

## Practical Sensitivity Testing

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### Keywords

- *Receiver Testing*
- *Sensitivity*
- *PER (Packet Error Rate)*
- *BER (Bit Error Rate)*

## 1 Introduction

To properly evaluate the receiver part of a transceiver, it is necessary to be able to find the sensitivity threshold, i.e. the lowest input signal the receiver can decode with acceptable signal quality. There are several approaches to find the sensitivity threshold of a receiver, but the various methods require different levels of instrumentation. Since our costumers can be equipped with anything from a full RF lab to no equipment at all, this design note covers both simple and more complex methods. The design note uses CC1100/CC2500 to illustrate the methods, but the principles can be used also for any other of our products.

The sensitivity measurements described in this document are:

- 1) PER test using RF generator with packet option and SmartRF<sup>®</sup> Studio to receive the packets.
- 2) Overview of PER test using LabView and dedicated RF generator with packet option (for automated testing).
- 3) BER test with dedicated BER tester, using the transceiver in “synchronous serial mode”.
- 4) BER test with oscilloscope to decide the received bit errors. Transceiver used in “synchronous serial mode”.
- 5) PER test using SmartRF<sup>®</sup> Studio packet test and attenuators to find the link budget.

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## 2 Abbreviations

AGC	Automatic Gain Control
BER	Bit Error Rate
CRC	Cyclic Redundancy Check
DUT	Device under Test
EB	Evaluation Board
EM	Evaluation Module
FIFO	First In First Out
FM	Frequency Modulation
FSK	Frequency Shift Keying
GDO	General Digital Output pin
PER	Packet Error Rate
RF	Radio Frequency

### 3 Test Description

All the tests described in this document are intended for either checking the receive performance of CC1100/CC2500, or to check the receive performance of a design using the CC1100/CC2500. In both cases it is required to have access to a development kit for the transceiver in question. Performance of the chip itself can be done by simply measuring on the development kit, while testing of a design that uses CC1100/CC2500 requires that the design is interfaced to the SmartRF<sup>®</sup>04EB board. (SPI lines and GDO lines must be strapped over to the test connectors on the SmartRF<sup>®</sup>04EB board). The tests described in this document need a certain amount of RF equipment. The only exception is the test described in section 3.5, which only requires a development kit and attenuators.

Two abbreviations that are used frequently in this document are BER (Bit Error Rate) and PER (Packet Error Rate). These terms are closely linked, i.e. with a given packet length and BER the PER can be calculated using the following formula:

$$PER = 1 - (1 - BER)^{packet\_length}$$

Note that the packet length includes both sync word and CRC in addition to the payload data since a bit error in those fields will result in a packet error (for the CC1100/CC2500 in buffered mode this applies if the sync word detection requires all 16 of 16 sync word bits to be detected correctly).

In all the tests described in this document it should be ensured that the receiver and transmitter work at the same RF frequency in order to measure the real (best case) sensitivity. This can be done by setting the DUT in TX and measuring the transmitted signal with un-modulated carrier (FSK and 0 deviation), or by measuring the centre of the transmitted spectrum. This requires access to a spectrum analyzer. Alternatively, the transmit frequency from a generator or transmitting device can be swept until the best sensitivity is found.

### 3.1 Sensitivity Test Using SmartRF® Studio and RF Generator w/ Packet Option

This test uses SmartRF®04EB and CCxx00 together with SmartRF® Studio as a receiver, and a RF generator with packet option as a transmitter. The RF generator is configured for the selected RF frequency, modulation format, deviation, and data rate. SmartRF® Studio is used in “packet RX” mode.

The format of the packets from the generator is somewhat limited by the functionality of SmartRF® Studio. I.e. variable packet length with length byte in the beginning of the packet must be used, and the CRC at the end must be correctly calculated and added to the transmitted packet. The packet format is illustrated in Figure 1, and the sections are described below:



**Figure 1. Packet Format for Receiving Packet with SmartRF® Studio**

#### Preamble

10101010 sequence (NRZ) or 10011001 sequence (1010 Manchester coded). Programmable length (2-24 bytes). Other preamble formats can be programmed on the RF generator (to emulate existing protocols), but it must be noted that the CC1100/CC2500 will not be able to generate these in normal mode. It should also be noted that using other preamble formats may affect PER and required preamble length.

