AN5532

Application note

Carrier cancellation for RAIN® RFID readers with ST25RU3993

Introduction

This application note aims to describe the purpose, the building blocks, and the benefit of a carrier cancellation system for a high-power RAIN® RFID reader based on ST25RU3993, found in ST25RU3993-EVAL and ST25RU3993-HPEV products.

1 Purpose of a carrier-cancellation system

High-power RAIN® RFID readers aim to read RFID tags at long distances or in challenging environments. In both cases, the tag responses can be very low in power. Therefore, it is important that high-power RAIN® RFID readers also have a high receive-sensitivity which means that the tag detection and decoding threshold of the readers are at very low-power levels. Due to the high RF power design, this category of RAIN® RFID readers faces a challenge to maintain their receive sensitivity. This challenge is related to two system attributes which are explained in the following paragraphs.

The first of these two attributes concern the way how readers and tags are communicating with each other. When communicating with a RAIN® RFID tag the RAIN® RFID reader is transmitting a command to which the tag usually is responding. Apparently, while a passive tag is in its responding phase the reader needs to activate its receiver but at the same time, the reader must keep transmitting CW (continuous wave) power. Easy to understand since a passive tag has no power source other than the electromagnetic field radiated by the reader from which the tag can harvest energy. Another reason why the reader needs to transmit CW is that passive and battery-assisted passive (BAP) tags alike use backscatter communication for their replies. Backscatter communication in short means that the tags can modulate their antenna's reflection coefficient and therefore are able to create a modulated reflection of the reader's CW signal which the reader can detect.

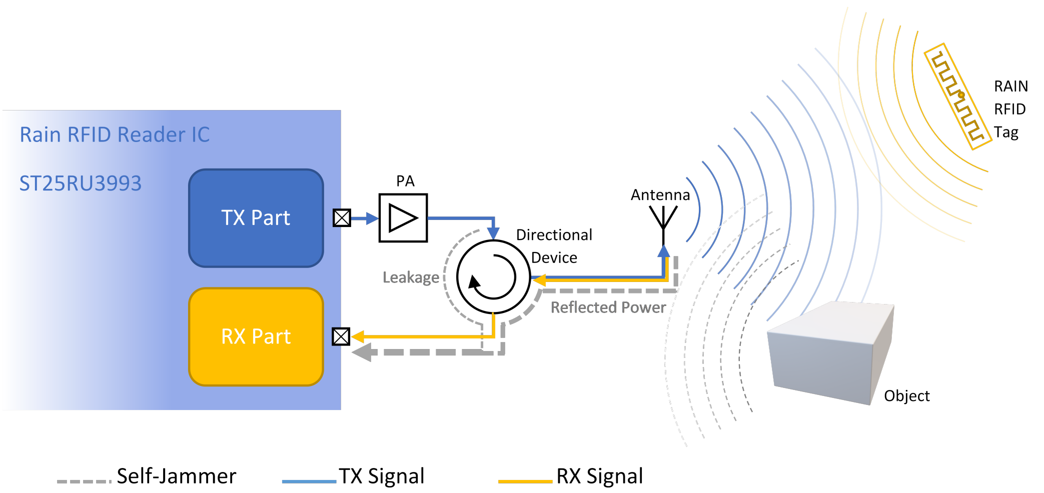
The second attribute involves the reader's antenna. Most RAIN® RFID readers use a monostatic antenna configuration which means the reader is employing the same antenna for transmitting and receiving. When transmission and reception happen at the same time, the transmitter and the receiver must not be directly connected to the antenna. It is essential to isolate the transmitting and the receiving part of the reader as best as possible. The way how this is achieved is by inserting a directional device for instance a directional coupler or a circulator.

Unfortunately, the isolation of such devices is not infinite which means there is still some level of transmit signal leaking to the reader's receiver input.

