

LabVIEW-Based UHF RFID Tag Test and Measurement System

Pavel V. Nikitin, *Senior Member, IEEE*, and K. V. Seshagiri Rao, *Senior Member, IEEE*

Abstract—In this paper, we describe a UHF radio-frequency-identification tag test and measurement system based on National Instruments LabVIEW-controlled PXI RF hardware. The system operates in 800–1000-MHz frequency band with a variable output power up to 30 dBm and is capable of testing tags using Gen2 and other protocols. We explain testing methods and metrics, describe in detail the construction of our system, show its operation with real tag measurement examples, and draw general conclusions.

Index Terms—Radio-frequency identification (RFID), tags, testing and measurement.

I. INTRODUCTION

RADIO-FREQUENCY identification (RFID) is an automatic wireless data-collection technology with a long history that can be traced back to the late 1940s [1]. Since then, RFID has significantly advanced [2] and experienced a tremendous growth due to developments in integrated circuits and radios and increased interest from retail industries and universities [3]. In a passive UHF RFID system, the reader alternates between transmitting continuous wave (CW) and modulated RF commands to the tag. The tag chip gets powered wirelessly, similar to energy transmission in inductive contactless systems [4]. The chip sends back information by varying its input impedance and thus modulating the signal backscattered to the reader, which receives it while simultaneously continuing to transmit CW to provide power to the tag. RFID products (readers, printers, and tags) are now used for a wide variety of applications and environments.

This paper describes a tag test and measurement system. This work was motivated by the fact that accurate testing and measurement of RFID tag parameters is extremely important in RFID industry, particularly for companies which either develop their own tags or include various commercially available tags as part of complete RFID system solution (readers, tags, printers, and software). We needed to develop a tag test and measurement system with the following properties:

- 1) accurate (0.1-dB power accuracy or better);
- 2) wideband (covering at least 860–960-MHz band);
- 3) fast (measurement time of 1 s per frequency point or less);
- 4) sensitive (receive sensitivity must be better than that in most commercial RFID readers, -80 dBm or lower);
- 5) flexible (easy to customize for future specific needs);

- 6) cost effective (one-time-only hardware investment);
- 7) easily modifiable (software controlled);
- 8) fully automated (minimum manual operations).

At the time when the work described in this paper was done, there were no such systems available on the market. To satisfy the criteria which we listed earlier, the system had to include RF signal generator (RFSG), capable of producing specific modulated signals, and RF signal analyzer (RFSA), such as real-time spectrum analyzer, capable of analyzing tag signals. The two must be operated together and controlled by the same software that can be custom modified by users. The only hardware suitable for that purpose and available on the market was National Instruments PXI RF platform, which included RFSG and RFSA, controlled by LabVIEW. We used it as a basis for our system, added some external hardware, and wrote custom LabVIEW software for tag testing and measurement.

RFID technology progressed very rapidly in the recent years. Tag design and construction issues are now well understood [5]–[7], together with the fact that tag performance strongly depends on the environment [8]–[10] and that reliable measurements of tag performance are crucial for quality tag design implementation and performance verification [11].

RFID tag-testing systems and methods have also significantly advanced in the recent years. Initially, tag characterization was performed empirically, using off-the-shelf RFID readers operating in a single frequency band [12]. Although this simple method remains popular [13], [14], more and more researchers recognize the need for using specialized reconfigurable wideband systems [15] similar to the one described in this paper. The testing industry responded to this demand with several commercial products. One is the RFID test and measurement solution by VISN [16], also based on National Instruments PXI hardware and LabVIEW. This solution requires a real-time field-programmable gate array (FPGA) module and is primarily destined for protocol conformance testing. Another is tag measurement solution by Voyantic [17], which is based on custom hardware and software that cannot be modified by user. These two solutions became popular and started being used now by RFID researchers [18], [19].

All solutions mentioned earlier are custom commercial products, with little information on specific implementation details. In this paper, we provide a detailed description of our test and measurement system. We hope that such information will be useful for university and industry researchers who would like to build similar systems. The described system is extremely versatile and can be used not only for tag characterization but also for other tasks such as development and testing of new modulation and coding schemes for RFID readers.

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The authors are with Intermec Technologies Corporation, Everett, WA 98203 USA (e-mail: pavel.nikitin@intermec.com; kvs.rao@intermec.com).

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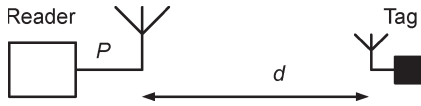


Fig. 1. Generic tag-testing setup.

