From February 2007 *High Frequency Electronics*

Spatially Selective Antenna for Very Close Proximity HF RFID Applications—Part 1

By Boris Y. Tsirline, PhD
Zebra Technologies Corporation

This multi-part article provides background on RFID antenna-transponder interactions, and presents an antenna technique that achieves greater discrimination when reading multiple transponders

This article introduces a novel HF antenna with high spatial selectivity—its performance and functional characteristics are analyzed for two orthogonal alignments of the antenna and the transponder using a simplified mathematical model. This model describes the relationship between the transponder interrogation zone and the Reader RF power, antenna and transponder geometries, and their electrical components.

In order to describe the properties of a transponder in a non-uniform magnetic field an integral parameter is introduced in place of the commonly used transponder activation magnetic field strength. A set of new measurable parameters for characterization of the antenna-transponder combination are introduced. The interaction of a conventional resonant loop antenna with nearby transponders is examined and the antenna's inability to differentiate the targeted transponder from the adjacent transponders is demonstrated.

Introduction

RFID (Radio Frequency Identification) technology, originally developed for automated identification of aircraft and ships as a secondary radar application, has today become a powerful tool in business process automation in many industries. HF RFID (High Frequency RFID) is based on magnetic coupling between the transponder and the antenna and is highly immune to the interferences typical for industrial environments. A great variety of HF RFID applications exist today. By 2006, most of the manufacturing and service industries had adopted this technology, including medication authentication in the pharmaceutical industry, patient identification in the health care industry, product identification and inventory tracking in the retail industry, access restriction for security systems and tickets processing in transportation service. A wide application spectrum spreads from commercial and military to home and entertainment sectors. Recently introduced Near Field Communication (NFC) technology is also based on the magnetic coupling technology [1] and is similar to Contactless Smart Card protocol. This technology opens new applications for the RFID technology, such as automatic payment using cellular phones in close proximity communication as a transaction vehicle.

Three key elements comprise every RFID system: a transceiver (Reader), a transponder, and an antenna. In order to satisfy the growing demands for HF RFID equipment, many vendors offer two of the three—the HF Readers and the transponders [2]. The third element of the system, the antenna, is not often readily available. Although HF magnetic antennas are widely offered for radio broadcasting, transmission sources location finders, and for EMI/RFI measurements, HF RFID antenna selection is limited. While RFID and non-RFID magnetic antennas share common features such as sensitivity to the magnetic component of RF wave and the ability to generate one (in the near field), two principal differences exist.

First, HF RFID antennas activate batteryless transponders by transferring the magnetic field energy to them. Second, antennas maintain the bidirectional data transfer between a Reader and transponders. The transponder data transmission is based on the "Load" modulation technique [3], which enables the Reader to detect an antenna impedance modulation caused by a transponder. Further discussions will assume that a Reader is sensitive enough to assure a reliable transponder interrogation as soon as it gets energized.

RFID magnetic antennas for conventional applications are aimed at activation and identification of multiple transponders at the longest possible range. The goal of the antenna design for such applications is to detect transponders' presence and provide a wide coverage area. Transponders are activated by uniform magnetic fields and the antenna interaction within the interrogation zone is largely independent of their parameters.

Antenna design methodology considerably changes for RFID applications that demand encoding a single, targeted transponder surrounded by others. For these applications the targeted transponder is positioned in very close proximity to the antenna and a specified interrogation region turns out to be comparable with the transponder dimensions. In this situation the antenna-transponder distance is only a small fraction of their sizes—transponders operate in a principally heterogeneous magnetic field and their interaction with an antenna is heavily dependent as much on the distance between them as on their dimensions and mutual alignment.

To be successful in performing an interrogation of only one transponder an antenna should have a feature we can call spatial selectivity (SS). Spatial selectivity is an antenna's ability to communicate with a single transponder, staying within the maximum available RF power from a Reader, and not communicating with neighboring transponders.