#### Sync Word

The CC1100/CC2500 offers a programmable sync word both in RX and TX. In TX, the sync word (16 bits) can be sent once or repeated. I.e. 32 bit sync is the same 16 bits repeated twice. In RX, the receiver can be set to receive the packet when a pattern of 15 of the 16 bits are found, or when 16 of 16 bits are found (alternatively when 30 of 32 bits are found in the case of repeated sync word).

If a sync word other than the default (0xD391) is to be used, it is necessary to do the following:

Set up normal “packet RX”, hit “copy settings to register view”, select the “manual init box”, and go to “register view” and update the `SYNC1` and `SYNC0` registers. When returning to “normal view”, the “packet RX” mode will use the updated sync word.

#### Length Byte

Length of payload field (not including the length byte). In TX, the length byte is the first byte written to the FIFO of CC1100/CC2500. On the RF generator, the length byte must be placed after the sync word.

#### CRC

16 bit CRC value is calculated automatically by CC1100/CC2500 in TX. On the RF generator, it is necessary to manually calculate the 2 byte CRC value that is appended to the end of the payload (see DN503 on how to calculate the CRC), or alternatively a pair of CC1100/CC2500 can be used to do the CRC calculation.

In the latter case one CC1100/CC2500 is set up in “packet TX”, transmitting the packet with the wanted payload repeatedly. The other CC1100/CC2500 is configured to operate in packet RX mode (it is a good tip to start RX with the “start buffered RX” button and then stop RX again to ensure that packets are coming in). The settings are then copied to “register view” with the “copy settings to register view” button. In “register view” the expected packet length is then set longer than the expected packet (`PKTLEN` register) and fixed packet length is selected (`PKTCTRL0` register). CC1100/CC2500 is then set in RX mode by using the SRX strobe button. The radio will end up in `RX_OVERFLOW` state, but by reading the FIFO, the

correct CRC value can be obtained. See Figure 2. To recheck the CRC value, the FIFO can be flushed with SFRX strobe, before returning to RX and reading the FIFO. The data seen after the CRC value in the FIFO is demodulated noise, and should be disregarded.