The monostatic antenna configuration brings along another complication which even has a greater impact and must be discussed in detail. A perfect antenna emits all the RF power which is fed into its terminal as electromagnetic radiation. Unfortunately, this is not the case in the real world. Aside from radiating (hopefully) most of the RF power, a real antenna converts some percentage of the RF power into heat and to some degree, it is reflecting RF power back to its source. It's the latter which is problematic since reflection back to its source means back to the directional device at which the reflection is diverted onwards to the receiver input of the RAIN® RFID reader. In other words, the reflected power at the antenna is taking the same route back as a normal tag response finds its way to the receiver of the reader.

The combination of CW leakage across the direction device and the CW signal reflection at the antenna is commonly referred to as self jammer. To some extent also reflections of the electromagnetic waves occurring at objects in front of the antenna add to the self jammer.

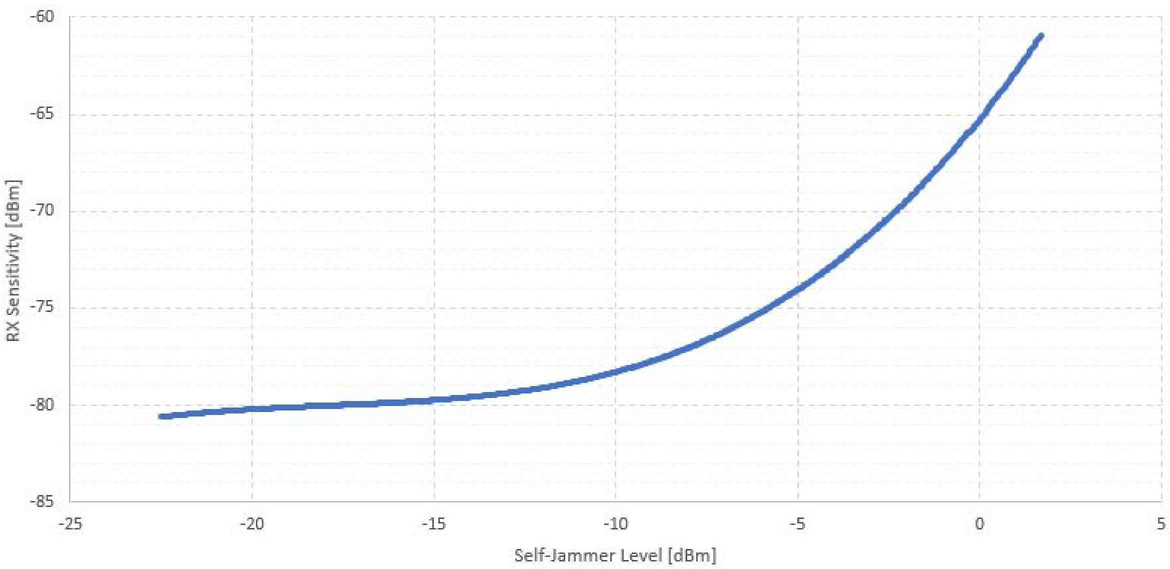
Figure 1. **Self jammer**



The self jammer is an amplitude and phase-shifted version of the reader's unmodulated high-frequency carrier (CW) which is active during the tag response. Once the self jammer reaches the receiver it is directly mixed down to DC (0 Hz) since it is exactly at the same frequency as the reader's internal local oscillator signal used by the I/Q demodulator. As a result, the noise level inside the receiver is elevated reducing the reader's sensitivity and thereby losing its ability to decode low power tag responses.

The higher the self-jammer level is, the more the reader's sensitivity is reduced, and this is not a linear dependency.

