

# Effect of Gen2 Protocol Parameters on RFID Tag Performance

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**Abstract**— In this paper, we analyze the effect of Gen2 protocol parameters on RFID tag performance (tag sensitivity and backscatter efficiency). We describe our measurement methodology and perform characterization of several tags with different latest Gen2 ICs available on the market (Monza, UCODE, and Higgs families). To confirm our findings, we repeat measurements using conducted tag setup. We analyze data and draw conclusions on how the protocol parameters affect the tag performance in forward and reverse links.

## I. INTRODUCTION

Today, the dependence of UHF RFID tag performance on various tag parameters (chip sensitivity, tag antenna gain, impedance matching) is well understood [1-3]. Tag performance characterization methods are also well known [4-5]. In practice, the observed tag performance often varies from installation to installation. Those variations are mostly due to differences in RF environment and reader sensitivity performance. However, there exist different RFID IC implementations [6-9]. Because of that, some variations of tag performance can be attributed to different physical behavior which tag exhibits when interrogated by the reader under various protocol settings. While the effects these settings have on read rate and other system characteristics are generally known [10-12] (for example, number of tags that can be read per second increases with tag backscatter data rate), their effect on physical tag performance has not been addressed yet.

In this paper, we explore how Gen2 protocol parameters affect such fundamental tag performance characteristics as power sensitivity and backscatter efficiency. We carry our measurements in isolated tag scenario using anechoic chamber and several commercial inlays with similar antennas but different RFID chips, representing all major Gen2 ICs available on the market (Monza 2, Monza 3, G2XM, and Higgs 3). We present measurement results and draw corresponding conclusions about the relationship between protocol settings and tag performance.

## II. PROTOCOL PARAMETERS

Gen2 protocol used in UHF RFID is well documented [13]. For the convenience of the reader, in this section we briefly outline some of its main parameters whose influence on the tag performance is studied in this paper.

A typical Gen2 reader transmission is shown in Fig. 1. At first, the reader transmits to the tag a carrier wave (CW) unmodulated RF signal followed by the modulated portion and another CW signal (CW2). The modulated portion consists of the preamble (it includes several critical time periods which define link timing between the reader and the tag) and the command to the tag. The parameters for those time intervals are shown in Fig. 1 and also summarized in Table I. The tag chip remains powered up during the whole reader transmission and sends back information by modulating the backscattered signal during the second CW period (CW2).

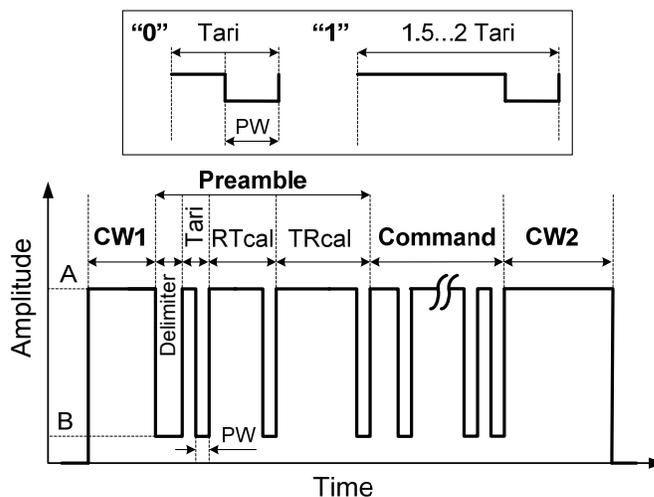


Fig. 1. Gen2 reader to tag baseband transmission (before filtering).

TABLE I. GEN2 PROTOCOL PARAMETERS

Name	Allowed values	Explanation
CW1	Unspecified	Power-up
Delimiter	12.5us +-5%	Start of frame
(A-B)/A	80%...100%	Modulation depth
Tari	6.25us...25us	"0" duration
PW	0.265Tari...0.525 Tari	Pulsewidth
RTcal	2.5 Tari...3 Tari	"0"+"1" duration
TRcal	1.1 RTcal...3 RTcal	Defines BLF
Command	Binary sequence	Command to tag
CW2	Unspecified	Tag backscatters

The parameters described in Table I above define the tag backscatter link frequency (BLF):

$$BLF = \frac{DR}{TRcal} \quad , \quad (1)$$

where  $DR$  is the divide ratio (either 8 or 64/3), specified in the command to the tag. The command to the tag also specifies  $M$ , the number of subcarrier cycles per symbol to be used in tag-to-reader link (either 1, 2, 4 or 8). The effective backscatter data rate is equal to  $BLF/M$ .

