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A UHF RFID measurement and evaluation test system

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UHF RFID tags have demonstrated considerable degradation of performance when being attached to products. Absorption, reflection, detuning, and other RF effects decrease the sensitivity of the tags. We are presenting an UHF RFID measurement and performance evaluation test system, which allows for evaluations of designs of labels and ICs. Furthermore, it provides means for quantifying tag performance in various applications through measurements and tests.

Keywords: UHF; RFID; measurements; evaluation; performance

UHF RFID Tag-Messtechnik und Evaluierungssystem.

UHF RFID Tags zeigen eine beachtliche Verschlechterung der Leistung, sobald sie an Objekten angebracht werden. Absorption, Reflexion, Verstimmung und andere RF-Effekte vermindern die Transponder-Sensitivität. Es wird ein UHF RFID-Mess- und Leistungsevaluationstestsystem vorgestellt, welches bei der Evaluierung von Labeldesigns und ICs zur Anwendung kommt.

Schlüsselwörter: UHF; RFID; Messtechnik; Evaluierung; Leistung; Test; Transponder-Charakteristik

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1. Introduction

Experience in implementing UHF RFID systems shows that tags optimized for a given frequency band can suddenly become hardly readable, while in other frequency bands they show an improved performance. Similarly, omni directional tags attached to a product suffer from dead-angle behaviors. Performance of applied tags varies according to product materials, sizes, and surrounding objects. Correct design of RFID hardware setups is therefore dependent on the knowledge of how individual materials and products influence the performance of tags. In this paper, we present a platform for real-time evaluation of UHF RFID tags, which is based on a modular hardware system. The platform is one part of a model-based methodology for real-time verification and optimization of UHF RFID systems (*Derbek, 2007*) as depicted in Fig. 1.

The novel method allows for considerations of operating setups in the design flow of components and brings a technique for verification of the system in application specific conditions. While the technique applied on the simulation platform is based on simulating models of UHF RFID systems, the real-time verification platform provides means for verifications of designs, system optimization and evaluation through measurements and tests. The proposed methodology closes the gap between design of components and optimization of real-world setups in which the components operate.

Manufactured products intended for labeling need to be evaluated in terms of their effects on tag performance degradation. On one hand this is necessary in order to quantify the effects and accommodate the tags design to the most possible insensitivity to the effects. On the other hand the information leads to a development of a matrix specifying tag performance requirements for product bins. In these terms, the performance of tags applied on various dielectrics is critical. Therefore the European EPC competence center (EECC) (*http://www.eecc.info*) has proposed a system to classify products labeled with RFID tags in order to determine tags that are best suitable for given applications. The proposed platform for real-time evaluation of UHF RFID tags is used to execute measurements and evaluations in the EECC lab in Germany (Fig. 1), which is specialized in RFID testing.

The remaining document is organized as follow. Section 2 provides an overview of UHF RFID performance. Section 3 gives more insight into the proposed solution. Section 4 presents typical test results and Sect. 5 concludes the work.

2. Overview of UHF RFID performance

The reliability of a tag in providing appropriate response to a reader query is important for the adoption of the UHF RFID technology in business processes. In real operating environments several effects take place that disturb this communication. The radio frequency (RF) field generated by the reader is the data and energy carrier for passive tags. Environmental noise has a major impact on disturbing the data channel between the reader and the tag. National regulations therefore set limits to control the utilization of communication channels and to minimize data collisions. The other aspect influencing the tags' operability is the availability of sufficient amount of energy and the ability to reflect (backscatter) part of this energy. The modulated backscatter power is the data carrier on the return link (i.e. from the tag to the reader).

