Received signal strength indicator (RSSI)
for ST25RU3993

Introduction

The ST25RU3993 UHF RFID reader IC comprises an integrated received signal strength indicator (RSSI) for the received I and Q signals. Thanks to this feature it is possible to gauge the power level of an incoming transponder signal or to detect external RF signal levels in the vicinity of the carrier frequency.

The received tag signal is split into an in-phase (I) and a quadrature (Q) version (I, Q), which are fed to two 4-bit logarithmic A/D converters. The result is two logarithmic absolute values, proportional to the input power at the mixer input ports. With the I and Q values it is possible to calculate the phase relation between the carrier signal and the received signal.

The ST25RU3993 datasheet, available on *www.st.com*, is to be considered as a reference for this document. Concerning notation, the 0x prefix indicates numbers in hexadecimal notation (example: 0x29), while binary numbers are followed by a b suffix (example: 00b).

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1 External RF - Input signal power

A listen before talk (LBT) or similar carrier sense functionality can be implemented for both the differential RX ports and the single-ended RX port.

The sensitivity for differential RX pins ranges from -86 dBm to -22 dBm, and from -88 dBm to -32 dBm for the single-ended RX pin.

When the low power output is activated, the local oscillator (LO) signal, internally used for the RX mixers, is tapped from the RFOPX and RFONX pins. If the internal power amplifier is active, the LO signal is tapped from the preamplifier stage in front of the internal power amplifier.

To sense external carrier signals (LBT / carrier sense) the power transmission must be disabled.

Depending on the TX port used in the application, there are different choices to achieve this goal. When using the differential low power output, typically connected to an external power amplifier, two options exist:

1. The low power output is enabled and provides the LO signal, and the external power amplifier is disabled via:
    –   power down function
    –   bias voltage
    –   supply voltage
2. The low power output is disabled and the LO signal source is the preamplifier of the PA stage (register 0x0C: 44). In this case TX ports of the internal PA can be left unconnected, but a 100 nF capacitor is required on the VDD_PA pin.

To sense external RF-signals using the internal power amplifier only one option is recommended: the internal PA output is disabled and the LO signal is connected to the low power output path (register 0x0C: 01). In this case RFOPX and RFONX pins must be connected to VDD_B via two 100 Ω resistors.

To enable the RSSI measurement for external RF signals, set the following configuration:

*   In the Protocol selection register set both rf_on and rec_on bits to "1"
*   Set the dir_mode bit in the Protocol selection register to "1"
*   Disable the no response interrupt in the Enable interrupt register 1 by setting the e_irq_noresp bit to "0".
*   The RSSI display register must be configured to show the Real time RSSI information through the Status readout page setting register (register 0x29: X[a]0)

Before acquiring the external signal level, check if the PLL is locked (pll_ok bit) and if the RF power is on (rf_ok bit), then send the direct command Enable RX (0x97), wait 500 µs, and read out the Real time RSSI from the RSSI display register (0x2B).

Sensing an external RF signal the non coherent down-conversion ensures that the RSSI values for both I and Q have a similar level.

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a. Don't care.

The equations to calculate the approximated received external RF signal input power are:

$$meanRSSI = [RSSI(I) + RSSI(Q)] / 2$$

$$P_{IN} \text{ (in dBm)} = 2.1 * meanRSSI - G$$

where:

- meanRSSI is the arithmetic mean value of the two RSSI(I) and RSSI(Q) values read-out from the RSSI display register (0x2B)
- P_{IN} is the input power at the reader IC pins, expressed in dBm
- G is a constant, depending on the settings of the RX filter settings register and of the RX mixer and gain register.

Components in the RF return path to the mixer input ports and PCB trace properties impact G value as well.

This procedure assumes that the ST25RU3993 is enabled, and that its RX section and the LO signal are both ON (EN = 1, stby = 0, rf_on = 1). If the reader device is disabled (EN = 0) or in standby mode (stby = 1), the MCU must wait 18 ms after enabling it and send the direct command Enable RX (0x97). If only TX and RX are disabled (rf_on = 0), the MCU needs to wait 7 ms after setting rf_on = 1 and sending the direct command Enable RX (0x97).

It is recommended to check the calculated power against the actual input power at the reader antenna port, and adjust the G constant accordingly for every PCB design.