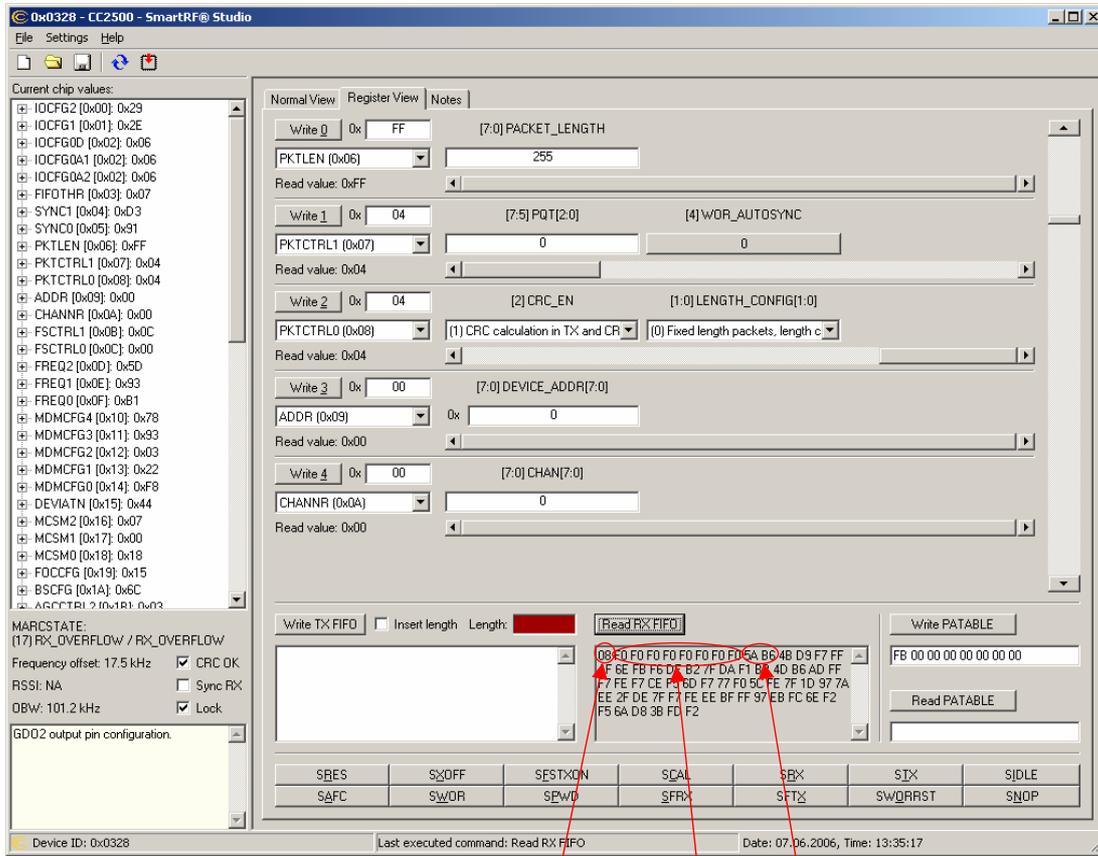


Figure 2. SmartRF® Studio Screen Capture with Received Packet and CRC

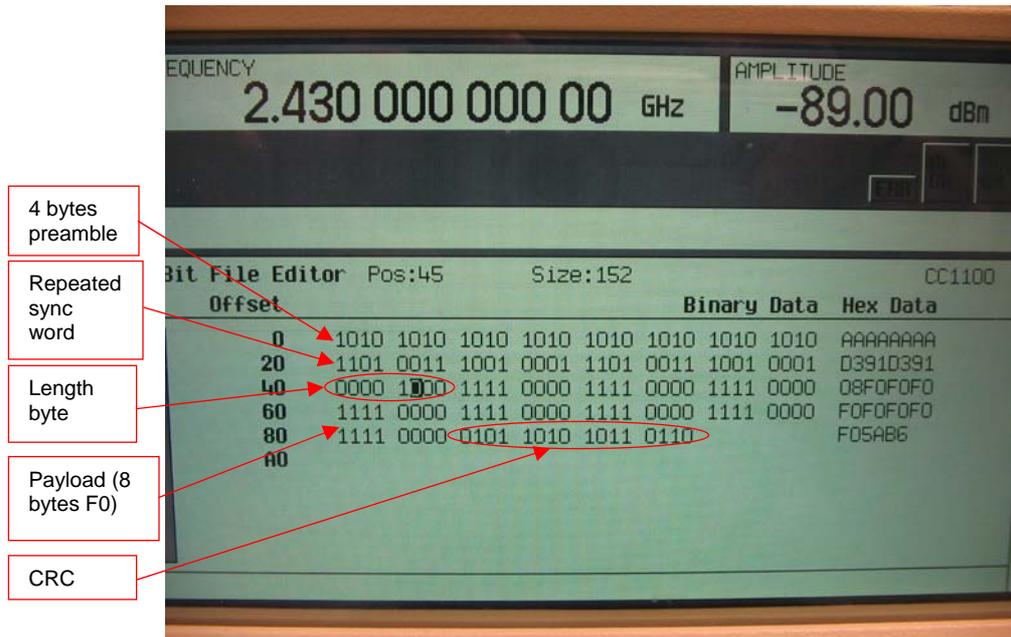


Figure 3. RF Generator Programmed with a SmartRF® Studio Compliant Packet

Figure 3 shows the same packet programmed into a RF generator. By retransmitting the same packet a known number of times and receiving with SmartRF® Studio “packet RX” mode, the PER can be calculated:

$$PER = \frac{Lost\_packets + CRC\_errors}{Transmitted\_packets} \cdot 100[\%]$$

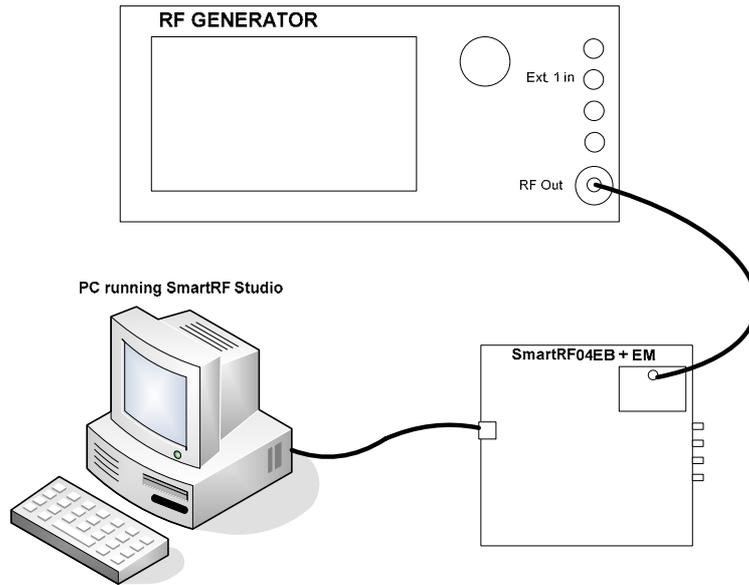
The sensitivity threshold is found by reducing the RF level from the generator until PER = 1%.

