# Flyback inductive sensing (ISX) design guide

## About this document

### Scope and purpose

This document provides a technical quick start guide for designing and implementing inductive-sensing solutions using the flyback inductive sensing technology from Infineon.

### Intended audience

The intended audience for this document is primarily developers, engineers, and designers who are interested in implementing sensing solutions using Infineon's flyback inductive sensing technology.

***Note**: The document assumes a basic understanding of Infineon's PSOC™ architecture, basic electronics, and electrical engineering principles as well as software development and programming experience. If you are new to the CAPSENSE™ and PSOC™ architecture offered by Infineon, see the References section to learn about these offerings.*

# Abbreviations

**Table 1 Abbreviations**

| Abbreviation | Description |
|---|---|
| ADC | Analog-to-digital converter |
| CMOD | Modulator capacitor |
| CAPDAC | Capacitive digital-to-analog converter (DAC) |
| $C_P$ | Parasitic capacitance |
| CSD | Self-capacitance sensing |
| $C_{SH}$ | Shield tank capacitor |
| $C_{V_{REF}}$ | Voltage reference capacitor |
| CSX | Mutual-capacitance sensing |
| EMC | Electromagnetic compatibility |
| ESD | Electrostatic discharge |
| GND | Ground |
| GPIO | General-purpose input/output |
| HID | Human interface device |
| HMI | Human machine interface |
| IDAC | Current-output digital-to-analog converter |
| IDE | Integrated development environment |
| IIR | Infinite impulse response (filter) |
| ISX | Flyback inductive sensing method |
| $L_S$ | Effective inductance of an ISX sensor |
| MCU | Microcontroller unit |
| MFC | Multi frequency scan |
| MSC | Multi-sense converter |
| MSCLP | Multi-sense converter version 3 – Low Power |
| PRS | Pseudo random sequence |
| PSOC™ | Programmable system on chip controllers offered by Infineon |
| SNR | Signal-to-noise ratio |
| SSC | Spread spectrum clock |
| VREF | Programmable reference voltage blocks available inside PSOC™ used for MSCLP and ADC operation |

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# 1 Introduction

Inductive sensing provides an innovative low-cost solution to detect the presence or movement of nearby metallic or conductive objects. The technology enables a robust low-cost HMI with metallic overlays that seamlessly integrates in the product. Inductive sensing addresses the short falls of capacitive sensing and enables new and creative methods for HMI.

## 1.1 Working principle

Inductive sensing works on the principle of electromagnetic coupling between a sensor coil and the metal/highly conductive object to be detected. When the metal target enters the electromagnetic field induced by a sensor coil, some of the electromagnetic energy is transferred into the metal target as shown in the following figure. This transferred energy causes a circulating electrical current called an eddy current. The eddy current flowing in the metal target induces a reverse electromagnetic field on the sensor coil, which results in a reduction of the effective inductance of the sensor coil.

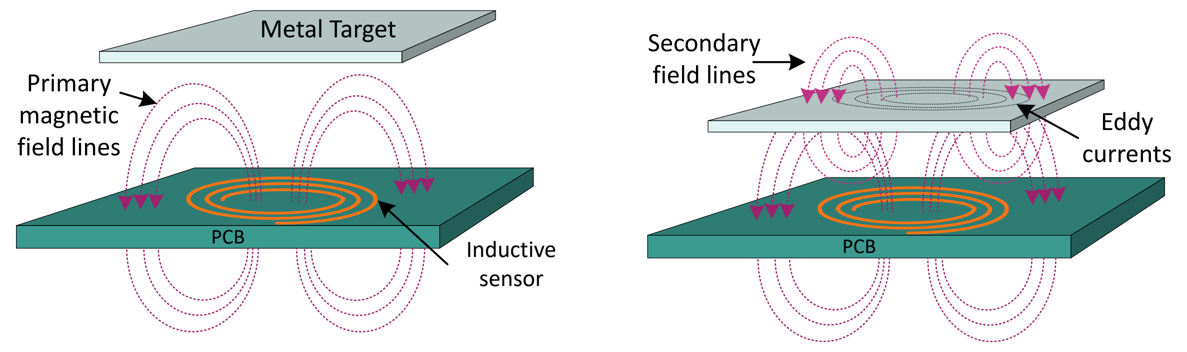


**Figure 1** **Field coupling between sensor and metal/conductive target**

## 1.2 Applications

The following applications are the typical uses of inductive sensing:

- Proximity metal detection
- Replacing mechanical open/close switches
- Buttons (industrial keypads and ON/OFF buttons)
- Rotation detection (rotary encoders, flow meters, fan speed RPM detection, rotary control knob)
- Linear encoders
- Spring compression detection
- Replacement for Hall sensor + Magnet attachment sensing

## 1.3 Features

The following features make the inductive sensing an appealing sensing solution:

- Force detection – for multi-level force triggers
- Inherently liquid tolerant
- Works with gloves
- Enables hermetically sealed HMIs
- Enables metallic-surface HMIs
- Seamless integration with existing applications
- Removes the need for cut-outs for metal enclosures

## 1.4 Methods of inductive sensing

There are various ways to implement inductive sensing solution, the two most popular are:

- Impedance-based with resonant capacitor
- Flyback inductive sensing (ISX)

The impedance-based with resonant capacitor method is implemented with a parallel combination of sensor inductance and the external capacitor called tank circuit as shown in the following figure. The reduction in the sensor coils effective inductance causes an upward shift in the resonant frequency of the tank circuit. This shift in resonant frequency changes the amplitude of the signal across the sensor coil. The change in the amplitude of the sensor coil signal is measured by the PSOC™ MCU to detect the presence of the metal target in the proximity-sensing distance. To know more about this method, see AN219207 - Inductive sensing design guide.