### III. TAG PERFORMANCE CHARACTERISTICS

Important forward and reverse link tag performance characteristics are tag sensitivity  $P_{tag}$  and tag backscatter efficiency  $\chi$ , explained below. Both of these characteristics are frequency-dependent and unique for each given tag and the material it is placed on. The derivatives of these tag characteristics are system characteristics, such as forward and reverse tag ranges, which depend on propagation environment, reader power, and reader sensitivity.

**Tag sensitivity**  $P_{tag}$  is important characteristic of the forward RFID link (“reader-to-tag”). It is a minimum incident power needed to read or write to the tag (these operations need different power levels). Tag sensitivity is linked to chip sensitivity and tag antenna parameters as:

$$P_{chip} = P_{tag} G \tau \quad , \quad (2)$$

where  $P_{chip}$  is chip sensitivity,  $G$  is tag antenna gain, and  $\tau$  is the impedance matching coefficient [3].

**Backscatter efficiency**  $\chi$  is important characteristic of the reverse link “tag-to-reader”). It shows how much of the received incident RF signal power is “converted” to the modulated backscattered power. The backscatter efficiency depends on chip parameters, tag antenna parameters, and polarization efficiency  $p$  between reader and tag antennas as:

$$\chi = p^2 G^2 \alpha |\rho_1 - \rho_2|^2 \quad . \quad (3)$$

where the coefficient  $\alpha$  depends on the modulated waveform details (for example,  $\alpha = 1/4$  for rectangular waveform with 50% effective duty cycle) and  $\rho_1$ ,  $\rho_2$  are the complex reflection coefficients between tag antenna and chip in modulating states 1 and 2 [3]. Note that the backscatter efficiency depends on the power incident on the tag, but can be uniquely defined when the incident power is equal to the tag sensitivity.

### IV. RADIATED MEASUREMENTS

We measured sensitivity and backscatter efficiency for four different UHF RFID tags (inlays) shown in Fig. 2. All these inlays, listed in Table II, have similar dipole-like antennas with similar gains (on the order of 1.5 dBi) but different RFID chips, representing all major Gen2 ICs available on the market today [14-16].

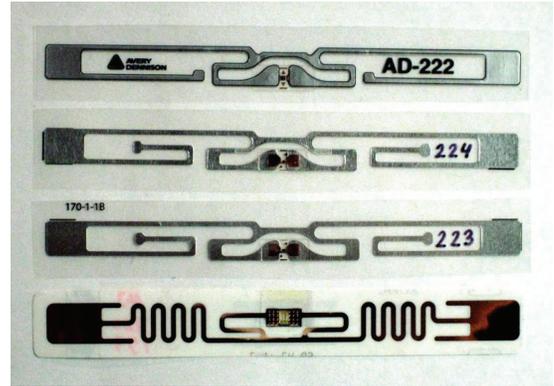


Fig. 2. Gen2 RFID tags used in measurements (from top to bottom: AD-222, AD-224, AD-223, ALN-9640).

TABLE II. DETAILS OF GEN2 TAGS USED IN MEASUREMENTS.

Inlay	Tag Manufacturer	Chip
AD-222	Avery Dennison	Impinj Monza 2
AD-224	Avery Dennison	NXP UCODE G2XM
AD-223	Avery Dennison	Impinj Monza 3
ALN-9640	Alien Technology	Alien Higgs 3

Our test measurement setup is shown in Fig. 3. RFID tag was placed on a foam stand at fixed distance (2 ft) from the 6 dBi reader antenna inside a compact (4 x 4 x 6 ft) anechoic chamber. The test equipment was National Instruments LabVIEW-controlled PXI RF platform [17] which functions as RFID reader with variable frequency, power, and controllable Gen2 protocol settings. We measured both the minimum power  $P_{min}$  needed for tag to respond (defined as the power of the CW portion of the reader-to-tag transmission) and the tag signal power  $P_{rec}$  received by the reader.

