

Crystal Oscillator Design Considerations

White Paper

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1 Introduction

An accurate crystal oscillator is needed in all RF designs. This document presents:

- the main RF parameters affected by the crystal oscillator accuracy.
- how to measure crystal oscillator accuracy.
- how to correctly design the crystal circuitry of nRF devices.

2 Background

All RF devices have a maximum offset in RF frequency that they can tolerate while still performing according to the device specification. All RF receivers have a limited frequency window where they can receive incoming RF signals with a minimum power equal to the specified receiver's sensitivity limit. You can find a device's sensitivity limit in its product specification. The limited frequency window is decided by the bandwidth of the filters in the receiver and is called the RX channel bandwidth as shown in Figure 1. on page 4. This bandwidth must be limited to reduce the impact of background noise and to separate the wanted RF signal from unwanted power received from other transmitters operating on frequencies that are in close proximity (called RX selectivity).

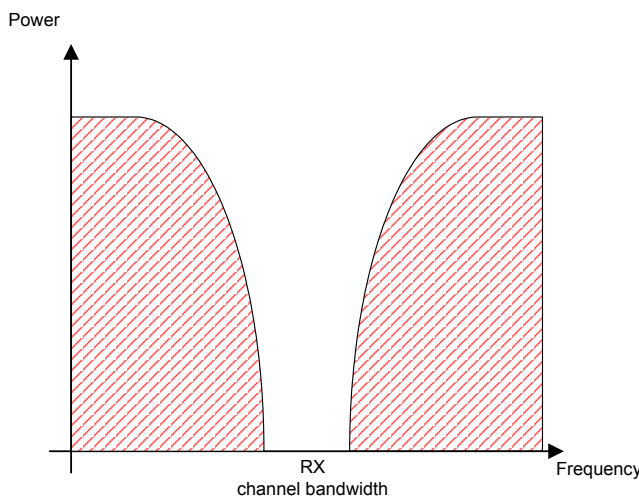


Figure 1. Receiver sensitivity vs. frequency

Incoming RF signals that fall inside the receive bandwidth will pass through the receiver. RF signals outside the RX bandwidth (shaded area in the 'Figure 1. Receiver sensitivity vs. frequency') will be filtered out. It is essential in all RF systems that the incoming RF signal from the transmitter is found within the receive bandwidth of the receiver. This is so that it can utilize the full sensitivity of the receiver. Any offset that brings the TX spectrum outside the RX bandwidth results in the receiver filtering out the incoming signal as noise, see Figure 2. on page 5.