Key terms that are important for understanding the tag performance issues are outlined in following paragraphs:

The tag's integrated circuit (IC) retrieves the RF energy from the field through an antenna and converts it into a DC power, which is necessary to operate the digital circuitry. The amount of the DC energy required for the operation of the circuitry is dependent on

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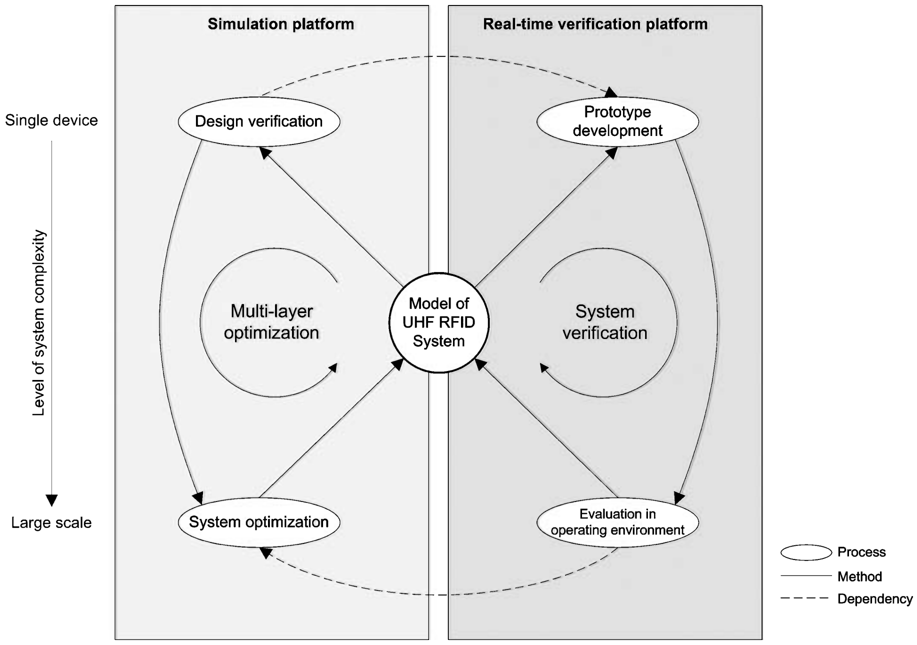

Fig. 1. Methodology for model-based real-time verification of UHF RFID systems

the technology of the IC manufacturing process and on the tag IC design. The lower the required DC energy, the more resistant is the tag against resets of its internal state due to low RF field strength. Low power designs are therefore the target (*Karthaus, Fischer, 2003*).

Impedance matching of the tag antenna to the IC is an important technique to utilize as much energy from the RF field as possible. The antenna is optimally matched to its IC at a certain frequency. The tag is then tuned to this frequency. It generally shows a worse performance on other frequencies (*Lam, Nikitin, Rao, 2005*). To achieve an acceptable performance world-wide, tags tuned to a whole frequency band are available.

UHF tag antennas are generally dipoles and single loops. Tag manufacturers provide various types of dipole-based antennas to maintain impedance match, broad-band character of tag operation, small tag sizes, and to overcome problems with orientation dependency of the tag performance. Furthermore, most tags can be operated both in the reader far field (typically pallet and case-level tagging) and in the magnetic near field (typically used for the item level tagging).

Different tag designs result in different tag performance. A study (*European EPC Competence Center, 2007*) examined the most critical tag parameters to provide an overview of strengths and drawbacks of major tag types available on market.

Performance evaluation of RFID systems based on measurements is a complex and costly task that requires significant investments into effort and knowledge. Automation of the measurements increases the effectiveness and thus also the level of precision that can be achieved with reasonable effort. This imposes demands on the target test equipment. Using commercial readers as a test equipment to determine performance of tags based on probabilistic measurements shown to be insufficient due to inconsistencies and high variation of parameters of such test equipment. On the other hand, not in all cases detailed information is needed and requirements on precision of collected results vary. *Puleston et al.* presented a testing framework for consistent evaluation of RFID tags in conceptual form of a pyramid (*Pulestone, Forster, 2005*). The test procedure is performed on primary, secondary, and tertiary systems that are response test systems, high speed inline and converter test systems, and application and end user test systems, respectively. *Murfett (2004)* analyzes the challenges of RFID integrated circuit (IC) testing. RFID ICs bring a unique problem into the development of standardized testing due to miniaturized sizes because of being high level integrated systems. The protocol level implements a certain degree of randomization and includes irreversible operations required to be implemented in the digital logic, like the destroy command. Mixed signal complexity of ICs makes testing of RF parts and digital logic equally important. Several proposals have been published and many are recently being reviewed by efforts of joint industrial and academic groups to develop an international standard on performance testing of RFID systems (*EPCglobal, RFID TAG Performance*).

