IOT: PROTOCOL STACK, CROSS-LAYER, AND POWER CONSUMPTION ISSUES

GEN2 RFID AS IOT ENABLER: CHARACTERIZATION AND PERFORMANCE IMPROVEMENT

PETAR SOLIC, ZORAN BLAZEVIC, MAJA SKILJO, LUIGI PATRONO, RICCARDO COLELLA, AND JOEL J. P. C. RODRIGUES

ABSTRACT

RFID has become an enabling technology for IoT implementation. In dynamic RFID scenarios, such as smart shops or industrial surroundings, it is crucial to identify every good, with an applied RFID tag, before it leaves the interrogation area. Currently, commercial reader solutions adopt DFSA protocol as a simple MAC that manages the communication between a reader and multiple tags. To increase DFSA throughput (the number of read tags in the unit of time) and thus speed up tag identification, simple calculations show that the number of tags should equal the frame size. However, the literature exhibiting RFID performance shows that tag responsiveness is stochastic, while this has been often neglected when considering the throughput. To investigate the influence and to define related research challenges in the RFID domain, this work provides the idea of the required measurements by using SDR technology, while arguing that PHY and MAC layers should be looked at integrally. If not, tag identification will be delayed, while at the same time unnecessary energy waste will occur. In the measurement campaigns, the metric of TRP is employed, given as tag response probability distribution, which can be used for modeling the MAC layer.

INTRODUCTION

Radio frequency idenitification (RFID) technology, based on wireless communication between a reader and tags, has become the most popular technology for item identification and tracking, and thus the main enabler for the Internet of Things (IoT)vision. Among all available RFID technologies, solutions compliant with the EPCglobal Class-1 Generation-2 (hereafter Gen2) standard [1], working in the ultra high frequency (UHF) band, are the most popular, thanks to both the best price-performance ratio and the capability to work worldwide. Indeed, Gen2 defines the physical and logical requirements for an RFID system and defines the guidelines for its interoperability across different country regulations. Besides the maximum emitted power and working frequency for each country, Gen2 defines and harmonizes other important aspects such as: air interface management, modulation, communication timing, bit rate, the number of bits (typically 96) of programmable memory for storing the Electronic Product Code (EPC), channel accessing rules, and the low-level reader protocol (LLRP) command set.

In addition to the global compliance provided by Gen2, the highly reachable reading range (about 10 m [2]) and the low cost (about US$0.1 per tag) definitely make RFID technology the main competitor of traditional barcode-based identification systems and therefore the more suitable solution for item or object identification. Both high performance and low cost are achievable at the same time thanks to simple and effective passive tag electronics, which consists of a flexible label-type antenna and an integrated circuit (IC) embedding a rectifier. The rectifier is capable of harvesting a portion of the electromagnetic energy transmitted by the reader antenna and energizing the internal circuitry of the IC. Once the IC is powered up, the tag uses the same incoming radio waves to transmit required data by utilizing the technique known as backscattering communication [2]. Tags vary their input impedance in a timely manner, which the reader sees as an amplitude modulated carrier.

In a complex scenario, in which a number of tags simultaneously backscatter their response on the same carrier frequency, the occurrence of multiple access on the same channel at the same time will cause signals to be summed up in the channel, thus making the reader potentially unable to decode them. This is usually referred to as a collision. Therefore, Gen2 specifies the usage of Dynamic Frame Slotted ALOHA (DFSA) protocol as the medium access control (MAC) mechanism [1]. In DFSA, the communication is divided in frames, which are later divided in slots. To communicate with the reader, each tag takes a random slot and responds when its slot is interrogated. In this way, theoretically, the slot can be empty (no tags inside), successful (one tag inside), or collisional (multiple tag responses that the reader is unable to decode). To achieve the maximum throughput, that is, to maximize the number of successful slots, simple calculations show that the frame size should be equal to the number of tags, and in this way the throughput reaches the upper bound of 37 percent [3].

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Some works [4, 5], focused on RFID tag performance, have already shown that there is some probability that a single tag, although found in the interrogation area, can be missed during its read process. The reasoning behind this is either tag antenna detuning when placed on different materials [5] or fading/interference in the wireless channel [6]. Furthermore, [7] shows that a Gen2 tag IC possesses a nonlinear input characteristic, that is, its input impedance is both frequency- and received-power-dependent. This means that, in certain scenarios, due to the mismatch between the IC and the antenna, a tag will not be able to harvest enough energy to respond properly. Therefore, the flops in tag readings seem to appear as a consequence of the cumulative effects of the different phenomena listed above.

