A Bidirectional Semi-Passive DS-CDMA-RFID Transponder for the UHF Band

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***Abstract*—This paper presents a first realization of a semi-passive UHF RFID transponder featuring a direct sequence code division multiple access channel access method for the RFID uplink, and, in addition, some limited downlink abilities, including carrier frequency and field strength measurements. The paper shows experimental results of the proposed transponder, which is already included within an UHF RFID system, containing an RFID reader being able to read out the transponders' data. The focus of this work is on the transponder's modulator, generating an ASK-like modulation scheme by impedance miss-matching techniques. This paper presents results obtained from real life measurements of a realized UHF RFID transponder qualified for the application in CDMA-based RFID systems.**

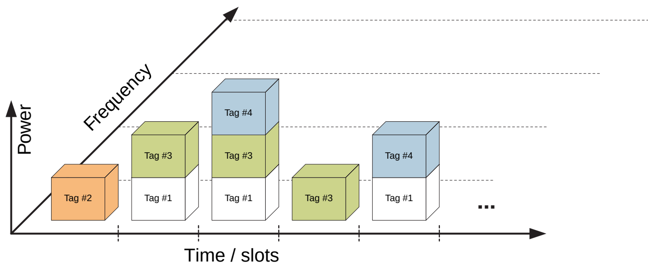
***Keywords*-Radiofrequency identification; UHF; transponder; Backscatter.**

I. Introduction

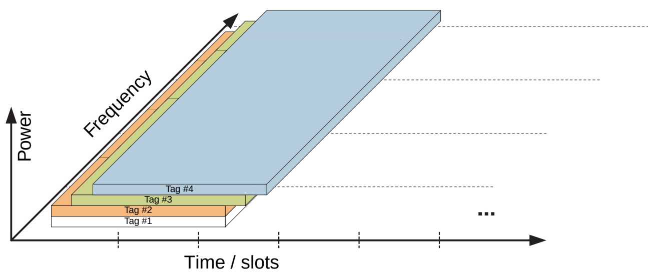
Through an increasing number of RFID (Radio Frequency IDentification [1], [2]) tags (transponders), particularly UHF tags [3]–[6], the need for a fast recognition of innumerable RFID tags puts great demand on future RFID readers [7]. If several tags are located within the range of a reader, signals from some of these tags collide [8]. This is the reason why anti-collision procedures [9] are widely used to prevent tags from broadcasting their information simultaneously. Existing RFID multiple access solutions are based on Time Division Multiple Access (TDMA [10]). Fig. 1a shows the TDMA method, pointing out that the tags in the reader's field transmit their data at different moments in time [1].

A simple TDMA protocol is the well known ALOHA protocol [11]. Basically, there are two modes the ALOHA protocol may be used with: pure (unslotted) and slotted ALOHA [12]. When using pure ALOHA [13], data are being send at any times the channel is available. Because there is no control over the starting time, a collision is difficult to predict. Slotted ALOHA, on the other hand, is based on time slots which synchronize the start of transmission. Collisions can be predicted more easily and only happen, if at least two tags are requesting at the same time a free slot (e.g., slot 2, 3 and 5 in Fig. 1a).

The anti-collision procedure of the commonly used RFID standard EPC Class1 Gen2 [14] is based on slotted ALOHA. A so called Q-parameter controls the inventory process by determining the maximum number of possible time slots,



(a) TDMA: Time Division Multiple Access



(b) CDMA: Code Division Multiple Access

Figure 1. Comparison of TDMA and CDMA communication channel access techniques for RFID

which is set to 2^Q. Each transponder in the reading range of an RFID reader fills its slot counter with a random number between 0 and $2^Q - 1$. Within each round, the slot counter is decreased by one. Once the slot counter of one or more tags reaches a zero state, the tag(s) send an acknowledgment command back to the reader. However, if tags chose equal random numbers, the tags will collide once their slot counters are zero. Hence, the choice of Q is a typical trade-off. Choosing a high Q will lead to a smaller number of collisions, at the expense of an increasing time needed for an inventory round. A smaller Q will lead to less acquisition time, but to more collisions, indeed. In addition, the usage of TDMA methods pushes the envelope of the system (time-wise) when a very high number of tags have to be scanned ion very short time.