II. METHODS AND METRICS

A. Testing Methods

There are two main methods of measuring tag performance described hereinafter, both based on a scenario where the reader transmits the power P , and the tag is located at a distance d away, as shown in Fig. 1.

First method is based on using fixed power and variable distance to the tag (P is constant, and d is variable). This method does not require special equipment and is often used in RFID field practice. The reader transmits constant power while the tag is being moved away until it cannot be read or written to. This allows an engineer to realistically measure tag range in various propagation environments where the tag behavior can significantly vary from free space.

Second method is based on using variable power and fixed distance to the tag (P is variable, and d is constant). The transmitted power is varied until the minimum power where the tag responds is found. This allows one to perform scientifically repeatable benchmark measurements in reflection-free environment (such as anechoic chamber, TEM cell, or simply antennas separated by short distance and placed far from nearby potential reflectors).

In either method, custom RF equipment can be used to perform testing in a wide frequency band. As an alternative, a standard off-the-shelf RFID reader can also be used where the reader power can be controlled either using the software or with external attenuators. The reader frequency can usually not be changed arbitrarily. At most, it can be parked on one of the channels of local UHF RFID band. However, one can modify or replace RF front end of the reader to allow for broadband operation while keeping the baseband (protocol) part intact.

An important design choice in RFID testing systems is RF front-end antenna configuration [2]. Two main choices are monostatic and bistatic configurations. Monostatic configurations use some RF isolator and a single antenna to transmit and receive. Bistatic configurations use separate transmit and receive antennas, often circularly polarized, and in general provide better transmit/receive isolation. When testing is performed, polarization mismatch between the transmitting/receiving antennas and the tag is taken into account, and tag orientation sensitivity (directly related to polarization mismatch) is often one of the tag characteristics being tested [15].

B. Tag Performance Characteristics

There are several tag performance characteristics described hereinafter. Some of them are important for forward link (reader-to-tag), while others are important for the return link (tag-to-reader). Some of the tag characteristics (such as tag sensitivity or backscatter efficiency) depend only on the tag, while others (such as read range and backscatter range) depend

also on the reader and the environment. All of these characteristics can be measured as functions of frequency in different scenarios (e.g., for tag in different orientations, on various materials, etc.).

Important forward-link tag characteristics are as follows:

- 1) tag sensitivity;
- 2) tag range.

Tag sensitivity is the minimum incident power (signal strength) at the tag location needed to either read or write the tag. Tag range is the maximum distance at which the tag can be read or written in free space. It is an easily understandable, directly measurable, and thus commonly used tag performance characteristic. In passive UHF RFID systems, the maximum range is currently limited by the forward link, and thus, the tag range is the same as the forward range.

In a fixed-distance testing setup, the fundamental measured quantity from which both of these characteristics are calculated is the measured minimum power P_{\min} needed to read or write to the tag. Other quantities (such as field sensitivity, etc.) can be easily calculated from this measurement. Both of these characteristics can be defined either for read or write operation. Write sensitivity differs from read sensitivity, typically by about 3 dB, because RFID IC needs more power for performing write operation. Accordingly, read and write ranges differ as well by about 30%. In this paper, we concentrate on measuring read sensitivity and read range.

Tag sensitivity P_{tag} and range r_{tag} in free space are related as

$$P_{\text{tag}} = EIRP \left(\frac{\lambda}{4\pi r_{\text{tag}}} \right)^2 \quad (1)$$

where λ is the wavelength and $EIRP$ is the equivalent isotropic power radiated power by the reader. In a fixed-distance free-space testing setup, tag sensitivity and range can be calculated from the measured minimum power P_{\min} as

$$P_{\text{tag}} = P_{\min} G_t \left(\frac{\lambda}{4\pi d} \right)^2 \quad (2)$$

$$r_{\text{tag}} = d \sqrt{\frac{EIRP}{P_{\min} G_t}} \quad (3)$$

where d is the distance to the tag and G_t is the gain of the transmitting reader antenna. The relationship between tag range and sensitivity given by (1) is shown in Fig. 2, where the reader transmits 4-W EIRP in free space at 915 MHz. The incident power (dBm) at the tag location defines whether the tag will be powered up or not. That power can be interpreted as the power which would be absorbed by the RFID chip if it was connected to a perfectly matched 0-dBi tag antenna.

Important return-link tag characteristics are as follows:

- 1) tag backscatter efficiency;
- 2) tag backscatter range.

Tag backscatter efficiency is the tag characteristic which shows how much of the incident RF power is “converted” by the tag to the modulated backscattered power.