Time interval between packets can be implemented by programming the RF generator (if applicable), or by inserting a long sequence of zeros after the CRC and looping the packet continuously.

A certain time between packets is necessary to ensure that all packets are received by SmartRF® Studio. This is due to limitations on the PC/USB side, and not a limitation of the radio. SmartRF® Studio transmits one packet every 150 ms, and transmitting packets faster than this might cause packets to be lost.

Note that inserting zeros between packets will be the same as transmitting a continuous carrier (when using FSK) and that this will to some extent reduce the preamble requirement. The reason is that the AGC is already settled at the start of the preamble when a carrier is present before the packet “starts”, and the result is that short preambles may show an “optimistic” sensitivity figure. It should also be noted that some RF generators do transmit an un-modulated carrier between packets even without programming a long sequence of zeros.

The measurement setup for the sensitivity test is shown in Figure 4.

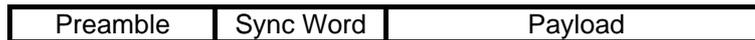


**Figure 4. Test Setup for Sensitivity Test Using RF Generator with Packet Support and SmartRF® Studio**

### 3.2 Sensitivity Test Using LabView and RF Generator with Packet Option

Most of the in-house sensitivity testing at TI Norway is done using automated tests with National Instruments LabView together with various RF test equipment. LabView code is not distributed or supported, so this section is given as an overview only.

The packet format used in the LabView sensitivity testing is illustrated in Figure 5 and described below. Fixed packet length mode is used. CRC check is not used since the automated test compares the transmitted and received packet bit for bit.



**Figure 5. Packet Format for Receiving Packet with LabView Automated Tests**

#### **Preamble**

4 bytes 10101010 for most data rates. 8bytes for 500 kbps.

#### **Sync Word**

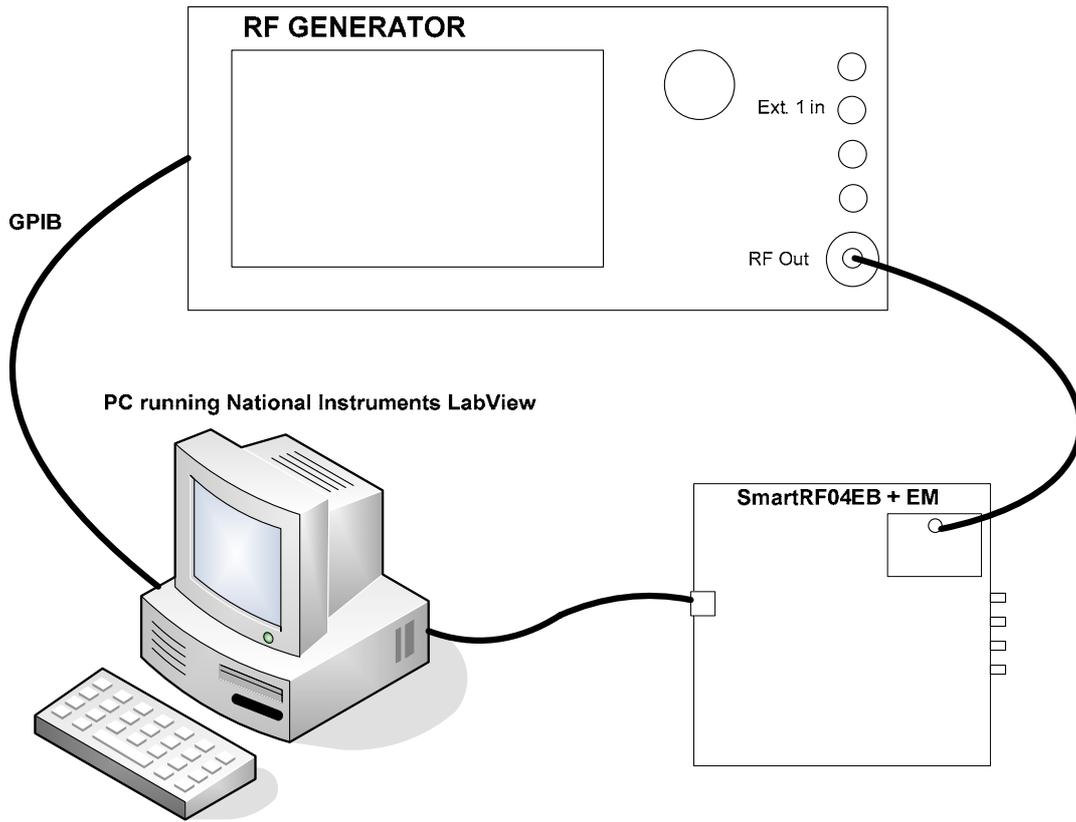
Repeated sync word 0xD391 (i.e. 32 bits)