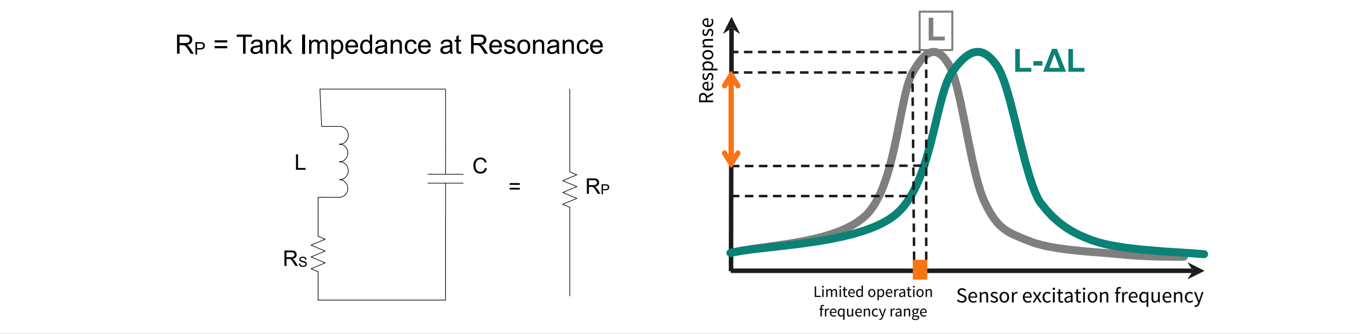


**Figure 2** **LC tank resonance circuit**

## 1.5 Introduction to flyback inductive sensing using ISX

ISX inductive sensing works on the principle of inductive flyback operation, where the energy is stored when current passes through the inductor coil and released when the power is removed.

A magnetic field created by the current in an inductor accumulates energy calculated by the formula as follows:

$$E = \frac{L \times I^2}{2}$$

**Equation 1** **Energy accumulated in an Inductor**

Where,

- L – coil inductance value
- I – coil current

This energy produces a back-EMF voltage that produces a current during a flyback operation period. Multi Sense Converter – Low Power (MSCLP) converts this current to digital code (raw counts). The produced current is proportional to the sensor coil inductance. The relative change of inductance due to the high-conductive object in proximity is measured to detect the object presence.

The sensing functionality is achieved using a combination of hardware and firmware. Figure 3 illustrates the flyback inductive sensor connection.

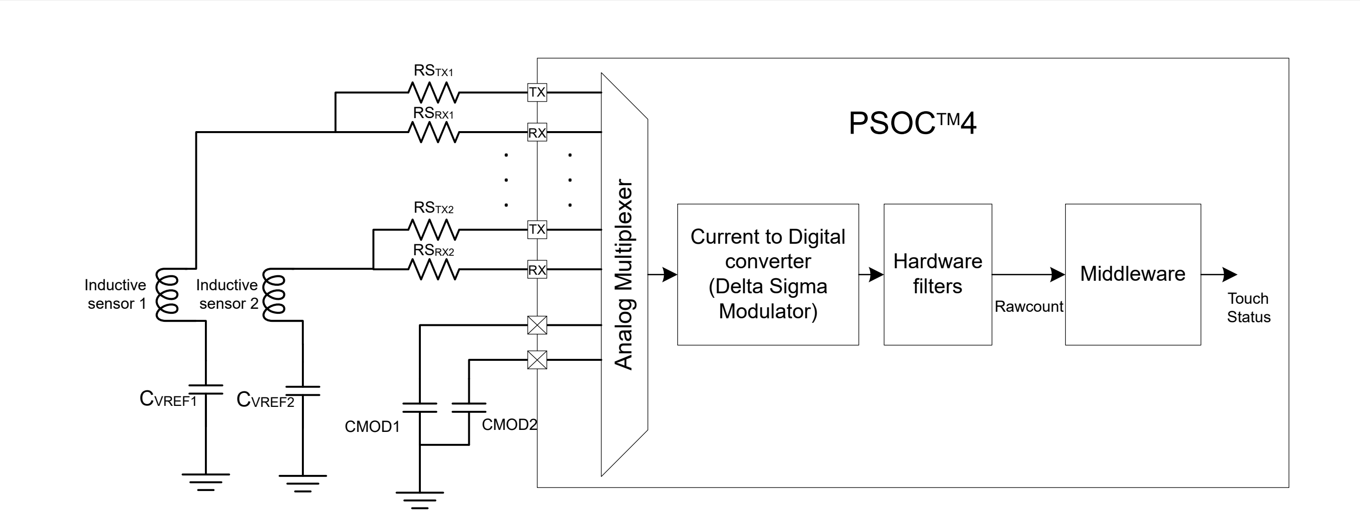


**Figure 3** Simplified diagram of PSOC™ 4 MSCLP with flyback inductive sensor

Direct inductance measurement using the flyback method allows wide operation frequency range and simplified schematics.

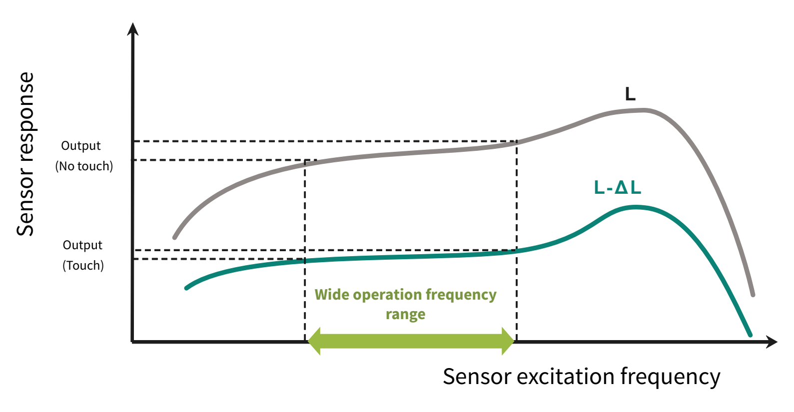


**Figure 4** Operating frequency range of flyback inductive sensing

Typically, the inductive sensors are circular metallic coils etched on a PCB. Figure 5 illustrates an example of the inductive sensor button.