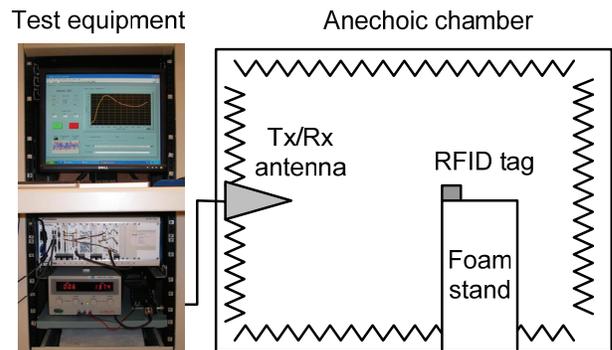


Fig. 3. Radiated measurement setup.

The tag read sensitivity was calculated as

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

where  $G$  is the gain of the transmit/receive antenna,  $\lambda$  is the wavelength, and  $d$  is the distance to the tag (this distance was frequency-dependent in our case because the phase center of log-periodic antenna used in measurements shifted with frequency).

The backscatter efficiency (at the incident power level corresponding to tag sensitivity) was calculated as

$$\chi = \frac{P_{rec}}{P_{min} G^2 \left( \frac{\lambda}{4\pi d} \right)^4}, \quad (5)$$

To measure the tag sensitivity, we sent *Query* command (**1000**) to the tag. During the test, the power of the query command transmitted at each frequency was gradually increased until the tag response (*RN16*) was detected. A typical recorded waveform is shown in Fig. 4.

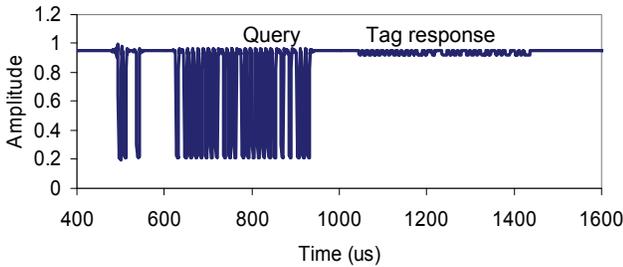


Fig. 4. Typical RFID command exchange during testing.

The detection of the tag sensitivity threshold was very precise: the transition from the noisy backscatter signal of unpowered tag to the easily recognized waveform of the modulated tag signal is shown in Fig. 5. Such change occurs over only 0.05 dB change in transmitter output power.

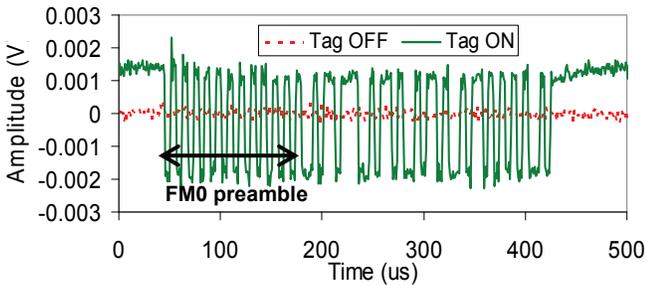


Fig. 5. Typical recorded tag response when the tag is OFF and ON. The transition occurs over 0.05 dB change in output power level. The tag response starts with 12 zeros in FM0 preamble.

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 set to 1, that preamble always contained 12 leading zeros as shown in Fig. 5.

## V. CONDUCTED MEASUREMENTS

To be able to verify the results obtained in our radiated measurements, we have also done conducted measurements on the same RFID chips but in different packages (except packaged Higgs 3 chip which was not available to us). The chips were matched to 50 Ohms (see Fig. 6) in narrow frequency band using a simple LC-type network shown in Fig. 7. The values of L and C components used for matching are given in Table III.

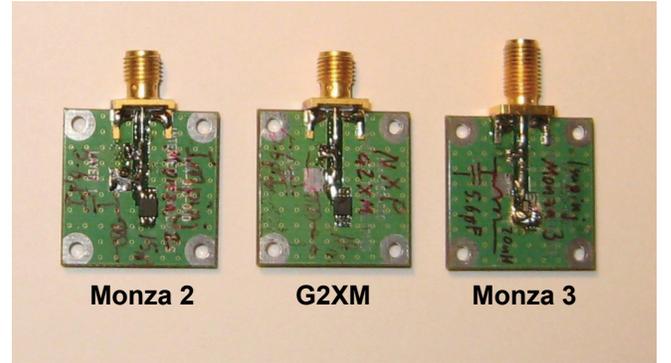


Fig. 6. Monza 2, G2XM, and Monza 3 chip assemblies matched to 50 Ohms.