#### **Payload**

20 byte payload with pseudo-noise pattern

Overview of the sequence implemented in LabView: (Assume that a transmit frequency that ensures 0 frequency offset between TX and RX is already found. In the LabView test this is ensured by measuring the DUT in TX, but this requires the addition of a spectrum analyzer in the test setup)

1. Program the CC1100/CC2500 with the wanted RF configuration (RF frequency, modulation format, deviation, data rate etc.), and put the device in RX.
2. Configure the RF generator with the corresponding RF settings.
3. Load the selected packet (bit sequence containing preamble, sync word, and payload) to the RF generator, and transmit the packet once.
4. Read the RXFIFO content and compare it to the known bit sequence bit for bit. Since each bit is checked a CRC check is redundant.
5. Repeat steps 3 and 4 for a sufficient number of packets (At least 100 packets is needed to give a reliable PER figure).
6. Adjust RF level from the generator and start from step 3 again. This is repeated until the wanted PER level is found. (in-house, a custom algorithm is used to adjust input level to minimize test time).
7. Around the sensitivity limit a larger amount of packets is sent to accurately find the limit.
8. Log the final result in an output file.



**Figure 6. Test Setup for Automated Sensitivity Test Using National Instruments LabView**

### 3.3 Sensitivity Test Using BER Tester and “Synchronous Serial Mode”

When the CC1100/CC2500 is used in “synchronous serial mode”, the received data is available on two GDO pins in the shape of serial data and a corresponding synchronized clock. These signals are routed out to SMA connectors DTEST0 and DTEST1 on the SmartRF<sup>®</sup>04EB.

To select the “synchronous serial mode” in SmartRF<sup>®</sup> Studio, simply program intended configuration in “normal view”, select the “simple RX” tab and hit the “start un-buffered RX” button. The routing of data and clock is shown in the bottom window of SmartRF<sup>®</sup> Studio, where they are labeled as “data/clock to external oscilloscope”.

With this mode the sensitivity measurement can be done using a dedicated BER tester in combination with a RF generator, or alternatively an RF generator with built in BER tester. In this case a baseband signal (usually with a pseudo-random pattern) is generated by the internal or external BER tester, this signal is modulated onto the RF carrier, and the RF signal is received by CC1100/CC2500. The received signal is then routed back to the BER tester and compared to the previously mentioned baseband signal. Bit errors are counted and a BER is displayed. The update rate of the BER indication is programmable on the BER tester or RF generator. The sensitivity threshold can then be found by lowering the level of the RF signal until a BER of  $1 \cdot 10^{-3}$  (typical definition of sensitivity) is displayed.

The measurement setup for using an RF generator together with a separate BER tester is shown in Figure 7. In the case of a RF generator with internal BER function, the BER tester in the figure is removed and the demodulated baseband signal (and synchronized clock) is instead connected to inputs on the RF generator.

Note that the baseband signal does not represent a series of packets in this case, but rather a continuous stream of data.