3. Real-time evaluation of UHF RFID tags

This section presents the platform for real-time evaluation of UHF RFID tags.

3.1 Evaluation of UHF RFID tags performance

Tags are capable of receiving, processing and transmitting data if they are provided with DC voltage sufficient for their operation. In that case the tag is in an operating mode. The DC voltage is dependent on the immediate power density in the tag's location and furthermore on the structure and energy dissipation of the analog and DC circuitry, and other factors. The DC voltage is desired to be between certain limits. The lower voltage limit is called voltage power-on-reset (POR) threshold (*Derbek et al., 2005*). It is the critical one for tag's operability. If the POR threshold is exceeded, the tag is put in the operating mode and stays there as long as the DC voltage level is above the POR threshold. In case of underrun the tag is reset. Due to common techniques, like voltage buffering and multiplying at the rectifier, short drop-offs of the RF power (e.g. due to modulation) are compensated by the tag analog circuitry to prevent from resetting the DC modules. The POR threshold refers to certain RF field strength.

The tag sensitivity is a performance metric that indicates the minimum field strength, which is required by the tag to detect the reader signal, to process data, and to send a response. The tag sensitivity value can be converted directly into a read range that

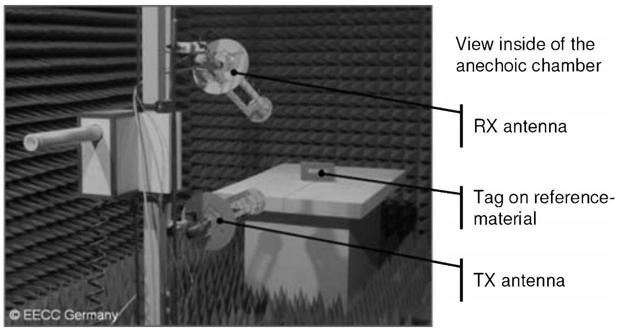

Fig. 2. A standard measurement setup at EECC for tag performance evaluations

would be achieved by the tag in a free space environment under certain frequency and power radiated by the reader.

The tag sensitivity is significantly influenced by objects to which tags are attached. Tagged product materials have an impact on the amount of power available to tags. Absorption, reflection and detuning are the major RF effects of the materials on the performance of tags. Absorption is an effect, in which a part of the RF energy radiated by the reader antenna is absorbed by objects that are found in the field. Reflection of RF waves results in distortions of the field homogeneity. In some locations, the field may be decreased, in other locations, the field may be increased. Detuning affects properties of the tag antenna by changing its impedance. The IC is then no longer matched to the antenna and the capability of the tag to receive and backscatter the RF energy of particular frequency is decreased.

Some materials like metals and liquids are responsible for reflection and absorption. These effects significantly decrease the RF field intensity in the tag's position. Other materials like plastic have a detuning effect. In most cases objects in the field cause a mixture of RF effects. The RF field in the vicinity of the objects is then generally decreased, which affects the performance of the mounted tag.

3.2 The RFID measurement and evaluation test system

The requirements on the implementation of the platform for real-time evaluation of UHF RFID tags are given by the operating range of tags. The power range used for testing has to cover both the maximum transmit power of 36 dBm and the tag operating power thresholds that are typically at −10 dBm. Further requirements are imposed on the receiver, which is expected to detect tag backscatter signals that can be as low as −70 dBm.

