Efficiency Problem of FMCG Identification in HF RFID System with Multiplexed Antennas for Commercial Refrigerator

Piotr Jankowski-Mihułowicz[1](✉), Mariusz Węglarski[1], Wojciech Lichoń[2], and Marcin Pilarz[2]

[1] Department of Electronic and Telecommunications Systems, Rzeszow University of Technology, Pola 2, 35-959 Rzeszow, Poland
{pjanko,wmar}@prz.edu.pl

[2] Talkin Things, Pulawska 182, 02-670 Warsaw, Poland
{wojciech.lichon,marcin.pilarz}@talkinthings.com

Abstract. The overriding goal of the research discussed in the article is to propose an RFID system with the set of multiplexed RWD antennas that could be implemented in a commercial refrigerator. The need to solve this type of a problem has been reported by the one of the authors' partner from the industry. The main assumptions for designing the demonstration system consist in the possibility of obtaining 100% efficiency for the identification of electronically marked bottles with beverages as well as lack of significant interferences in the construction of the refrigerator that could disturb the operating and maintaining conditions. According to these requirements and meeting the partner's needs and expectations, several configurations of the set of multiplexed RWD antennas have been designed, simulated and examined on the experimental stand in the authors' laboratory. On the basis of obtained results the conclusions have been drawn regarding the construction of the RFID system, its implementation in the commercial refrigerators and suggestions for structural changes in the devices at manufacturing process. In addition, the usefulness of the proposed system should be considered in a broader context since the transponders applied to the bottles could be used in the whole life cycle of a FMCG product (production, logistics, marketing services, recycling and others).

Keywords: RFID · Read/write devices · Multiplexed antennas Refrigerator

1 Introduction

Automation of object identification processes is an important factor that leads to improvements of economic activity in the logistics, industry, trade, transport and other various socio-economic areas. These changes are especially visible in the scope of intelligent systems, which operation is covered by the current trends in Internet of Things (IoT) or automation and data exchange in manufacturing technologies (Industry 4.0) [1, 2]. Nowadays, the radio frequency identification (RFID) technology is more and more often used in this kind of advanced developments [3] and its usability is

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confirmed by growing number of practical implementations [4, 5]. It results from availability of system devices on the market and also forecast in terms of their applicability within the next years [6]. On the other hand, better recognition of the essence pertinent to the operation of these devices as well as methods of determining their parameters confirm the statement in technological terms [7].

The problem presented in this paper is inscribed in the conception of IoT that is dedicated for the fast moving consumer goods (FMCG). According to this idea, commonly used bar codes will be replaced by RFID transponders in the nearest future, and the electronic product code (EPC) defined by the EPCglobal Tag Data Standard is dedicated for these aims [8]. The development works are conducted to ensure that automatic identification will be effectively and smoothly applied to the FMGC in the supply chain management [9].

The need to conduct the presented research and development works has been announced by one of the authors' partners active in the FMCG industry. The problem has been connected with selecting appropriate RFID transponders operating in various frequency bands (HF or UHF) as well as practical methods of dealing with such kind of tasks. It is especially important in the scope of automation effectiveness when a whole life cycle of a FMCG product is taken into consideration (production, logistics, marketing services, recycling and others). The works related to solving this issue have been divided into stages and have been realized under the cooperation between FMCG industry partners as well as the Department of Electronic and Telecommunications Systems (DETS) in Rzeszow University of Technology (RUT) and Talkin Things Company. Although both HF and UHF systems can be implemented in the solution under development, the first one is used in the elaborated demonstrator due to the requirements set by the industrial partner.

The overriding goal of the stage discussed in this article is to propose a set of multiplexed RWD antennas dedicated to a commercial refrigerator. The possibility of obtaining 100% efficiency for identification of electronically marked bottles with beverages is assumed for the demonstration RFID system. A remote automatic inventory of the objects inside the refrigerator can be performed by means of such a system in the nearest future. Further, sales reports and orders can be generated and directed to a distribution center of desired FMCG products.

The problem of RFID system implementation in refrigerators can be encountered in the subject literature. It is considered for example in aspects of specialized medical implementations (location based blood bag management [10], medication monitoring [11, 12], and other intelligent systems with refrigerator [13]) but also some publications refer to industrial applications (e.g. traceability system of milk samples [14]) as well as to household equipment (e.g. IoT refrigerator at smart home [15–20]). Most of these cases, however, concern the manual registration of electronically marked products in an RFID system (the single RFID system). The solution presented by the authors is unheard of in the subject technology. It is based on an automatic recognition of a large number of electronically marked objects (the anti-collision RFID system) that additionally can be located in a large space. The authors' concept of determining the three-dimensional interrogation zone (IZ) by using the Monte Carlo method in inductively coupled anti-collision RFID systems is applied in the solution [21].

2 HF RFID System with Multiplexed Antennas

A typical single or anti-collision RFID system consists of transponder(s) and read/write device (RWD) with its antenna(s) [3]. The RWD connected to a computer and their software form a management centre whereas the electronic transponders are used for marking objects.

The HF RFID systems (the carrier frequency of f_0 = 13.56 MHz) operate in the space Ω_{ID} that is characterized by an inhomogeneous magnetic field (expressed by the magnetic field strength H) and strong coupling (expressed by the mutual inductance M) between antennas of the arrangement component (Fig. 1). The inhomogeneous magnetic field generated in the RWD antenna vicinity is a medium for both energy transfer and wireless communication. The communication mechanisms in the HF band are implemented in adequate protocols (typically ISO/IEC 14443, 15693, 18000-3).

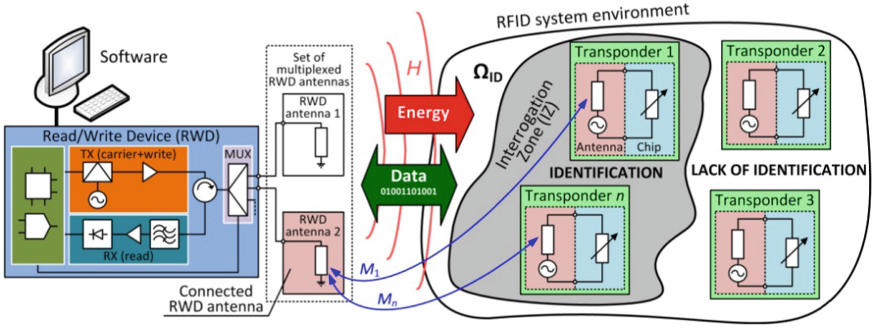

Fig. 1. Anti-collision HF RFID system with multiplexed antennas

The communication process can be carried out only when transponders are in the interrogation zone. It means that the operational capability of RFID systems is characterized by the IZ, which covers problems of energy and communication activity with regards to a specified hardware and software configuration. It also determines and comprehensively describes possibilities of an RFID system application in desirable automated processes.