As the tag responsiveness seems to be purely stochastic, some metrics should be employed to better understand tag responsiveness at the PHY layer in different environments (called unresponsive and weak tags in [8]), since it is crucial for optimization of the MAC layer, and consequently for all other layers. If not clearly understood, the tag presence will be late, causing unnecessary latency in its identification process, implying energy waste, critical for mobile RFID readers due to their limited battery lifetime. This rather important information, which models tag responsiveness and fits the gap between theory models and real system behavior, still seems to be missing in the literature. Therefore, this article shows, in tutorial fashion, how to utilize the cost-effective software defined radio (SDR) platform to conduct a set of measurements validating the interrogation process of a Gen2 RFID system.

SDR is an innovative technology in which all the physical parameters of a radio front-end are completely software defined. Different from the traditional hardware-based radios in which low-level functionalities are permanent, in SDR devices all functionalities can be modified and personalized easily and inexpensively, by means of software upgrades on standard hardware architectures. For instance, a Gen2 reader can be completely software-defined to emphasize some features and detect specific metrics while reading tags.

This custom-based reader architecture enables collecting the information on responsiveness, while at the same time using it to optimize the required time to identify tags at the minimum required energy. Understanding this gap completely leads toward employing IoT systems to different environments, knowing at the same time what cons to expect. For this purpose, a Universal Software Radio Peripheral 1 (USRP1) SDR platform with a Gen2 RFID reader application [9] is used, while its configuration and data interpretation are explained. Reported results are obtained in an indoor scenario, where the channel is measured to be without deep fades/nulls. The reader is configured to retrieve the tag responsiveness at the robust communication settings. Data is interpreted through a metric that gives the probability of the tag to be detected at the single read command: tag read probability (TRP). First, the article presents how the specified platform can be used to extract the minimum value of irradiated power able to wake up a tag (i.e., tag sensitivity), considering the tag attached to different materials. Then it shows robust measurements that extract full TRP for a given tag-on-Styrofoam scenario. These experiments show that the variation of both output power and frequency affects the throughput. Further, it shows what has to be done in order to include such behavior and thus optimize the reading rate. The given results describe actual savings in both time and energy when applying the described corrections to standard models.

Employing IoT on a worldwide scale still presents a big issue due to the problem of powering such tiny devices. Although they are power-efficient, replacement of depleted batteries complicates things for consumers. As technology is advancing, less energy is required for its operation, and wireless power transfer becomes a feasible way to power it. Therefore, modeling and analysis given in this article are of great importance for all IoT systems that wirelessly power their devices. As described in this article on an RFID use case, such remotely powered devices sometimes do not receive enough energy, leading to failure in the procedure of transmitting and receiving data, and hence waste both time and energy. Therefore, to optimize these links, the behavior described in this article should be taken into account when modeling such systems.

The article is structured as follows. The following section summarizes the tag interrogation procedure, and describes the measurement setup. Following that we give the measurement result analysis, along with modeling the MAC layer. The final section reports our main conclusions.

Radio Frequency Idenitification (RFID) technology, based on wireless communication between reader and tags, has become the most popular technology for item identification and tracking, and thus the main enabler for the Internet of Things vision.

Gen2 RFID Read Process, Measurement, and SDR Reader Setup

In this section, the Gen2 RFID tag interrogation procedure is described while providing influences of the real RFID system on the throughput in such an interrogation procedure. Then, to ensure the repeatability of the procedure, the details on SDR Gen2 RFID configuration and measurement setup are given, while describing the procedure for measuring the tag sensitivity and extracting TRP.

Gen2 RFID Read Process

The read process in Gen2 RFID is organized into cycles that contain multiple frames. Each frame starts with the reader transmitting a *Query* command, containing all relevant information for tags to respond. Within *Query*, the Q parameter is specified, which determines the size of a given frame. Upon reception of Q, all tags set the counters to the random value between zero and $2^Q - 1$. The generated number actually presents the slot counter, that is, the position within the frame where the tag is responding. The reader decrements the slot counters by transmitting the QRep command after the interrogation of each slot. Once the tag's slot counter reaches zero, the reader begins the tag interrogation process (depicted in Fig. 1). The tag answers with a 16-bit random number (RN16), which the reader acknowledges with ACKRN16, and the successfully read tag means that finally the tag's EPC (i.e., its ID) has been read successfully. New frames will restart the upper procedure until all tags are read, which denotes the end of the cycle. It is