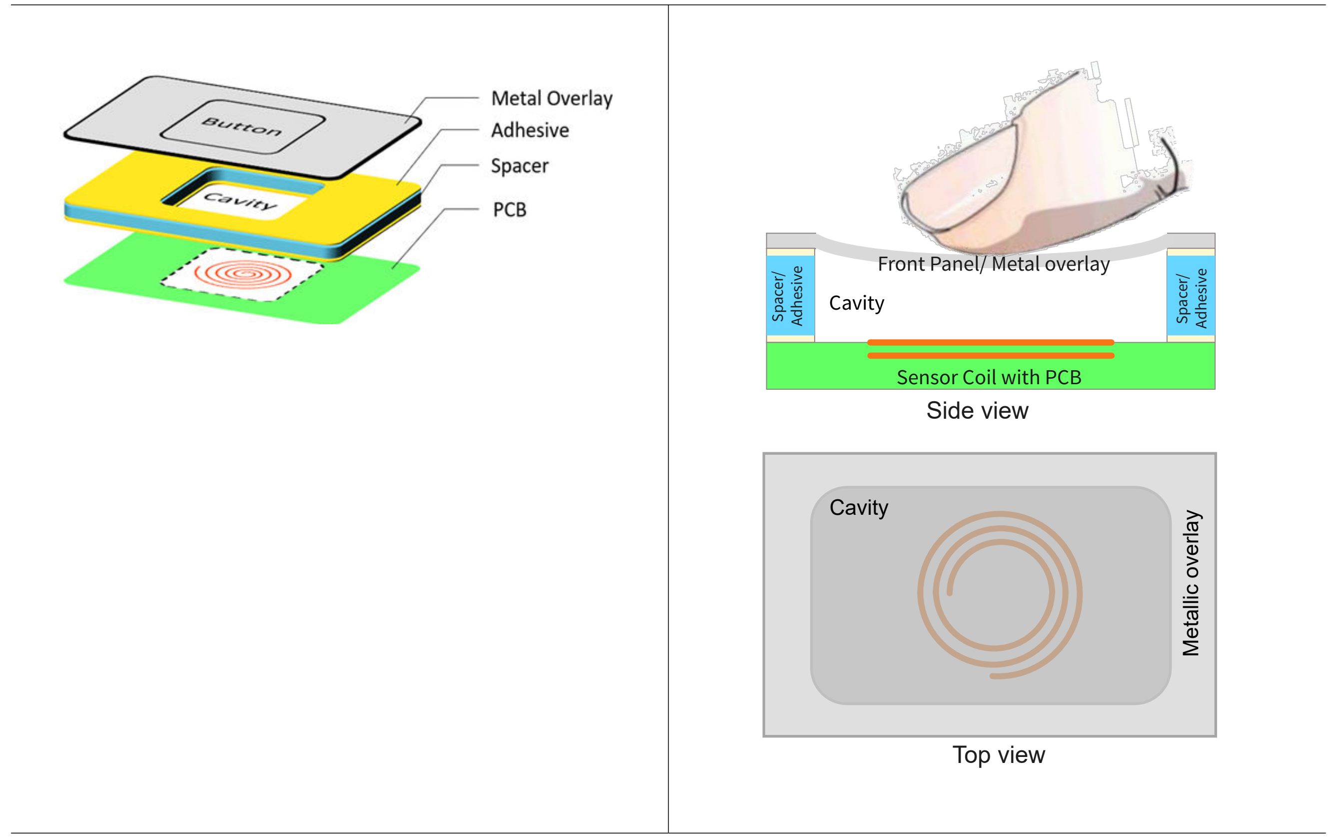


**Figure 5** Illustration of an inductive touch sensor

Figure 6 shows a plot of raw count over time for an inductive sensor. When a conductive object approaches the sensor, the effective sensor inductance ($L_S$) decreases, and the converter output decreases. The firmware normalizes the raw count such that the raw counts increase when $L_S$ decreases. By comparing the change in the raw count to a predetermined threshold, firmware logic decides whether the sensor is active.

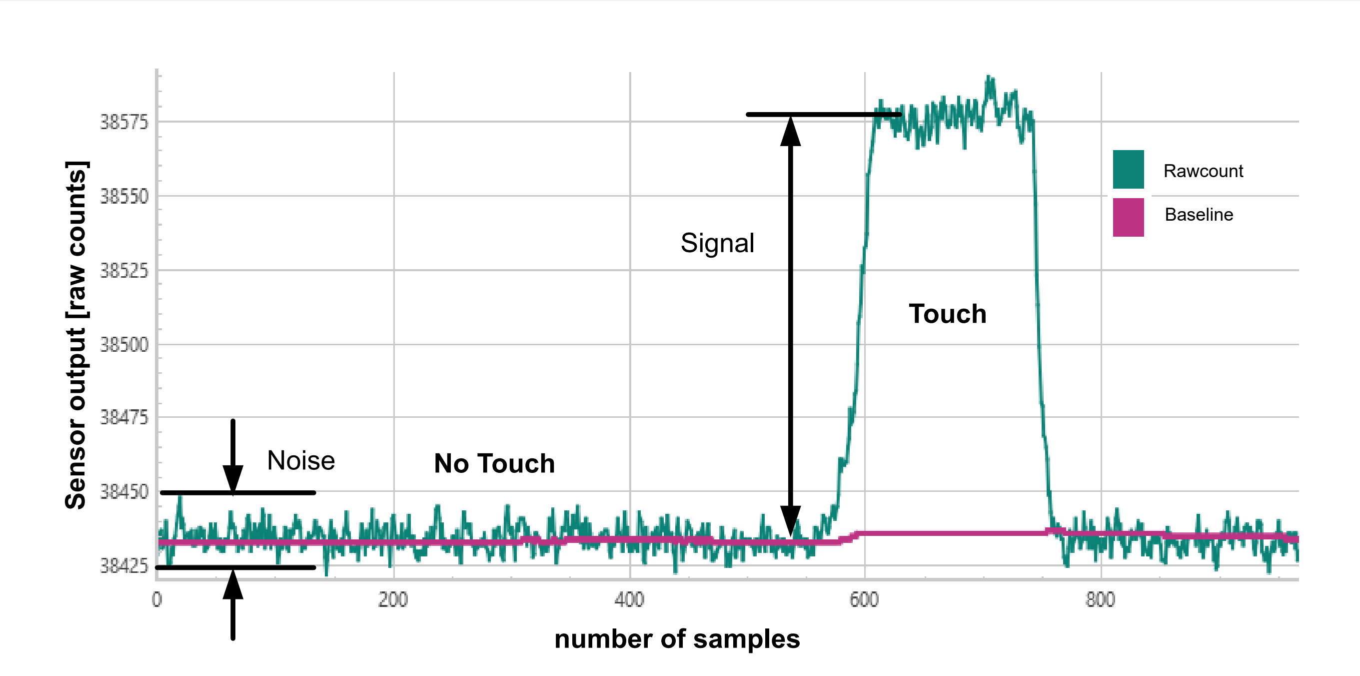


**Figure 6** **Raw count vs. samples**

The output raw count of the multi-sense converter is a digital value that is proportional to the inductance of the sensor as mentioned in the following equation.