The effectiveness of the anti-collision RFID system is defined on the basis of the IZ synthesis for a group of n-transponders which are located in the space Ω_{ID}, and for a given automatic identification process (for example objects that are localized in a commercial refrigerator). The interrogation zone is determined for an assumed efficiency of identification η_{ID}:

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

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

From a practical point of view, the IZ should be as large as possible regardless of the variable location/orientation of activated transponders. However in the RFID system with only one RWD antenna, it is not possible to identify all transponders at any point in the space Ω_{ID}. The problem stems from the fact that energy can be conveyed from the read/write device to transponders only on a limited distance [22]. The energy is not transferred (like in a far-field region) but stored in an inhomogeneous magnetic field (near-field region). At the present stage of knowledge, it is the main reason why practical implementations of anti-collision identification are restrained.

In the HF RFID systems, the wavelength λ is about 22 m for the carrier frequency of f_0 = 13.56 MHz. Therefore, the RWD antennas are made in a form of loop (typically as a square [23], rectangle [24], circle [25] or other polygons [26]), which is small in relation to λ. The primary way to enlarge the size of interrogation zone consists in conveying more energy to transponders that are freely deployed and oriented in the space Ω_{ID}. The greatest flexibility in developing RFID applications and shaping the IZ space can be achieved by using the system in which a multiplexer (MUX) and more than one RWD antenna is applied [21]. So, the different configurations of multiplexed RWD antennas are considered in this paper in order to present the described idea of FMCG identification in a commercial refrigerator.

3 Research Problem

The demonstration RFID system under test is build on the base of glass door merchandiser (single swing glass door refrigerator with hydrocarbon refrigerant and LED lighting from the True Food Service Equipment, model GDM-26-LD [27]). This kind of device is widely used in bars, restaurants, retail shops and markets (Fig. 2).

Fig. 2. GDM-26-LD

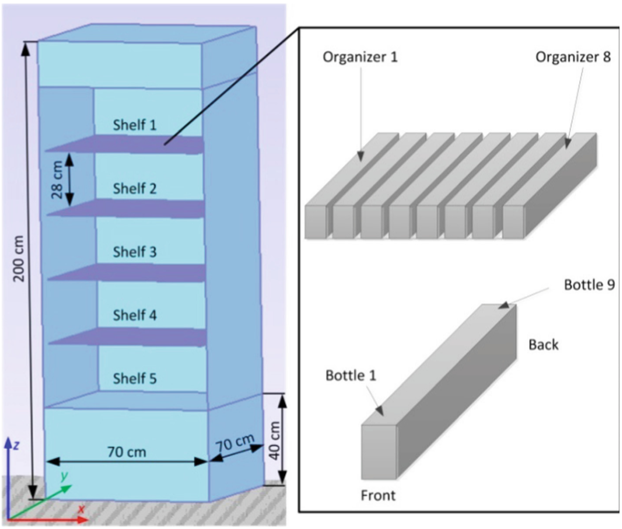

Fig. 3. Refrigerator model with element numbering

The inside of this commercial refrigerator is made of metal: the side walls and the upper part – white-painted aluminum sheet, the bottom – stainless steel sheet. The casing is made of plastic (laminated vinyl), the appearance of which can be adapted to the customer's requirements. The space between the internal and external walls is filled with a polyurethane foam seal (Ecomate). The tested model of the refrigerator has 5 shelves manufactured from metal wire covered with a layer of white plastic.

A selected batch of 360 bottles is the exemplary research object in the complete RFID identification process on the demonstration stand. Each of the 500 ml bottles is factory-filled with liquid. They are placed in the same orientation in plastic gravity feed organizers that are dedicated equipment of GDM-26-LD. It is possible to place maximum of eight 9-bottle cassettes on one shelf, hence, for the whole refrigerator, it gives the number of 360 objects intended for the process of anti-collision RFID identification (Fig. 3).

All of the bottles in the demonstration system under consideration are marked with HF RFID transponders. The NXP I-CODE SLIX chip that is used in the selected class of electronic tags (model SL2 S2002/SL2 S2102) operates in accordance with the ISO/IEC 15693 protocol (Fig. 4). The transponders are placed in the middle of the bottle labels. Extra paper stickers with information about location in the refrigerator as well as with the last 3 bytes of the unique identifier (UID of RFID transponders) are attached to all of the bottles. The coordinates of an object in the space are described by the shelf number (P1…5), the cassette number (K1…8) and the position of a bottle in it (B1…9). The use of these stickers provides the opportunity to determine the location of unidentified bottles during the experimental research. It should be emphasized, that other standards of RFID systems could be used in the glass door merchandiser with regards to requirements of a target application or a desired period of life cycle of FMCG products. Semi-passive or passive transponders operating with ISO/IEC 14443 protocol of the HF band or ISO/IEC 18000-63 for the UHF band as well as dual-band HF + UHF models (Fig. 5) and other contemporary RFID devices are considered in other research projects conducted in cooperation with authors' partners from the industry.

The realized preparatory activities constitute the basis for conducting research and development works. Furthermore, the method developed in [21] is implemented in application experiments what confirms its usefulness in this scope. Various configurations of multiplexed RWD antennas dedicated to RFID systems of the HF band are subjects of the conducted analysis. The designs that are the most perspective from the practical point of view are presented in Sect 4. Even though, they are considered for a representative case of one shelf, the system for entire refrigerator can be elaborated by

Fig. 4. Selected organizer with electronically marked bottles

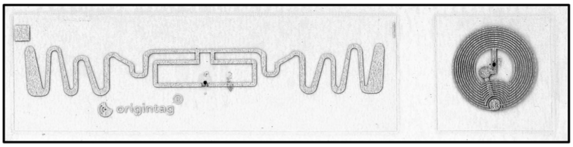

Fig. 5. POIR.01.01.01-00-0226/15 hybrid RFID transponder

increasing number of RWD multiplexer inputs and duplicating the solution for subsequent shelves. The numerical model EMCoS Antenna Virtual Lab is prepared for each configuration. Calculations of the current distribution and the inhomogeneous magnetic field are made using the TriD solver based on the Method of Moments (MoM). The necessity to carry out such extensive preparatory and calculation steps was forced by the diversity of materials from which the refrigerator is made. Moreover, the potential modification of the refrigerator structure is analyzed in the research works, because the components of RFID systems are considered to be possible for future integration with construction of the device. The positive results of numerical calculations yield the design brief for preparing and assembling the set of multiplexed RWD antennas, and then for conducting tests in a demonstration RFID system. Although demonstration installation was tested for 100% identification efficiency, the proper configuration set of multiplexed RWD antennas that would enable periodic removal of the shelves was also searched for. This is caused by additional hygienic-sanitary requirements that have to be met during the operational maintenance of the refrigerator inside. Equipment and software of Feig company were used in this stage of the works.