The introduction of Code Division Multiple Access (CDMA [15]) may find a remedy (Fig. 1b). The transponders, each equipped with a unique quasi-orthogonal spreading code, may use the radio channel whenever the transponders are ready to. The objective is the realization of a DS

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(direct sequence)-CDMA-based RFID system using semi-passive UHF transponders [16], with the reader providing the recognition of multiple transponders simultaneously. This means that the transponders are transmitting data within the same time range and frequency band (Fig. 1b), in contrast to the existing systems based on TDMA.

The realized UHF transponders operate in semi-passive mode, meaning that the digital part of the transponder, i.e., the data generation, has an active power supply, whereas the high frequency (HF) part works in passive mode taking advantage of the backscatter principle. The attendant RFID reader, though, is separated into two parts. Part one, described as transmitting system, generates a carrier wave at around 867 MHz. Part two, the receiving system, mainly demodulates the incoming backscattered signals of the RFID tags.

The work described in this paper is based upon previous work, e.g., described in [17]. Also, prior work may be found in this reference. Although it seems there are no big differences between this work and previous work it can be stated that this is not a given fact. Several improvements (e.g., modulator with higher efficiency, new downlink capabilities of the transponder, higher range, etc.) have been carried out to push the system's performance. Also, a complete new receiving part has been realized in order to accelerate the inventory rounds.

The remainder of the paper is organized as follows. Section II depicts the system at a whole, Section III describes in more detail the structure of the UHF transponder, mainly focusing on the modulator. The section concludes with experimental measurements. Section IV outlines the results, particularly pointing out the received superimposed signals of multiple transponders. Finally, the paper concludes by showing references for future work in Section V.

II. System Overview

The whole RFID system is built upon three parts; a transmitting part and a receiving part, both defined as RFID reader, and a third part, involving one or more CDMA-based RFID UHF transponders. However, the RFID reader parts will not be specified in much detail in this section. Fig. 2 shows the system's setup.

The transmit part consists of a simple sine wave generator (TX source) and an antenna (TX antenna) creating the carrier wave on which the transponders respond using the backscatter method [1]. The carrier signal is created upon a tunable, PLL-based RF synthesizer board (within the setup as in Fig. 2, the PLL is substituted by two frequency synchronized signal generators). This PLL generates two sine waves (shifted π in phase), one for the transmitting part and one for the receiving part (i.e., the demodulator). The receiving part consists of an antenna (RX antenna), a LNA (low noise amplifier), an IQ-demodulator and a succeeding DSP-based platform for the baseband processing.