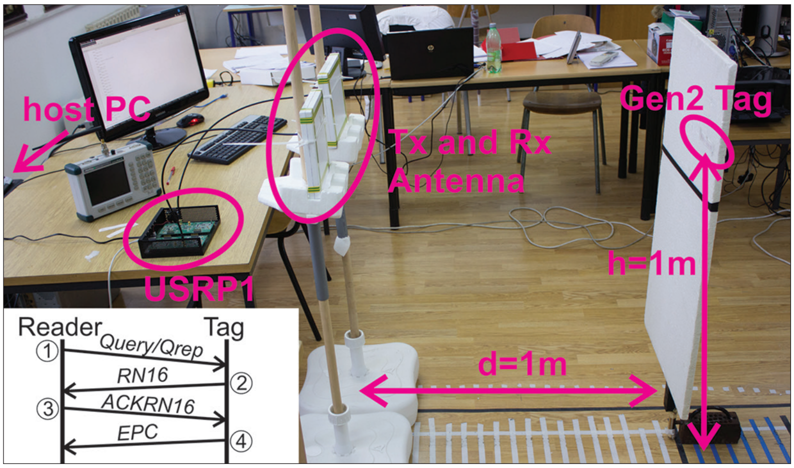

FIGURE 1. Measurement setup and Gen2 tag interrogation process.

Param.	Value	Description
Tari	24 µs	Duration of data-0 reader to tag symbol
RTCal	72 µs	Duration of (data-0 + data-1) reader to tag symbol
BLF	40 kHz	Backscatter link frequency (tag to reader)
TRext	1	Denotes the addition of pilot tone to tag preamble
M	4	Number of Miller-cycles per symbol in tag response

TABLE 1. SDR Gen2 reader [9] interrogation parameters.

important to note that each of these steps may fail due to a number of reasons creating a necessity of a new interrogation procedure in order to read all missed tags.

DFSA Throughput: The upper procedure is actually a version of DFSA), where tags pick the slots randomly and respond back to the reader. During the interrogation, it may happen that the slot is occupied by a single tag (successful slot), no tag (empty slot), and multiple tags that, theoretically, could not be decoded by the reader (collision slot). Related analysis available in the literature shows that in order to maximize the number of successful slots, the frame size should be equal to the number of tags [10]. However, the number of tags participating in the communication may not be the same as the one located in the reader interrogation area. Then, to achieve the maximum throughput, this information should be incorporated in the models, and its influence should be emphasized. The reasons for such behavior are the impedance mismatch between tag and antenna (due to RFID tag IC nonlinearity), noisy channel, the material to which the tag is being attached, and so on. Therefore, the study of responsiveness on the single read command is required and has to be deeply understood in order to provide its influence on the throughput.

SDR Gen2 RFID Reader Setup

To obtain the results, the measurements were carried out in an indoor environment containing tables, chairs, wooden cabinets, and laboratory equipment, depicted in Fig. 1. The USRP1 reader uses two RFX900 boards with Tx and Rx patch antennas (both 6 dBi gain). The tag (Alien-9640 [11]) was placed 1 m away on the Styrofoam panel and located within the direct beam of reader antennas; both reader antennas and tag were located 1 m above the ground and away from the objects (Fig. 1). The measurements were conducted for 1 MHz hops of the U.S. Gen2 frequency band (902–928 MHz [2]), taking 2 MHz out of the given band, while attenuating output power levels (by steps of 1.5 dB) starting from the maximum output power of the reader (26 dBm). Actually, the variation of the reader's output power gives off an effect as if the tag is being moved toward or away from the reader. In addition, the spectrum was analyzed, and it showed that the used RFID system was the only one operating at the tested frequencies. Furthermore, the communication channel between the reader and the measured tag (at measured frequencies) was measured, and it showed that there were no deep fades/nulls that could additionally degrade tag performance.

It is important to note that the SDR platform we used does not include automatic gain control (AGC), and therefore the receiver gain should be changed manually. This is an important feature as it gives the relationship between the amplitude of tag responses in different cases, and thus it is easier to understand the tag behavior in different surroundings and to provide conclusions. Moreover, when a bistatic RFID setup is used, there is always some power leakage from the transmitting to the receiving reader antenna that affects the value of optimum receiver gain. In our case, the leaked power is 33 dB below the one supplied to the transmitting antenna. Its degrading effects are likely to pronounce themselves when the transmitting power is high because the maximum power a tag is able to return to the reader is limited.