Previously proposed solutions to increase an antenna's SS were based on shielding and suppression of magnetic field in adjacent areas. The disadvantage of such an approach is that dimensions of shielding components are greatly dependent on transponder geometry and must be adjusted for every new transponder type. The shielding of adjacent areas is only suitable for RFID applications which use one, exclusive form-factor transponder. For RFID applications working with a variety of transponders, the shielding method inevitably complicates an RFID system, including antenna design.

The scope of this article is to demonstrate another strategy for achieving high SS. This approach is based on an antenna magnetic flux forming technique and a specific antenna-transponder alignment.

The considerations will include:

- Classification of RFID applications and parametric analysis of HF transponders—"RFID Applications Utilizing HF Transponders"
- Implementation of Transponder Activation Magnetic Flux parameter for a transponder in a non-uniform magnetic field, and its association with geometry and electrical properties—"HF Transponders"
- Justification of new characterization parameters for an antenna-transponder structure and qualitative analysis of the interaction between a closely spaced conventional HF resonant loop antenna and transponder—"Antenna-Transponder Characterization"
- New SS antenna development and its mathematical model correlating system performance parameters with a transponder and antenna geometry and their mutual orientation—"Magnetic Flux through Transponder"
- Quantitative analysis of spatially selective antenna-transponder interaction for their two orthogonal alignments—"Antenna-Transponder Interaction"
- Antenna circuit components justification based on the specified activation magnetic field, available Reader RF power and transponder coupled impedance—"Antenna Circuit."

RFID Applications Utilizing HF Transponders

HF RFID applications and their relevant antennas, magnetically coupled with the transponders working at 13.56 MHz, can be at least divided into two industry independent groups. The first group, as mentioned before, represents the "spatially distributed items" application type. Antenna design for this group is aimed at achieving maximum operational range with the transponders, which are in the uniform magnetic field and located relatively far from an antenna or, in any case, weakly coupled with it. This group can be simply characterized by an inequality

$$S_{MAX} << D \qquad (1)$$

where S_{MAX} = maximum size of an antenna or transponder, and D = distance between an antenna and transponder.

Although the numerous wide-ranging technical papers, articles and surveys analyzing an antenna optimization for this group have been written [3, 4, 5] there are no works known to the author that are devoted to development of antennas working in very close proximity to transponders.

The distance-dimensions relation (1), meaning a homogeneous magnetic field for transponders, significantly simplifies calculations of antenna parameters. Under condition (1) an antenna magnetic flux density distribution is calculated for a point in place of a transponder. An antenna can be designed almost independently of a transponder's position because their presence does not practically influence antenna electrical properties.

Among the huge variety of RFID applications, a second group can be distinguished. This group represents a "conveyor" type, or item-level RFID. The demand for an item-level identification can be encountered, for example, in PCB fabrication, automotive parts manufacturing and assembly, IC manufacturing, book sorting in libraries, ticket processing in transportation service, monetary value certificate handling, enhancement in gaming industry, home automation, pharmaceutical manufacturing, implantable medical devices, walking and reading assistance for visually impaired people, and smart packaging.

The conveyor type of application is a scenario where transponders (attached to the items) are arranged one after another and prepared for a sequential interrogation in a short distance to an antenna (Fig. 1). A Reader has to identify only one targeted object that is surrounded by adjacent items (transponders). This group can be characterized by the inequality:

$$D << S_{MIN} \tag{2}$$

where S_{MIN} = the minimum size of an antenna or transponder.

A few divisions of the second group of RFID applications can further include "static-object" and "dynamic-object" sub-groups. A "static-object" is the item (a transponder) that is always positioned for an interrogation in close, but fixed distance to an antenna. The degree of antenna-transponder coupling and their mutual alignment remain unchanged for every conveyor stop-cycle. A "dynamic-object" sub-group is the one where an aimed transponder is also surrounded by other adjacent transponders. In difference from the "static-object" case a longer interrogation range should be made available for a transponder as it travelings on a continuously moving conveyor. And again, a Reader should selectively interrogate only one predefined transponder among others.