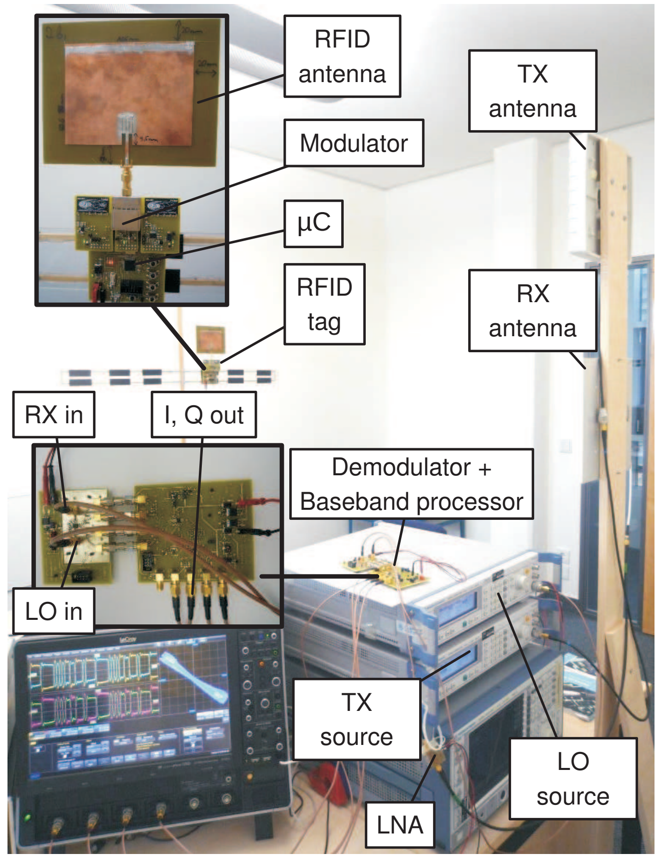

Figure 2. Setup of CDMA-based UHF-RFID system

The reflected signals from the transponders are low-noise amplified and directly mixed into baseband using a zero-IF demodulator. The demodulator's output consists of two I- and two Q-signals, each of them processed differentially. The following filtering and amplifying stages handle the signals differentially, too, in order to hold the current signal-to-noise ratio at a high level. As an example, the measured baseband signals at the demodulator's output, are shown in Fig. 2 (see oscilloscope) and Subsection III-B. Subsequently, these preprocessed signals are A/D-converted and pipelined to a DSP-based acquisition board, dealing with the mandatory baseband processing. The DSP is in charge of providing an appropriate despreading scheme to separate, in terms of data, various transponders from each other. This is mostly done through cross-correlation techniques. Some of these methods are evaluated in [17].

III. DS-CDMA Transponder

The proposed transponders consist of four main parts. Part one, the tag antenna, is designed as patch antenna. Part two (see subsection III-A) is known as *backscatter* modulator. This part generates different impedance values seen by the tag antenna (see [17] for more details) in order to generate the wanted backscatter modulation scheme [1]

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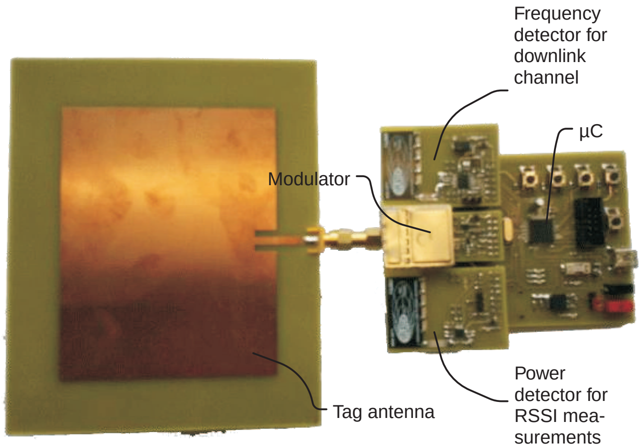
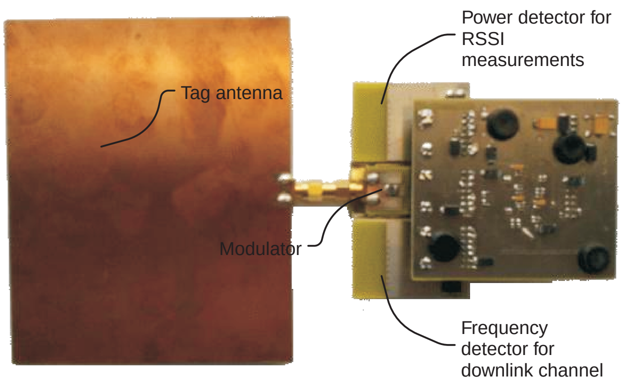