1.1 Differential input mixer

Typical values for the G constant used to calculate an external RF signal (LBT / carrier sense) input power and available input signal ranges for the differential mixer are shown in *Table 1*.

Table 1. G values vs. RX gain settings - Differential mixer

Register settings 0x0A[1], 0x09[2]	G value [dB]	Available sensitivity range Min/Max [dBm]		Comments
0xC1, 0xFF	53	-50	-22	Attenuator stage ON, lowest base band gain
0x01, 0xFF	62	-59	-31	Attenuator stage ON, nominal base band gain
0x00, 0xFF	71	-68	-40	Nominal mixer gain, nominal base band gain
0x02, 0xFF	80	-77	-49	Mixer gain stage ON, nominal base band gain
0xE2, 0xFF	89	-86	-58	Mixer gain stage ON, highest base band gain (best LBT / carrier sense sensitivity)

1. RX mixer and gain register.

2. RX filter settings register.

G values in *Table 1* are valid for the detection of external RF-signal sources that have a frequency offset of 50 kHz from the reader LO frequency. Filter setting 0x09 provides a flat filter response characteristic suitable for LBT / carrier sense.

Note: *For reader designs using a directional coupler the G constant is reduced by the coupling factor.*

Figure 1. Input power (dBm) vs. RSSI - Differential mixer - BB = 300 kHz
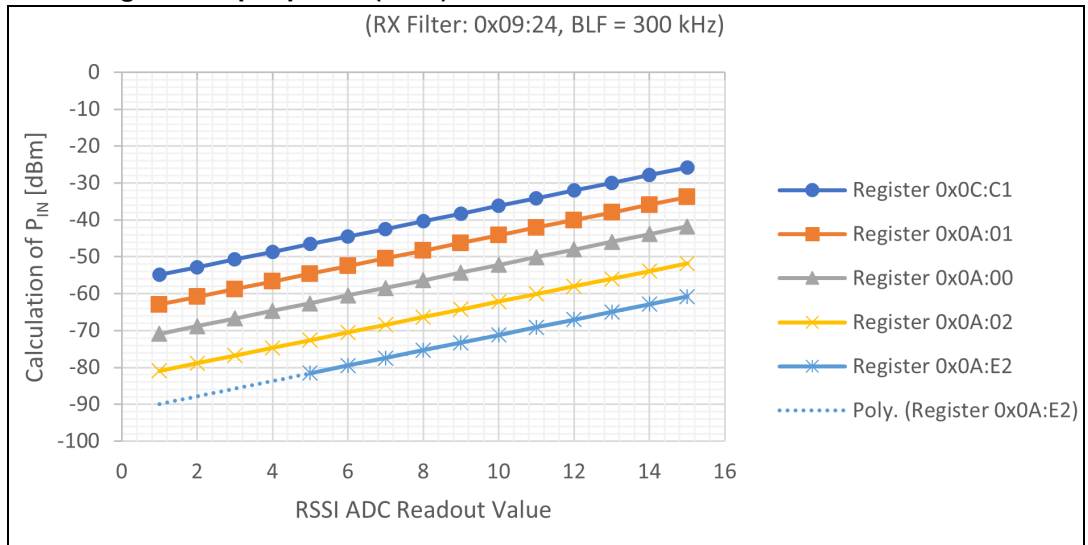