Under the conditions of eq. (2), antenna-transponder coupling in relation to their mutual alignment changes significantly. An antenna with low SS will activate the targeted transponder and two (or more) closely-spaced adjacent transponders. Although a Reader's anti-collision function can manage an identification of many simultaneously activated transponders, it is unable to confine a targeted transponder. To discriminate a targeted transponder at a predefined location using such an antenna, all transponders (items) must be appropriately spaced along their traveling path. Unfortunately, the extension of the separation interval substantially increases total interrogation time. In case of smart label encoding in RFID printers. an increase of the transponder's pitch causes noticeable carrier material waste.

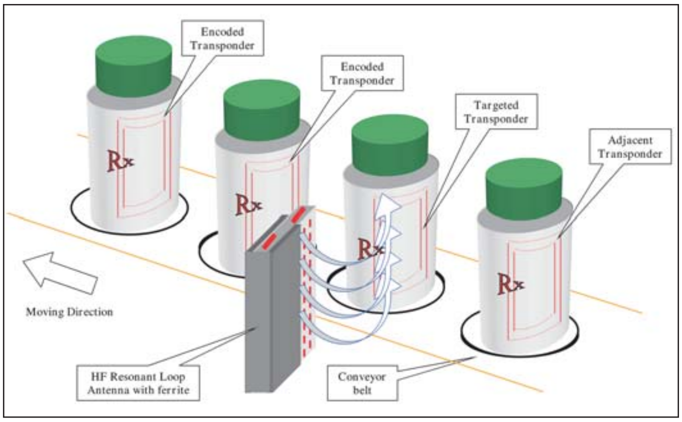

Figure 1 · HF antenna for item-level RFID on conveyor.

In close proximity to an antenna, the 3D magnetic flux density is non-uniform, and the magnetic flux through a transponder depends on its location and orientation withregard to the antenna. Thus, for RFID applications described by eq. (2), an antenna should be developed with consideration for transponder geometry and its electrical characteristics.

HF Transponders

The dimensions of typical transponders (commonly called tags) used for HF item-level RFID and other applications vary from approximately 20 by 35 mm, for a device made by Texas Instruments [6], up to 85 by 135 mm for one made by UPM Rafsec [7]. A transponder specification usually includes the IC types, a resonant frequency with its tolerance, and the most important parameter for an antenna design—maximum required activation magnetic field strength H_A in the uniform field. The field strength ranges approximately from 98 to 120 [dBµA/m] depending on ICs used, transponder inductors and their dimensions and also on how well a transponder is tuned to an operational frequency. In practical design it is more convenient to use H value expressed in [A/m] units. The conversion [dBµA/m] to [A/m] unit gives

$$H[A/m] = 10^{((H[dB\mu A/m]-120)/20)}$$

Consequently, the transponder activation magnetic flux density B_A [Vs/m^2] for the uniform field can be obtained using

$$B_A = \mu_0 H_A \left[Vs/m^2 \right] \tag{3}$$

where μ_0 = 4π*1E–07 [Vs/Am] (the free-space magnetic permeability).

The parameter H_A is specified for the uniform magnetic field and can be directly used in calculations of the antennas satisfying the inequality in (1). For applications compliant with the inequality of (2) the transponders are in the heterogeneous magnetic field with the spatially depended flux density. Antenna calculations for such a case cannot utilize eq. (3) and a Transponder Activation Magnetic Flux (TAMF) Φ_A should be engaged instead. TAMF for the transponder, which is perfectly tuned to an operational frequency, can be found as

$$\Phi_A = B_A A[Vs] \tag{4}$$

where A = a transponder loop area (m^2).

The value A in (4) is the geometry mean dimensions (GMDm) must be used instead of the transponder coil physical dimensions [8].