$$Rawcount = G_{ISX}.L_s$$

**Equation 2** **Raw count and sensor inductance relationship in ISX**

Where,

- $G_{ISX}$ = Inductance to digital conversion gain
- $L_S$ = Effective inductance of the sensor

### 1.5.1 Advantages of flyback inductive sensing

**Table 2** **Advantages of flyback inductive sensing**

| Feature | Description | Advantage |
|---|---|---|
| Direct inductance measurement | ISX method measures the inductance directly without using a resonant capacitor | Simplifies sensor design requiring very few components |
| High resolution and sensitivity | High clock frequency and sampling rate | Better sensitivity than resonance method to sense small deflections. |
| Broad operating frequency | System can operate over a wide range of frequencies with support for MFS[1] , SSC, and PRS<br>Similar sensors can have a common frequency | Simple design for EMC<br>Little to no impact of manufacturing variations on sensor response |

**(table continues...)**

**Table 2** **(continued) Advantages of flyback inductive sensing**

| **Feature** | **Description** | **Advantage** |
|---|---|---|
| Linear response curve | Does not need to be tuned to operate at a resonance frequency. Change in operating frequency does not have a significant impact on response | Handles manufacturing variations. Easy tuning and development |
| Lower temperature drift | Slow drift due to device temperature change is compensated by base line tracking | Low sensitivity to temperature changes |
| Simple schematics | Simple schematics and fewer discrete components | Cost effective |

*1)* Multi Frequency Scan (MFS) is not supported with Common mode filter feature. See Common mode noise filter (CMF).

### 1.5.2 Terminology

This section defines ISX-related terms that are used throughout the document:

**Table 3** **Terminology**

| **Terms** | **Description** |
|---|---|
| Sensor coil | Inductive coil etched on PCB |
| Overlay | Metal plane over the sensor coil. It is a touch surface exposed to user. This is made of materials like Aluminum, Stainless steel, copper, etc. |
| Spacer | Non -conductive material used to hold the overlay on top of the coil |
| Air gap | Air gap refers to distance between the sensor coil on the PCB to the overlay surface on the top. This cavity between the PCB and overlay is recommended to be kept unfilled with any material |
| Deflection | This term refers to deflection of metal overlay (target) present on the Inductive sensing sensor coil in the button |
| Detection distance | Detection distance is the distance where the reduction in inductance exceeds some threshold values. The detection distance depends on the sensor's magnetic field propagation. A longer propagation distance provides a longer detection range |
| Target object | Object of which presence or movement is to be detected by sensor. It is made of metal or ferrite |

**(table continues...)**

**Table 3** (continued) Terminology

| Terms | Description |
|---|---|
| Raw count | The effective sensor inductance is converted into a count value by the MSCLP hardware. The converted digital count value is referred to as the raw count. Processing of the raw count results in ON/OFF states for the sensor |
| Baseline | A value resulting from a firmware algorithm that estimates a trend in the raw count when there is no conductive object/movement of target object present over the sensor, and when the raw count is within noise thresholds. The baseline is less sensitive to sudden changes in the raw count and provides a reference point for computing the difference count |
| Signal (Difference count) | Subtracting the baseline level from the raw count produces the difference count that is used in the decision process. The thresholds are offset by a constant amount from the baseline level |
| Signal-to-noise ratio (SNR) | As the name suggests it is the measure of the quality of the information in a signal to noise present in the signal. In a capacitive proximity sensing system, SNR implies reliable and accurate detection |

## 1.6 Resources for getting started with ISX

This section describes the resource offered by Infineon to get started on designing inductive sensing solutions.

### 1.6.1 Online resources

- Infineon inductive sensing webpage
- Infineon ModusToolbox™ webpage
- ModusToolbox™ software help on GitHub

### 1.6.2 Getting started kits

#### 1.6.2.1 CY8CPROTO-040T-MS Multi-Sense Prototyping Kit

The CY8CPROTO-040T-MS Multi-Sense Prototyping Kit enables evaluation and development of capacitive, inductive and liquid-level sensing solution using the PSOC™ 4000T device with fifth-generation CAPSENSE™ and multi-sense technology offering ultra-low power touch HMI solution (MSCLP).

**Figure 7** CY8CPROTO-040T-MS kit contents

For more information about the kit, see the kit documentation.

### 1.6.2.2 CY8CPROTO-041TP PSOC™ 4100T Plus CAPSENSE™ Prototyping kit

The CY8CPROTO-041TP PSOC™ 4100T Plus CAPSENSE™ Prototyping kit enables evaluation and development of capacitive, inductive, and liquid-level sensing solution, using the PSOC™ 4100T Plus device with fifth-generation CAPSENSE™ and multi-sense technology, offering ultra-low power touch HMI solution (MSCLP). The expansion boards that are part of the CY8CPROTO-040T-MS Multi-Sense Prototyping Kit packaging are also compatible with this kit.