4 Results

4.1 Gate Type of Multiplexed RWD Antennas

Model. According to the specified assumptions, the space between shelves of the glass door merchandiser is the most prospective location for the set of multiplexed RWD antennas. The basic conception consists of four opposite antennas that form two orthogonal gates (Fig. 6). In such a configuration, each pair of antennas is dedicated to identify bottles with selected orientation in which the central plane of label is set in parallel to the loop arrangement. Since there is no need to interfere in the construction of the commercial refrigerator when installing the antennas, it should be considered as a crucial advantage for the proposed solution. It should be also noted that the possibility of removing the shelves during the devices operation is retained.

Two numerical models (for Gate 1: antenna 1 and 2, for Gate 2: antenna 3 and 4) are considered for the proposed concept. In the first case (Gate 1), the loops are moved 10 cm from the door and from the rear wall of the refrigerator whereas in the second case (Gate 2 v.1) there is the 1 cm separation of antennas from metal walls. The components of the arrangement are modeled as loops made of a coaxial cable with a core diameter of 0.3 mm to which a 50 Ω current source with amplitude of 1 A is connected.

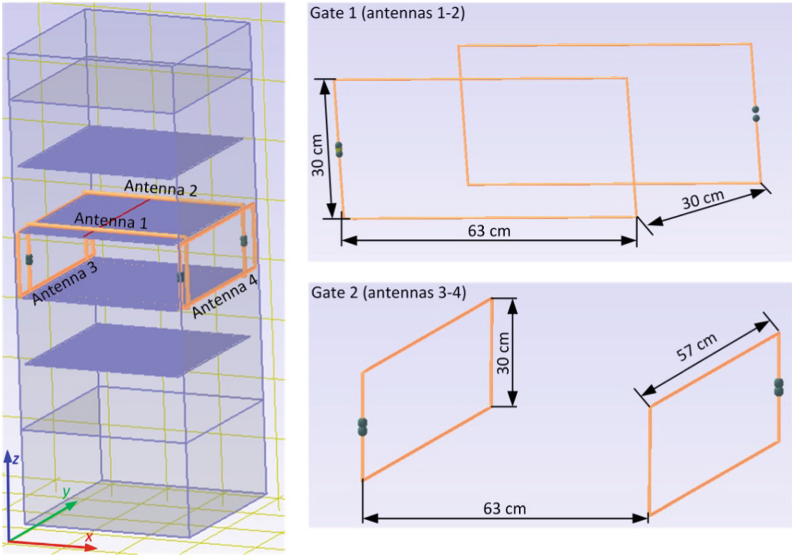

Fig. 6. Model of gate type antennas

Numerical Calculation. In the next step, the magnetic field strength distribution inside the refrigerator is determined with respect to the *x*-*z* plane for the Gate 1 (Fig. 7) and *y*-*z* for the Gate 2 (Fig. 8). The locations where magnetic field strength may be sufficient to supply passive RFID transponders properly ($H > H_{min}$) are estimated on the basis of the obtained results. It should be noted that the data are analyzed qualitatively. Such an assessment is caused by a significant simplification of the refrigerator numerical model. But, it allows for efficient calculation and justifies decision to move on to the experiment phase in the demonstration RFID system.

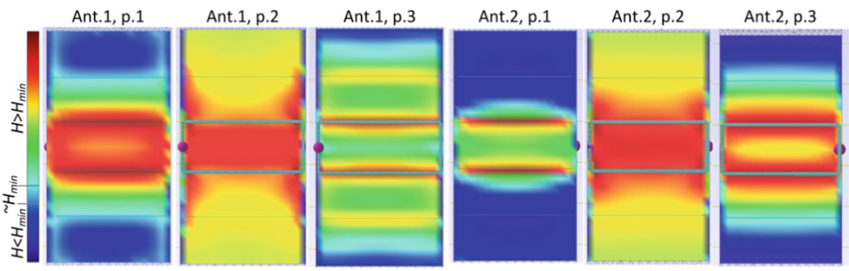

Fig. 7. Total magnetic field strength (*x*-*z* plane, Gate 1, p. 1–5 cm from the door, p. 2 – middle, p. 3–5 cm from the rear wall)

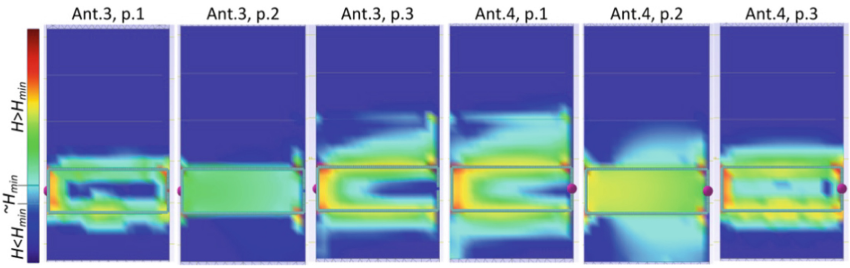

Fig. 8. Total magnetic field strength (*y-z* plane, Gate 2 v.1, p. 1–5 cm from the left side, p. 2 – middle, p. 3–5 cm from the right side)

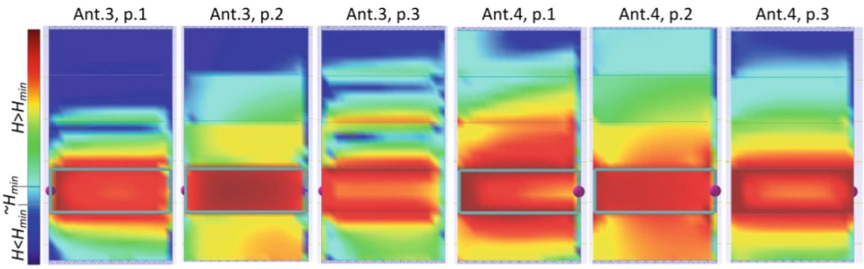

Fig. 9. Total magnetic field strength (*y-z* plane, Gate 2 v.2, p. 1–5 cm from the left side, p. 2 – middle, p. 3–5 cm from the right side)

The magnetic field intensity distribution is determined for the carrier frequency of f_0 = 13.56 MHz, and the calculations are carried out for selected planes related to the door and side walls of the refrigerator. For the antennas located parallel to the door (Fig. 7), the magnetic field strength should be sufficient to supply passive RFID transponders. In the case of the second pair (Fig. 8), eddy currents are generated in the side walls which make it impossible to implement an object identification process correctly – the value of magnetic field intensity is lower than H_{min} for most locations in the considered space.