The time varying magnetic flux induces the voltage V_C in the transponder coil tuned at resonance equal to the operational frequency f_0 [Hz], thus

$$V_C = 2\pi f_O Q \mathrm{BAN}_T$$

or using magnetic flux it gives

$$V_C = 2\pi f_O Q \mathrm{N}_T \Phi \tag{5}$$

where Q is the transponder quality factor and N_T = number of turns of transponder coil.

If the transponder resonant frequency is f_R and different than the frequency f_0 then the transponder voltage amplification will depend on a degree of frequency deviation $(f_R - f_0)$ from the operational frequency. Linking the voltage V_C (5) of the parallel resonant circuit, which is typical for HF transponders, with the IC's specified supply voltage V_A, gives

$$V_C = V_A \sqrt{1 + \left[\left(\frac{2(f_R - f_O)}{f_R}\right) Q\right]^2} \tag{6}$$

Equation (6) concludes the more the transponder is detuned the higher voltage V_C is required to achieve the voltage V_A. Then the transponder activation flux Φ_A can be derived equating (6) and (5) and is given by

$$\Phi_A = \frac{V_A \sqrt{1 + \left[\left(\frac{2(f_R - f_O)}{f_R}\right) Q\right]^2}}{2\pi f_O Q \mathrm{N}_T} \tag{7}$$

From the formula (7) it follows that a detuned transponder with low Q-factor will have a higher activation magnetic flux compared with a tuned, high Q transponder.

In general case a quality factor of the parallel resonance circuit can be found by considering a transponder equivalent schematic (Fig. 2), which includes a resonant tuning capacitor C (comprising an imaginary part of an IC's impedance), a coil inductance L, a resistor R_L presenting an inductor losses and a resistor R_P, which simulates a real part of an IC's impedance. The Q-factor for the LCR parallel circuit is determined as

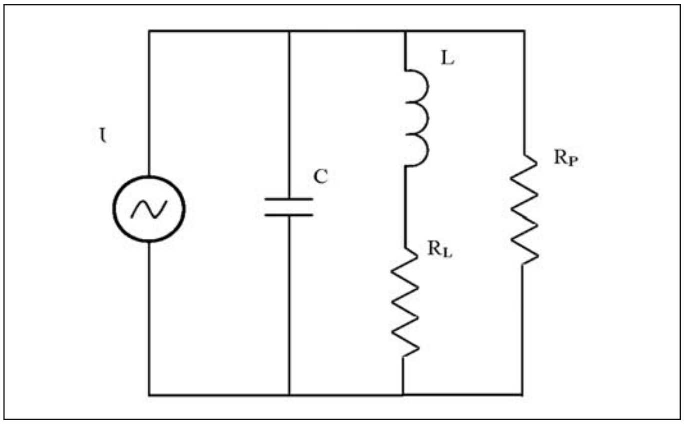

Figure 2 · Transponder equivalent circuit.

$$Q = \frac{1}{\frac{R_L}{2\pi f_R L} + \frac{2\pi f_R L}{R_P}} \tag{8}$$

Considering (7) and (8) the Φ_A value given by (7) is higher than the activation flux calculated in (4) for the tuned transponder.

In the non-uniform magnetic field a transponder gets activated when Magnetic Flux through Transponder (MFT) Φ_T exceeds Φ_A value. Then the activation flux Φ_A can be used in an antenna-transponder evaluation and analysis as a threshold that defines the boundary conditions for a transponder activation interval. The integral parameter MFT characterizing an antenna-transponder structure is given by

$$\Phi_T = \iint_A \overline{B_{X,Y,Z}} * d\vec{A}[Vs] \tag{9}$$

where $B_{X,Y,Z}$ is the 3D distribution of the magnetic flux density (normal to a surface of a transponder coil) and linear function of the current I circulating in antenna coil.