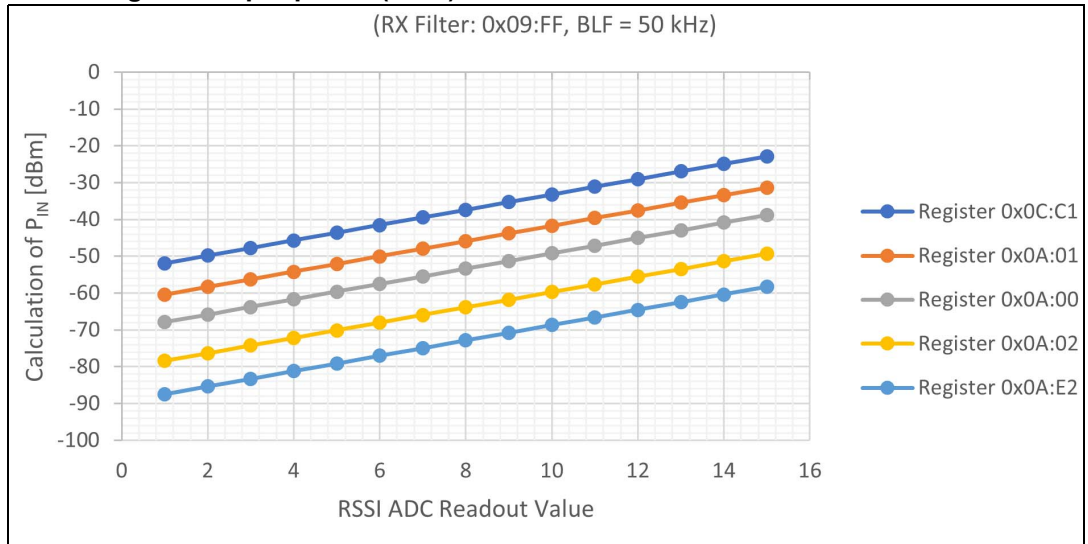**Figure 2. Input power (dBm) vs. RSSI - Differential mixer - BB = 50 kHz**

Figure 1 and *Figure 2* show the typical relation between RSSI readout value (code) and input signal power (P_{IN}) for differential mixer inputs at, respectively, 300 kHz and 50 kHz BB signal frequencies. P_{IN} is calculated according to the equations above.

1.2 Single-ended input mixer

The typical values for the G constant used to calculate the external RF signal (LBT / carrier sense) input power and available input signal ranges for the single-ended mixer are shown in *Table 2*.

Table 2. G values vs. RX gain settings - Single-ended mixer

Register settings 0x0A[1], 0x22[2], 0x09[3]	G value [dB]	Available sensitivity range Min/Max [dBm]		Comments
0xC0, 0x14, 0xFF	63	-60	-32	Attenuator stage ON, lowest base band gain
0x00, 0x14, 0xFF	71	-68	-40	Attenuator stage ON, nominal base band gain
0x01, 0x12, 0xFF	77	-74	-46	Nominal mixer gain, nominal base band gain
0x03, 0x11, 0xFF	83	-80	-52	Mixer gain stage ON, nominal base band gain
0xE3, 0x00, 0xFF	91	-88	-60	Mixer gain stage ON, highest base band gain (best LBT / carrier sense sensitivity)

1. RX mixer and gain register.

2. RX filter settings register.

3. Emitter-coupled mixer options register.

G values in *Table 2* are valid for the detection of external RF-signal sources that have a frequency offset of 50 kHz from the reader LO frequency. The filter setting 0x09: FF provides a flat filter response characteristic suitable for LBT / carrier sense.

Note: *For reader designs using a directional coupler the G constant is reduced by the coupling factor.*

Figure 3 and *Figure 4* show the typical relation between RSSI readout levels (code) and the input signal power [dBm] for the single- ended mixer input for, respectively, 50 kHz and 300 kHz BB signal frequencies. The corresponding RX filter settings are 0x09: FF and 24.