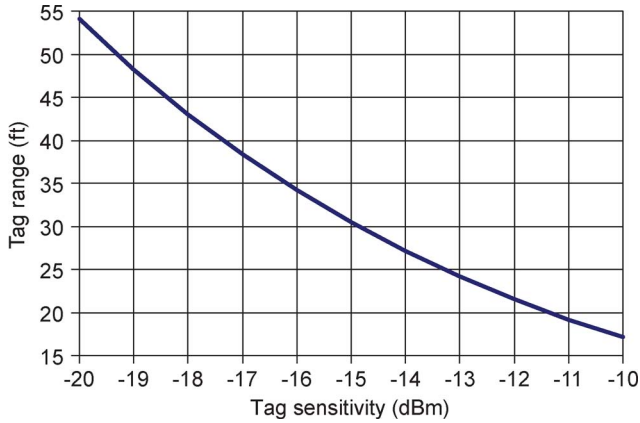


Fig. 2. Tag read range (ft) versus tag sensitivity (dBm). Other parameters: free space, 915 MHz, and 4-W EIRP.

The backscatter range is the maximum distance at which the reader with certain receiving sensitivity can decode the backscattered tag signal. In semipassive (battery-assisted) UHF RFID systems, the maximum range is currently limited by the return link.

In the fixed-distance setup, the fundamental measured quantity from which both of these characteristics are calculated is the power of the received tag signal. Other quantities (such as modulation loss, backscatter efficiency, delta RCS, differential EIRP, link margin, etc.) can also be easily computed from this measurement.

For monostatic antenna configuration in free space, assuming that tag sensitivity is not a limitation, power-dependent tag backscatter efficiency χ and backscatter range $r_{\text{backscatter}}$ are related as

$$P_{\text{reader}} = P_t G_t^2 \left(\frac{\lambda}{4\pi r_{\text{backscatter}}} \right)^4 \chi \quad (4)$$

where P_{reader} is the receive sensitivity of the reader and P_t is the output power of the reader. Another quantity often used for characterization of the tag backscatter is the differential radar cross section $\Delta\sigma$ [20] (also known as delta RCS), which defines the power of the modulated backscattered signal. Backscatter efficiency and delta RCS are functions of incident power but can be uniquely defined for each tag at the power level where the incident power is equal to the tag sensitivity. At this threshold power level, both of these characteristics, as well as the backscatter range, can be calculated from the measured minimum power P_{min} and corresponding received tag signal power P_{received} as

$$\Delta\sigma = \frac{\lambda^2}{4\pi} \chi = \frac{P_{\text{received}}}{P_{\text{min}} G_t^2} \frac{(4\pi)^3 d^4}{\lambda^2} \quad (5)$$

$$r_{\text{backscatter}} = \frac{\lambda}{4\pi} \sqrt{\frac{P_{\text{tag}} \chi}{P_{\text{reader}}}} = d \sqrt{\frac{P_{\text{received}}}{P_{\text{reader}}}}. \quad (6)$$

The relationship between tag backscatter range and tag backscatter efficiency given by (4) is shown in Fig. 3, where the reader has sensitivity of -80 dBm and transmits with 1-W output power using a 6-dBi antenna in free space at 915 MHz.

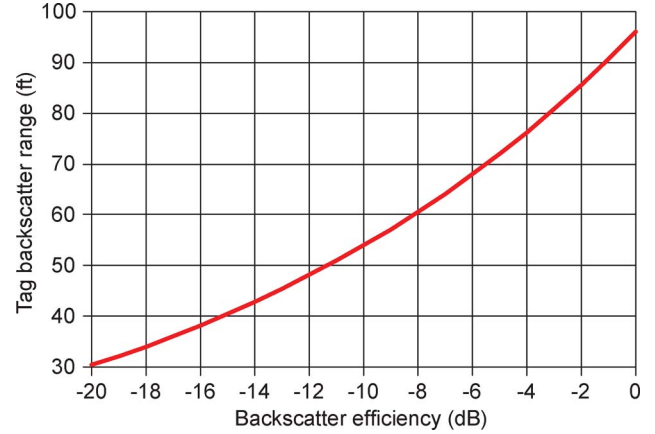


Fig. 3. Tag backscatter range (ft) versus tag backscatter efficiency (dB). Other parameters: free space, 915 MHz, -80 -dBm reader sensitivity, 1-W power, and 6-dBi antenna.