This current is defined by Reader RF power and antenna equivalent impedance. The impedance of the loop antenna tuned to resonance can be presented by few components. It consists of a radiation resistance, a resistance that is equivalent to resistive losses of the coil, including tuning and matching elements, and an impedance that is induced by a transponder via magnetic coupling. Considering the fact that a total circumference of an antenna coil is much shorter than an operational wave-length, the radiation resistance can be neglected. To simplify further an initial analysis of an antenna-transponder interaction it is assumed that the magnetic flux in an antenna coil that is produced by the current in a transponder is insignificant compared with the magnetic flux produced by an antenna itself. This assumption therefore implies that the impedance induced by a tuned transponder is much smaller than the tuned antenna resistive losses.

Antenna-Transponder Characterization

An HF antenna and a transponder working in immediate proximity to each other form a virtual device with one bi-directional RF port. Properties of this device are defined by both elements—an antenna and a transponder, and the traditional antenna characteristics such as directivity or antenna gain become inappropriate for a description of such a combined structure. Being a one-port RF device further complicates its performance assessment. Only two characteristics of an antenna-transponder conglomerate are practically available for testing. They are antenna impedance and an RF power level for which a Reader indicates whether a transponder interrogation process (including a completion of Write and Read commands) has been successful or not. With the aim of finding a proper way for characterizating an antenna-transponder combination, a set of new parameters was established and implemented. Among them are Spatial Selectivity (SS) introduced earlier, RF Power Margin, Relative Activation Power and transponder activation interval. These parameters are measurable and capable of describing the antenna-transponder properties and performance such as the transponder activation interval and the system robustness.

Spatial Selectivity (as much as other parameters) is not an attribute of an antenna itself but rather a characteristic of an antenna-transponder combined structure. By definition, a high SS implies that for an activation of a targeted transponder, located in an encoding interval, an antenna requires much less power than maximum power available from the Reader. Upon assigning P_{TAT} for minimum RF power to activate a transponder in a targeted area and P_{TAA} for power required for transponder activation in adjacent areas, the SS parameter is obtained as

$$SS = 10 Log \frac{P_{TAA}}{P_{TAT}} [\mathrm{dB}] \tag{10}$$

SS can also be defined by the magnetic flux ratio using the value Φ_A (4) and the flux through an adjacent transponder Φ_{TAD}

$$SS = 20Log\frac{\Phi_A}{\Phi_{TAD}}[\text{dB}] \tag{11}$$

RF power margin Ψ is another important parameter directly related to a transponder activation interval or an operational range. As was mentioned above, a one-port device allows a practical measurement of antenna minimum RF power when the Reader indicates it's establishing a communication with the transponder for its different positions inside an activation interval. Obviously, as lower power is applied to an antenna, the shorter this interval is. By attenuating the maximum available Reader RF power P_0 to the level P_{MIN} when a specified activation interval is achieved, the power margin Ψ can be defined as

$$\Psi = 10Log\frac{P_0}{P_{MIN}}[\text{dB}] \tag{12}$$

Applying the same power suppression method as was used for (12), a Relative Activation Power Ξ can be defined as the ratio between the Reader RF power P_0 and the power P_A applied to an antenna that changes a transponder status from non-activated to activated (and vice versa) for any position inside an activation interval

$$\Xi = 10Log\frac{P_0}{P_A}[\text{dB}] \tag{13}$$

The RF power margin (12) and the Relative Activation Power (13) are two versatile parameters describing an antenna-transponder energy transfer regardless of the impact their individual characteristics might have on environmental conditions.

High SS might be achieved by changing antenna properties to decrease the magnetic field strength for adjacent areas and shrink an activation interval for a targeted transponder. A properly designed antenna with high SS does not activate adjacent transponders even at maximum available RF power. For applications working with multi-dimensional transponders, a short activation interval is the most preferable. Ideally, this interval should be equal or less than the length of the shortest transponder type engaged.