The reader is configured to send 50 cycles of interrogation with 1 *Query* per cycle, and fixed $Q = 4$. In this way, tags are forced to respond 50 times. Other reader parameters that ensure a reliable radio link are based on [6] and specified in Table 1. To describe the tag performances, the metric of TRP was used, which is calculated as the number of correctly decoded tag responses (EPCs) within 50 trials.

Measurement Results and Tag Read Probability

First, the procedure to obtain the sensitivity (minimum RF power required to obtain tag response) and extract TRP is described. Then the full analysis of tag behavior by the received power, gain, and frequency is given. Finally, the last subsection contains the discussion about the influence of the tag responsiveness on the throughput.

Measuring the Sensitivity

As tags power themselves remotely by using the RF energy transmitted by the reader, the minimum energy must be collected by the tag antenna and supplied to the IC through AC/DC conversion in order to obtain the tag's response. The amount of the harvested energy depends on various factors, such as the antenna directivity and matching, and the conversion loss at the power level received by the antenna. In practical usage, the tag is likely to be attached to certain materials that may influence antenna radiation pattern, input impedance, and resonant frequency, which may also introduce loss. Thus, the same tag attached to different materials is expected to exhibit different RFID performance.

In order to address this issue, the SDR platform is used while the tag is being attached to different materials: a Styrofoam board (permittivity ε_r close to that of air), empty glass bottle $\varepsilon_r < 10$, negligible specific conductivity σ), a plastic bottle filled with fresh water of $\varepsilon_r = 80$ and $\sigma = 0.9$ S/m approximately, and a plastic bottle filled with salty water of much greater specific conductivity. The results presented in Fig. 2 show tag performances in the cases given above with the optimum gain control in 5 dB steps. The comparisons of the TRP measurements at two selected frequencies are given. As expected, the results show that the tag sensitivity deteriorates with increasing permittivity and conductivity of the material to which the tag is attached. At the same time, the optimum receiver gain exhibits inconclusive correlation with the material, but the changes of its value with the transmitted power show a similar trend to a degree. This manual change of gain appears to be extremely useful for debugging and retrieving tag amplitude, useful for extracting the amplitude of collided tags and then the probability of detecting one of them — this effect is called the capturing [12].

TRP: Power, Gain, and Frequency Dependency

Complete responsiveness can be obtained by putting the tag in the interrogation area, and by changing the output power, frequency and receiver gain.

The results of measurements at a fixed SDR gain of 24 dB, depicting TRP vs. frequency and the reader output power, are presented on the left side of Fig. 3. It also includes the situation in which the tag correctly transmitted its EPC, even though the reader decoded it wrongly for certain reasons (denoted as ERR). The distinct compact areas of high TRP (marked by warm colors), clearly separated from those of low TRP (marked by cold colors), can be noticed. The areas of erroneous readings are concentrated mainly at greater power levels, along the borderline regions between high and low TRP areas. The frequency span between roughly 905 MHz and 915 MHz exhibits reliable TRP performance regardless of the transmitted power. In order to assess the TRP limits that can be reached by the USRP setup, special attention is given to frequencies greater than 915 MHz where wide areas of low readability exist.

Since, as previously verified, neither appreciable fading nor interference affect the channel, the observed power-dependent performance degradation effect could likely be due to three main factors, and above all due to a combination of these factors when varying the frequency. The first factor is the dipole-like structure of the tag antenna. The second one is the quality of the conjugate impedance matching between RFID IC and