Figure 2. **Sensitivity versus self-jammer level**

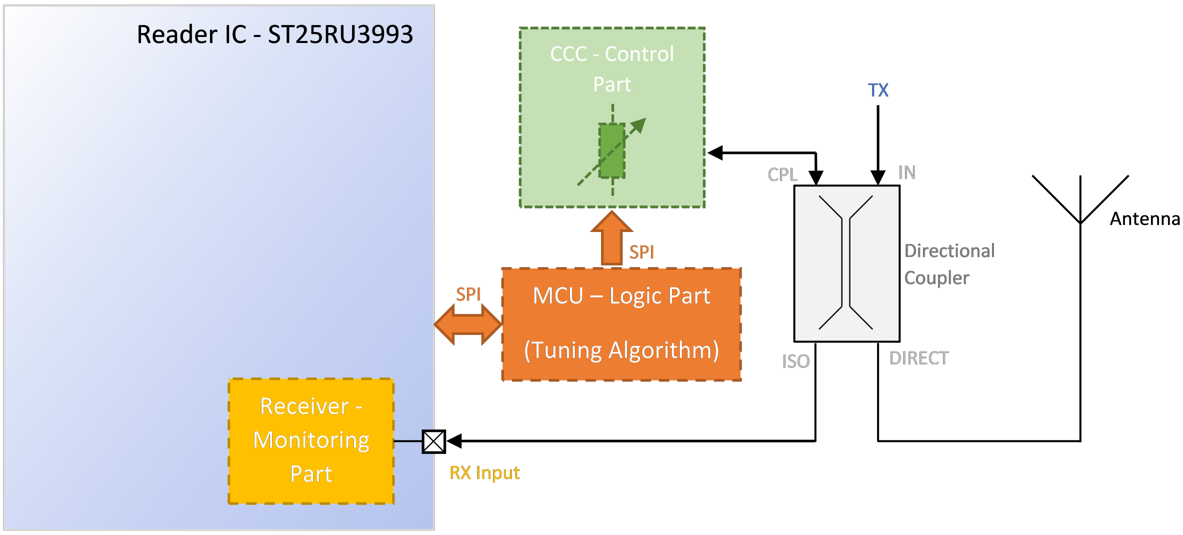


To reach the best receive sensitivity levels the self jammer has to be essentially zero. To achieve this, high-power readers need a way to eliminate the self-jammer signal, need a sub-system which cancels the high-frequency carrier reaching the receiver of the reader. What is needed is a carrier-cancellation system otherwise a high output-power reader is pointless. It only activates tags at great distances, but their responses go undetected by the reader. An undesired situation which is referred to as reverse link limitation.

2 Building blocks of a carrier-cancellation system

There are several possibilities on how a carrier-cancellation system can be implemented. This application note describes a system which on the top level is comprising of three parts. A control part, a monitoring part, and a logic part. The logic part is handled by the MCU of the reader and manages the other two parts following a tuning algorithm. The monitoring part is integrated into the reader IC ST25RU3993. The control part is realized by a carrier-cancellation circuit outside the reader IC acting at the directional coupler.

Figure 3. Carrier cancellation building blocks



2.1 Control part - Carrier-cancellation circuit (CCC)

The CCC is connected to the coupled port of the directional coupler in transmit direction and consists of three variable capacitors forming a π-circuit. Additional lumped components help to center the tuning (impedance) range of the CCC around 50 ohms and define the overall resolution of the CCC. The variable capacitors in the case of the ST25RU3993-EVAL or the ST25RU3993-HPEV can be digitally controlled via an SPI interface. These variable capacitors can be set by the MCU with a resolution of 5 bits. By changing the capacitor values the impedance of the CCC changes. As the termination impedance of the CPL port is changed a reflection of the RF signal at the CPL port is created. Since the directional coupler is a reciprocal component this created CCC-reflection when input at the CPL port will pass through the directional coupler and is output at the ISO port. There the self jammer and the CCC reflection can interfere. The self-jammer signal vanishes if the CCC reflection is phase-shifted by 180° and is of the same amplitude.