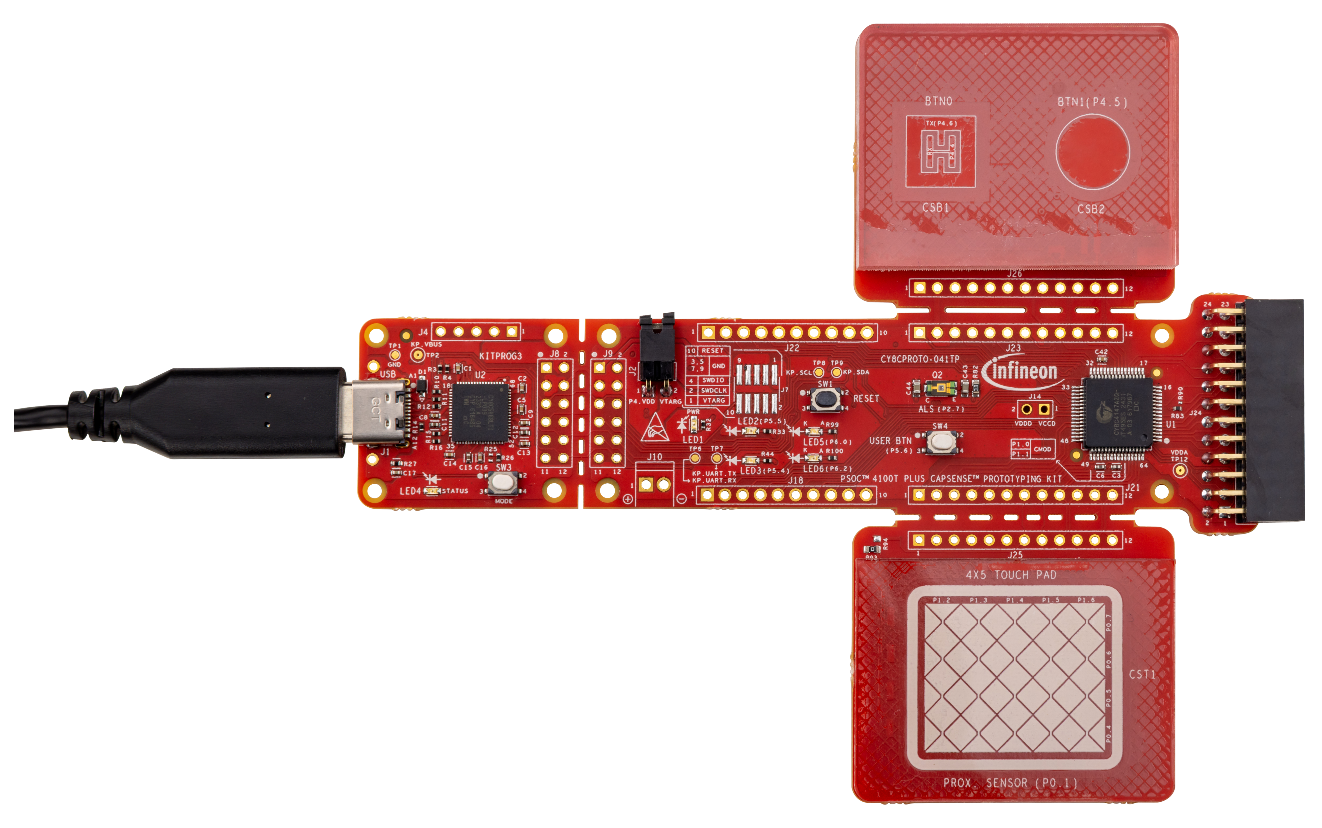


Figure 8 CY8CPROTO-041TP kit

For more information about the kit, see the kit documentation.

## 1.6.3 Development tools

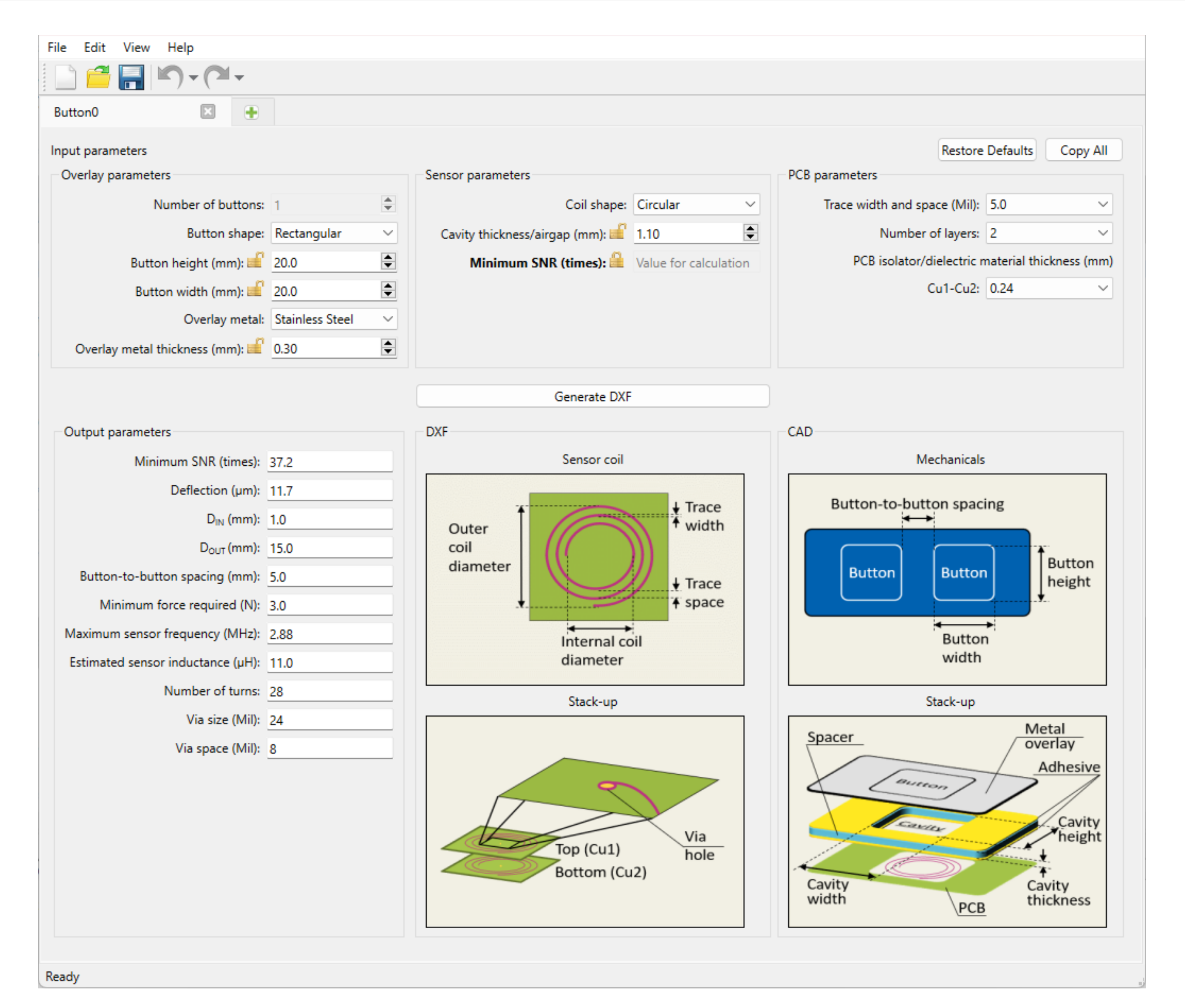
### 1.6.3.1 ModusToolbox™

ModusToolbox™ software suite is used for the development of PSOC™ 6- and PSOC™ 4-based CAPSENSE™ applications. You can download ModusToolbox™ from Infineon Development Center. Before you start working with this software, it is recommended that you go through the quick start guide and user guide. ModusToolbox™ software trainings can be found here. If you have ModusToolbox™ IDE installed in your system, you can create a CAPSENSE™ application for the devices supported in ModusToolbox™.