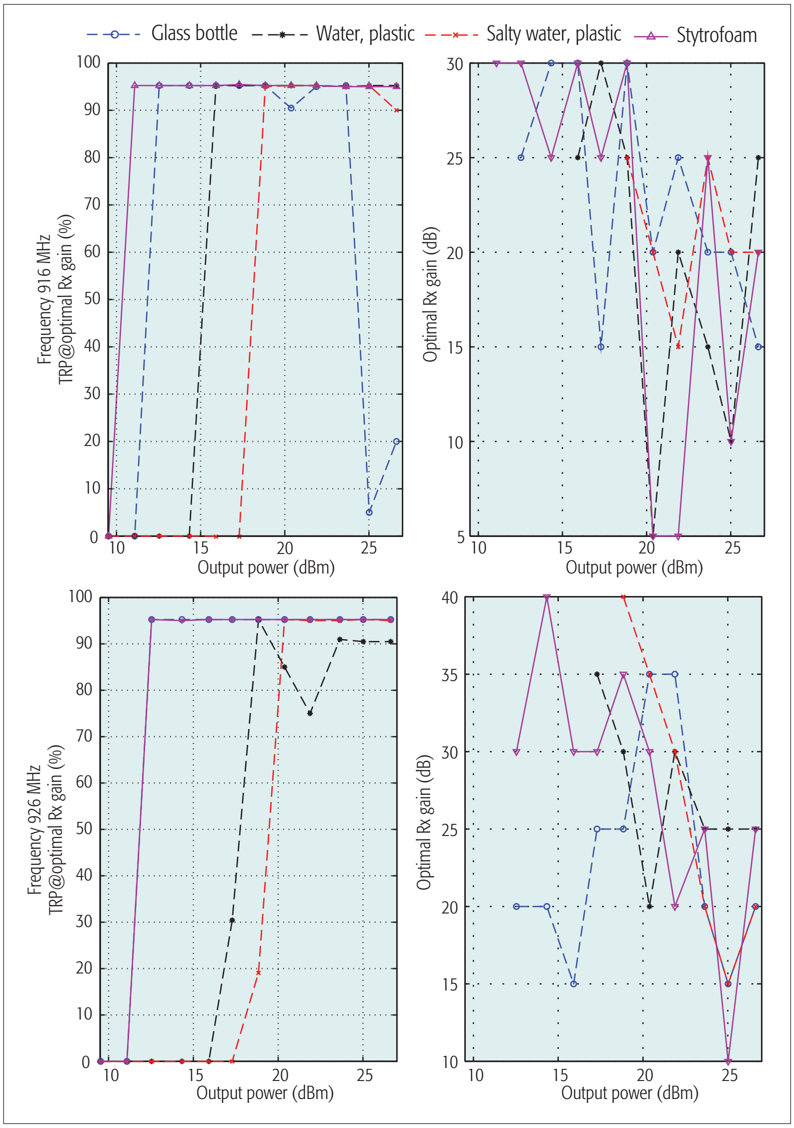

Figure 2. Measurements - tag sensitivity measurements and the optimum receiver gain of used SDR platform at two transmitting frequencies. Tag is located 1 m away from reader; 1 m above the floor; and in the direction of maximum radiation of reader antennas.

the antenna. The third one is the intrinsic dependence of the RFID IC's impedance on the input power level. Regarding the tag antenna structure, the Alien-9640 antenna is essentially a narrowband meandered dipole with two capacitive top loadings [2] at the end of dipole arms. Regardless of the fact that these last structures tend to spread the antenna working band, an ideally flat response in the whole U.S. RFID range cannot be obtained. As for the second reason, when an RFID tag is designed, the optimum conjugate impedance matching is typically performed at a certain frequency (generally the center one), considering above all the chip reference impedance evaluated at the sensitivity threshold. This condition makes the tag highly responsive at the reference frequency, but introduces virtually unpredictable behavior when the working frequency is varying. Finally, as for the third reason, it is worth highlighting that the input impedance of an RFID IC is not constant. On the contrary, it can easily be demonstrated that due to the presence of the RF energy