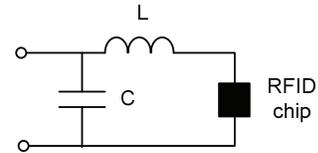


Fig. 7. Passive lossless LC-network used for matching chips to 50 Ohms.

TABLE III. DETAILS OF GEN2 CHIP ASSEMBLIES USED IN MEASUREMENTS.

Chip	Manufacturer	Package	L	C
Monza 2	Impinj	TSSOP	15 nH	5.6 pF
G2XM	NXP	TSSOP	18 nH	5.6 pF
Monza 3	Impinj	uDFN	20 nH	5.6 pF

To ensure good matching, the return losses of the chip assemblies were measured with network analyzer at different output power levels and are shown in Fig. 8 for -10 dBm output power level. The RF network analyzer used for return loss measurements was Agilent E5071C. The conducted test setup is shown in Figure 9. The 20 dB attenuator was included between the RFID chip assembly and the test equipment to ensure that the chip assembly load would not affect the isolation performance of the circulator inside the test equipment.

The minimum threshold power to read chip assemblies was measured in exactly the same way as it was done for radiated measurements. The modulation efficiency at that minimum threshold power level (which varied with frequency) was calculated as the difference between the power of the received chip signal and the minimum threshold power to read the chip.

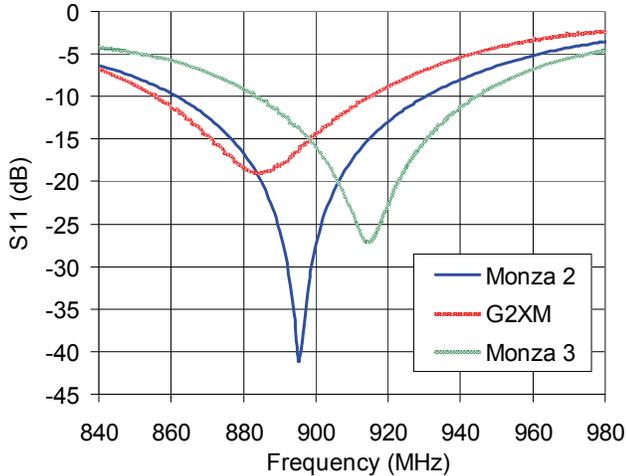


Fig. 8. Return loss of 50 Ohm RFID chip assemblies measured with network analyzer at -10 dBm output power (Monza 2 is matched around 895 MHz, G2XM around 885 MHz, and Monza 3 around 915 MHz).

### Test equipment

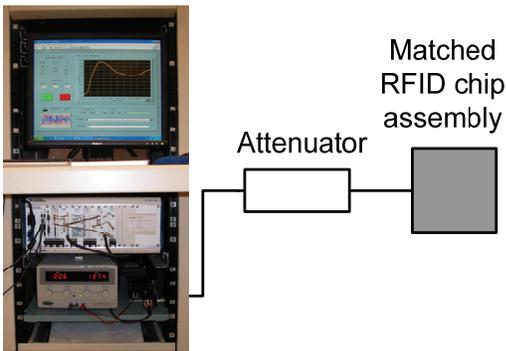


Fig. 9. Conducted measurement setup.

## VI. RESULTS AND DISCUSSION

We studied the effect of several different Gen2 protocol parameters on tag performance in radiated and chip assembly performance in conducted setups. The results and discussion are presented below.

### A. Modulation Depth

In our measurements, varying the modulation depth of the reader-to-tag link within the limits specified by Gen2 (80-100%) did not have any significant effect on tag performance neither in forward nor in reverse link.

### B. $RT_{cal}$ , $TR_{cal}$ , $DR$

Varying these parameters within Gen2 limits allows one to specify different backscatter link frequencies. In our measurements we did not observe any significant impact of these parameters on tag performance.