Likewise (13) the Relative Activation Flux Θ can be acquired as

$$\Theta = 20Log\frac{\Phi_T}{\Phi_A}[\text{dB}]$$

Thus boundary points of an interaction interval can be found using (13) when $\Xi = 0$. Practically, an interaction interval is measured by registering two transponder positions where the Reader starts and stops its communications while supplying an antenna with maximum RF power. The parameter Ξ inside an interaction interval for any transponder position is measured by attenuating maximum available RF power from the Reader up to the point where its communication with a transponder fails. An attenuation value expressed in dB corresponds to Ξ.

A collection of test results allows reconstruction of a transponder performance map for its activation interval. This map assures a detection of any inconsistencies an interrogation region might have. Together with the measurement of RF power margin Ψ (12), Ξ test data enable system robustness analysis and antenna design verification. These actions are necessary because antennas and transponders parameters have natural deviations from their nominal values. Transponder activation flux, as an integral characteristic of antenna-transponder coupling, is sensitive to these deviations and so is Relative Activation Power. An antenna tuning frequency shift, RF port impedance mismatch, transponder resonant frequency detuning and its excessive losses, and IC impedance variations, just to name few, can occur in the manufacturing process or be caused by the influence of operational environmental conditions. High power margin compensates for an increase of TAMF in RFID systems and thus makes an interrogation process more reliable.

Introducing characterization parameters is instrumental in an analysis of an antenna-transponder interaction and will be demonstrated first on an example of a conventional electrically small HF resonant rectangular loop antenna. This antenna for the conveyor scenario is located in a parallel plane apart from a transponder but in very close proximity to it. The total magnetic flux through transponder, which is contributed by a few spatially distributed antenna elements, changes along a transponder traveling above an antenna (Fig. 3) depending on an antenna-transponder's alignments at a given instant. When the transponder approaches the antenna it makes use of the flux primarily from the element 3 (Fig. 3a). The elements 1, 2, and 4 make an insignificant flux contribution. The flux via transponder attains first maximum value when the transponder leading edge is right above the element 3 (Fig. 3b). While the center of the transponder is approximately above the element 3 (Fig. 3c), the antenna element 1 also supplies the transponder with magnetic flux, which has a direction in opposition to flux from element 3, thus dropping the total magnetic flux through the transponder to zero. As soon as the transponder becomes co-centered with the antenna coil (Fig. 3d) all 4 elements supply the transponder with the unidirectional magnetic flux. A further transponder movement causes the same interaction (Fig. 3e and 3f) as was described

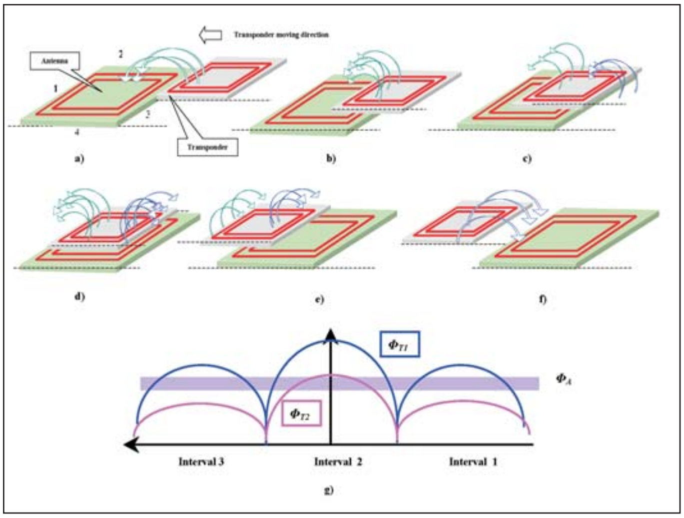

Figure 3 · Transponder interaction with a conventional antenna.