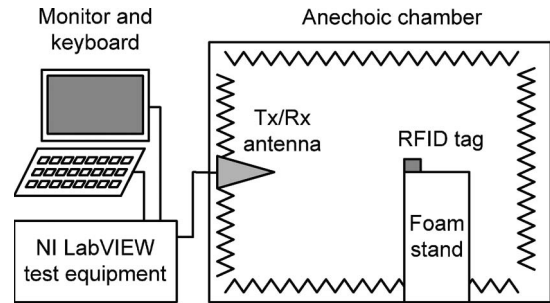


Fig. 4. Test and measurement setup.

III. SYSTEM DESCRIPTION

A. Test and Measurement Setup

Our test and measurement setup is shown in Fig. 4. An RFID tag is placed on a piece of material at a fixed distance from the 6-dBi reader antenna. The distance between the reader and the tag ($d = 3$ ft) is chosen such that RFID tag is in the far-field zone of the antenna and in the quiet zone of the chamber. Consequently, this distance is the minimum tag range which can be measured for maximum radiated power (4 W) in our setup. For most far-field applications, this is more than enough. In a few cases, when near-field testing is needed, the tag can be positioned closer to the transmitting antenna. The transmitting antenna is connected to the measurement equipment (system hardware is described in the next section) with coaxial cable. Correction factors, such as transmitting antenna gain variations with frequency, connector and cable losses, etc., have also been measured and taken into account in our measurements. The anechoic chamber is compact ($4 \times 4 \times 6$ ft), but from our experience, the results of the tag range testing even in such modest chamber correlate very well with real outdoor range measurements.

B. System Hardware

The system hardware was based on National Instruments LabVIEW-controlled PXI RF platform which functioned as RFID reader with variable frequency and output power and measured both the minimum power needed for tag to respond

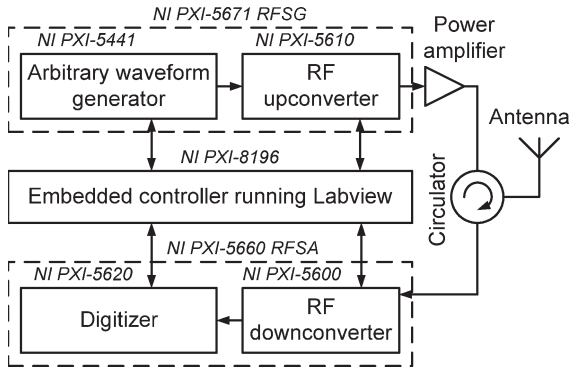


Fig. 5. Block diagram of the system.

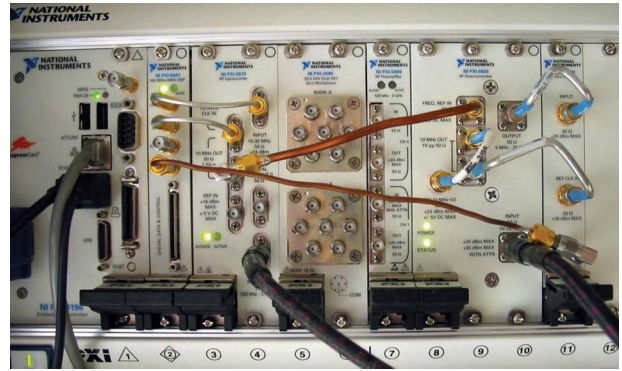


Fig. 7. Front panel of the PXI rack with RFSG and RFSA.

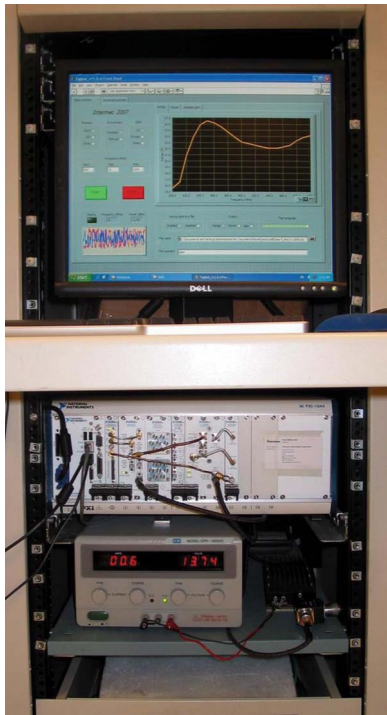


Fig. 6. Photograph of the system.

and the tag backscatter signal strength. The block diagram and the photograph of the system are shown in Figs. 5 and 6. The external power amplifier was needed to transmit at levels up to 30 dBm. The circulator was needed to provide good transmit/receive isolation.