The proposed test system is implemented on the real-time verification platform of the Model-based Methodology for Real-time Verification and Optimization of UHF RFID Systems (*Derbek et al., 2007*). The system comprises a software configurable RF hardware, external RF components like amplifier and antennas, CPU controller and electro-mechanical devices to support for an automation of the measurement process. The platform is based on the PXI open industry standard (*PXI System Alliance; National Instruments*). PXI is a modular system, which is designed for measurement and automation applications. PXI stands for PCI eXtensions for Instrumentation. Hardware modules communicate over standard PCI bus, PXI trigger bus, and local busses. The system developed for the RFID test bed employs a 2.7 GHz RF Vector Signal Analyzer with Digital Downconversion and 2.7 GHz RF Vector Signal Generator with Digital Upconversion from National Instruments. The logical structure of the RFID measurement and evaluation test system comprises four main blocks as depicted in Fig. 3.

The digital and baseband processing block is responsible for processing waveforms and low frequency baseband signals. On the transmitter side, this includes the generation of the test stimuli that are various reader commands. On the receiver side, this block provides calculation of significant metrics, like read- and backscatter-range.

The modulator and RF transmitter block provides appropriate waveform shaping to the digital test sequence and modulation.

The demodulator and RF received block performs a demodulation of received signal, noise suppression, and tag response detection.

The measurement controller block is a CPU-based unit, which controls the measurement cycle, provides HW resource management and input/output data handling operations.

The signal received by the RF receiver is made up of two components: (i) Signal T transmitted by the reader damped by the reader's circulator and coupled back to the receiver and (ii) received tag backscattered signal B. The signal R received by the reader (not considering noise for this moment) has thus following general form:

$$R\sin(\omega t+\varphi_R)=T\sin(\omega t+\varphi_T)+B\sin(\omega t+\varphi_B)$$

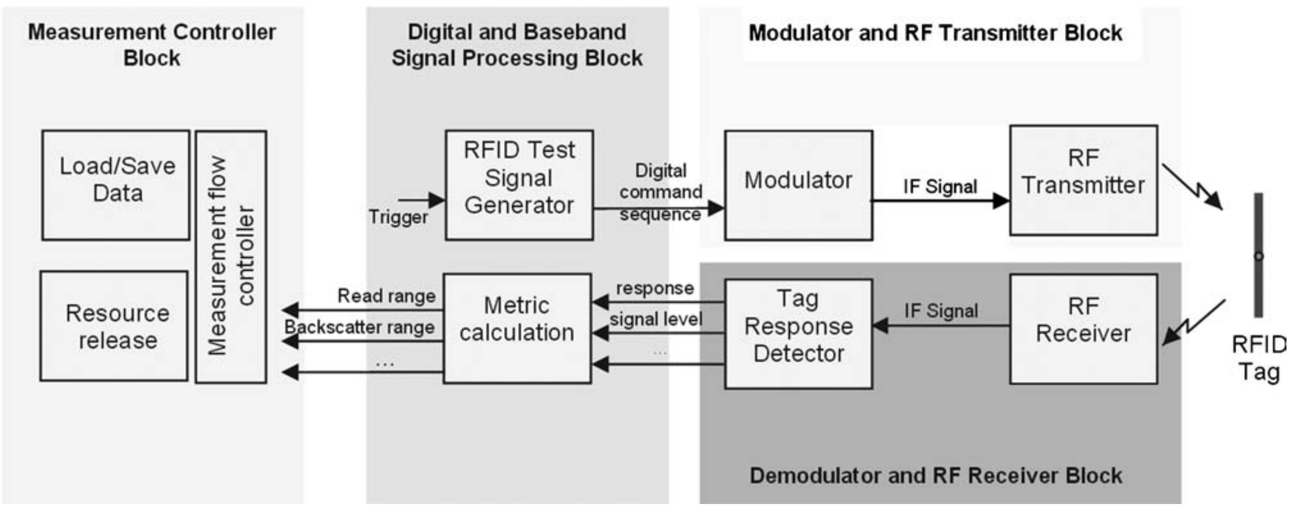

Fig. 3. Modular structure of the platform for real-time evaluation of UHF RFID tags