above. It can be concluded that, during its travel, the transponder encounters three distinct intervals 1, 2, and 3 where its flux Φ_{T1} exceeds a Transponder Activation Magnetic Flux Φ_A (Fig. 3g). For the conveyor type of RFID applications these three intervals exactly cover the positions of the targeted and two adjacent transponders. In accordance with eq. (11) the antenna is not spatially selective and it creates a collision situation. Analyzing the total flux through the transponder at different positions (Fig. 3g) one can suggest to attenuate RF power from the Reader in order to reduce the magnetic flux (Φ_{T2}) and achieve a single interrogation interval thus improving the antenna SS. While this suggestion is valid it works only under one condition—an RFID system always using single form-factor transponders with zero parameter tolerances. In reality an RFID system must be capable of working with different transponder dimensions. Moreover, the transponders from the same group have normally distributed parameters around their specified values and the flux Φ_A becomes a zone (Fig. 3g). The expansion of the line Φ_A is related, for example, to the transponder's resonance frequency (7) and Q-factor (8) deviation effects. Decreasing an antenna's magnetic flux worsens flux margin and could cause a low encoding yield of transponders because of a low RF power margin (12).

By following a good design rule of "3 dB" it can be concluded that in order to achieve high antenna performance, the SS for the intervals 1 and 2, and the power margin Ψ for the interval 1 (Fig. 3g), should be equal to or exceed 3 dB.

Coming in Part 2

Part 2 will continue the discussion with the topic "Magnetic Flux Through the Transponder," and will be published in the next issue (March 2007).

References

1. P. Albert, D. Ruffieux, O. Zhuk, "Understanding the Role of NFC-Based RFID Devices in the Consumer/Mobile Market," Emerging Wireless Technology/A Supplement to *RF Design,* pp. 2-4, August, 2005.

2. "Find a Vendor," *RFID Journal,* 2006. www.rfidjournal.com/article/findvendor.

3. K. Finkenzeller, *RFID Handbook–Fundamentals and Applications in Contactless Smart Cards and Identification,* Second Edition, John Wiley & Sons, 2003. ISBN: 0-470-84402-7.

4. Y. Lee, "Antenna Circuit Design for RFID Applications," AN710, Microchip Technology Inc., 2003. ww1.microchip.com/downloads/en/appnotes/00710c.pdf.

5. "Tutorial Overview of Inductively Coupled RFID Systems," UPM Rafsec, May 2003. www.rafsec.com/rfidsystems.pdf.

6. "Tag-it HF-I Standard Transponder Inlays," Reference Guide. Lit number: 11-09-21-062, Texas Instruments Incorporated, December 2005. www.ti.com/rfid/docs/manuals/refmanuals/HF-IStandardInlays-RefGuide.pdf.

7. "HF tags and inlays, standard products," UPM Raflatac, 2006. www.rafsec.com/hf_availability.htm.

8. G. Zhong, C-K. Koh, "Exact Closed Form Formula for Partial Mutual Inductances of On-Chip Interconnects," IEEE 20th International Conference on Computer Design, Freiburg, Germany, 2002. www.iccd-conference.org/proceedings/2002/17000428.pdf.

Author Information

Boris Y. Tsirline is the senior RFID research engineer at Zebra Technologies Corporation in Vernon Hills, IL. He received a BS and MS degrees in RF & Microwave Engineering from Moscow Aviation University, Russia in 1973 and a PhD in EE from Moscow State University in 1986. Before moving to the US in 1992, he served as a Director of R&D at Automotive Electronics and Equipment Corp., Russia, developing military and aerospace electronic systems. He has been in the Automatic Identification and Data Capture industry since 1995; first as an RF Engineer involved in LF RFID design of automotive immobilizers at TRW (Automotive Electronic Group) and then at Zebra Technologies Corporation since 1998. He managed the development of Zebra's first HF RFID printer-encoder and established the design methodology for HF and UHF spatially selective antenna-transponder structures used throughout the corporation divisions for RFID labels and cards printers. Dr. Tsirline holds three non-classified Russian and two US patents and has numerous pending patents for RFID enhancements.