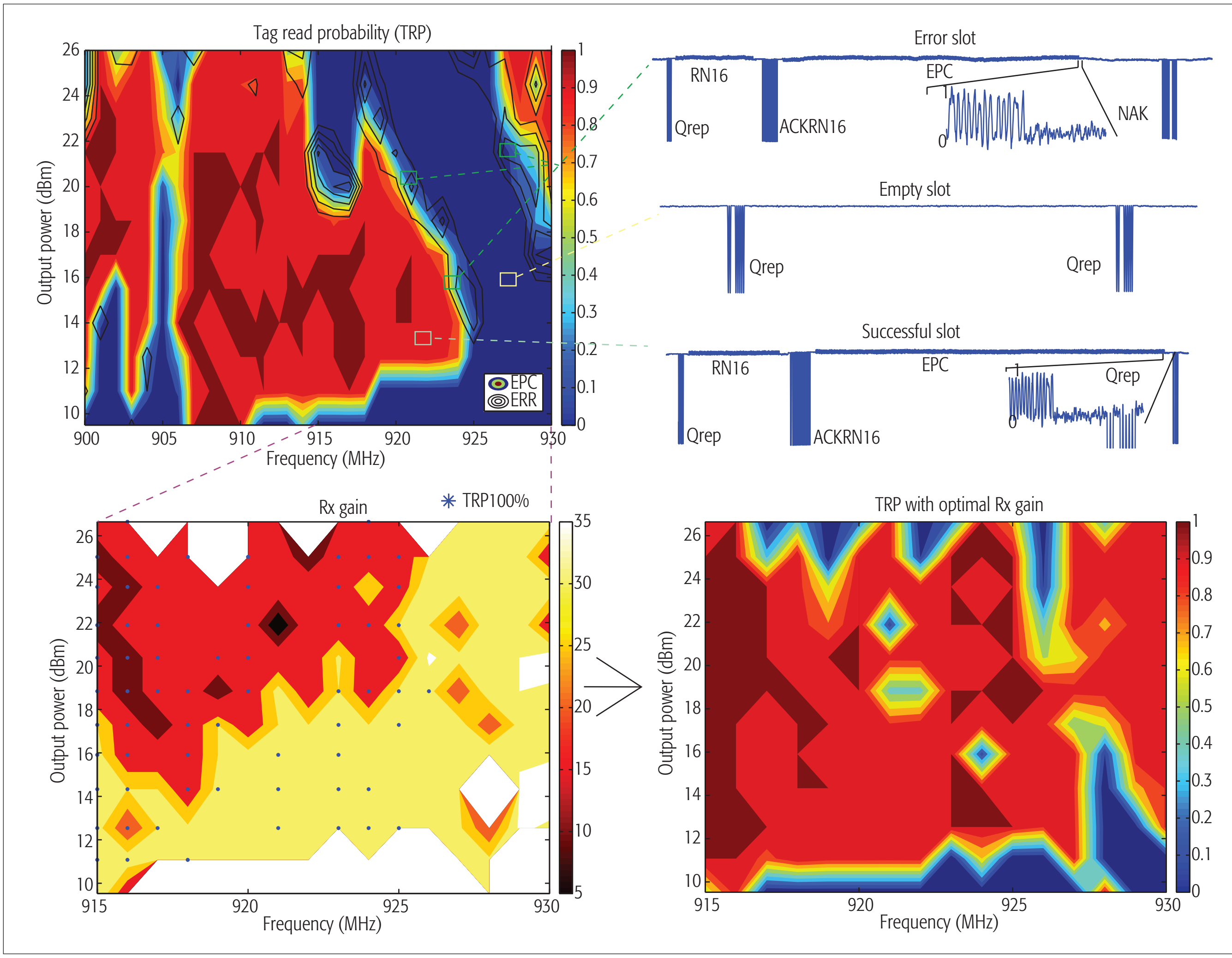

FIGURE 3. Measurements: TRP and the optimum receiver gain vs. central frequency and transmitted power. The upper right figures present time-domain signal in the reader-tag communication. The first (most frequently found in the areas bounded by closed lines) shows EPC read fail. It can be noticed that the tag has lost energy and could not complete the whole transmission. The second (most frequently found in the cold colored areas) shows that no tag is found in the slot. The third (most frequently found in the warm colored areas) shows a successful slot. The tag responds with EPC, and the reader sends another QRep to interrogate the next slot.

harvesting block and the absence of a maximum power point tracking (MPPT) system, the input impedance is rather power-dependent.

In a standard RFID system, where functionalities such as frequency hopping or multiple interrogations are active, the effect of these three factors on tag performance is averagely attenuated and, consequently, the whole system is more reliable. Differently, where the tag is interrogated at a single frequency, with a single power level, and for a limited time, as in the proposed study, the performance degradation due to the combination of the above mentioned effects becomes appreciable. Consequently, it can be observed, analyzed, and, when possible, compensated.

Indeed, in Fig. 3 (lower left), the optimum gain at which the maximum TRP is obtained for the examined power-frequency span is depicted. Note that the lower frequency and higher output power setup requires lower receiver gains, and that the optimum receiver gain increases as the transmission frequency increases. Hereby, the blue markers show the results where TRP is found to be equal to one. Other spaces missing the blue marker mean that TRP is below one, and tag behavior is unstable.

The maximum TRP obtained by the optimal gain is depicted on the right side of Fig. 3, where higher TRP performance improvements are clearly shown. Again, manual change in gain appears to be extremely useful for debugging the results and retrieving tag responsiveness.

By inspecting the received waveforms (examples are provided in Fig. 3), the cause of errors is the lack of the energy to complete the data transmission or bit errors. By comparison of the obtained data and those given in [13] for 20 dBm output power, the same tag type, and similar measurement layout, it can be concluded that they are well coordinated. The best TRPs were obtained exactly in the frequency span where the tag's differential radar cross-section (RCS) is the greatest, whereas lots of erroneous TRPs coincide with the frequencies of lower and fluctuating signal-to-noise ratios (SNRs) above roughly 915 MHz measured in [13].