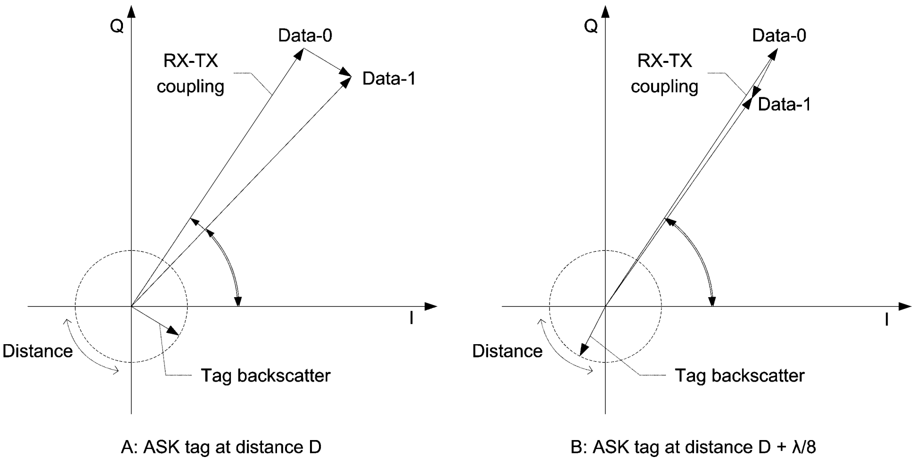

Fig. 4. Reader demodulator: phase vs. amplitude

where

$$T = \eta T_0$$
$$B = B(d)$$
$$\varphi_B = \varphi_B(d).$$

η is the transmitter-to-receiver coupling factor and T_0 is the amplitude of the transmitted signal. Both amplitudes and phases of its two components T and B are different. Amplitude and phase of the received backscattered signal are further functions of distance between the reader and the tag. The dependency of the phase φ_R of the received signal on the reader-to-tag communication distance d is expressed with Eqn. (3.2).

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta d$$

Hence, information received by a real receiver from a backscattering ASK tag is generally present both in amplitude and phase components. This is shown in

Figure 4. Shifting the tag by the distance of $\lambda/8$ away from/towards to the receiver prolongs the path of the signal by the distance of $\lambda/4$ and thus shifts the phase by $\pi/2$.

In the implementation of the Platform for Real-time Evaluation of UHF RFID Tags, the RF receiver is equipped by a full IQ demodulator, which is able to detect both ASK and PSK signals. The proposed system provides a fully automatic evaluation of the identification performance and properties of RFID tags, even when attached on product packaging. On the basis of the measurement results the optimal physical tag construction and ideal positioning on the relevant object can be identified. The reliability and repetitious accuracy is provided by eliminating external influences and adaptive compensation of internal HW attenuation like carrier cancellation to minimize the effect of the transmitter-receiver coupling.

3.3 Test setup

Tests were performed in the EECC laboratory in Neuss, Germany. The laboratory provides a controlled RF environment free of reflections and RF disturbances. The testing was performed on 30 randomly chosen tags among a large population of functional samples of each tag type. The applied test methods were following international standards of ISO/IEC and specifications of EPCglobal^{TM} on tag performance (*EPCglobal, RFID TAG Performance; ISO/IEC 18046-3*) and related standards (*ISO/IEC 18047-6; EPCglobal RFID Protocol for Communications at 860 MHz – 960 MHz; ISO/IEC 18000-6*).

The UHF tag performance tests were executed on reference objects. Major materials that appear in the field were classified into five bins. Each bin is represented by one reference object. The reference objects are possibly homogeneous materials of known properties to allow for traceability and reproducibility of results. Table 1 displays the reference materials that were used as substitutes for real products. Figure 5 shows the placement of two tags on two different reference materials.