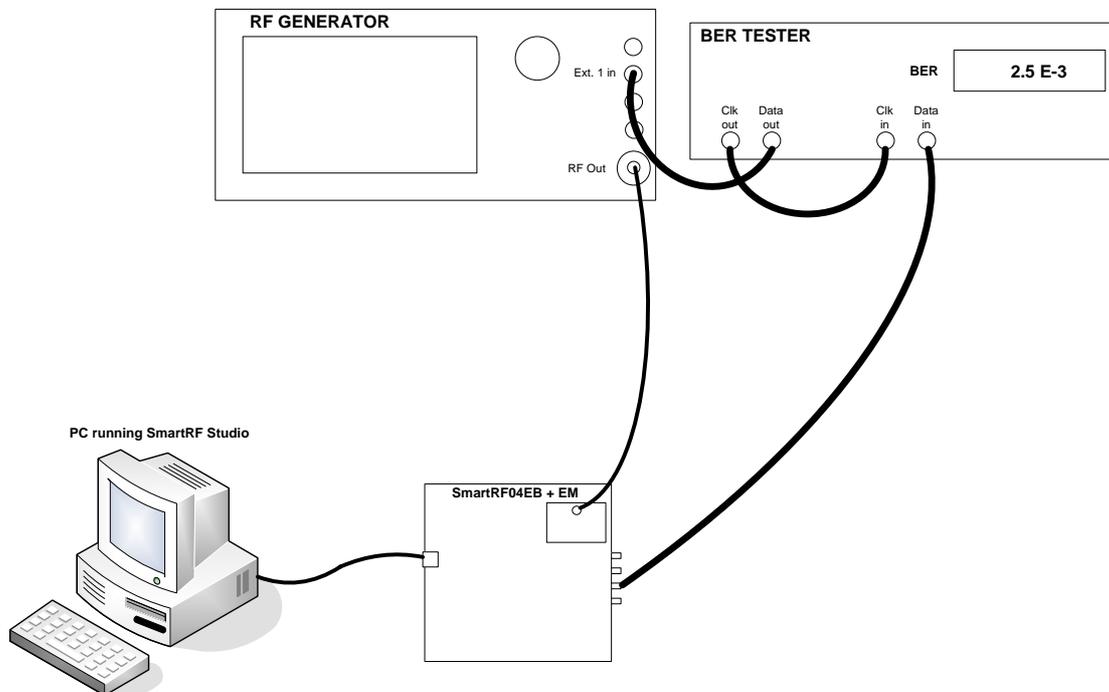
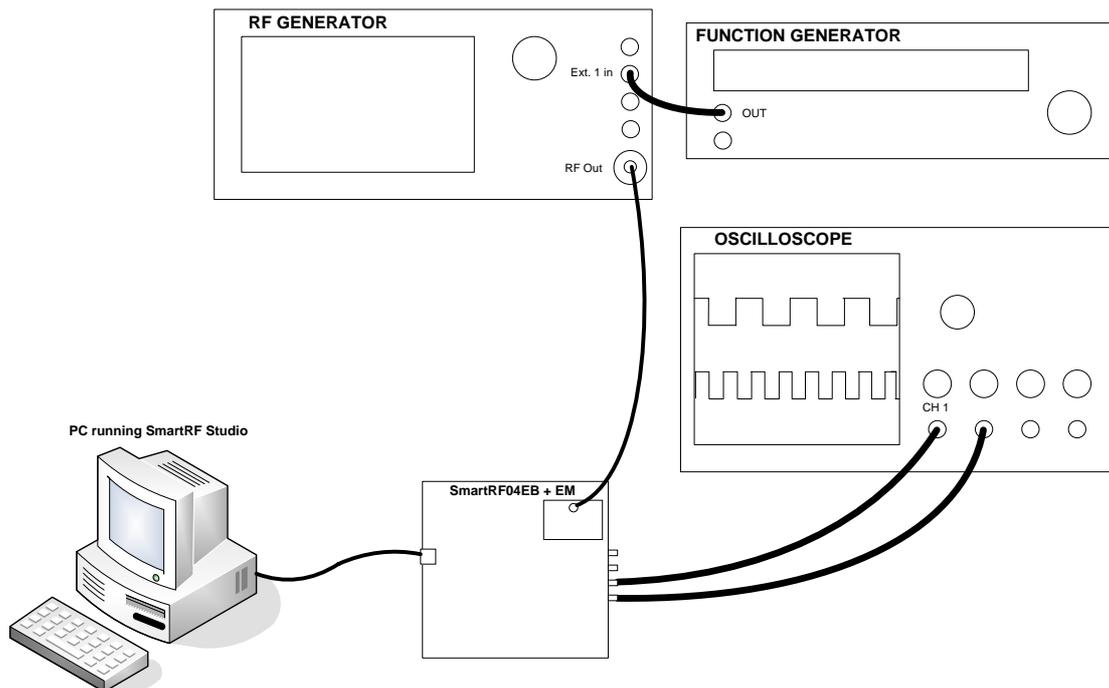