The National Instruments hardware was housed in a 14-slot PXI chassis as shown in Fig. 7. The RFSG PXI-5670 consisted of an arbitrary waveform generator PXI-5421 and an RF up-converter PXI 5610. The RFSA consisted of RF downconverter PXI-5600 and the digitizer PXI-5620. Detailed characteristics of the equipment are listed hereinafter.

The system had the following hardware components:

- 1) PXI-5671 RF vector signal generator
 - a) PXI-5441 arbitrary waveform generator
 - Sampling rate of 100 MS/s
 - b) PXI-5610 RF upconverter
 - 300 kHz–2.7 GHz
 - Output power up to 13 dBm
 - < 0.1-dB accuracy
- 2) PXI-5660 RFSA
 - a) PXI-5600 RF downconverter
 - Sensitivity < -100 dBm
 - Dynamic range > 80 dB
 - b) PXI-5620 digitizer
 - 20-MS/s sampling rate
- 3) PXI-8196 computer controller
 - a) 2-GHz processor, 2-GB RAM
 - b) Runs LabVIEW 8.0
- 4) PXI-1044 14-slot chassis
- 5) Minicircuits ZHL-4240W RF amplifier
 - a) 10–4200-MHz frequency range
 - b) Gain > 40 dB
 - c) Output power up to 1 W
- 6) M/A com RF circulator 7N195
 - a) 800–1000-MHz frequency range
 - b) Tx/Rx port isolation 25 dB
- 7) Sinclair SRL441U antenna
 - a) 800–1000-MHz frequency range
 - b) 6-dBi gain
- 8) Agilent E3620A power supply
 - a) 15-V dc (needed for RF power amplifier)

C. LabVIEW Software

The National Instruments hardware was controlled by a program whose flow is shown in Fig. 8. The program read input parameters, generated and sent RFID commands to the tag, acquired the backscattered signal, and analyzed it for the presence of tag response for various powers (up to 30 dBm at antenna input) and frequencies (800–1000 MHz). The program was capable of sending commands and analyzing tag responses in different modulation and coding formats conforming with ISO 18000-6B and ISO 18000-6C (a.k.a. Gen2) protocols.

To test tag read range and sensitivity, we sent *Query* command (1000) to the tag and detected the tag response by its *RN16* reply as described hereinafter. Our system can generate Gen2 commands with different protocol parameters. Typical Gen2 query which we used had the following parameters:

- 1) Preceding CW duration: 2 ms
- 2) Preamble
 - a) Delimiter = 13 μs
 - b) Tari = 24 μs
 - c) Pulswidth = 0.5 Tari

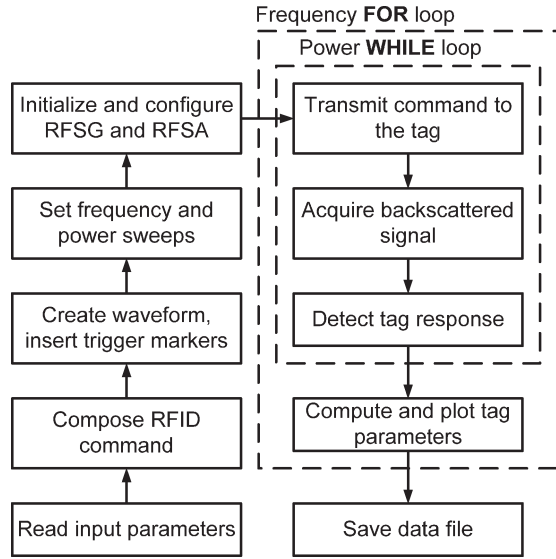


Fig. 8. LabVIEW program flow.

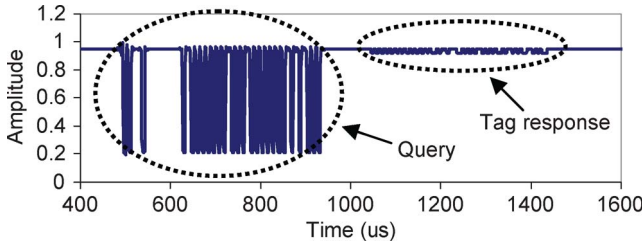


Fig. 9. Typical RFID command exchange during tag testing.

- d) $RT_{cal} = 2.5 T_{ari}$
- e) $TR_{cal} = 3 RT_{cal}$
- 3) Command: **1000000100100000011100**
 - a) $DR = 8$ (backlink frequency of 44.44 kHz)
 - b) Tag backscatter encoding: FM0 ($M = 1$)
 - c) Pilot tone: on
- 4) Following up CW duration: 2 ms
- 5) Modulation depth: 80%

A typical reader-tag command exchange is shown in Fig. 9.