The identification of objects oriented perpendicular to the door can be implemented in two other ways that should lead to improvement the second case. The first one consists in increasing the separation of antennas 3 and 4 from the metal walls of the refrigerator. As a result, the induction of eddy currents is significantly lower. Hence, it reduces the impact of this phenomenon on impedance parameters of the antennas. The limitation of the exhibition space and the possibility of damaging antennas during maintaining the device (e.g. when pushing/pulling out a bottle with a drink) are significant disadvantages of the proposed solution. The second way involves the necessity to make changes in the construction of the glass door merchandiser. For example, if the metal side walls were replaced with plastic sheets, it would resolve all the problems with the antenna disruption issue.

New numerical models for improved constructions of the Gate 2 are proposed to fulfill above mentioned remarks. The separation of 10 cm from metal walls of the refrigerator to the 3rd and 4th antenna is taken into account in the Gate 2 v.2 version

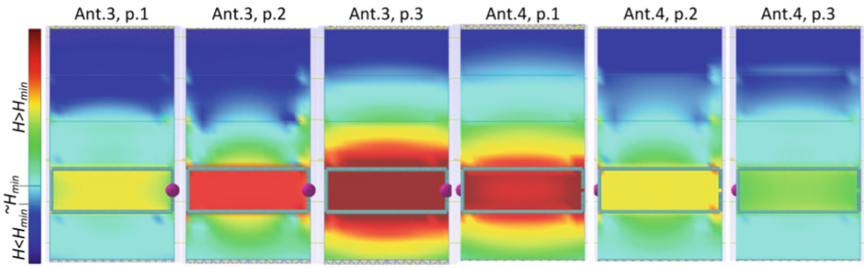

Fig. 10. Total magnetic field strength (y-z plane, Gate 2 v.3, p. 1–5 cm from the left side, p. 2 – middle, p. 3–5 cm from the right side)

(Fig. 9). It can be noticed when comparing obtained results with the Gate 2 v.1 (previously described as Gate 2) case (1 cm separation – Fig. 8) that the space – in which transponders are supplying with sufficient power – is enlarged significantly. The next modification consists in changing the glass door merchandiser construction and is described as the third version of the Gate 2 model (Gate 2 v.3). A new type of materials that are commonly used to build side walls of some commercial refrigerators is introduced in the model (Fig. 10). Plastic planes with a thickness of 1 cm and relative permittivity $\varepsilon_r = 2.3$ are analyzed in this case. Although the antennas are placed as in the Gate 2 v.1 model (Fig. 8), it can be noticed that the dimensions of the space where the passive RFID transponders are powered properly is also increased significantly. Hence, the modification of the glass door merchandiser construction is the best choice in the discussed implementation of the RWD antenna set. It guarantees the possibility of identifying bottles in any location and orientation.

Experiment. The experimental verification of the multiple identification process was the goal of this research stage. It was carried out in the prepared demonstration system based on the commercial glass door merchandiser. A set of multiplexed RWD antennas were installed in the refrigerator according to the model Gate 1/Gate 2 v.1. The experimental works were divided into two steps. In the first one, the arrangement of the 1st and 2nd antenna – Gate 1 that is dedicated to identify objects with labels oriented towards the door was subjected to the verification. In the second step, 3rd and 4th antenna – Gate 2 that is responsible for identifying orthogonally oriented bottles was tested.

The antenna loops are made of coaxial cable RG-58 in plastic cable raceways constituting supporting construction (Fig. 11). The vertical wires are run parallel to metal shelf mounting rails while the horizontal wires – above and below surfaces of the shelves. In this way, unused parts of the internal space are occupied while the exhibition area in the refrigerator is not reduced at all. The terminals of the each loop are attached to a dynamic antenna tuner (FEIG ID ISC.DAT). This device with automated matching circuits is designed for tuning RFID antennas with an operating frequency of 13.56 MHz. It enables to match antennas to impedance of 50 Ω with the use of dedicated control software tool. All matching circuits are connected by coaxial cables to the selected ports of the 8-channel multiplexer (FEIG ID ISC.ANT.MUX). This device also provides power and control commands to the dynamic antenna tuner.

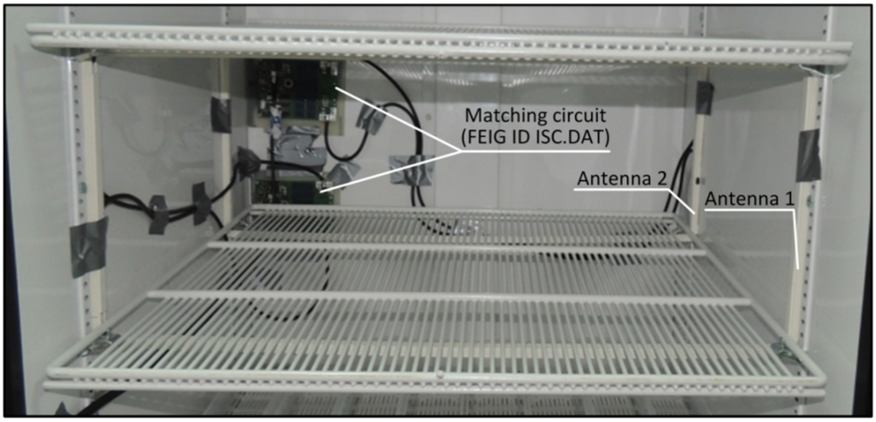

Fig. 11. Gate 1 of multiplexed RWD antennas

The multiplexer is connected to the antenna port in the ISO/IEC 15693 long range RWD module (FEIG ID ISC.LRM2500-B). The RWD module provides output power equal 4 W and is controlled by ID ISOStart V09.09.10 software. The read/write device is set in Host Mode during the measurement procedure, what enables to send orders manually.

RFID transponders attached to the bottles are directed towards the door (Fig. 12a) or a side wall of the refrigerator (Fig. 12b). Conducted experimental tests allow to verify the RFID system's ability to identify electronically marked objects. The procedure consisted in implementation of the inventory round as well as the localization of the recognized objects on the basis of UID. The obtained results are summarized in Tables 1, 2, 3, 4, 5 and 6. The OK means UID recognition and NOK – lack of object identification in the inventory round.