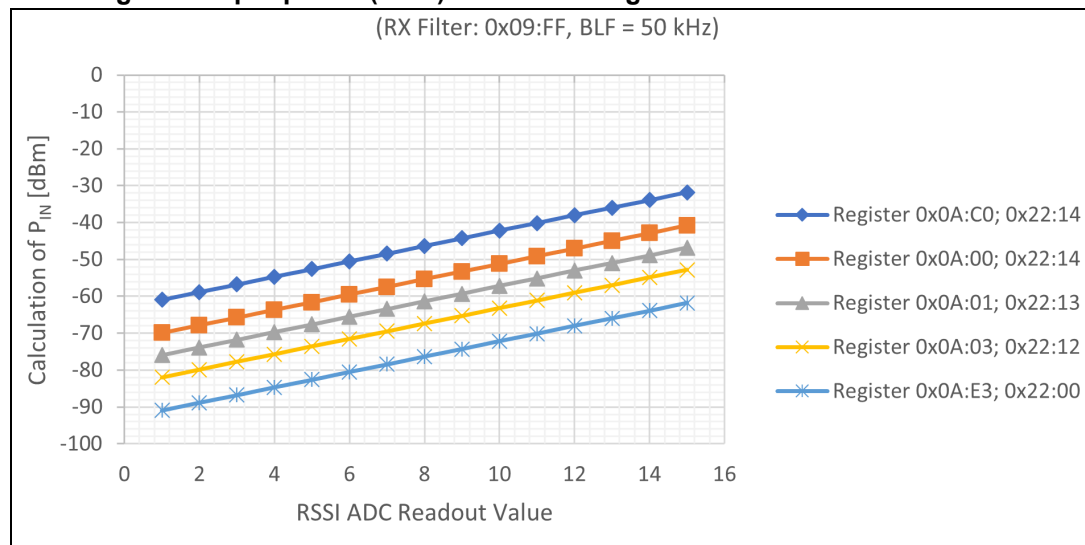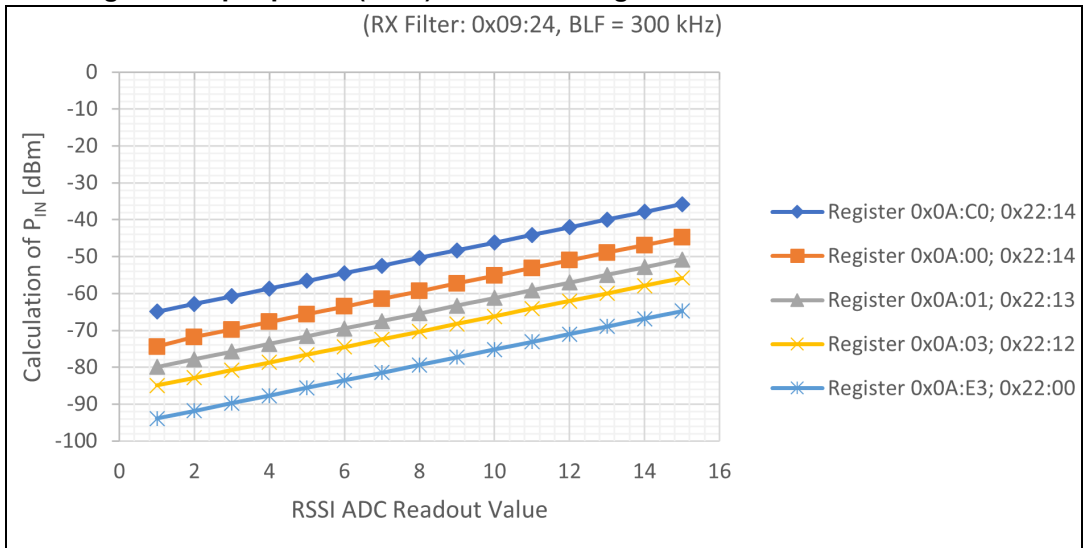**Figure 3. Input power (dBm) vs. RSSI - Single-ended mixer - BB = 50 kHz**

Figure 4. Input power (dBm) vs. RSSI - Single-ended mixer - BB = 300 kHz

(RX Filter: 0x09:24, BLF = 300 kHz)

2 Transponder input signal power

During the reception of the transponder signal, the amplitude of the I and Q channels is continuously monitored. During the pilot tone phase of the transponder preamble the RSSI level is measured and stored in an internal register. This type of RSSI measurement is defined as RSSI-1-pilot and can be configured in the Status readout page setting register (0x29). Once RSSI-1-Pilot is configured accordingly the values for I and Q can be fetched from the RSSI display register (0x2B). The MCU can access the acquired RSSI-1-pilot (I) and RSSI-1-pilot (Q) values (valid until the start of the next data transmission) during data reception or after the end of the reception.

The modulated transponder signal is coherent with the local oscillator (VCO). Consequently, the down-converted signal can be seen in the I and/or in the Q channel.