### 1.6.3.2 Sensor Designer

Sensor Designer tool simplifies the process of designing flyback inductive sensors and the mechanical stackups for the target application. With just system-level requirements, it can create optimal designs and recommendations. The tool allows export of .dxf files, which can be seamlessly integrated into your PCB and product enclosures/mechanicals.

The Sensor Designer tool can be launched from the Quick Panel in ModusToolbox™. Figure 9 shows the tool interface.



Input parameters

Overlay parameters

Number of buttons: 1

Button shape: Rectangular

Button height (mm): 20.0

Button width (mm): 20.0

Overlay metal: Stainless Steel

Overlay metal thickness (mm): 0.30

Sensor parameters

Coil shape: Circular

Cavity thickness/airgap (mm): 1.10

**Minimum SNR (times):** Value for calculation

PCB parameters

Trace width and space (Mil): 5.0

Number of layers: 2

PCB isolator/dielectric material thickness (mm)

Cu1-Cu2: 0.24

Output parameters

Minimum SNR (times): 37.2

Deflection (µm): 11.7

$D_{IN}$ (mm): 1.0

$D_{OUT}$ (mm): 15.0

Button-to-button spacing (mm): 5.0

Minimum force required (N): 3.0

Maximum sensor frequency (MHz): 2.88

Estimated sensor inductance (µH): 11.0

Number of turns: 28

Via size (Mil): 24

Via space (Mil): 8

**Figure 9** **ISX Sensor Designer tool**

Based on the input parameters, *.dxf files are generated which can then be imported into the CAD software. To learn more about the tool, click the **Help** tab in the toolbar or press F1. The same tool also helps create liquid level sensor designs (see the Liquid-level sensing with PSOC™ 4 CAPSENSE™ application note for details)

### 1.6.3.3 CAPSENSE™ Configurator

The CAPSENSE™ Configurator tool in ModusToolbox™ is used to configure the hardware and software parameters of the inductive (as well as capacitive) sensing application project. For more details on configuring CAPSENSE™ in ModusToolbox™, see the ModusToolbox™ CAPSENSE™ Configurator guide and CAPSENSE™ middleware library. Figure 10 shows how to open the CAPSENSE™ configuration tool in ModusToolbox™. Alternatively, it can also be launched from the **Quick panel** in the ModusToolbox™.

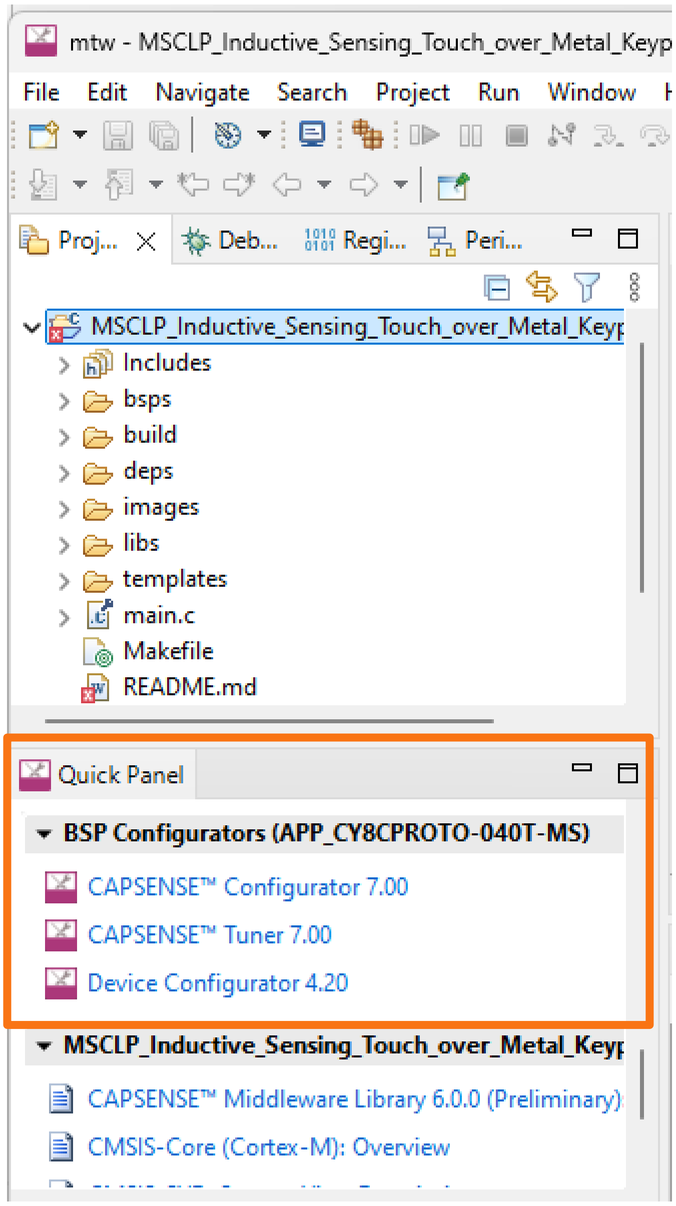


**Figure 10** **ModusToolbox™ - Quick panel**

### 1.6.3.4 CAPSENSE™ middleware

ModusToolbox™ provides CAPSENSE™ middleware, which can be used to create a inductive sensing and capacitive sensing application with PSOC™ devices by simply configuring parameters in the CAPSENSE™ configuration tool. The middleware also provides an application programming interface (APIs) to simplify firmware development. See the Middleware library and APIs section for more details.

### 1.6.3.5 CAPSENSE™ Tuner

ModusToolbox™ also offers a GUI CAPSENSE™ Tuner provides an easy-to-use interface to visualize the sensor data and tune widgets and sensors parameters as configured in the application. This tool can be opened from the Device Configurator by selecting **Launch CAPSENSE™ Tuner** as shown in Figure 10. See the CAPSENSE™ Configurator user guide for more details.

### 1.6.4 Code examples

#### 1.6.4.1 Two buttons keypad demo

The PSOC™ 4: MSCLP inductive sensing touch-over-metal keypad-2 code example demonstrates the implementation and tuning procedure of two keypad ISX buttons using fifth-generation CAPSENSE™ (MSCLP).