### C. $M$

Varying this parameter allowed us to specify different tag backscatter modulation formats (FM0 when  $M=1$  or Miller when  $M=2, 4, 8$ ) but did not have any significant impact on measured tag performance (sensitivity and backscatter efficiency). However, it is known from practice that in many scenarios the tag read rate is higher when  $M=4$ . In this case, it takes tag longer to send back its data than with  $M=1$  (FM0). The transmitted data is effectively replicated several times and the bit error rate is smaller because of this redundancy, as is well known in classical information theory [18].

### D. $Tari$ and $Pulsewidth$

We found that the main parameter which affected tag performance was the pulsewidth PW. Because the pulsewidth is usually specified as a fraction of  $Tari$ , changing  $Tari$  also affects the pulsewidth. As a representative result, we present here measurements for a few different cases with different pulsewidth values. Table IV shows the parameter combinations used in three representative test cases.

TABLE IV. GEN2 PROTOCOL PARAMETERS USED IN MEASUREMENTS FOR THREE DIFFERENT CASES.

	Case A	Case B	Case C
<b>CW1</b>	1.5 ms	1.5 ms	1.5 ms
<b>Delimiter</b>	12.5 $\mu$ s	12.5 $\mu$ s	12.5 $\mu$ s
<b>(A-B)/A</b>	90%	90%	90%
<b>Tari</b>	6.5 $\mu$ s	12 $\mu$ s	24 $\mu$ s
<b>Pulsewidth</b>	0.29 $Tari$	0.5 $Tari$	0.5 $Tari$
	1.89 $\mu$ s	6 $\mu$ s	12 $\mu$ s
<b>RTcal</b>	2.5 $Tari$	2.5 $Tari$	2.89 $Tari$
	16.25 $\mu$ s	30 $\mu$ s	69.4 $\mu$ s
<b>TRcal</b>	1.25 $RT_{cal}$	1.11 $RT_{cal}$	2.89 $RT_{cal}$
	20.3 $\mu$ s	33.3 $\mu$ s	200 $\mu$ s
<b>DR</b>	8	64/3	8
<b>M</b>	1	1	1
<b>Pilot tone</b>	On	On	On
<b>CW2</b>	2 ms	2 ms	2 ms
<b>BLF</b>	394 kHz	640 kHz	40 KHz

The measured tag sensitivity and backscatter efficiency for the four tags in radiated setup are shown in Fig. 10 and Fig. 11 for 840-980 MHz frequency band (which was chosen to cover global 860-960 MHz UHF RFID frequencies  $\pm$  20 MHz). Two extreme cases, A and B, which showed the most difference in tag sensitivity, were chosen for plotting the radiated tag performance. The maximum observed tag sensitivity variation between these two cases was 1.2 dB (AD-222 with Impinj Monza 2 at 920 MHz). In general, Monza-based tags showed slightly larger sensitivity dependence on pulsewidth compared to NXP and Higgs based tags.

As one can see, smallest pulsewidth (case A) resulted in the best tag sensitivity. On our opinion, this effect can be attributed to different RF front ends and discharge times of Gen2 ICs which all together result in different response sensitivity to modulated commands with various duty cycles.

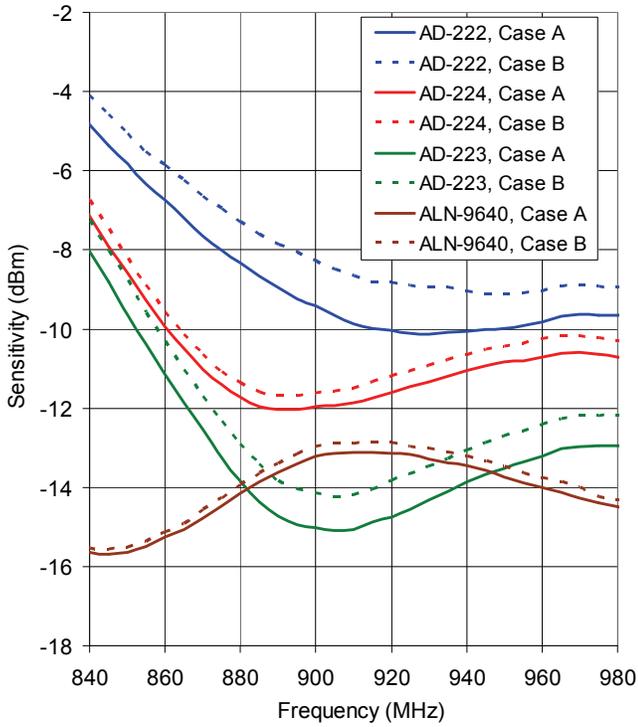


Fig. 10. Measured tag sensitivity (at 980 MHz ALN-9640 has the best sensitivity, then AD-223, then AD-224, then AD-222).