Figure 7. Test Setup for Sensitivity Testing Using a Dedicated BER Tester

### 3.4 Sensitivity Test Using Oscilloscope and “Synchronous Serial Mode”

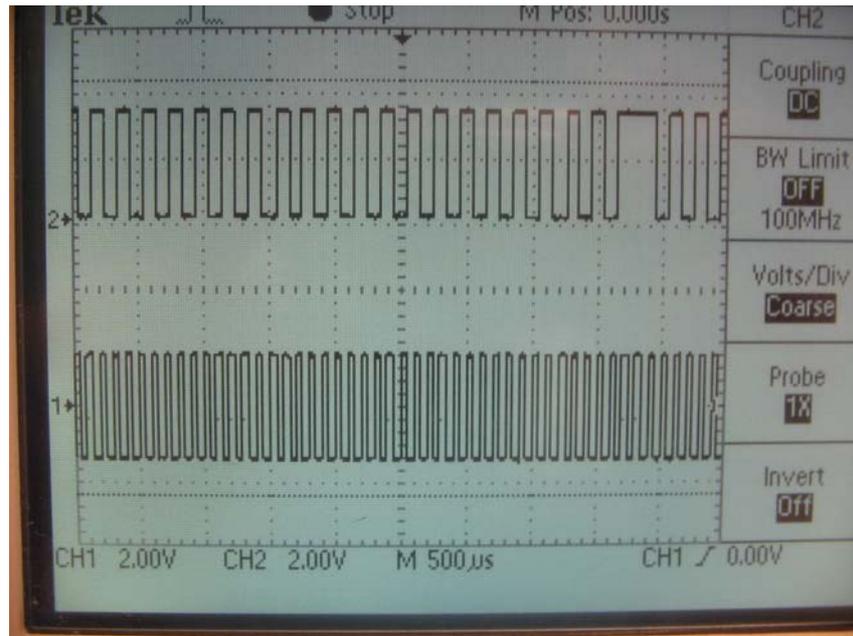
It is also possible to test sensitivity with the “serial synchronous mode” without having access to a dedicated BER tester. With only a RF generator and an oscilloscope a relatively accurate sensitivity measurement can be made. Even with a very basic RF generator (without FSK modulation) it is possible to do a FSK sensitivity measurement. In this case a function generator is used to create a square wave baseband signal, and the RF generator is set up for FM and external modulation. The function generator is set up to output a square wave with a frequency equal to half the programmed bit rate (remember that the effective bit rate is reduced in half when selecting Manchester coding for CC1100/CC2500). This is identical to a 01010101 sequence, and this sequence can easily be recognized on the oscilloscope. The amplitude from the function generator must be within the limitations of the external input on the RF generator, and it should be confirmed that the deviation produced by the RF generator is as programmed on the CC1100/CC2500. This can be done with for instance a spectrum analyzer connected to the RF generator.

The test setup for sensitivity testing with RF generator, function generator and oscilloscope is shown in Figure 8. In the case of RF generator with internal FSK modulation the function generator can be omitted. The configuration of SmartRF® Studio is done as in section 3.3.



**Figure 8. Test Setup for Sensitivity Testing Using Oscilloscope**

Figure 9 shows a typical oscilloscope plot taken close to the sensitivity threshold. The demodulated data is shown in the top curve (with one bit error) and the synchronized clock is shown below.



**Figure 9. Oscilloscope Screen Capture of Demodulated Data and Synchronized Clock near the Sensitivity Limit**

Two issues should be mentioned with relation to this sensitivity test. One is that it is not easy to determine an accurate BER (e.g.  $1 \cdot 10^{-3}$ ) by looking at the oscilloscope. However, the increase in BER near the sensitivity threshold is quite abrupt so it will be possible to find a good approximation. The other issue is that demodulating a 01010101 sequence is easier than demodulating a PN sequence for the receiver (due to high amount of transitions), and thus the measured sensitivity will be slightly optimistic.