The in-phase (I) and quadrature (Q) components of the receiver signal are composed of dc and ac parts

$$I = I_{DC} + I_{AC} \quad Q = Q_{DC} + Q_{AC}. \quad (7)$$

The dc parts are due to transmitter–receiver leakage, impedance mismatch of the reader antenna, and various static reflections in the environment, including static reflection from the tag antenna itself. The ac parts are due solely to the tag modulated backscatter. A typical RFID reader removes the dc part, essentially centering the tag constellation diagram at zero. Our test system does exactly the same and measures instantaneous I and Q of the tag signal as well as the received tag signal power and phase given by

$$P_{received} = \frac{I_{AC}^2 + Q_{AC}^2}{Z_0} \quad \varphi = \arctan \frac{Q_{AC}}{I_{AC}} \quad (8)$$

where Z_0 is the input impedance of the receiver (50Ω).

We found that tag backscatter detection could be performed very simply by calculating unfiltered $I^2 + Q^2$, normalizing

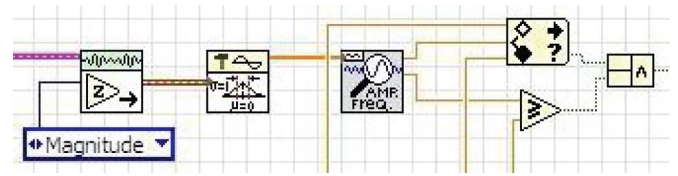


Fig. 10. LabVIEW code for tag response detection.

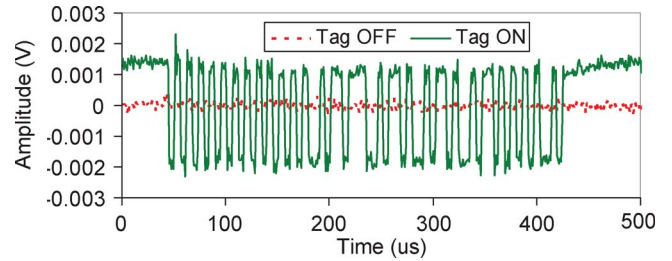


Fig. 11. Received tag backscatter when tag is off (red, $P_t = 9.2$ dBm) and on (green, $P_t = 9.3$ dBm). The frequency is 915 MHz; the transition occurs over 0.1-dB change in transmitter output power level.

this quantity (removing the dc component and rescaling to $-1, \dots, +1$ interval) and computing the amplitude and frequency of the dominant spectral component of the backscatter. If that component (either on I , Q , or their combined magnitude) fell into $\pm 10\%$ of the expected backlink frequency (known from query parameters) with the amplitude exceeding threshold value (typically, one), the tag was considered to be responding. A piece of LabVIEW code that performed the detection is shown in Fig. 10.

This frequency-domain detection by analyzing the spectral content of the tag signal was simple and worked very reliably in most cases. In the time domain, tag turn-on looks like a sharp transition from the noisy backscatter signal of unpowered tag to the easily recognized rectangular waveform of the modulated tag signal as shown in Fig. 11. Such change occurs over only 0.1-dB change in transmitter output power when it crosses the corresponding tag activation threshold.

The power of the backscattered signal was calculated from the time-averaged power in the FM0 preamble of the $RN16$ tag response. Because the pilot tone in the *Query* command was turned on, that preamble always contained 12 leading zeros as shown in Fig. 11.

During the test, the power of the query command transmitted at each frequency was gradually increased until the tag response was detected. To increase the speed of testing without sacrificing the desired accuracy, this power increase was first performed in large steps, and then, the last step was repeated with smaller steps. Typically, coarse and fine step values were 1 and 0.1 dB accordingly. The flow of the frequency and power loops is shown in Fig. 12.

The graphical user interface for the LabVIEW program of our test system is shown in Fig. 13. The basic controls were designed to be simple so that they can be used for everyday tag testing by technically inexperienced people.