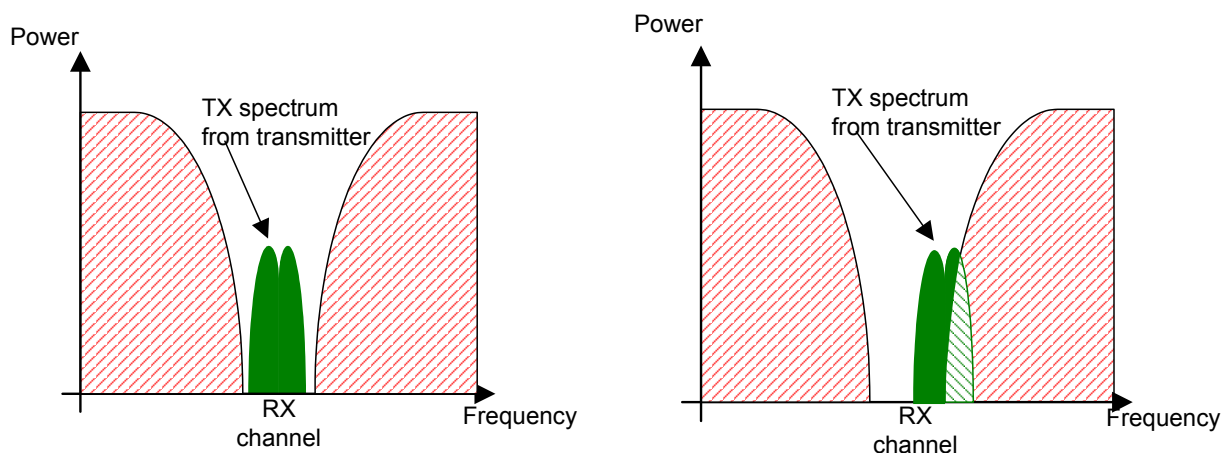


Figure 2. TX frequencies outside the RX BW will be filtered out

The accuracy of the crystal reference is the only deciding factor of this frequency accuracy on all nRF devices. Any offset in crystal frequency is directly mirrored in offset in TX frequency and RX windows. As shown in Figure 2. on page 5, if the offset between the crystal in a TX and RX unit becomes too large, the signal from the transmitter will be filtered out by the receiver. In the system it will look like the receiver has lower sensitivity than specified in the device's product specification and this cuts the range of the application.

The frequency accuracy needed to ensure a good match between transmitted frequency and receiver window position is mirrored directly to a crystal accuracy specification for each nRF device. This accuracy is given as a maximum part per million (ppm) offset requirement and is a standard part of any crystal specification.

Note: The crystal accuracy specification for nRF products is limiting the SUM of:

1. Absolute accuracy at 25 degree Celsius.
2. Temperature drift.
3. Aging.

These three parameters are usually separated in crystal data sheets.

3 Measuring crystal oscillator accuracy

Measuring the accuracy of a fixed TX carrier wave transmitted from a nRF device will verify crystal oscillator accuracy directly since the crystal frequency is the only variable. Measuring the RX window of a nRF device is a time consuming task, but by measuring the TX carrier wave frequency accuracy the RX window follows by design. You should also measure TX carrier accuracy on units that are going to be receivers only.

The crystal oscillator accuracy is OK if:

$$\frac{|F_0 - F_{DUT}|}{F_{DUT}} \leq M \cdot 10^{-6}$$

Variable	Description
F_0	Measured TX carrier frequency
F_{DUT}	The frequency Device Under Test (DUT) is programmed to send (EX: 2.403 GHz)
M	Frequency accuracy of crystal at room temperature in ppm (Ex: 20)

Table 1. Frequency accuracy parameters

Note: M must be the accuracy of the crystal at room temperature and not the total crystal accuracy requirement of the nRF device. This is because this measurement is conducted at room temperature and crystal frequency offset due to temperature drift should not be present.

Please refer to the Nordic Semiconductor white paper 'nRF TX measurements' for procedures on how to measure TX frequency accuracy on nRF devices.

If the TX carrier wave frequency is found to be outside the specified window, the first parameter to check is the crystal specification. If the crystal accuracy is not according to the Nordic Semiconductor specifications, it must be replaced by one that is.

4 Crystal oscillator design

Another issue that causes offsets in the crystal oscillator frequency is wrong capacitive loading of the crystal. All nRF devices utilize parallel load compensated crystals and all such crystals are specified for operation with a specific external capacitive load (C_L).

The crystal will NOT oscillate on the frequency specified in the crystal data sheet if the passive crystal load circuitry does not provide the C_L that is specified for the crystal.

Too low capacitive load will result in a crystal oscillator frequency higher than specified, or too high a load results in a lower oscillation frequency. This frequency offset will be translated directly to an offset in the operating frequency of the nRF device.

4.1 Choosing C_L value

When buying crystals you can usually choose from a range of capacitive loads (ex: 8-20pF). When ordering a crystal you must choose a C_L (ex: 12 pF) that is within the range of the C_L specified for the nRF device. The C_L range that nRF devices can operate in is only limited by the maximum C_L (ex: $C_L < 16$ pF). This maximum C_L depends on the on-chip crystal oscillator design and is specified in the device data sheet.

Choosing a low value C_L gives a lower current consumption in the on-chip crystal oscillator because of the lower load. Crystal oscillator current consumption is the dominant parameter in device stand by modes, where the device operation is suspended but the crystal oscillator is kept active. A low value on C_L should be your preferred choice.

However, the effects of errors in the C_L that you load the crystal with will be more severe on the crystals. To avoid any please read section 4.2 carefully.