(a) UHF Transponder: Top



(b) UHF Transponder: Bottom

Figure 3. Implemented UHF transponder

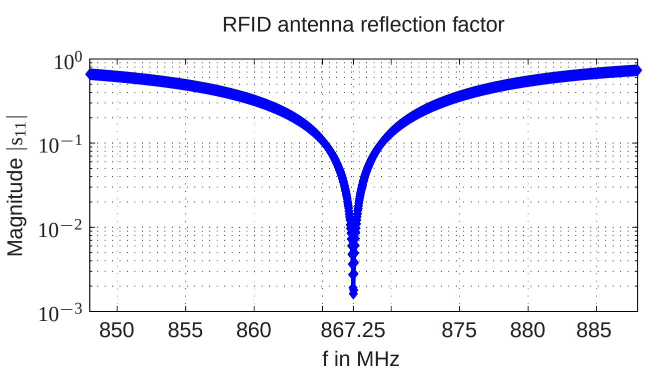


Figure 4. Measurement (vector analyzer) of reflection factor of RFID tag antenna within a range of 40 MHz

used along with non-inductive and non-capacitive working RFID systems. In most RFID systems, the realized backscatter modulation is a mixture between amplitude and phase modulation [2], [16].

Part three handles the baseband processing of the transponder, which includes mostly the generation of appropriate spreading codes, e.g., gold codes, and data spreading techniques for the CDMA scheme.

The last part describes a first realization of equipping the transponders with downlink (reader to tag) functionalities. This is realized using two elements; a frequency counter (referred to as frequency detector in Fig. 3a, 3b) and a detector of the incoming field strength (referred to as power detector in Fig. 3a, 3b). By implementing these two functionalities, the transponder may respond with different data to different incoming carrier frequencies. On the other hand, the transponder may use longer respectively shorter spreading codes according to the incoming field strength (lower respectively higher). This should mild the Near-Far effect [18], CDMA-based systems have to deal with. Anyway, the main part of the work focuses on the Antenna - Modulator effects, i.e., the uplink (tag to reader). A top and bottom view of the UHF transponder is given in Fig. 3a and Fig. 3b, respectively.

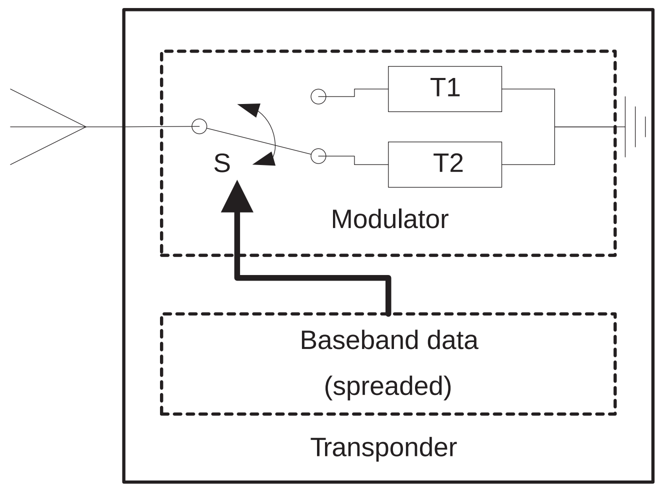


Figure 5. RFID transponder with HF switch as modulator

A. Backscatter Modulator

The RFID tag antenna is designed for the usage with linear polarized waves at approximately 867 MHz at an impedance of 50 Ω. The antenna's gain has been calculated to $G = 6.1$ dBi. The measurement of the antenna reflection factor is shown in Fig. 4. The current dimension of the antenna is still quite high (around 3.5×ISO card size) but will be reduced to current tag sizes, certainly with the effect of a lower gain.