The main input parameters (basic controls) were as follows:

- 1) protocol [Gen2 (ISO 18000-6C) or ISO 18000-6B];
- 2) EIRP [U.S. (4 W EIRP) or Europe (3.3 W EIRP)];

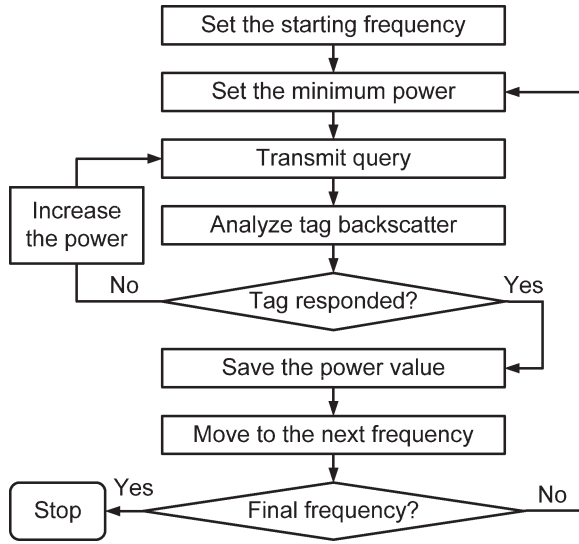


Fig. 12. Flowchart of frequency FOR loop and power WHILE loop for finding the minimum power at which the tag responds.

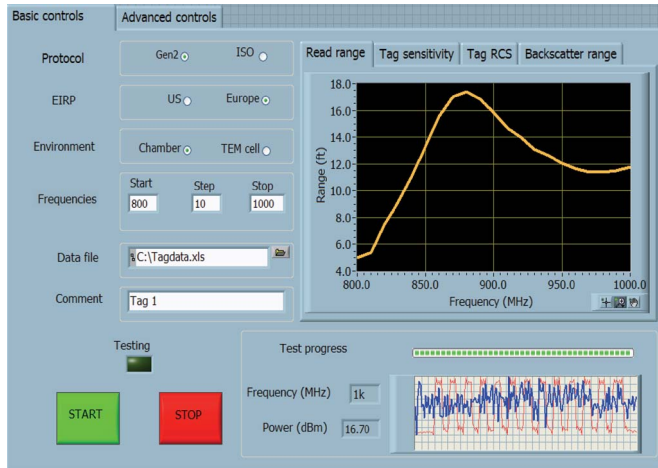


Fig. 13. User interface of the test system.

- 3) environment (anechoic chamber or TEM cell);
- 4) frequencies (start, stop, and step);
- 5) data file name;
- 6) comment on what is being measured.

The advanced controls included the following:

- 1) RFID query command details (Gen 2 command and its timing parameters, including preamble);
- 2) modulation index;
- 3) baseband filter bandwidth;
- 4) start and stop trigger marker times;
- 5) backlink frequency window and threshold amplitude (for tag response detection);
- 6) power sweep settings (start/stop and coarse/fine steps);
- 7) antenna gain versus frequency;
- 8) distance to the tag versus frequency (phase center of different antennas, such as log-periodic arrays, may shift with frequency);
- 9) interval between the queries;
- 10) system link budget offsets (versus frequency):
 - a) amplifier gain;



Fig. 14. Tags used in measurements. (Left) Alien Squiggle. (Middle) RSI Spyder. (Right) Raflatac Rabbit.

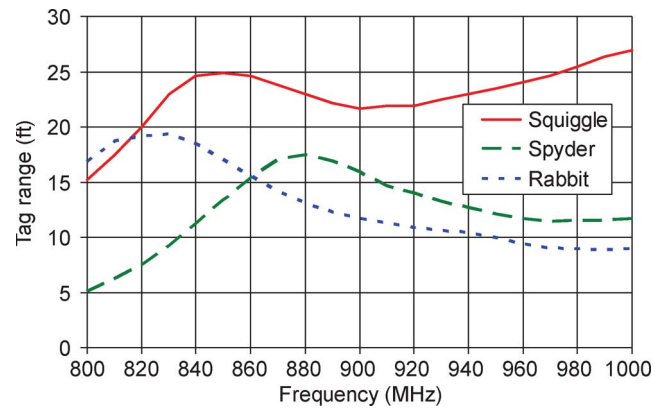


Fig. 15. Tag range (ft) versus frequency for tags in Fig. 14. Other parameters: free space and 4-W EIRP.

- b) cable loss;
- c) antenna gain.

IV. MEASUREMENT EXAMPLE

The test system described in this paper was extensively used for measuring and characterization of multiple RFID tags. As an example, we show the operation of our system using three standard commercially available EPC Gen2 tags shown in Fig. 14: Alien Squiggle (ALN-9540) [21], RSI Spyder (IN-33), and Raflatac Rabbit [23].

For each of these tags, the minimum power needed to read the tag and the corresponding backscatter signal strength were measured in 800–1000-MHz frequency band. From those measurements, tag sensitivity, backscatter efficiency, delta RCS, read range, and backscatter range were calculated. For illustration, read range of these tags (which remains the most important characteristic of passive UHF RFID tags) is shown in Fig. 15, calculated for 4-W EIRP in free space.