#### 1.6.4.2 Four buttons keypad demo

The PSOC™ 4: MSCLP inductive sensing touch-over-metal keypad-4 demo code example demonstrates the implementation of four keypad ISX buttons using fifth-generation CAPSENSE™ (MSCLP).

For more code examples, see GitHub.

#### 1.6.4.3 Capacitive and inductive sensing buttons example

The PSOC™ 4: MSCLP capacitive and inductive sensing buttons code example demonstrates the implementation of a CSD button, a CSX button, and four keypad ISX buttons using fifth-generation CAPSENSE™ (MSCLP) in the same project.

For more code examples, see GitHub.

# 2 Designing an ISX inductive-sensing solution

Figure 11 illustrates the typical flow of an ISX inductive-solution design. This flow is like any other electronic product design flow except that these designs involve an additional step called “Tuning”.

Like any other product, defining the requirement specifications is recommended before designing an inductive-sensing solution. These specifications will act as design objective to be met for the system. The specifications for inductive-sensing design can be listed as follows:

- Type/material of the object to be detected
- Type of sensors, for example,
    - Touch-over-metal (ToM) buttons
    - Force-touch
    - Slider
    - Rotary encoder
    - Presence detection, etc.
- Maximum sensing distance required
- Behavior in the presence of nearby metal
- Operation in extreme environmental conditions
- Operation in areas with high EMI noise

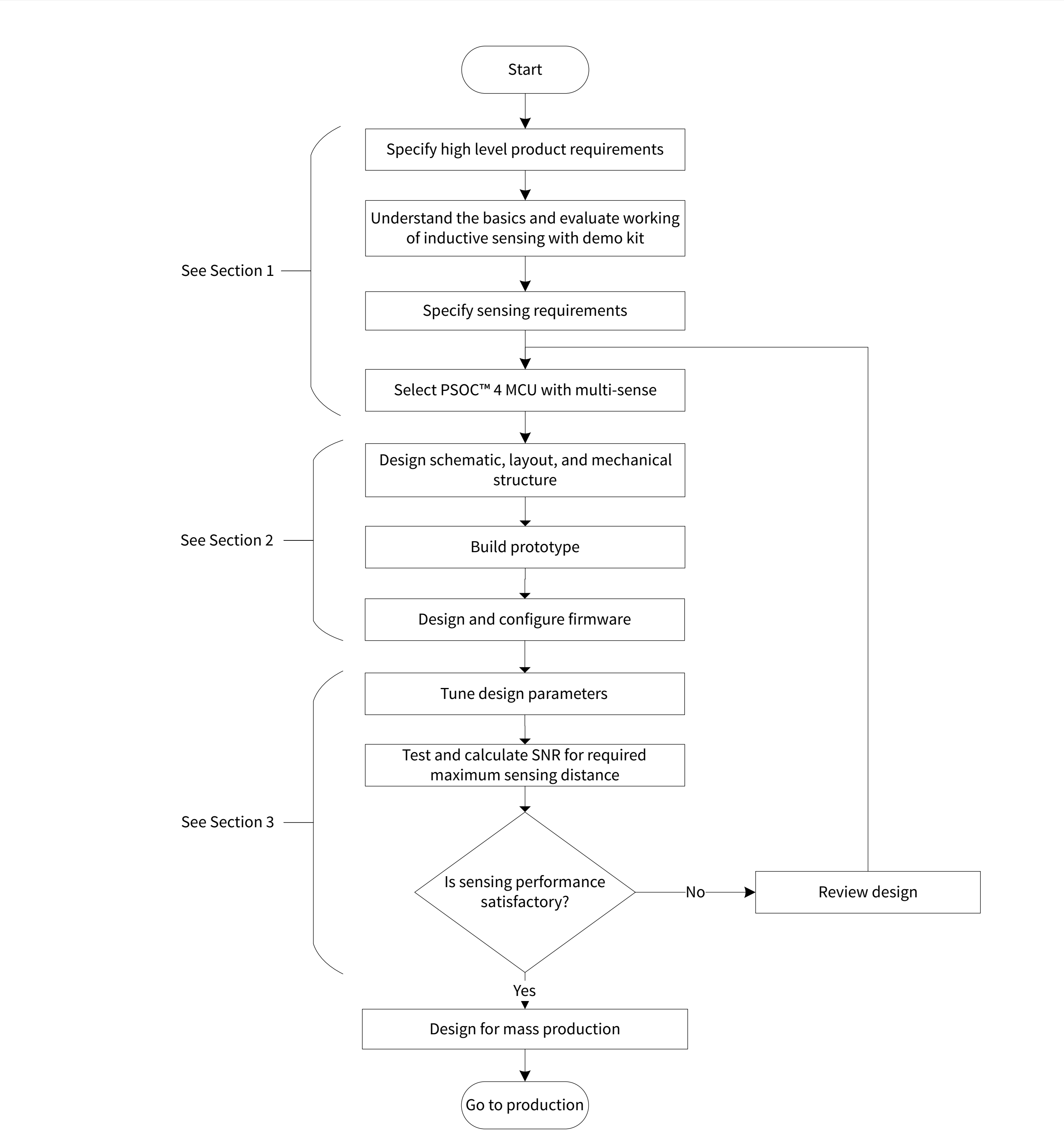


**Figure 11** **Recommended ISX system design flow**

## 2.1 Application use cases

Based on the features offered by the flyback inductive sensing, the use cases and target applications can be categorized as follows:

### 2.1.1 Touch-over-metal

Flyback inductive sensing enables touch-over-metal buttons offering:

- Enhanced design of everyday objects with seamless, hermetically sealed metallic surfaces with integrated inductive touch buttons on metal surfaces.
- Cost-effective and highly reliable buttons that are immune to moisture and dirt.
- Flexible sensor design supporting a wide variety of sensor sizes and stack-ups.