Furthermore, the contour plot in Fig. 3 clearly shows that radiation of excessive power is often

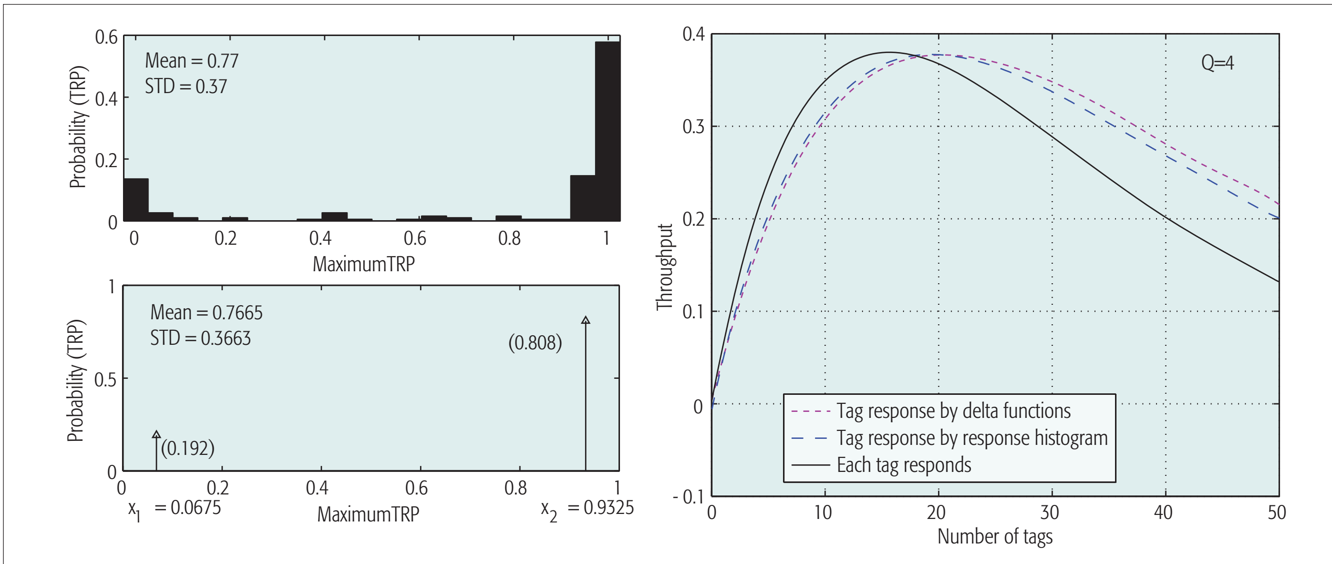

FIGURE 4. The impact of responsiveness on the throughput.

not convenient for achieving satisfactory tag responsiveness, especially for the ones settled in the reader's proximity. On the other hand, lowering the output power means sacrificing the read range (due to the limited tag sensitivity, see [14] for details), and consequently, a careful trade-off is requested. Therefore, it is worth noting once again that output power and central frequency settings are of crucial importance when considering RFID system performance.

THE IMPACT ON GEN2 RFID THROUGHPUT

To communicate with multiple tags, Gen2 RFID uses DFSA. As demonstrated in this article, there is a certain probability that tags are missed (failed in reading) during the interrogation process. As optimal throughput can be achieved only when the frame size equals the number of tags, some metrics should be employed to describe tag responsiveness, and thus to optimize the throughput. In order to do that, TRP results given in Fig. 3, can be described by histogram given in Fig. 4. Furthermore, it could be modeled with a random variable X containing two-state delta distribution-analytic form [15], which can be used for TRP modeling:

$$p(X) = A_1\delta(X - x_1) + A_2\delta(X - x_2) \quad (1)$$

where A_1 and A_2 denote the probability of the low and high responsiveness state, respectively, and amplitudes x_1, x_2 are probabilities of a tag being read if found in given states. The throughput for all scenarios — all responsive tags, histogram-based, and delta-based responsiveness — are shown in Fig. 4. Note that the capturing effect, as mentioned in the previous section, is the phenomenon that occurs in a real interrogation scenario. Its impact on the throughput in this approach has been neglected, and requires in-depth statistical analysis.