Figure 4. **Carrier cancellation circuit (CCC) - Principle schematic**

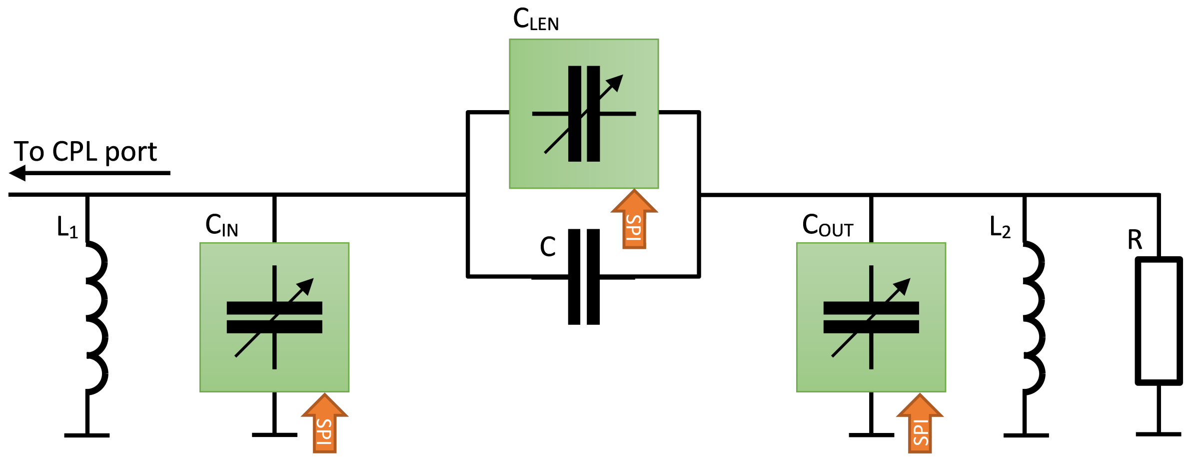


Figure 5. **CCC schematic of ST25RU3993-HPEV**

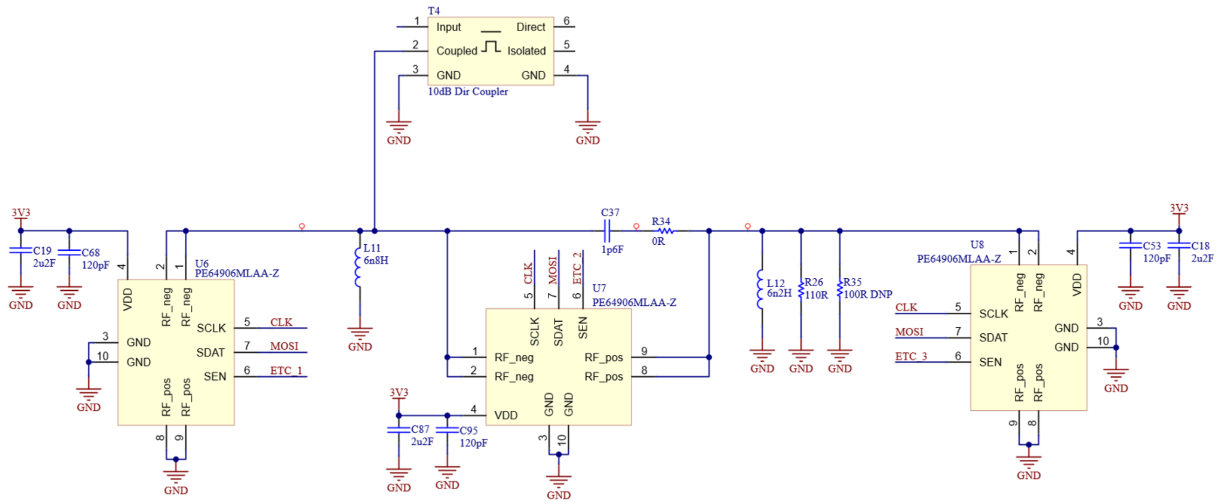
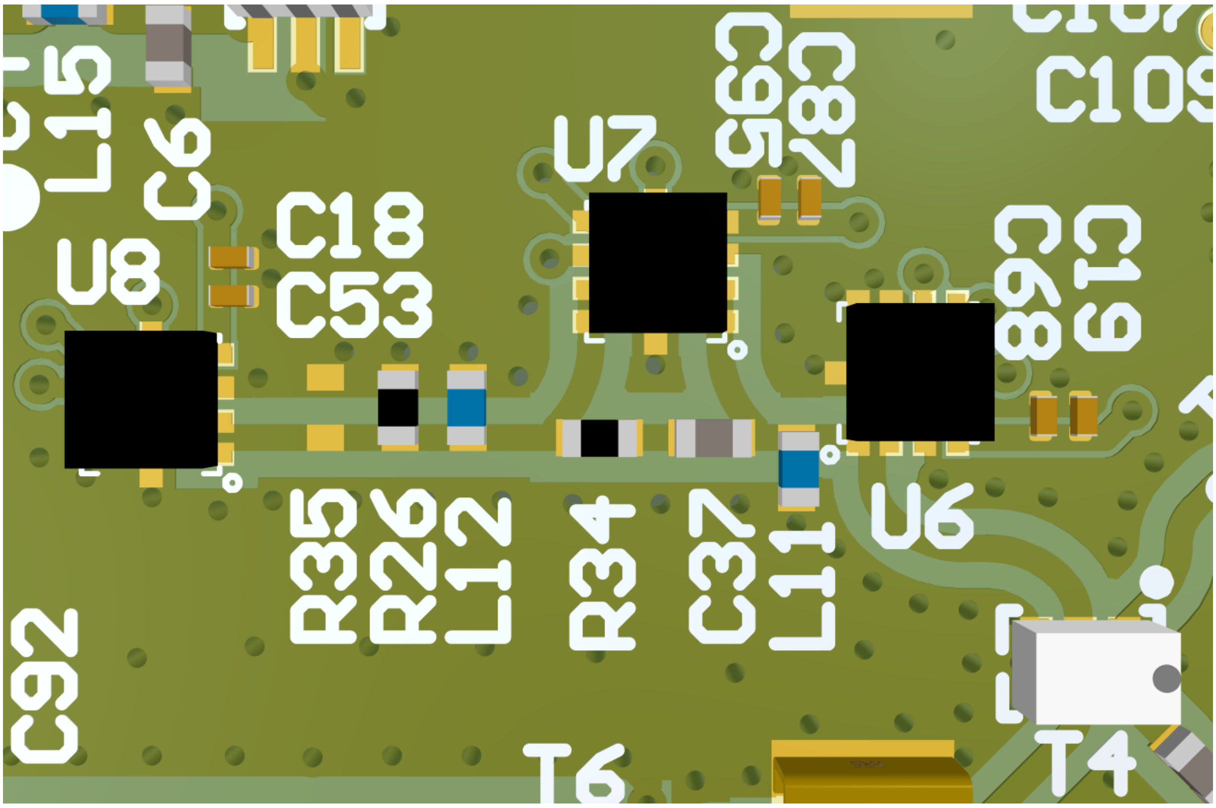