The applied method to evaluate the tag performance is based on a periodical stimulation of the tag with a predefined reader command sequence at various transmit power levels and on continuous measurement of the tag backscatter signal and validation of tag response. A complete tag performance characteristic is derived from several sets of measurements. In the frequency dependent sensitivity measurement, the above described method is applied to a set of regularly spaced frequencies in the band from 800 MHz to 1 GHz. A tag sensitivity threshold, read range and backscatter range are obtained for every measured frequency from the measured complex tag characteristic. The test bed was furthermore equipped with a controllable turntable to allow for measurements of directional characteristics of tags.

Table 1. Mounting materials *(European EPC Competence Center, 2007)*

Reference material	Reproducible substitute for
Free air	Apparel hanger
Teflon (2 mm thick) of dimensions 200 mm × 100 mm	Paper or boxes with relative high air content. For example: diapers, disposable paper, large detergent boxes
Teflon (10 mm thick) of dimensions 200 × 100	Plastic cases, e.g. Beverage case (if distance to bottles is grater than 3 cm)
PET bottle with distilled water and 2 mm spacer	Products containing water, e.g. Ketchup, Dressings, Milk
Metal reflector of dimensions 200 mm × 100 mm with 4 mm spacer	Packages containing metal, e.g. Chocolate, Tetra-Pack, Coffee wrapper

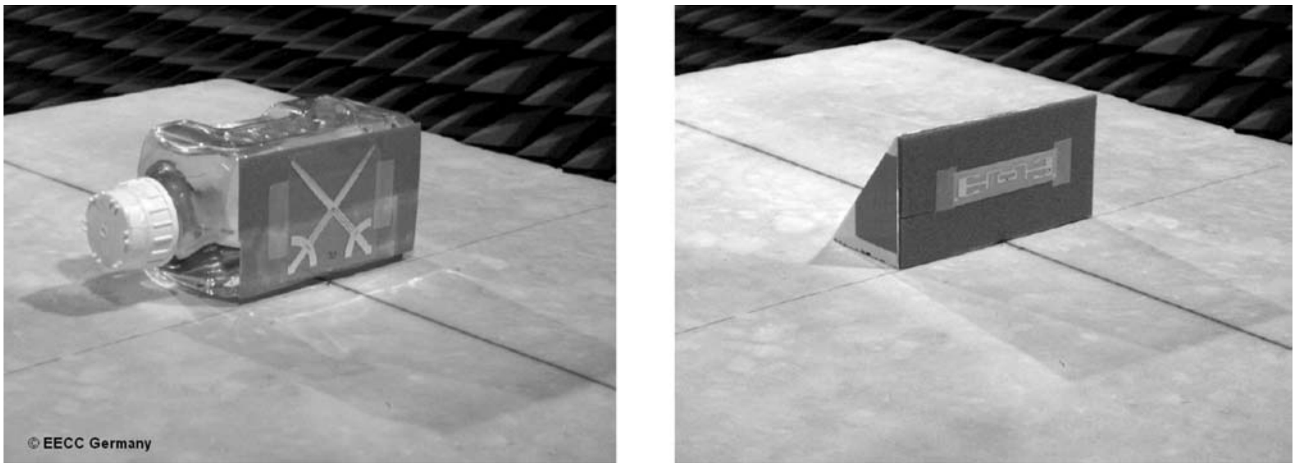

Fig. 5. Two different tags placed on a water container with a spacer of 2 mm and a metal surface with a spacer of 4 mm

4. Test results

As indicated in earlier chapters tag power effectiveness is one of the key factors that influence the identification rate. It plays a major role in optimal setting of the communication protocol and field setups. While the power effectiveness of tag IC is dependent on the design, the effectiveness of tag antenna is further influenced by objects surrounding the tag.