The following formulas can be used to calculate the received transponder signal level at the mixer input ports:

$$highRSSI = max [RSSI(I), RSSSI(Q)]$$

$$deltaRSSI = abs [RSSI(I) - RSSSI(Q)]$$

$$P_{IN}[dBm] = 2.1 * highRSSI + 10 \log (1 + 10^{-deltaRSSI / 10}) - G - 3$$

where

- highRSSI is the maximum value between the RSSI(I) and RSSI(Q) values read from the RSSI display register
- deltaRSSI is the absolute value of the difference between the two RSSI values
- $P_{IN}[dBm]$ is the input signal power of the transponder at the mixer input ports in dBm
- G is a constant depending on register settings, components in the RX path to the ST25RU3993, and PCB traces. G values for different register settings are listed in *Table 1* (differential RX inputs) and *Table 2* (single-ended RX input).

Since the contribution of deltaRSSI is relatively small, the calculation for P_{IN} can be simplified (especially for the MCU) using the formula:

$$P_{IN}[dBm] = 2.1 * highRSSI - G - C$$

where C is a constant depending upon deltaRSSI.

The behavior of C with respect to deltaRSSI is shown in *Figure 5*. By using a single C value of 1.5 the error contribution due to the simplified calculation can be up to 1.5 dB. With a set of C values P_{IN} can be approximated with higher accuracy.

Figure 5. C (in dB) vs. deltaRSSI
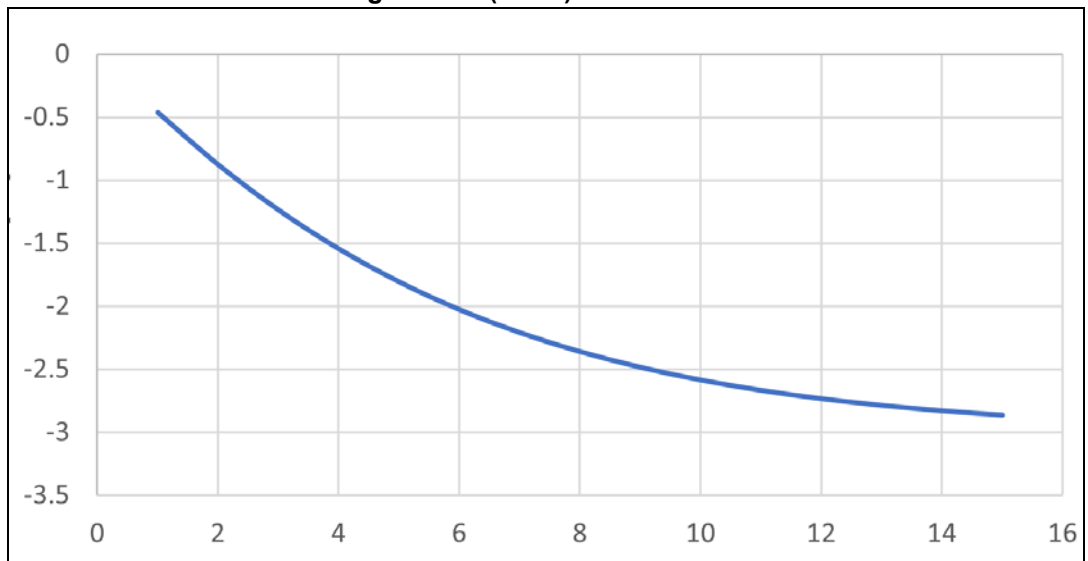
3 RSSI calculation using AGC

When AGC is enabled the calculation of the RSSI must be adapted. The level of AGC engagement can be retrieved from the AGC and internal status display register (0x2A) by checking bits agc[2:0].

AGC values 5, 6 and 7 are related to base band gain stages (-3 dB each) affecting the RSSI and digitizer circuitry.

AGC values 1 to 4 are related to the digitizer hysteresis, which are not changing the RSSI and therefore can be skipped for the calculation.

To calculate the RSSI of an external RF signal (LBT mode), the constant G value from *Table 1* and *Table 2* must be corrected according the following formulas:

$$G_{AGC} = G - 3 \text{ dB} * (AGC - 4), \text{ if } AGC > 4$$

$$G_{AGC} = G, \text{ if } AGC \leq 4$$

where:

- AGC is the value of the status bits from register 0x2A
- G_{AGC} is the constant for the AGC based RSSI calculation
- G is the constant from *Table 1* and *Table 2*.

4 Values of G for ST25RU3993-HPEV

If the application demands a higher accuracy of the transponder input power, the G value must be calibrated. This section details how to evaluate this value for a specific reader design, and provides examples of selected values used by the evaluation reader ST25RU3993-HPEV.