The case of RFID transponders directed towards the door is verified in the first step (Tables 1, 2 and 3). The inventory round is carried out during the tests separately for the each antenna of the Gate 1 and results are presented in Table 1 (for the 1st antenna) and 2 (for the 2nd antenna). The sum of the cases from the switched antennas is collected in Table 3. It can be seen that all objects on the test shelf are identified. In addition, partial areas of correct identification obtained from the individual antennas overlap themselves. It proves the reliability of the proposed solution.

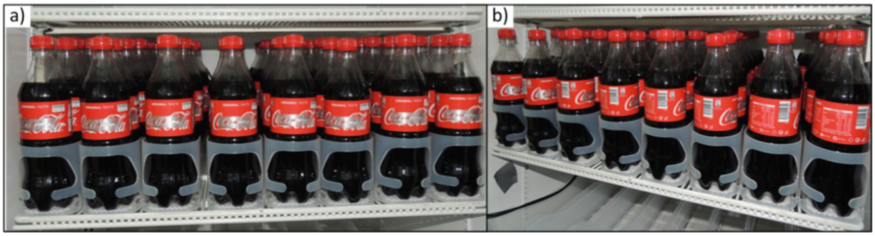

Fig. 12. Electronically marked bottles with transponders directed towards: (a) door, (b) side walls of the refrigerator

Table 1. Results for labels oriented towards the refrigerator door (antenna 1)

	K1	K2	K3	K4	K5	K6	K7	K8
B1	OK	OK	OK	OK	OK	OK	OK	OK
B2	OK	OK	OK	OK	OK	OK	OK	OK
B3	OK	OK	OK	OK	OK	OK	OK	OK
B4	OK	OK	OK	OK	OK	OK	OK	OK
B5	OK	OK	OK	OK	OK	OK	OK	OK
B6	OK	OK	OK	OK	OK	OK	OK	OK
B7	OK	OK	OK	OK	OK	OK	OK	OK
B8	OK	OK	OK	OK	OK	OK	OK	OK
B9	OK	OK	OK	NOK	NOK	OK	OK	OK

Table 2. Results for labels oriented towards the refrigerator door (antenna 2)

	K1	K2	K3	K4	K5	K6	K7	K8
B1	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B2	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B3	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B4	NOK	OK	NOK	OK	NOK	OK	OK	OK
B5	OK	OK	NOK	OK	NOK	OK	OK	OK
B6	OK	OK	OK	OK	OK	OK	OK	OK
B7	OK	OK	OK	OK	OK	OK	OK	OK
B8	OK	OK	OK	OK	OK	OK	OK	OK
B9	OK	OK	OK	OK	OK	OK	OK	OK

Table 3. Summary results for labels oriented towards the refrigerator door (Gate 1)

	K1	K2	K3	K4	K5	K6	K7	K8
B1	OK	OK	OK	OK	OK	OK	OK	OK
B2	OK	OK	OK	OK	OK	OK	OK	OK
B3	OK	OK	OK	OK	OK	OK	OK	OK
B4	OK	OK	OK	OK	OK	OK	OK	OK
B5	OK	OK	OK	OK	OK	OK	OK	OK
B6	OK	OK	OK	OK	OK	OK	OK	OK
B7	OK	OK	OK	OK	OK	OK	OK	OK
B8	OK	OK	OK	OK	OK	OK	OK	OK
B9	OK	OK	OK	OK	OK	OK	OK	OK

The operation of the set of multiplexed RWD antenna (in the range of the Gate 1) is verified in a similar way for the second spatial orientation of bottles. In this case RFID transponders are located towards the side wall of the refrigerator. As before, the inventory round is carried out separately for the each antenna (Table 4 and 5). The results obtained for this orientation are much worse than in the previous study. This is due to the fact that energy of the magnetic field produced by the RWD antennas is less

Table 4. Results for labels oriented towards the side wall (antenna 1)

	K1	K2	K3	K4	K5	K6	K7	K8
B1	NOK	NOK	OK	OK	OK	OK	OK	OK
B2	OK	NOK	OK	NOK	NOK	NOK	NOK	NOK
B3	NOK	OK	OK	NOK	OK	NOK	NOK	NOK
B4	NOK	NOK	NOK	NOK	NOK	OK	OK	OK
B5	NOK	NOK	OK	NOK	OK	NOK	NOK	NOK
B6	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B7	OK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B8	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B9	OK	NOK	NOK	NOK	NOK	NOK	NOK	NOK

Table 5. Results for labels oriented towards the side wall (antenna 2)

	K1	K2	K3	K4	K5	K6	K7	K8
B1	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B2	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B3	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B4	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B5	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B6	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B7	NOK	NOK	OK	NOK	NOK	NOK	NOK	NOK
B8	NOK	NOK	NOK	OK	NOK	OK	OK	OK
B9	OK	OK	NOK	NOK	NOK	NOK	OK	NOK

Table 6. Summary results for labels oriented towards the side wall (Gate 1)

	K1	K2	K3	K4	K5	K6	K7	K8
B1	NOK	NOK	OK	OK	OK	OK	OK	OK
B2	OK	NOK	OK	NOK	NOK	NOK	NOK	NOK
B3	NOK	OK	OK	NOK	OK	NOK	NOK	NOK
B4	NOK	NOK	NOK	NOK	NOK	OK	OK	OK
B5	NOK	NOK	OK	NOK	OK	NOK	NOK	NOK
B6	NOK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B7	OK	NOK	OK	NOK	NOK	NOK	NOK	NOK
B8	NOK	NOK	NOK	OK	NOK	OK	OK	OK
B9	OK	OK	NOK	NOK	NOK	NOK	OK	NOK

absorbed by transponder antennas. Hence, the value of voltage that is induced at the antenna terminals of transponder is not sufficient to power an RFID chip. Only 35% of the electronically marked bottles are identified in the presented case (Table 6).

Studies on the antenna arrangement that is dedicated to recognizing objects with RFID transponders oriented towards the side walls of the refrigerator are planned in the second stage of the experimental works. The 3rd and 4th antenna is made according to assumptions considered in the first model and placed in the close proximity of the side walls. Unfortunately, it is not possible to tune these antennas to the impedance of 50 Ω by using the selected automated matching circuits. It is caused by the proximity of the metal components of the refrigerator. It yields the effect of reducing the loop inductance to a level that could no longer be compensated by the elements built into the dynamic antenna tuner (tuning range inductance 0.7–2.5 μH).