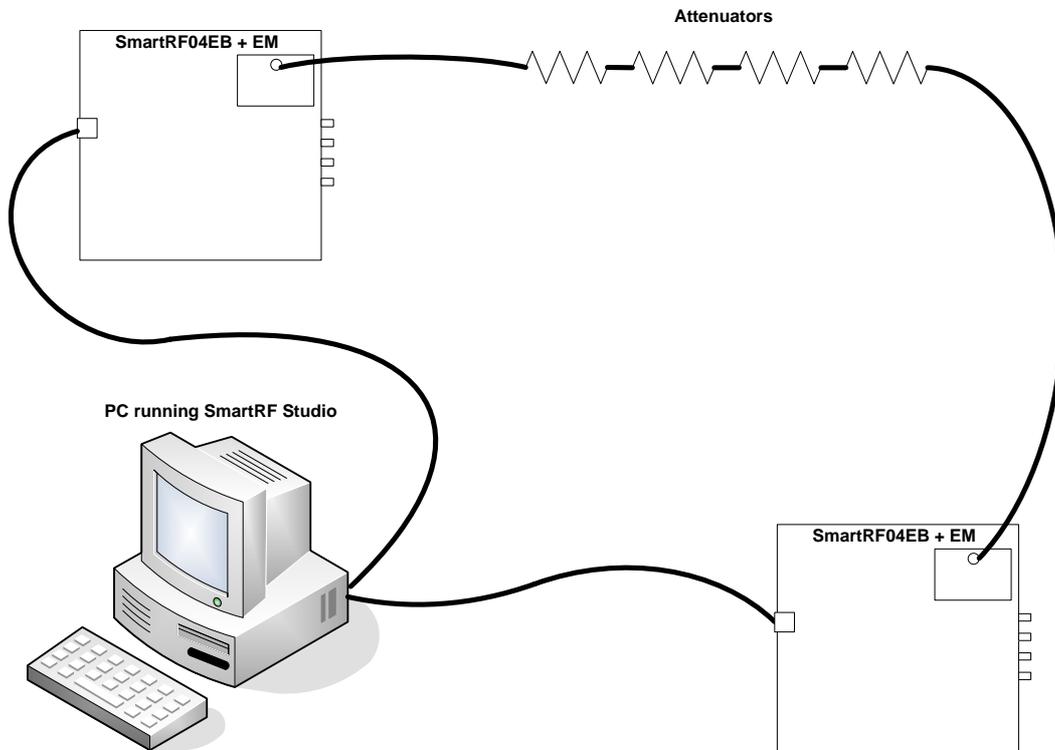
### 3.5 Sensitivity Test Using Attenuators and SmartRF® Studio Packet Test

The simplest form of sensitivity testing is to use a CC1100/CC2500 both as transmitter and receiver, i.e. omitting use of all RF test equipment. The challenge in this case is to accurately control the RF level at the receiver, and the obvious approach is to use a set of attenuators.

The test setup is shown in Figure 10

To determine the PER, the packet test option in SmartRF® Studio can be used. I.e. configure both TX side and RX side with the appropriate RF settings, select the “packet TX” or “packet RX” tab, select an appropriate packet format (for example the one suggested in section 3.1, page 4) and select a sufficient number of packets. Then start up the receiver first by clicking the “start buffered RX” button, and the transmitter by clicking “start buffered TX”. The PER is calculated as in section 3.1, and the attenuation is increased until the PER reaches 1%. This defines the sensitivity threshold.

One issue to remember with this setup is that RF power can reach the receiver outside the path through the coax cable and attenuators. This is specially an issue if the two boards are placed very close together and the receiver is operated with very good sensitivity (low data rate and receiver bandwidth). The symptom is then that the receiver can decode packets even with very high attenuation, and it is not possible to find the sensitivity threshold correctly. To avoid this one of the boards should be placed in a shielded box where the shield is grounded and the only opening in the box is a small hole for cables to exit. This will reduce radiation to a minimum. Such a box can be made of any box of conductive material (e.g. a biscuit tin).



**Figure 10. Test Setup for Sensitivity Test Using Attenuators and SmartRF® Studio**

## 4 General Information

### 4.1 Document History

Revision	Date	Description/Changes
SWRA097	2006.07.06	Initial release.

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