To determine the G-value, it is required to know the transponder input power level at the reader antenna port. If this information is not available, the transponder input power must be measured.

Figure 6 shows a test setup to measure the transponder response power with a spectrum analyzer. By gathering the transponder response power, it is possible to calculate the transponder power incident at the reader antenna port.

Figure 6. Measurement setup
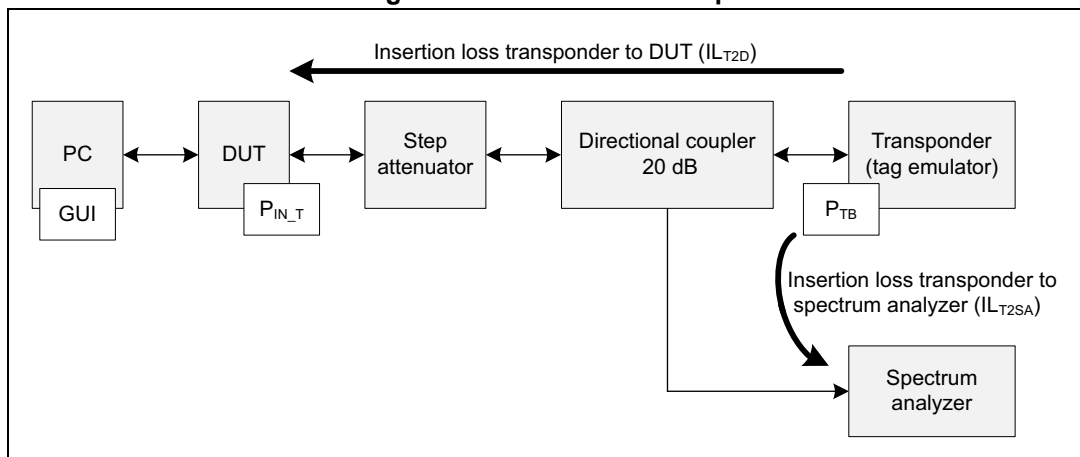
The reader (DUT) RF output is connected to a directional coupler via a step attenuator. The direct output of the directional coupler is then connected to a transponder or a tag-emulator. The input coupled port is terminated by 50 Ω (not shown). The output coupled port of the directional coupler is connected to a spectrum analyzer (SA). The insertion loss of the signal path from the transponder to the SA (IL_{T2SA}) is entered as the amplitude offset in the SA configuration. The insertion loss of the signal path transponder to DUT is measured and stored (this parameter is needed for calculations).
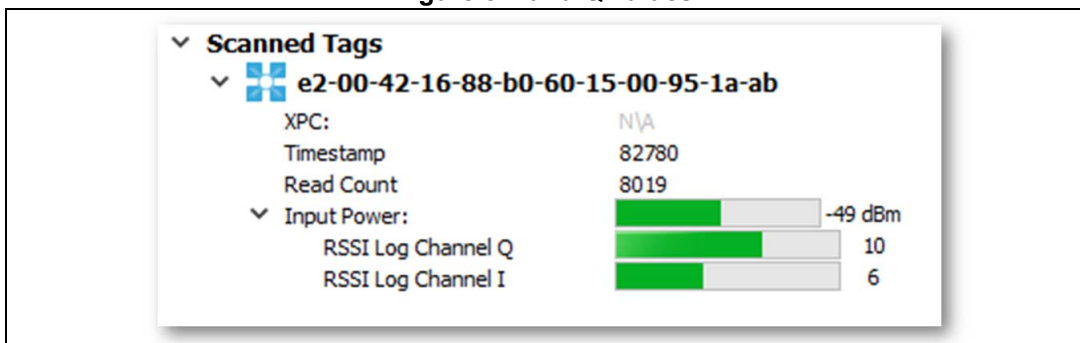
The reader is then activated to measure the RSSI values for I and Q, this can be done by using the PC GUI software of the ST25RU3993-HPEV. The RSSI value reading can be activated in the GUI View menu.