It can be stated on the basis of the conducted research that the modification of the refrigerator structure proposed in the Gate 2 v.3 model is compulsory. It is a factor that determines the high efficiency of automated identification of electronically marked objects regardless of the bottle position and orientation in the refrigerator equipped with the discussed set of multiplexed RWD antennas.

4.2 L Type of Multiplexed RWD Antennas

Numerical Model. The new conception is proposed on the basis of previously elaborated solutions. The multiplexed set with two spatial L-shaped antennas is considered in order to simplify the structure of RFID system (Fig. 13). It is assumed that despite using a reduced number of necessary RFID devices the improved construction is enough to enable recognizing variously oriented objects.

The numerical model of multiplexed set with the L type RWD antennas is developed on the basis of the proposed conception. Specific conditions for integrating the new construction with the glass door merchandiser are also taken into account. The model includes the previously discussed parameters of structural materials and antenna power supply.

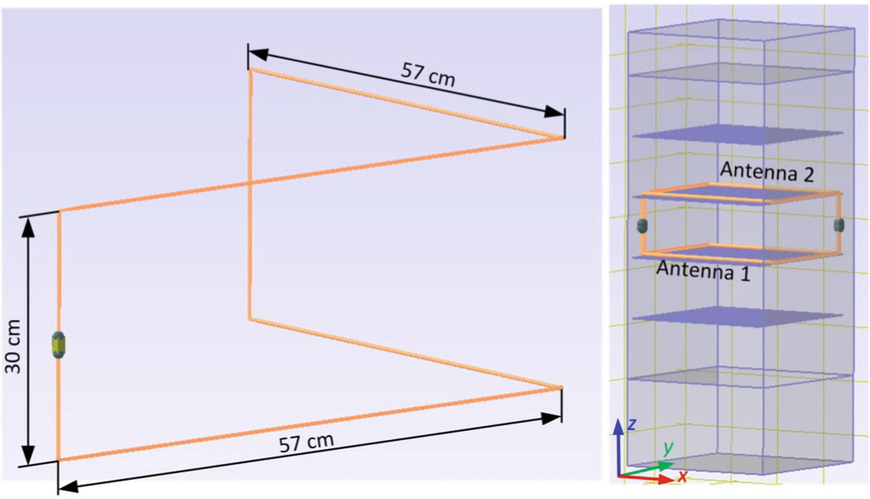

Fig. 13. Model of set with L type antennas

Numerical Calculation. As it is described in the previous models, the magnetic field strength distribution is determined for the carrier frequency of f_0 = 13.56 MHz. Due to the shape of the antennas, calculations are carried out for the *x*-*z* (Fig. 14) and *y*-*z* plane (Fig. 15).

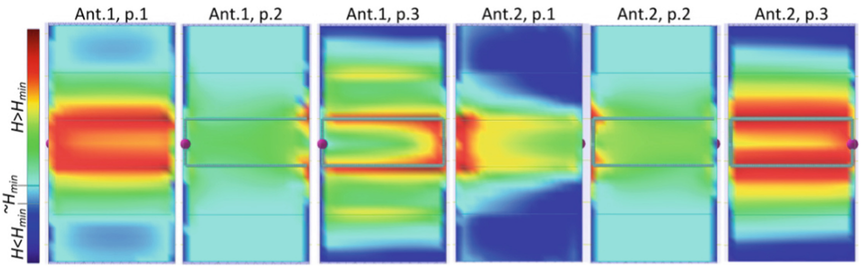

Fig. 14. Total magnetic field strength (*x-z* plane, L v.1, p. 1–5 cm from the door, p. 2 – middle, p. 3–5 cm from the rear wall)

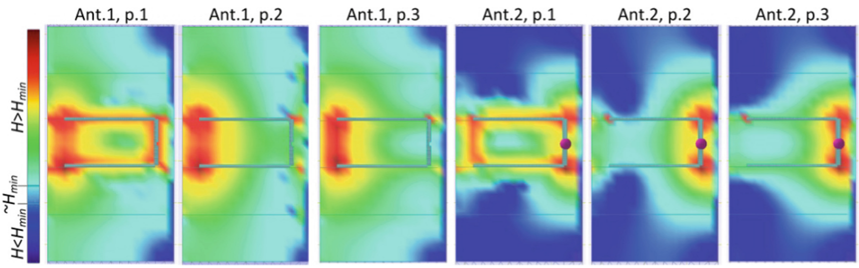

Fig. 15. Total magnetic field strength (*y-z* plane, L v.1, p. 1–5 cm from the left side, p. 2 – middle, p. 3–5 cm from the right side)

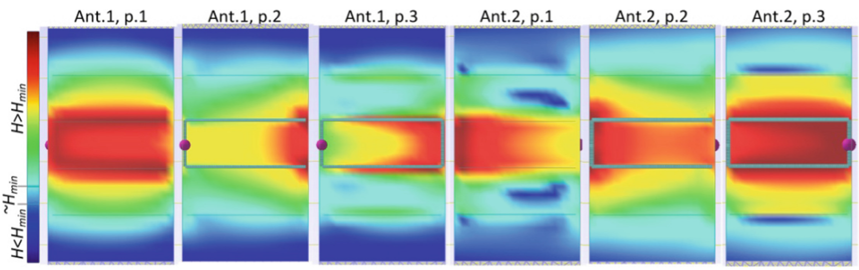

Fig. 16. Total magnetic field strength (*x-z* plane, L v.2, p. 1–5 cm from the door, p. 2– middle, p. 3–5 cm from the rear wall)

The analysis of calculations shows that it is possible to recognize the objects with the transponders that are oriented in *x-z* plane (parallel to the door of the refrigerator). However, it should be noted that there are areas on the shelf where transponders may remain without power. In the case of *y-z* plane, object identification is only possible in the close proximity to the RWD antenna. It should be noticed that changes in refrigerator construction could improve the RFID system also in this conception. If metal elements were replaced with plastics the identification effectiveness could be increased for all orientations of market objects. Considerations of the spatial separation between antennas and metal walls are not practical here due to the operational aspects of the glass door merchandiser.