4.2 The crystal circuitry

To see what influences the capacitive crystal load has, we must study the crystal circuitry. 'Figure 3. nRF crystal circuit diagram' shows the crystal circuit diagram as you will find it in Nordic Semiconductor documentation. The crystal X1 is loaded with capacitors C1 and C2 and the resistor R1 provides bias for the crystal oscillator found inside the nRF device. R1 is not critical and is usually set to a large value, for example, 1 Mohm.

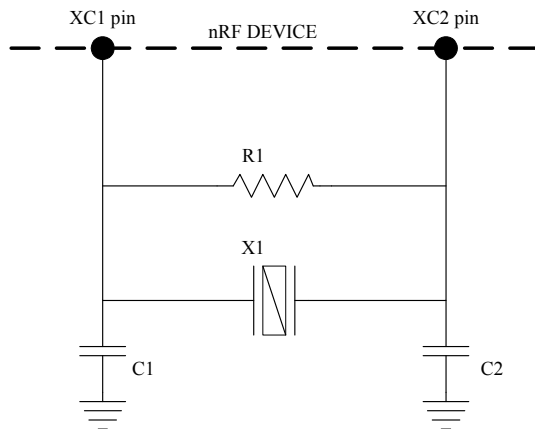


Figure 3. nRF crystal circuit diagram

To see how the capacitive load of the crystal is realized, you must take a look at the small signal equivalent of the circuit in 'Figure 3. nRF crystal circuit diagram'; this is shown in 'Figure 4. Small signal equivalent crystal circuitry'. In this representation you can see that C1 and C2 are found in series and form the capacitive load (C_L) parallel to the crystal. Consequently, we have the term 'parallel load compensated crystal'.

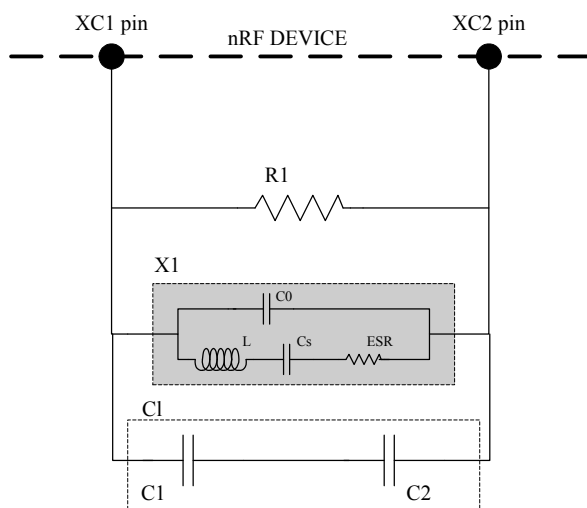


Figure 4. Small signal equivalent crystal circuitry

But this circuit does not present the whole picture. Since the actual C_L seen by the crystal is ALL capacitance outside the crystal pins we must also account for all parasitic capacitive loads found in the crystal circuitry. The crystal circuitry including parasitic capacitances can be seen in 'Figure 5. nRF Crystal circuit diagram including parasitic capacitances'.

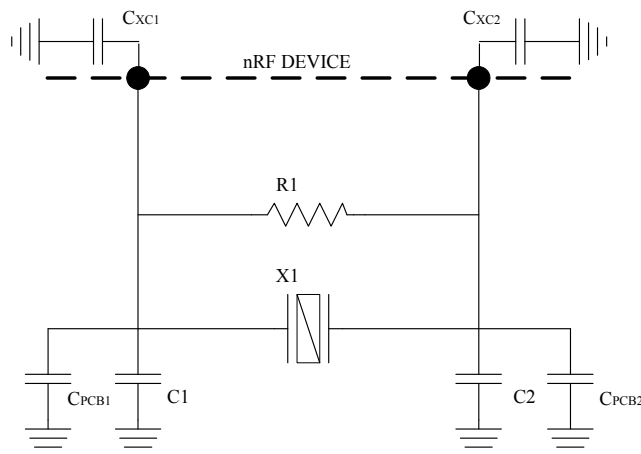


Figure 5. nRF Crystal circuit diagram including parasitic capacitances

In Figure 5. on page 9 the input capacitances of the nRF device crystal oscillator pins are added as C_{XC1} and C_{XC2} . C_{PCB1} and C_{PCB2} represent the parasitic capacitances between the PCB pads of the crystal, the tracks in the crystal circuitry and, the pads of the nRF device to ground.