Figure 6. **CCC layout of ST25RU3993-HPEV**



When replicating the CCC for another reader design it is recommended to keep the layout of this sub-circuit unchanged otherwise the centering of the tuning range around the 50 Ω point must be re-checked. In case the tuning range is not centered anymore adjusting the lumped component values of L1, L2, R, and C is necessary.

2.2 Monitoring part - Reflected power measurement

The reader IC ST25RU3993 is used to gauge the level of the self-jammer signal by performing a reflected power measurement. Since ST25RU3993 has an I/Q demodulator inside two ADC conversions are needed – one for Mixer_DC_I and one for Mixer_DC_Q - to complete the reflected power measurement. For more details on the reflected power measurements refer to the application note (AN4970). If the reflected power measurement returns a low value (close to zero) then the self-jammer signal is low as well and hence a high-sensitivity level is reached.

2.3 Logic part - Carrier-cancellation circuit tuning

The MCU is managing the control and the monitoring part and attempts in an iterative tuning algorithm to change the configuration of the CCC that yields the least self-jammer signal level. A CCC configuration comprises the capacitance values for each of the three variable capacitors CIN, CLEN, and COUT. At the beginning of the tuning algorithm, the MCU is initiating the ADC conversions for the reflected power at the reader IC. With the results of the conversion, the MCU calculates the current reflected power. The next step in the algorithm is to change one capacitance value of a variable capacitor in the CCC. With this new CCC configuration, the ADC conversions are repeated and again the MCU calculates the reflected power. Comparing the previous reflected power value with the new one the MCU decides whether to continue changing the variable capacitor value in the same direction, changing the variable capacitor in the other direction or modifying one of the other two variable capacitors. Obviously, if the new reflected power level is lower the algorithm is on a good path and continues to change the variable capacitor in the same direction. When the MCU has reached a point at which several attempts to change the values of the variable capacitors did not yield a decrease in reflected power it halts the tuning algorithm leaving the CCC in a configuration that yielded to lowest reflected power.