Figure 6 shows results of dipole tag directional power effectiveness measurements performed on the above described test bed in free space. The testing hardware stimulates the device under test (tag) with signals and evaluates its responses. The performance of the tag was quantified by the number of tag responses provided to reader packets in a correct and timely manner. The measurement was taken on one frequency with a horizontally positioned tag that was rotating around the vertical axis. The target was to evaluate the angular characteristic of tag sensitivity. In addition, Fig. 1 shows the orientation dependent sensitivity of an omni-directional tag.

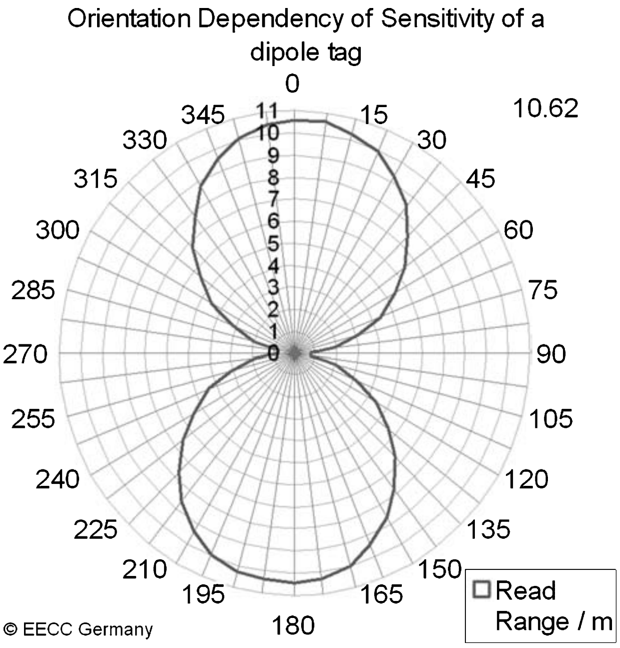

Fig. 6. Orientation dependent sensitivity of a dipole tag

In the tag sensitivity measurements, the result can be expressed also as read-range. The read range is not only dependent on the tag performance itself, but also on the carrier frequency and the maximum power transmitted by the reader. Therefore the same