To be flexible in designing the modulator and in measuring various effects of the impedance, the choice fell upon an HF switch (single pole, double throw) for tuning respectively switching the two different impedances (binary modulation). Fig. 5 shows the principle of the modulator designed as HF switch (S in Fig. 5). Examining the resulting backscatter effect, one has to say, that the well-directed two miss-matchings between the HF switch terminations (T1, T2) and the RFID patch antenna generate different

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amounts of energy scattered back to the receiving part of the RFID reader [2], [16], [19]–[22]. These reflected waves of the transponder differ in amplitude and/or phase. This difference, indeed, is used by the reader's demodulator to recognize the binary states of the transponder's data and demodulate them accordingly. The values of the impedances and therefore the amount of reflected energy can be tuned by varying the terminations (T1 and T2 in Fig. 5) of the HF switch. A good first approach is achieved by inserting a short circuit on termination T1 and an open circuit on T2. Feeding the HF switch with spreaded data from the transponder (i.e., binary '0's and '1's), leads to impedance alternations between short and open circuit state, thus generating backscattered waves with differing phase changes, leading to a BPSK-like modulation scheme. However, these signals are superimposed by various scattered waves of the carrier from the reader, finally forming an ASK-like modulation at the demodulator's input. The following results of carried out experiments were received by using the setup as in Fig. 2.

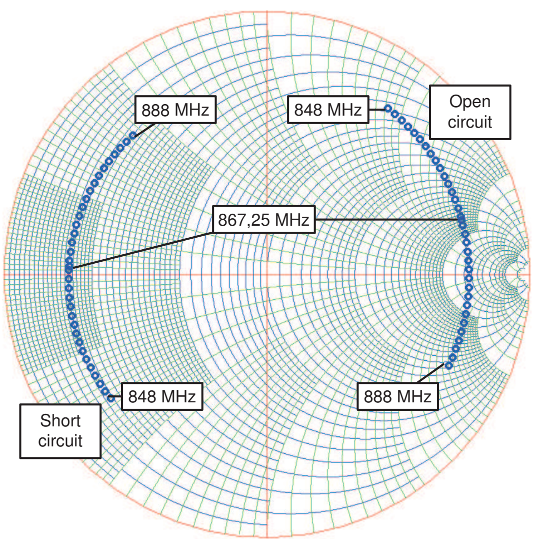

Figure 6. Smith Chart of the two different binary states of the modulator (short and open circuit)

B. Measurements

To show the working principle of the proposed system, measurements were carried out. The first measurement includes the reflection factor (i.e., s_{11}) of the RFID transponder's patch antenna. The second measurement involves the impedance measurement (i.e., reflection factor) of the modulator for both binary states, open and short circuit. The last measurements carried out within the setup as of in Fig. 2, show the demodulated baseband signals of the backscattered power from one or more tags within IQ constellation and timing diagrams.

The result of the first measurement is shown in Fig. 4, indicating the absolute value of the measured reflection factor $|s_{11}|$ of the tag antenna used. It can be shown that the proposed (simulated) s_{11} at a frequency of $f_c = 867$ MHz could be approximately hit with an offset of only 250 kHz. The measurement was carried out in a laboratory environment.

The measurement results of the modulator are shown in Fig. 6. As expected, the results of the short circuit states are on the left side of the Smith chart, whereas the open circuit states are located at the right side. The frequency range was limited to 40 MHz with around 867 MHz at the center. It can be stated, that the measured values show a good approximation of a BPSK modulation scheme.

The measurement, showing the whole effect of the transponder's properties and the principle of the demodulator board, is shown in Fig. 7. The resulting values of this measurement are the processed (i.e., filtered and amplified) baseband signals of the transponder's backscatter response. The four underlying signals (i.e., two differential signals for the I- and two for the Q-channel, respectively) were sampled by an oscilloscope. After building the differences ($I_+ - I_-$ and $Q_+ - Q_-$) in order to receive the pure I- and Q-signals, the resulting signals are shown in an IQ constellation diagram. It is important to keep in mind, that the measured signals are sampled DC-free to show the effect of the BPSK modulation. Showing the full DC-afflicted signal, would result into an ASK modulation scheme (which, of course, is received at the receiving antenna). Anyway, Fig. 7 not only shows the baseband signals, it shows signal regions, sorted colored (white to black) according to their frequency of occurrence. The more often particular signal states are present within a given region, the darker the region is. That means, that the two darkest states at the upper left and lower right, actually represent the two states of the modulator, i.e., open circuit and short circuit. The gray states in between the darker states show the switching operation of the HF switch. A more detailed view on the measurement showed, that the switching process from one stable state to the other, is executed in two different ways (non-reciprocal), as the gray region in Fig. 7 is divided by a white region. The distance between RFID reader antenna and transponder is approximately 3 m. However, further experiments showed a verified distance of around 15 m.