A CCC configuration is valid for a specific antenna setup such as an instance of an antenna type or model or even is specific for the antenna feed line length. If anything is altering the reflection coefficient of the antenna the CCC potentially needs to be re-tuned. The same applies to the transmit frequency. For some radio regulations as for instance for the FCC regulations, the reader is required to change transmit frequencies on a regular basis. When the transmit frequency of the reader is changed the CCC most likely needs to be re-tuned to minimize the self jammer. To avoid that re-tuning needs to be done every time the reader changes transmit frequency a lookup table is used which links transmit frequency with a CCC configuration. The look-up table also keeps track of the reflected power level that is reached with the CCC configuration. When the reader is setting up a new transmit frequency it retrieves the CCC configuration from the look-up table and sets the three variable capacitors accordingly. This look-up table is built by tuning the CCC for each hopping frequency. This initial tuning can be performed at the final test at the reader production line or during the first start-up of the reader. These are merely suggestions as other useful procedures may exist. The MCU keeps this tuning look-up table in its non-volatile memory. The self jammer level may change over time if for instance, the environment of the reader antenna has changed. While the reader is operating it is constantly monitoring if the self jammer for the current frequency is sufficiently low by checking the current reflected power value and comparing this one with the stored value inside the look-up table.

In case the reflected power has changed by an amount that exceeds a predefined threshold, the CCC is re-tuned and the corresponding look-up table entry is updated with a new CCC configuration and the corresponding reflected power value. The look-up table update parameters such as the time interval for checking the reflected power and the re-tuning threshold for the reflected power are user-defined.

Several different tuning algorithms have been developed that are either optimized for convergence speed of the tuning algorithm or for lowest attainable self-jammer suppression.

3 Benefits of a carrier-cancellation system

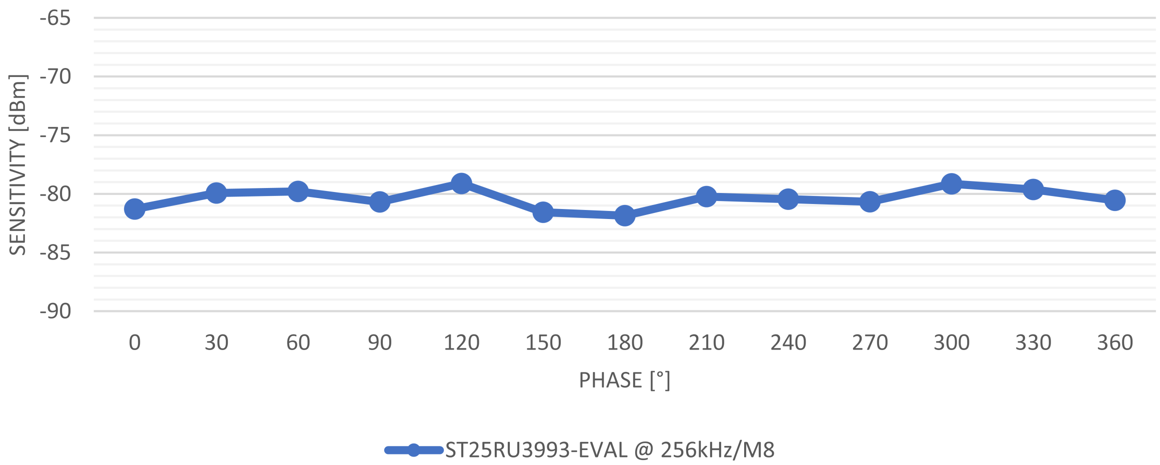
As a rule of thumb, a reader with an output power of more than 27 dBm (500 mW) must have a carrier-cancellation system implemented otherwise the sensitivity of the reader may be reduced. If the reader antenna environment is likely to change or even is prone to be obstructed as it may be the case for a handheld reader it is a good design choice to implement a carrier-cancellation system as well.