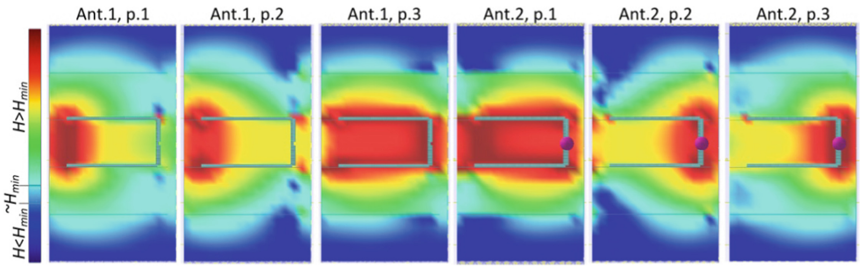

Fig. 17. Total magnetic field strength (*y*-*z* plane, L v.2, p. 1–5 cm from the left side, p. 2 – middle, p. 3–5 cm from the right side)

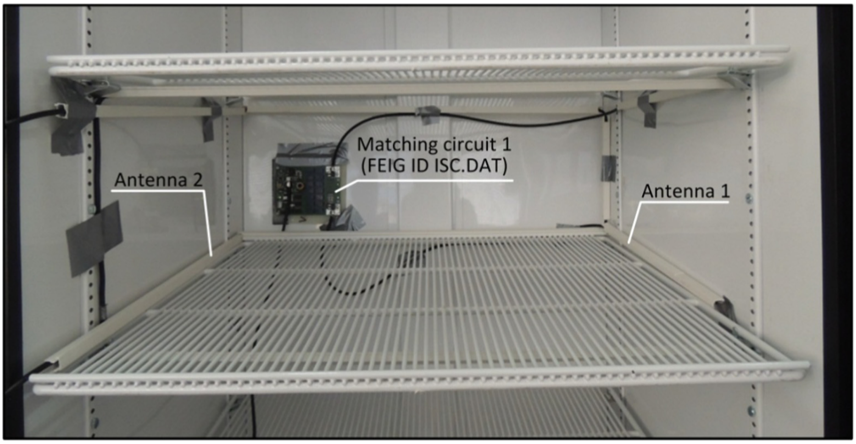

Fig. 18. L type of multiplexed RWD antennas

The above mentioned observations are the basis for developing the next numerical model (L v.2) with some modifications of the refrigerator construction. Instead of metal side walls, a casing made of plastic is considered. Hence the walls are modeled with a plane of 1 cm thickness and relative permittivity of ε_r = 2.3. The calculation results are compiled for the *x*-*z* (Fig. 16) and *y*-*z* plane (Fig. 17).

A significant increase in the geometry of the area in which it is possible to supply passive RFID transponders with energy is noticeable in the calculation results. It should be noted, however, that despite the modification of the refrigerator construction, the distribution of the magnetic field around the antenna loop is not as homogeneous as it is in the concept of Gate 2 v.2.

Experiment. The effectiveness of identification process with regards to the new model was also verified by experimental works. Multiple objects were subjected to identification processes in the modified demonstration system. In the first approach, the antenna arrangement was made in accordance with the model shown in Fig. 13. Unfortunately, an automatic impedance matching in such a system was incorrect despite many experimental attempts. The inner side of single swing glass door is covered with a transparent antibacterial layer of metal and it was identified as the reason of the troubles. It strongly affected the antenna impedance. Hence, one of the 1st antenna's arms was shortened for solving the problem. As a result, the loop was separated from the fridge door (Fig. 18). Since the material parameters of the antibacterial layer are not designated and the numerical calculations have only qualitative nature it was decided not to prepare the next version of the model for these changes.

Table 7. Summary results for labels oriented towards the refrigerator door

	K1	K2	K3	K4	K5	K6	K7	K8
B1	OK	OK	OK	OK	OK	OK	OK	OK
B2	OK	OK	OK	OK	OK	OK	OK	OK
B3	OK	OK	OK	OK	OK	OK	OK	OK
B4	OK	OK	OK	OK	OK	OK	OK	OK
B5	OK	OK	OK	OK	OK	OK	OK	OK
B6	OK	OK	OK	OK	OK	OK	OK	OK
B7	OK	OK	OK	OK	OK	OK	OK	OK
B8	NOK	NOK	NOK	OK	OK	OK	OK	NOK
B9	NOK	OK	NOK	OK	OK	OK	OK	OK

Table 8. Summary results for labels oriented towards the side wall

	K1	K2	K3	K4	K5	K6	K7	K8
B1	OK	OK	OK	NOK	NOK	NOK	NOK	NOK
B2	OK	OK	OK	NOK	OK	NOK	NOK	NOK
B3	OK	OK	OK	NOK	OK	NOK	OK	NOK
B4	NOK	NOK	NOK	NOK	OK	OK	OK	OK
B5	NOK	NOK	OK	NOK	NOK	NOK	OK	NOK
B6	NOK	NOK	OK	NOK	NOK	NOK	NOK	NOK
B7	OK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B8	OK	OK	OK	NOK	NOK	NOK	NOK	NOK
B9	OK	OK	OK	NOK	NOK	NOK	OK	OK

As previously, the inventory procedure was carried out separately for each of the antennas and summary results of experiments for different orientation of transponders are compiled in Table 7 and 8. As it was expected, the best identification efficiency (about 92%) is obtained for the case in which RFID transponders are directed towards the door of the refrigerator. The effectiveness at orthogonal spatial orientation of objects is significantly worse and it is equal only 39%. These results coincide with their numerical representation.

4.3 X Type of Multiplexed RWD Antennas

Numerical Model. An arrangement consisting of two mutually intersecting antenna loops is the last of the considered configuration (Fig. 19). It is assumed once again that despite using a reduced number of necessary RFID devices the improved construction is enough to enable recognizing variously oriented objects.

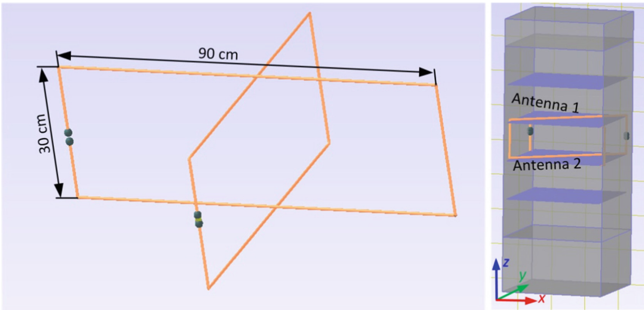

Fig. 19. Model of X type antennas

The numerical model of multiplexed set with the X type RWD antennas is developed on the basis of the proposed conception. Specific conditions for integrating the new construction with the glass door merchandiser are also taken into account. The model includes the previously discussed parameters of structural materials and antenna power supply.

Numerical Calculation. As it is described in the previous models, the magnetic field strength distribution is determined for the carrier frequency of f_0 = 13.56 MHz. Due to the shape of the antennas, calculations are carried out for the *x*-*z* (Fig. 20) and *y*-*z* plane (Fig. 21).