Figure 7. Activate RSSI via View menu
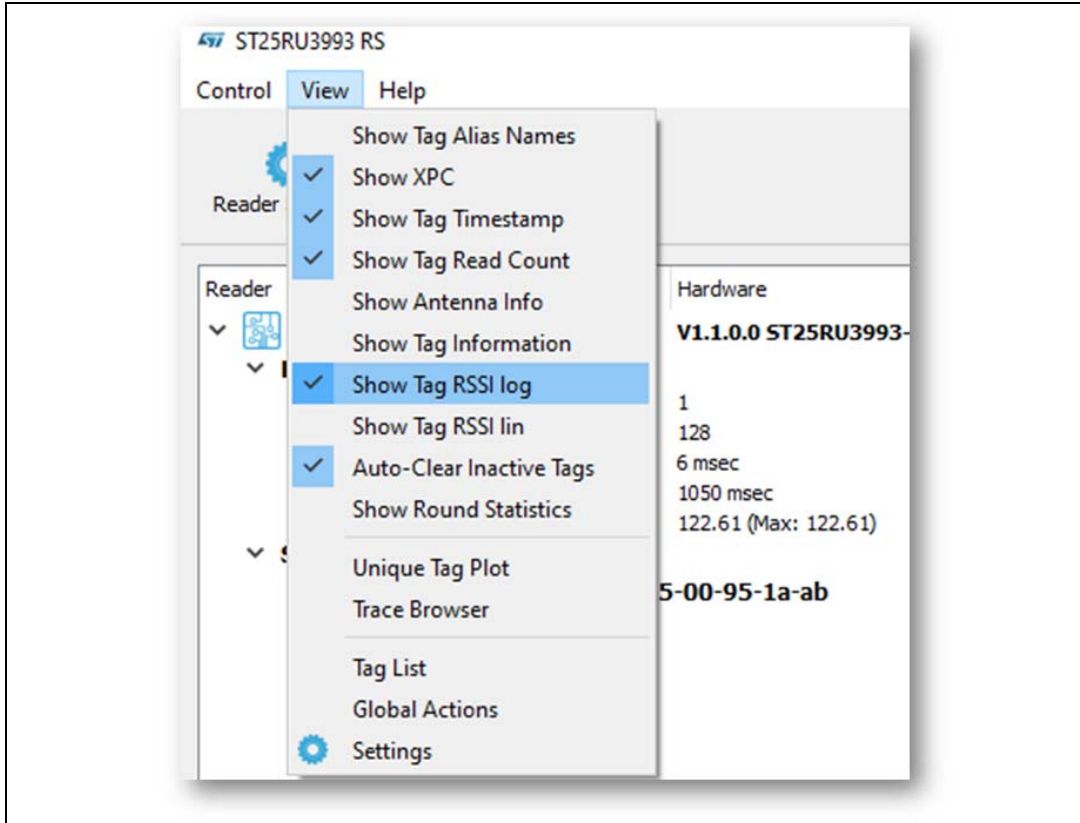
The step attenuator is adjusted so that the transponder response gives a mid-range RSSI reading.

Figure 8. I and Q values

The RSSI values for I and Q are stored for the following calculations.

It is recommended to set up a gated spectrum measurement at the SA. The gate window should be set so that the SA only focuses on the transponder signal. This blanks out the reader modulated carrier and makes possible a more accurate measurement of the spectral upper and lower sidebands of the transponder response signal. By using a band power measurement feature of the SA it is possible to measure the integrated transponder response power of the upper and lower side band. For a guidance on how to configure the band power measurement intervals it is recommended to follow the side band range values shown in Annex E of the ISO 18046-3 standard.

By combining the upper and lower side band power measurements the correct transponder response power can be determined. In case the SA amplitude offset is set as described above, this calculated power is the backscatter power of the transponder (PTB).

The transponder input power (P_{IN_T}) at the reader antenna ports can be calculated by subtracting the insertion loss of the signal path, transponder to DUT (ILT2D)

$$P_{IN\_T} \text{ [dBM]} = P_{TB} \text{ [dBm]} - IL_{T2D} \text{ [dB]}$$

where:

- P_{IN_T} is the transponder input power at the reader antenna port
- P_{TB} is the backscatter power of the transponder
- IL_{T2D} is the insertion loss of the signal path from the transponder to the DUT.