V. DISCUSSION AND CONCLUSION

There are several general lessons which we have come across while building our test and measurement system.

The first lesson was that timing synchronization between RFSG and RFSA (which had separate RF oscillators) was crucial for detecting tag response. For comparison, RFID readers typically use one oscillator, so that transmitter and receiver are always perfectly synchronized (coherent detection). To ensure reliable synchronization, digital triggers from the markers in the RFID query had to be sent from the arbitrary waveform generator to the digitizer directly via front-panel PF1 hardware coaxial cable connection.

The second lesson was that the absolute phase of the tag backscattered signal could not be determined, only relative (differential) measurements were possible. This, again, was caused by the fact that RFSG and RFSA had separate RF oscillators, synchronized only via 10-MHz backplane bus in PXI chassis. While RFSG and RFSA were synchronized during acquisition of RF signal is in process, turning them off and on resulted in the new random phase shift. This was not crucial for tag testing but limited the use of the system for exploring other advanced applications which required accurate tag phase measurements. Note that most recent versions of PXI RFSG and RFSA from National Instruments have a separate RF input through which they can be synchronized using an external RF oscillator.

The third lesson was that the communication with the tag in our system had to be based only on one reader command and one tag response. This was caused by the fact that the signal processing of the acquired tag response was performed in LabVIEW on a PC and could not be done within a very short time window (T_2) dictated by strict timing requirements of Gen2 protocol. We could accurately measure the read threshold by detecting tag backscatter but could not send subsequent commands (which are necessary, for example, if one wants to read tag ID or write data to the tag). Because of the same reason, we could not singulate multiple tags and our system use was limited to a single tag-testing scenario. If multiple tags were placed inside the anechoic chamber, they could not be individually distinguished and their responses superimposed on each other. However, we found that for majority of tag design and characterization tasks which deal with only single tag read operation, our system capabilities were more than adequate. Now there is a separate FPGA module available from National Instruments that can be used for real-time applications which require fast computation times, such as RFID protocol conformance tests [16].

To summarize the point, the key features of our test and measurement system are its simplicity, flexibility, and the fact that it is based on widely available National Instruments PXI RF hardware and LabVIEW software. It operates in 800–1000-MHz frequency band and is capable of testing RFID tags operating under Gen2 (ISO 18000-6C) and other protocols with various power levels for determining tag parameters. It can be used with various propagation environments (anechoic chamber, TEM cell, and conducted measurements) as well as with monostatic or bistatic antenna setups. The system can measure the minimum power level to read the tag and the amplitude and relative phase of the received differential tag signal (I and Q). From these measurements, tag sensitivity, backscatter efficiency, delta RCS, read range, and backscatter range can be easily calculated. The system is modular and versatile, and the

LabVIEW application, which controls our system, can be easily customized for any specific RFID testing needs.

We hope that the detailed system description which we provided in this paper will be useful for the wide RFID community, including university and industry research laboratories which are involved in development and testing of RFID tags and readers.

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Pavel V. Nikitin (S'98–M'02–SM'07) received the B.S. degree in physics from Novosibirsk State University, Novosibirsk, Russia, in 1995, the M.S. degree in electrical engineering from Utah State University, Logan, in 1998, and the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, in 2002.

He was with Ansoft and IBM Corporations and had a postdoctoral position with the University of Washington. He is currently a Lead Engineer with Intermec Technologies Corporation, Everett, WA, where he is involved in research, design, and development of radio-frequency-identification systems. He has authored over 50 technical publications in journals and conference proceedings and has more than 20 patents pending or issued.



K. V. Seshagiri Rao (S'78–M'84–SM'91) received the Ph.D. degree from the Indian Institute of Technology (IIT), Kharagpur, India, in 1984.

He is currently a Technologist with Intermec Technologies Corporation, Everett, WA, where he also manages a group in the area of radio-frequency-identification (RFID) transponder design and development. Prior to joining Intermec, he was with the IBM T. J. Watson Research Center as a Research Staff Member. He is an active participant in the RFID standards with organizations ISO, EPC, and SAE representing Intermec. He was with the faculty of the Department of Electronics and Electrical Communication, IIT, until 1988, and spent two years as a Research Associate with the University of Ottawa, Ottawa, ON, Canada, on sabbatical leave from IIT. During his stay at IIT, he was involved in sponsored projects in the area of antennas and radar engineering. He has coauthored around 50 technical publications in journals and conference proceedings and the book *Millimeter-Wave Microstrip and Printed Circuit Antennas* (Artech House, 1991). He also has 15 U.S. patents issued in the area of RFID.