The given results imply that tag responsiveness brings some additional uncertainty into the DFSA mechanism (i.e., its proper frame size selection). Further, the optimization in the sense of the proper frame size selection has direct impact on energy consumption. As shown in Fig. 5, the reading rate (in terms of the total time required for tag identification) is significantly increased by the optimization. It can be seen that for the reader with constant output power, the time saved by the procedure is directly proportional to the saved ener-

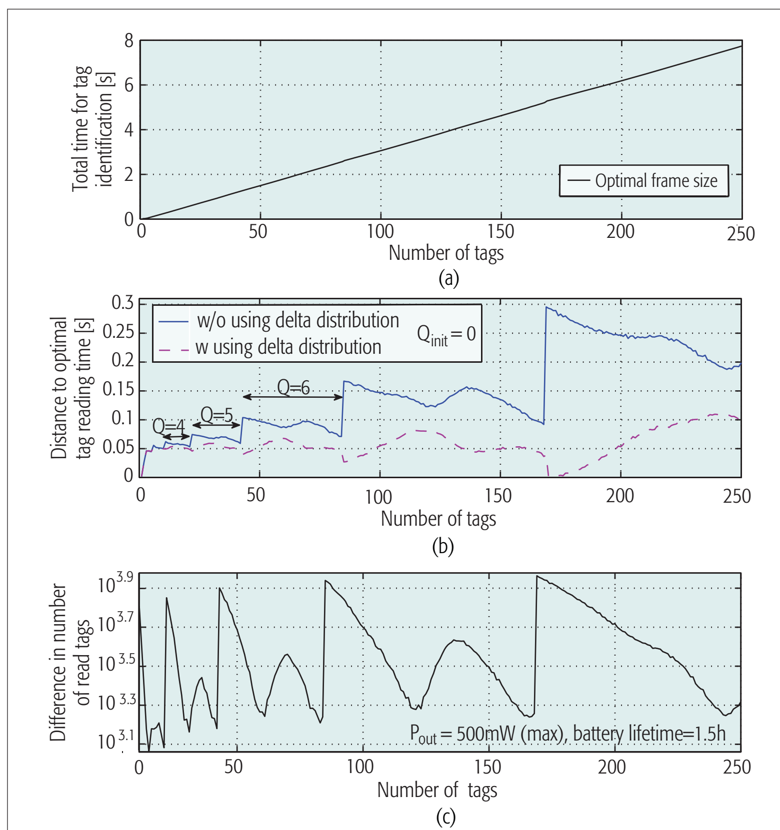

FIGURE 5. Impact of tag responsiveness on the tag identification time in our SDR setup: a. Time (lower bound) to identify all tags with optimal frame size; b. Distance from lower bound with using or without using delta distribution model; c. Additional number of tags that can be read by using delta distribution model for limited battery lifetime scenario.

It is worth noting that this approach should be applied to all IoT systems that have some uncertainty regarding device responsiveness in communication/wireless power transfer links. In such systems the corrections described in this article should be applied in order to achieve the best possible performances.

gy, that is, to the increment of the RFID battery life span. Take an example from [10], where it is noted that a mobile RFID reader with the maximum RFID output power of 500 mW drains the battery of 3000 mAh within 1.5 h. Considering the battery voltage of 3.3 V, it discharges at the maximum rate of 6.7 W. The gain in the overall number of read tags due to the prolonged battery life achieved by the shortening of the tag reading procedure vs. the number of tags (in one reading block) is depicted in Fig. 5c. It shows a tendency of mild increment with the number of tags.

It is worth noting that this approach should be applied to all IoT systems that have some uncertainty regarding device responsiveness in communication/wireless power transfer links. In such systems the corrections described in this article should be applied in order to achieve the best possible performance.

Conclusions

This article presents how to utilize the SDR platform to retrieve the actual performance in Gen2 RFID systems for IoT applications, while showing how to interpret the obtained data. First, the results are obtained in the manner of tag responsiveness on different materials, and then the robust analysis for tag-on-Styrofoam responsiveness is provided. The important feature in this kind of analysis is the control of the receiver gain, where the amplitude in tag response can be retrieved. Finally, this stochastic behavior is modeled, and the impact on the throughput is shown. In terms of tag identification time, a significant impact of tag responsiveness on the latency is shown, which, at the same time, has consequences on energy consumption. As a consequence, the optimization of tag reading rate and power consumption should be looked at integrally while using the correct tag responsiveness model.

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Biographies

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Riccardo Colella, Ph.D., is a research fellow in electromagnetic fields at the University of Salento. His main research interests are in the area of RFID technology with the design of novel devices and antennas enabling RFID sensing in the Internet of Things. He authored more than 70 scientific papers, two book chapters, and a patent.

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