With the values gathered by using the proposed measurement setup and the procedure described above it is now possible to calculate the G* value for the current transponder input power:

$$G^* = 2.1 * highRSSI + 10 \log (1 + 10^{deltaRSSI \, / \, 10}) - P_{IN\_T} - 3$$

where:

- highRSSI is the maximum value between the RSSI(I) and RSSI(Q) values read from the RSSI display register or GUI
- deltaRSSI is the absolute value of the difference between the two RSSI values
- P_{IN_T} is the transponder input power at the reader antenna port
- G* is a constant depending on ST25RU3993 register settings and reader design.

It is recommended to repeat the same measurements and calculations for various step attenuator settings to cover the entire ADC range (0-15) of the RSSI I and Q values. Finally, average G across all gathered G* values.

For improved transponder input power readings, repeat the measurements for various backscatter link frequencies, transponder encodings and RX gain settings, resulting in a specific G value for each configuration.

The tables below show the G values used by ST25RU3993-HPEV for various link settings an RX gain settings.

Table 3. G values for 256 kHz / M4

Register 0x0A		Base band gain						
Mixer gain		-9 dB 110x xxxx	-6 dB 100x xxxx	-3 dB 010x xxxx	Nominal 000x xxxx	+3 dB 011x xxxx	+6 dB 101x xxxx	+9 dB 111x xxxx
Attenuation	xxxx xx01	42	45	48	51	54	57	60
Nominal	xxxx xx00	50	53	56	59	62	65	68
Gain	xxxx xx10	60	63	66	69	72	75	78

Table 4. G values for 320 kHz / M4

Register 0x0A		Base band gain						
Mixer gain		-9 dB 110x xxxx	-6 dB 100x xxxx	-3 dB 010x xxxx	Nominal 000x xxxx	+3 dB 011x xxxx	+6 dB 101x xxxx	+9 dB 111x xxxx
Attenuation	xxxx xx01	42	45	48	51	54	57	60
Nominal	xxxx xx00	50	53	56	59	62	65	68
Gain	xxxx xx10	60	63	66	69	72	75	78

Table 5. G values for 640 kHz / FM0

Register 0x0A		Base band gain						
Mixer gain		-9 dB 110x xxxx	-6 dB 100x xxxx	-3 dB 010x xxxx	Nominal 000x xxxx	+3 dB 011x xxxx	+6 dB 101x xxxx	+9 dB 111x xxxx
Attenuation	xxxx xx01	44	47	50	53	56	59	62
Nominal	xxxx xx00	52	55	58	61	64	67	69
Gain	xxxx xx10	62	65	68	71	74	77	79

5 Conclusion

Thanks to the integrated RSSI measurement capability, the ST25RU3993 allows the user to measure the power level of an incoming transponder signal or to detect external RF signal levels close to the reader LO frequency. The received signals (I, Q) are processed and an optimized gain is set by the internal AGC.

This application note provides the formulas to calculate the dBm level of the external RF carrier with the aid of a constant (G value), shown in a tabular format for both receiver types, to help the user select the correct value for a given receiver gain and filter configuration.

To optimize performance it is recommended to check the calculated power against the actual input power, and to adjust the G constant accordingly for every PCB design.

6 Revision history

Table 6. Document revision history

Date	Revision	Changes
03-Jan-2017	1	Initial release.
05-Oct-2021	2	Updated *Introduction*, *Section 1: External RF - Input signal power*, *Section 1.1: Differential input mixer*, *Section 1.2: Single-ended input mixer*, *Section 2: Transponder input signal power* and *Section 3: RSSI calculation using AGC*. Added *Section 4: Values of G for ST25RU3993-HPEV*. Updated *Table 1: G values vs. RX gain settings - Differential mixer* and *Table 2: G values vs. RX gain settings - Single-ended mixer*. Updated *Figure 1: Input power (dBm) vs. RSSI - Differential mixer - BB = 300 kHz*, *Figure 2: Input power (dBm) vs. RSSI - Differential mixer - BB = 50 kHz*, *Figure 3: Input power (dBm) vs. RSSI - Single-ended mixer - BB = 50 kHz*, *Figure 4: Input power (dBm) vs. RSSI - Single-ended mixer - BB = 300 kHz* and *Figure 5: C (in dB) vs. deltaRSSI*.

IMPORTANT NOTICE – PLEASE READ CAREFULLY