When the carrier-cancellation system is well-tuned, the sensitivity of the reader is only limited by the maximum sensitivity of the reader IC ST25RU3993 and by the coupling factor of the directional coupler. The directional coupler used in the ST25RU3993-EVAL and ST25RU3993-HPEV design has a nominal coupling factor of 10 dBm. The maximum reader IC sensitivity is typically at -90 dBm and is described in its datasheet as LBT (listen before talk) sensitivity – without the RF carrier being ON and hence without self jammer.

This results in a maximal obtainable reader sensitivity of typical -80 dBm. Frequency dependencies, parameter variations and tolerances of the components used in the reader design can shift this maximal reader sensitivity up or down. A sensitivity variation of ±2 dB is a practical assumption.

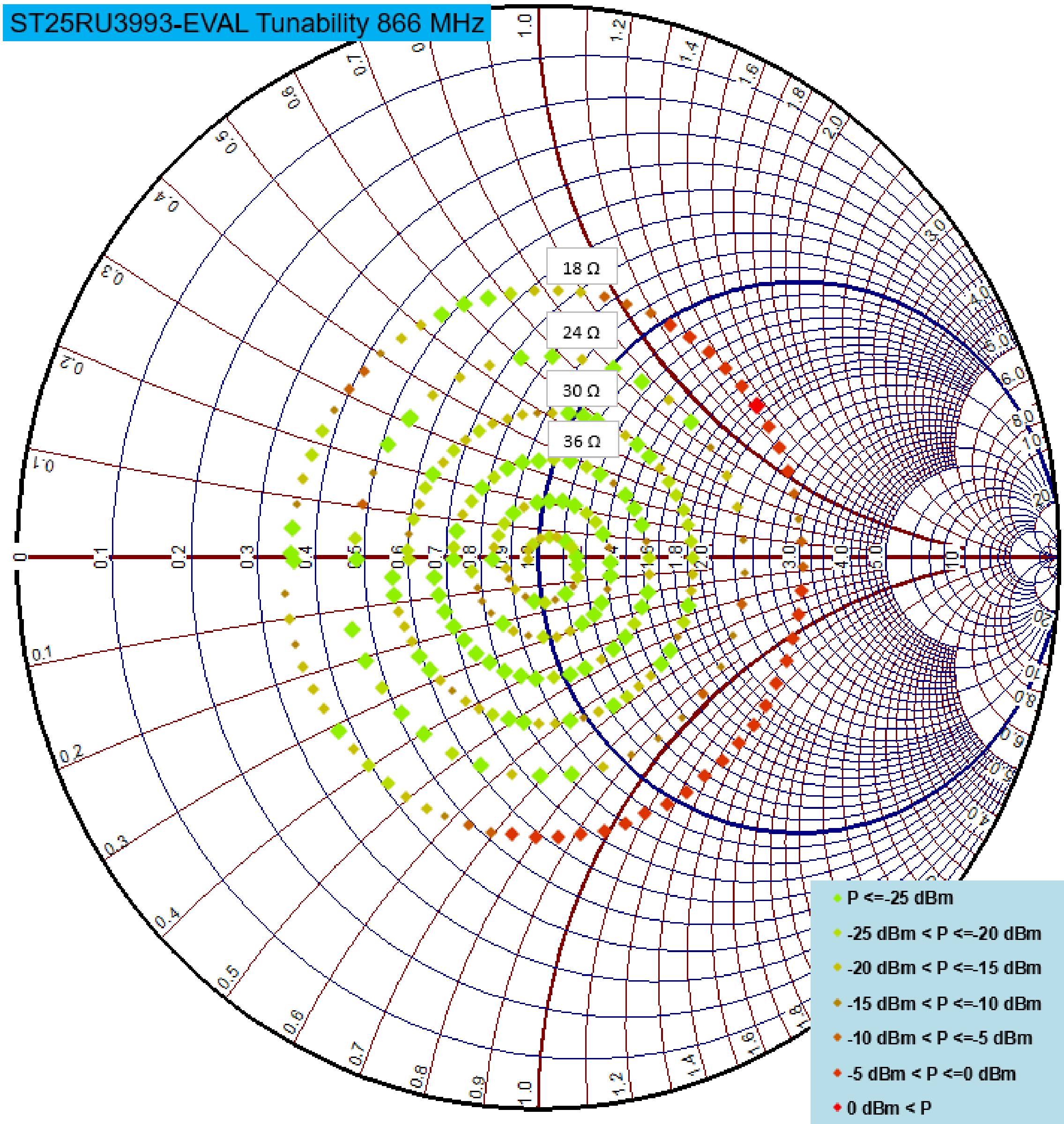
In the graphic below the maximum sensitivity of the ST25RU3993-EVAL reader over the RX-phase is shown. This sensitivity chart is generated at a specific operating point (default TX power, BLF = 256 kHz, M8). The reader IC ST25RU3993 provides many different settings and therefore the receive sensitivity can change along with them. The changes in sensitivity levels depending on the reader configuration are not in the focus of this document.