The remaining measurements show the complex baseband signals after mixing and filtering by the demodulator. These measurements were carried out using up to three transponders in the reader's field. Current baseband signals with 2 transponders in the field are shown in Fig. 8. The number of fixed signal states is 4, corresponding to 2 transponders. The reason for that is given by the fact, that the two transponders respond on the same "wave" emitted by the reader (coherent backscattering). Therefore, both transponders backscatter their very own signature on the coherent carrier of the reader. As each transponder inherits two stable states, the resulting

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waveform consists of 2^2 states. This issue is exemplary shown in Fig. 9. Fig. 9a shows the complex baseband signal with 1 transponder, Fig. 9b with 2 transponders, and Fig. 9c with three transponders in the field. However, the results describing the currently used CDMA methods (spreading, despreading) are part of coming up work.

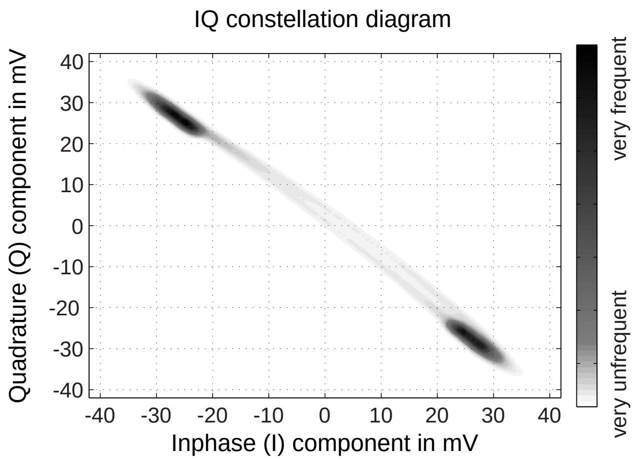

Figure 7. IQ constellation diagram showing baseband I- and Q-signals according to their frequency of occurrence, with black being very frequent and white being no occurrence at all

IV. Results

The measurement results presented in Subsection III-B show the basic operation principles of the proposed CDMA-transponder. Using above realized impedance states, i.e., open and short circuit for the transponder's modulator, the RFID reader, particularly the receiving system, may receive ASK-like modulated and spreaded transponder data, although a BPSK modulation scheme is provided by the transponder. Having this in mind, the receiver may easily recognize a lot more transponders simultaneously, by downconverting the spreaded and overlapped data of the individual transponders into baseband, and by evaluating the modulated phase and/or amplitude [17] through despreading techniques. The methods describing these despreading techniques in detail are part of different work.

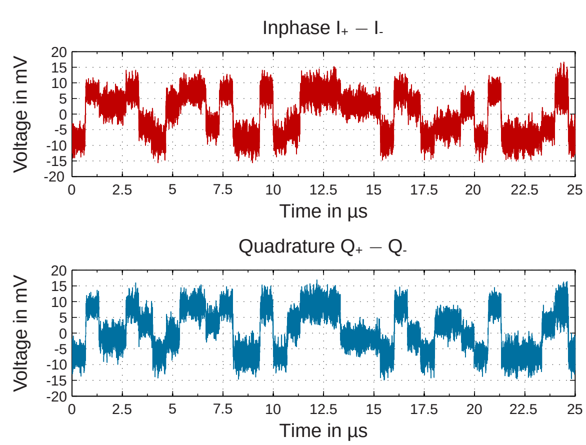

Figure 8. Differential signals of I- and Q-component at the output of the demodulator showing two transponders with superimposed CDMA signals