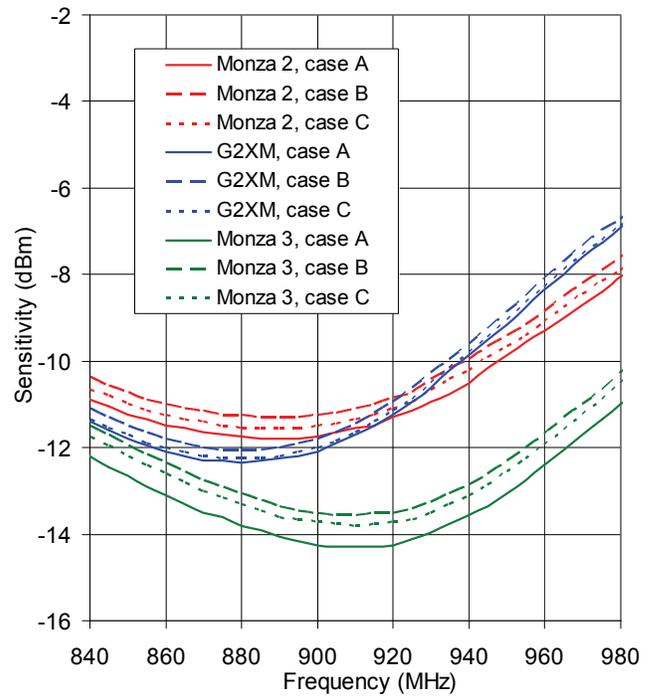


Fig. 12. Measured chip assembly sensitivity (at 840 MHz Monza 3 has the best sensitivity, then G2XM, then Monza 2).

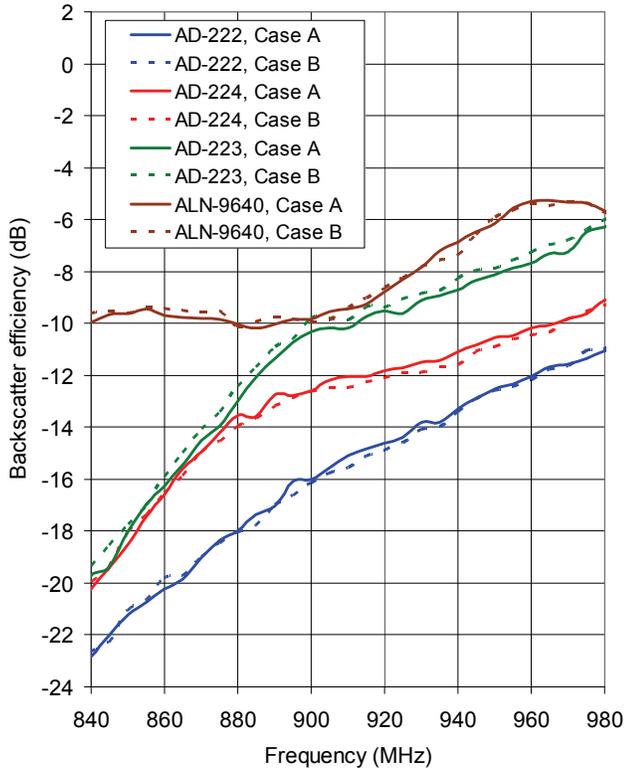


Fig. 11. Measured tag backscatter efficiency (at 980 MHz ALN-9640 has the highest efficiency, then AD-223, then AD-224, then AD-222).