Figure 7. RX sensitivity versus phase of ST25RU3993-EVAL



The ability to suppress the self jammer has its limits. An ideal reader antenna must have an impedance of 50 Ω for its entire specified frequency bandwidth. For a real antenna, this is usually not the case. Depending on the frequency used, the antenna impedance wraps more or less tightly around the 50 Ω point. The closer the impedance for a given frequency is to the 50 Ω point, the better the antenna is matched, which is another way of saying that it produces fewer reflections back to its source. By obstructing an antenna, for instance by placing an object directly in front of it or by just touching it the antennas impedance may jump significantly and therefore may have a larger reflection coefficient. The reflection the antenna is producing then may be too large for the tuning range of the CCC. If the antenna impedance is near or even outside the tuning range of the CCC the ability to effectively cancel the self jammer is limited. The following graphic shows the ability of the CCC to cancel the self jammer for a given load impedance.

Figure 8. **Ability of the carrier-cancellation circuit versus the load impedance**



This graphic shows numerous different load impedances that simulate the (detuned) antenna connected to the antenna port of ST25RU3993-EVAL. The load impedances are spaced almost concentric around the ideal 50 Ω point. The color-coding of the dots represents different levels of reflected power that result after the CCC is tuned. The green color is assigned if the self jammer strongly suppresses. Impedances for which the self jammer cannot be highly canceled are red.

4 Conclusion

This application note explains why for high-power RAIN® RFID readers it is difficult to provide a high-sensitivity receiver without a carrier-cancellation system. The common monostatic reader architecture which employs a single antenna for transmission and reception in combination with the active RF carrier during signal reception creates a self-jamming signal which reduces the reader's sensitivity. Furthermore, the design of the carrier-cancellation system as it is used for the evaluation reader ST25RU3993-EVAL and ST25RU3993-HPEV is shown. The three building blocks of this specific carrier-cancellation system, the CCC, ST25RU3993's capability to measure the reflected power, and the tuning algorithms running on the MCU have been described in detail. To demonstrate the effectiveness and the benefit of the carrier-cancellation system the sensitivity plot vs. the RX phase of the ST25RU3993-EVAL reader is shown. This plot proves that the sensitivity of the reader is basically at the same level as the reader IC's listen-before-talk sensitivity only reduced by the coupling factor of the directional coupler. This means ST25RU3993-EVAL is operating at its highest possible sensitivity leaving aside other measures to increase the sensitivity further such as adding an external LNA or a bi-static reader architecture all of which deserves to be discussed in dedicated application notes.

This application note concludes with a graphic showing the substantial tuning range of the carrier-cancellation circuit (CCC) maintaining a high sensitivity while the antenna is severely detuned.

Revision history

Table 1. **Document revision history**

Date	Version	Changes
10-Jul-2020	1	Initial release.

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