It can be concluded on the basis of obtained data that it should be possible in the case under consideration to identify any objects inside the modeled refrigerator regardless of orientations of transponders. According to predictions, the magnetic field

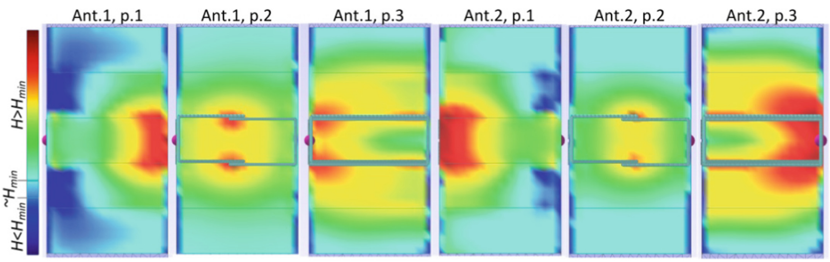

Fig. 20. Total magnetic field strength (*x*-*z* plane, p. 1–5 cm from the door, p. 2 – middle, p. 3–5 cm from the rear wall)

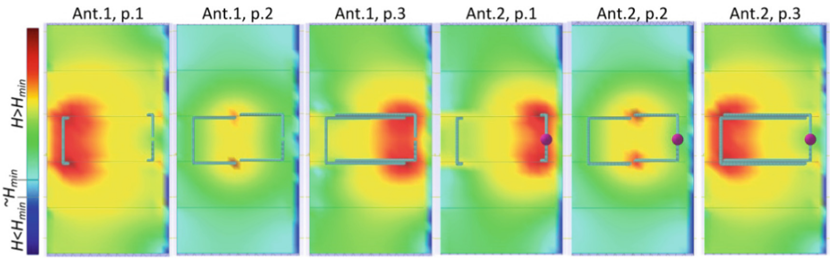

Fig. 21. Total magnetic field strength (*y-z* plane, p. 1–5 cm from the door, p. 2 – middle, p. 3–5 cm from the rear wall)

strength has the highest values in the immediate vicinity of the antenna loop. Moreover, it does not significantly decrease inside the entire shelf.

Experiment. The effectiveness of identification process with regards to the last model was also verified by experimental works. Multiple objects were subjected to the identification processes in the modified demonstration system (Fig. 22).

Fig. 22. Experimental stand of multiplexed set with X-type antennas and group of marked bottles in considered case of RFID process

Table 9. Summary results for labels oriented towards the refrigerator door

	K1	K2	K3	K4	K5	K6	K7	K8
B1	OK	OK	OK	OK	OK	OK	OK	OK
B2	OK	OK	OK	OK	OK	OK	OK	OK
B3	OK	OK	OK	OK	OK	OK	OK	OK
B4	OK	NOK	OK	OK	OK	OK	OK	OK
B5	OK	OK	OK	NOK	OK	OK	OK	OK
B6	OK	OK	OK	OK	OK	OK	OK	NOK
B7	OK	OK	OK	OK	OK	OK	OK	OK
B8	OK	OK	OK	OK	OK	OK	OK	OK
B9	OK	OK	OK	OK	OK	OK	OK	OK

Table 10. Summary results for labels oriented towards the side wall

	K1	K2	K3	K4	K5	K6	K7	K8
B1	OK	NOK	NOK	NOK	NOK	NOK	NOK	NOK
B2	OK	OK	NOK	OK	NOK	NOK	NOK	NOK
B3	OK	OK	OK	OK	OK	OK	OK	NOK
B4	OK	OK	OK	OK	OK	OK	NOK	NOK
B5	OK	OK	OK	OK	OK	OK	OK	NOK
B6	OK	OK	OK	OK	OK	OK	OK	NOK
B7	OK	OK	OK	OK	OK	OK	OK	NOK
B8	OK	OK	OK	OK	OK	OK	OK	NOK
B9	OK	OK	OK	OK	OK	OK	OK	OK

As before, the inventory procedure was carried out separately for each of the antennas and summary results of experiments for different orientations of transponders are compiled in Table 9 and 10. The identification efficiency is equal to 96% for the *x*-*z* plane and 74% for the *y*-*z* plane.

It can be concluded on the basis of the conducted research that the X type of multiplexed RWD antennas is characterized by high application potential. However, the construction of the glass door merchandiser would need to be changed significantly. So, the practical implementation of this solution in contemporary commercial refrigerators is not achievable, because one of the basic requirements is not met – it has to be possible to remove the shelves from the device.

5 Conclusion

The implementation of RFID system in the glass door merchandiser was the aim of the conducted research. The possibility to identify any oriented electronically marked bottles with only one transponder attached to the central point of product label was considered in this paper. Taking into account economic and marketing benefits it does seem to be rational to equip commercial refrigerators with the complete set of multiplexed antennas regardless of the overall construction of the devices that are commonly used in the FMCG distributors. Nevertheless the necessity to complicate the hardware part of the system (increased number of multiplexer inputs and antennas with tuning circuits, the need to use a long range read/write device with higher output power in the transmitter) is one of the identified problems that has to be overcome. Moreover, operating and maintaining requirements (removed shelves, free access to bottles, etc.) of the refrigeration equipment have to be included in a designing solution. On the other hand, the implementation of RFID system for conducting the automated identification process only for one selected orientation of electronically marked bottles is the reasonable application (it meets the industry partner's needs and expectations). However, it is necessary to use an appropriate structural construction of the RWD antenna system. The possibility to use the gate that consists of antennas placed in the space between the shelves confirms the usefulness of such an application. It gives 100% efficiency of identification process (labels oriented towards the refrigerator door) and the shelves can still be removed from the refrigerator. This configuration confirms the requirements of the assumed FMCG identification in a commercial glass door merchandiser specific for the considered application. It should be emphasized that the RFID transponders applied to the bottles can be used in the whole life cycle of a FMCG product (production, logistics, marketing services, recycling and others) for different tasks.

The obtained test results should constitute the initial conditions for the next stage of research and development works. The target construction of the set of multiplexed RWD antennas can be designed taking into account conducted analysis with regards to manufacturing potential, for implementation in a commercial refrigerator. In addition, it can be stated on the basis of the presented results that modification of the device construction is a crucial requirement and important factor for developing RFID applications in this scope. If materials used to build its interior were changed, it could be possible to synthesize an effective antenna system for the RFID identification of electronically marked objects regardless of their location and orientation. And then, although both L and X type of multiplexed RWD antennas is characterized by high application potential and it is possible to reduce the complexity of RFID system by using such an improved construction, the first shape is better choice according to simulation results and manufacturing requirements of integration.

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