practically useful parameter when the RFID system is considered. They also revealed that the classical theory of antennas cannot be applied to solve some problems (e.g., antenna and chip matching, radiation pattern determination, etc.) and new measurement methods have to be developed in which the nature of RFID technology is taken into consideration—it is seldom mentioned in the branch literature. Accordingly, they systematized measuring procedures, elaborated own methods and constructed sophisticated test stands implemented in their common RFID and electronic technology (HYBRID) laboratories that could be useful to characterize the transponder and RWD chips or antennas as well as whole real system applications. They supplement the knowledge in the field of literature and verification of well-known methods used in synthesis of transponder and RWD antennas and the interrogation zone.

It can be found in this work that the considered problems are completely different for the HF and UHF band cases. In this distinction, several of crucial analyses, syntheses and experiments are carried out in relation to: (1) determination of transponders’ and RWDs’ chip parameters; (2) antenna synthesis for both transponders and RWDs; (3) estimation of antenna impedance and radiation pattern; and (4) simulation, modeling and prediction of the interrogation zone and also possibility of its enlargement. Finally, on the basis of described items, the conceptions of autonomous semi-passive RFID sensor/transponder and system with an antenna multiplexer (phased antenna array) are revealed. Moreover, impact of the material and electronic technology is also discussed as it substantially influences the process of antenna synthesis and determining operation parameters. As an example, the possibility of manufacturing the flexible antenna in the inkjet technology is considered in the discussion.

The proposed ideas contribute significantly to the development of automatic identification. On their basis, the authors point out the third stage of RFID progress in which the transponders provide not only details about marked objects but also extended variable data gathered from surroundings by built-in sensors of different physical quantities. Moreover, the transponders are developed toward the capability of being powered from the electromagnetic field of common radio communication systems.

In order to achieve this level of research, some special software tools (e.g., *JankoRFIDchip'UHF*, *JankoRFIDmuxHF*, *NmAntPat*, *RFID(UHF)SysAntPat*) had to be elaborated in different kinds of design environments (e.g., Mathcad, Mentor Graphics HyperLynx 3D EM, LabView, uVision). Thanks to them, researchers could effectively conduct investigations on antenna synthesis, radio wave propagation phenomenon, system simulations, radiation pattern determinations, and protocol parameter modifications in both newly developed and approved standards and so on.

In the course of research, each time it was assumed that it is necessary to achieve essential utility values. Therefore, the published results were positively confirmed experimentally, and then, practical applications were found in industry, institutions and other places where automated systems were implemented. The special untypical investigation stands were prepared for carrying out the research tasks in the authors' laboratories.

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Author details

Piotr Jankowski-Mihułowicz* and Mariusz Węglarski

*Address all correspondence to: pjanko@prz.edu.pl

Department of Electronic and Telecommunications Systems, Rzeszów University of Technology, Poland, Rzeszów, Poland

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