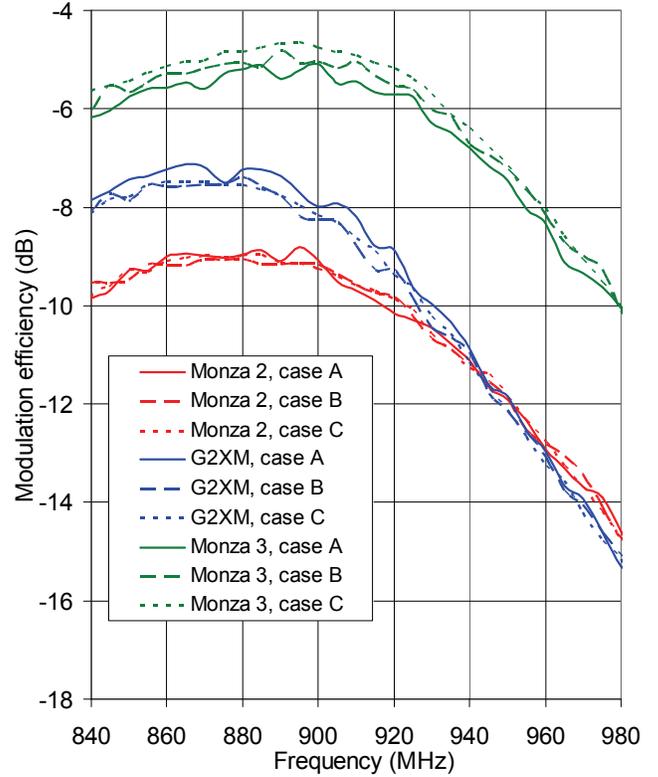


Fig. 13. Measured chip assembly modulation efficiency (at 840 MHz Monza 3 has the highest efficiency, then G2XM, then Monza 2).

As for the tag backscatter efficiency, we did not observe any significant dependence on the pulsewidth or any other parameters (the observed differences were less than 0.5 dB). This can be explained by the fact that the tag backscatter efficiency is a function of the tag antenna impedance (which is defined by antenna geometry and is independent of protocol settings or power) and the impedances of the two chip modulating states (which are defined by the chip RF front end architecture and depend on the power absorbed by the chip but are not affected much by different protocol settings).

The results shown in Fig. 10 and Fig. 11 were verified in the conducted setup for three test cases (A, B, and C) which are presented in Fig. 12 and Fig. 13. These results also indicate that chip sensitivity, similar to tag sensitivity, is affected by the protocol settings while the modulation loss of the chip assemblies has relatively small dependence on protocol parameters (although stronger dependence when compared to backscatter efficiency behavior in radiated setup). In our measurements, we also noted that the tag sensitivity is not a monotonic function of pulsewidth duration (this can be seen from Fig. 12). All these observations require further studying and analysis.

## VII. CONCLUSIONS

In this paper, we explored the effect of Gen2 protocol parameters on RF performance of UHF RFID tags. We performed multiple measurements with four RFID tags (AD-222, AD-223, AD-224, and ALN-9640) based on different chips, representing latest Gen2 ICs available on the market (Impinj Monza 2 and 3, NXP UCODE G2XM, and Alien Higgs 3). We also performed conducted measurements using the same set of chips (except for Alien Higgs 3).

We conclude that the main parameter that affects tag performance is the duration of pulsewidth in reader-to-tag signaling which has direct effect on tag sensitivity. Smallest pulsewidth results in the best tag sensitivity. In two extreme cases presented here, the maximum observed tag sensitivity variation was 1.2 dB (for AD-222 tag with Impinj Monza 2 chip). We did not observe any significant dependence of the backscatter efficiency of the analyzed tags on any combinations of Gen2 protocol parameters.

In our measurements, we concentrated on a single reader and single tag scenario. Because we only had a limited number of tags, we did not include statistical averaging of the measurements performed on multiple tag samples which may become the subject of future work. Also, in real-world implementations, a “competing” reader operating in adjacent channels and other tags in proximity can become important factors which affect individual tag performance and need to be studied as well.

Since the dependence of the tag performance on protocol parameters in single tag, single reader scenario is primarily dictated by the specific RFID chip behavior, the results presented in this paper for four particular tags can also be applied to many other tags which use the same RFID chips.

We hope that this paper will be useful for engineers who need to understand the behavior of practical RFID systems and tag performance dependence on various system parameters.

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