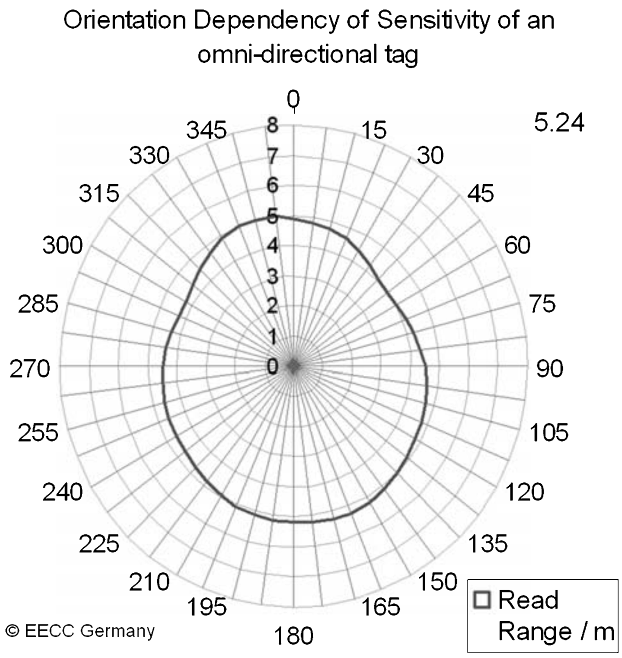

Fig. 7. Orientation dependent sensitivity of an omni-directional tag

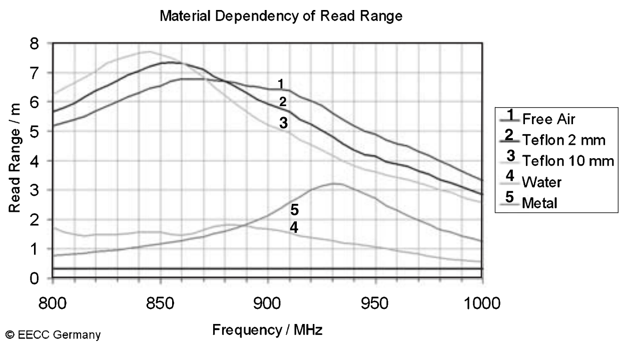

Fig. 8. Material dependency of read range

tag will have different read ranges in individual regions around the globe due to different frequencies and power levels used. In the frequency-dependent sensitivity measurement (see Fig. 2), the tag sensitivity is evaluated for each of the predefined discrete frequency levels.

The backscatter range is a metric that determines the strength of the tag response assuming a reader with certain sensitivity and antenna. Figure 9 shows a result of such measurement, displaying a theoretical backscatter range of up to 38 m. This result gives clear evidence that the performance of the particular tag is not limited by the return link. Additional measurements were covered by a production consistency test, in which a large set of tags of the same type were tested to determine the performance variation due to production inaccuracy.

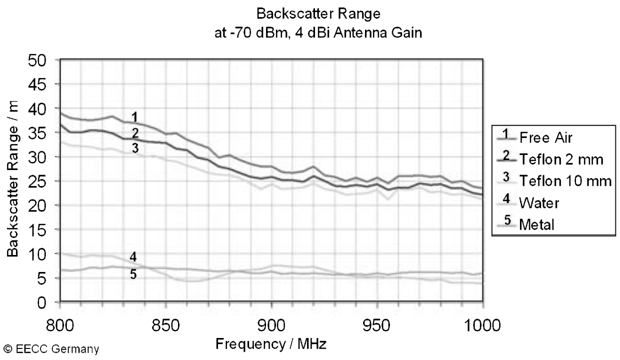

Fig. 9. Backscatter range measurement

The evaluation of 20 tag types can be summarized as follows:

- dramatic differences between different ICs
- large variances on production consistency
- not all tags are good performing at global operations
- large differences between orientation sensitivity
- read Range of more than 10 m was measured
- read Range always limited by forward link at typical applications (Backscatter Range is greater that forward link range)
- some tags have problems at higher power-levels

A full report that contains results of all performed measurements and the evaluation of all 20 tested tags is available at (*Derbek, 2007*).

5. Conclusion

The RFID industry has been strongly concerned about the issue of achieving a reasonable performance in tagging products containing various materials. The proposed platform provides means of quantification tag performance and to reveal potentials for enhancements. The platform has verified at an extensive set of tests that were performed by the EECC Germany. The obtained results provided a comparative overview of strengths and weaknesses of various tags in individual application cases.

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Currently, he is active participant in several standardization groups in the ISO/IEC JTC1/SC31 area, convenor of the ISO/IEC JTC1 SC31 WG3/SG1 for RFID performance + conformance, which is responsible for ISO/IEC 18046 and ISO/IEC 18047, and convenor of the Austrian standardization group responsible for RFID. Furthermore, he is project editor for the ISO/IEC 18000-6 and worked on the amendment for type C, which is the EPCglobal^{TM} UHF Class 1 Generation 2 integration into this ISO standard. Under his leadership CISC joined the EPCglobal Inc. in 2004. He is also deeply involved in the EPCglobalTM work. Currently he coves the co-chair positions of SB JRG (Sensor and Battery Joint Requirements Group) and HACET (Hardware Action group ad hoc advisory Committee to ETSI). Inside CISC he set up the BU RFID + RFComm with its major activities in modelling, simulation, design and evaluation of RFID systems and RFID applications for LF, HF and UHF. The major focus in RFID system design is to support product and system design with simulation and measurement tools. This includes a full simulation environment for EPCglobal^{TM} UHF Class 1 Generation 2 based application considering protocol, identification software and detailed RF aspects.

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