V. Conclusion and Future Work

The work shown in this paper proposes a new semi-passive DS-CDMA-based RFID transponder system for the UHF frequency band. The RFID reader uses a transmitting part to generate the carrier wave, again used by the transponders to reflect the incoming electromagnetic wave using different reflection states. These different states are achieved within the transponder's modulator, mainly consisting of an HF switch, creating impedance miss-matchings (open and short circuit) against the $50\,\Omega$ RFID tag patch antenna, in order to generate two different reflected waves (in terms of energy). These backscattered waves are received by the receiving part of the RFID reader for further processing. The applied CDMA channel access method is used to recognize transponders responding at an arbitrary point in time.

Further work has to be done by verifying the downlink part for the transponders, and the data respectively signal despreading of various transponders in the reading range of the RFID reader.

Tuning the impedance miss-matchings between modulator and antenna by applying other elements such as resistors, capacitors or inductors, or a mixture between them to the modulator, could provide better readability of the tags.

Acknowledgment

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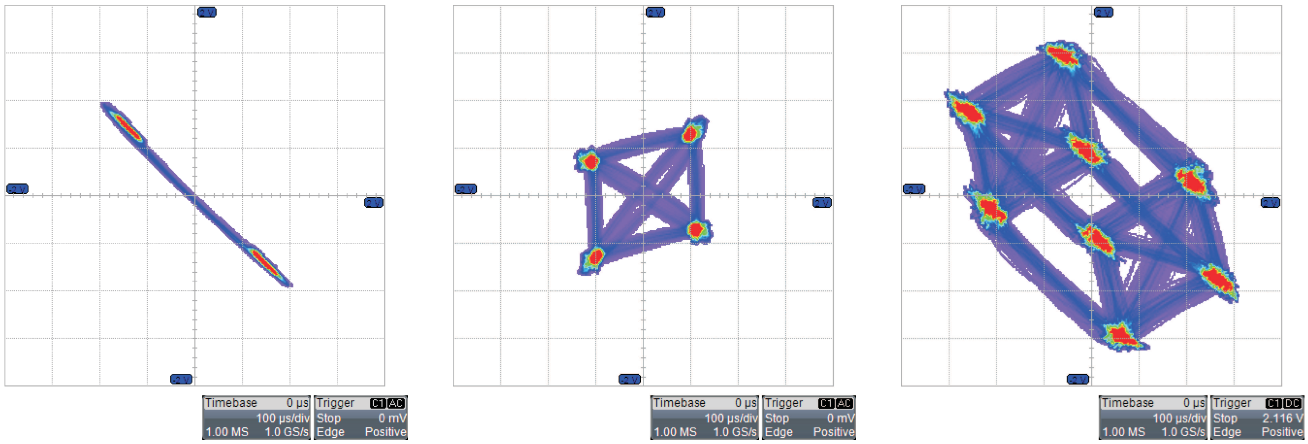

(a) Measurement: IQ constellation diagram with 1 transponder in the field; signal is sampled at baseband (1 GSps); $2^n = 2$ signal states correspond to $n = 1$ transponder(s)

(b) Measurement: IQ constellation diagram with 2 transponders in the field; signal is sampled at baseband (1 GSps); $2^n = 4$ signal states correspond to $n = 2$ transponder(s)

(c) Measurement: IQ constellation diagram with 3 transponders in the field; signal is sampled at baseband (1 GSps); $2^n = 8$ signal states correspond to $n = 3$ transponder(s)

Figure 9. Baseband measurements (IQ constellation diagrams) with 1, 2 and 3 transponders in the reading range of the RFID reader; signals are sampled after baseband processing, i.e., IQ demodulated, filtered and amplified

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