These parasitic capacitances will be significant in all RF designs because RF layouts need to use ground planes for good performance. Ground will hence surround all tracks and pads on the PCB. When we add these parasitic components to $C1$ and $C2$, the total load capacitance on each side of the crystal will increase.

The total load capacitance is now given by:

$$C1' = C1 + C_{XC1} + C_{PCB1}$$

$$C2' = C2 + C_{XC2} + C_{PCB2}$$

Referring to 'Figure 4. Small signal equivalent crystal circuitry', $C1'$ and $C2'$ replace $C1$ and $C2$ and form the real C_L :

$$C_L = \frac{C1' \cdot C2'}{C1' + C2'}$$

The layout of any crystal circuitry should be symmetrical (that is, the same capacitive load present on both crystal pins) to ensure stable oscillation. If we set $C1' = C2' = C_t$ the equation simplifies to:

$$C_L = \frac{C_t \cdot C_t}{2 \cdot C_t}$$

$$C_L = \frac{C_t}{2}$$

or

$$C1' = C2' = 2 \cdot C_L$$

The total capacitive load to ground on each crystal needs to be two times the C_L chosen when selecting the crystal.

The input capacitance of the nRF device crystal pins are equal and ~ 1 pF. C1 and C2 are off the shelf capacitors. Obtaining a symmetrical crystal load is straightforward as long as you select $C1 = C2$. The parasitic capacitances found on the PCB must be made as equal as possible through symmetrical PCB routing.

The actual value of the parasitic PCB capacitance may vary from layout to layout and is very difficult to calculate accurately. Fortunately, knowing the exact value of the parasitic PCB capacitance is not needed as you can easily measure the influence of all the parasitic capacitances on the PCB through the TX frequency accuracy measurement.

If you do find an offset outside the frequency accuracy limits, this can be corrected by adjusting the value of C1 and C2. The TX carrier frequency will also be within specification when the total C_L seen by the crystal is according to the crystal specification.

Note: It is very important to do this measurement on several crystals and/or PCB's (that is, different capacitors) to take variations in crystal and load capacitors into account.

Note: The frequency error that arises from wrong capacitive load on the crystal will be the same on all PCB's with the same layout, crystal and, load capacitors. A transmitter and a receiver that have identical layout and components fitted will communicate correctly even if the actual RF frequency they operate on differs from the RF frequency they are programmed to operate on.

If you do not pay attention to crystal oscillator accuracy, you may have problems when communicating between a transmitter and a receiver that have differences in crystal, capacitive load or, crystal layout. Now the frequency on the TX and RX may be different. The RF frequency generated by the transmitter will not match the receiver window and you will experience a **loss of range**.

5 Conclusion

As we have seen the frequency accuracy of a nRF design relies solely on the accuracy of the crystal frequency. It is essential to follow the crystal accuracy specification set in each nRF device product specification. The crystal oscillator frequency is not only set by the crystal specification but, the total capacitance the crystal circuitry loads the crystal with must match the specification of the crystal.

Measuring TX frequency accuracy on a prototype will immediately tell you if the crystal oscillator design is correct. If required, the values of the crystal load capacitors (C1 and C2 in this document) must be adjusted to compensate for parasitic capacitive loads in each crystal circuitry layout. Once the frequency accuracy of a prototype is found to be within specified limits, no more tuning is needed in production.

Consequence:

The capacitor values found in the crystal circuitry of Nordic Semiconductor documentation is correct ONLY if:

1. You use a crystal with the same C_L specification as Nordic Semiconductor.
2. The layout, that is, the crystal footprint and PCB routing are equal.

The value of the load capacitors you fit your crystal circuitry MUST match the C_L specification of YOUR selected crystal and complement the parasitic capacitances found in YOUR layout. It must NOT be a blind copy of Nordic Semiconductor schematics.