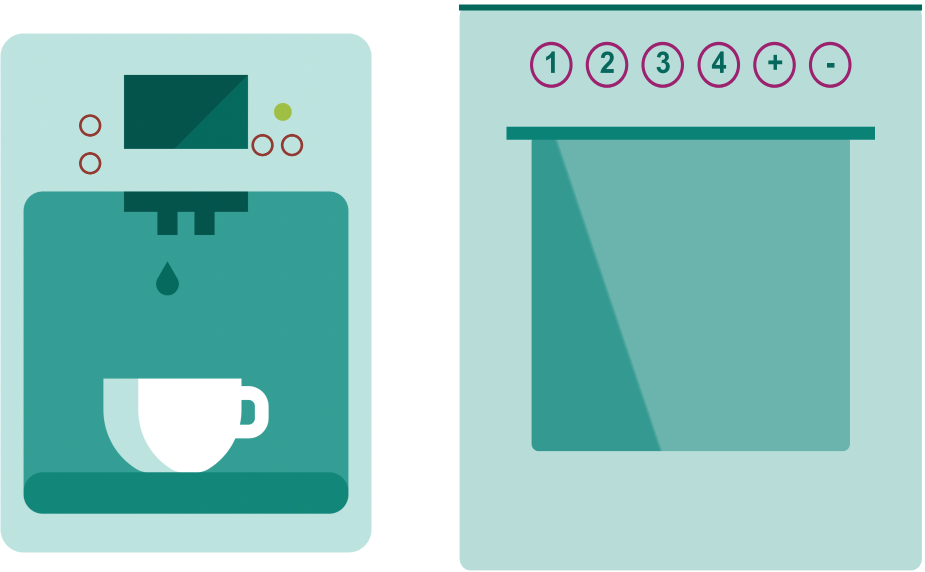


**Figure 12** **Example application use cases of metal over touch**

The use cases and applications of metal over touch can be:

- Coffee machines
- Microwave
- Oven
- Refrigerator
- Washing machine
- Dish washer

See Table 4 for the typical requirements for the touch-over-metal use cases.

### 2.1.2 Underwater/waterproof touch

Flyback inductive sensing is inherently immune to water/liquid which make it ideal for underwater and waterproof touch interface/button applications such as:

- Underwater cameras
- Personal care products (shaver)
- Intercom, EV charging, and other systems that are exposed to harsh and wet environments
- Washing machines

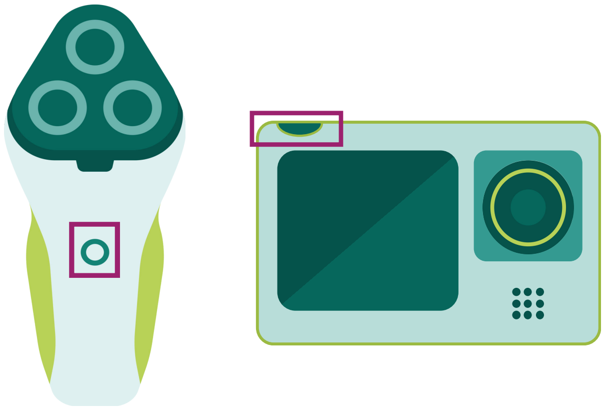


Figure 13 Example application use cases of waterproof buttons

See Table 4 for typical requirements for the waterproof sensing use cases.

### 2.1.3 Force touch buttons

Inductive sensing-based buttons need deflection of (or movement of metallic) in the vicinity of the sensor coil, which means that pressure is required to turn the button ON. This feature is ideal for applications where buttons need to sense the amount of force being applied to their surfaces and shall not be activated accidentally. Different thresholds can be set to enable detection of different levels of force.

The use cases and applications are:

- Personal computer products (computers, tablets)
- Outdoor keypads (smart locks, security products)
- Headphones wear detection
- Power tools, buttons, and grip detection

Figure 14 Example application use cases of force touch buttons/sensing

See Table 4 for typical requirements of the force touch application use cases.

### 2.1.4 Proximity sensing and reed switch replacement

Inductive sensing exploits the fact that the effective inductance of a current-carrying coil decreases when a metal is in its vicinity. This property of the inductive sensing is ideal for detection of nearby metal which enables metal proximity sensing and reed switch replacement applications such as:

- Proximity sensors and reed switch replacements
  - Smart home (door locks, security systems, etc.)

  - Home appliances (washing machines, ovens, refrigerators, etc.)
  - Industrial applications
- Position detection/counting and rotary/shaft encoders
  - Motor applications
  - Rotary encoders/knobs
  - Product counting

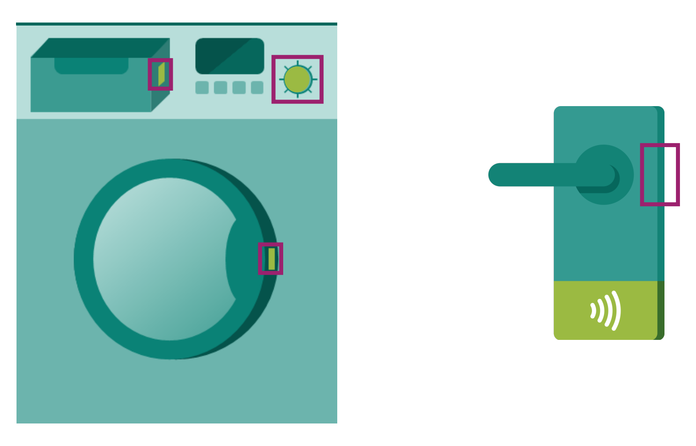


**Figure 15** **Example use cases of metal-proximity/reed switch replacement**

See Table 4 for typical requirements of the force touch application use cases.

## 2.2 Typical parameters for different use cases

The following table provides the typical requirements of the buttons for the different use cases.

**Table 4** **Typical parameters for different use cases**

| Parameters | Touchovermetal (ToM) | Waterproof sensing | Force touch | Reed switch replacement |
|---|---|---|---|---|
| Power sources | Mains powered/ Battery powered | Battery powered/ Mains powered | Battery-powered | Mains-powered |
| Overlay | 0.5 mm to 0.8 mm thick stainless steel, seamless | 0.3 mm thick metallic (SS or Al), rubber, or plastic | 0.3 mm thick metallic (SS or Al), rubber, or plastic | Target metal sensing through rubber or plastic (Al target is preferred) |
| Button size | Typically, 25 mm | Typically, 3.5 mm to 8 mm | Typically, 5 mm to 8 mm | Typically, 10 mm to 20 mm |
| Number of buttons/ sensors | Typically, 4 | Typically, 1 or 2 | Typically, 12 for keypads and 2 for other applications | Typically, 1 or 2 |
| Sensor - overlay air gap | 3 mm to 4 mm | 0.2 mm to 1 mm | 0.2 mm to 1 mm | N/A |
| Button to button spacing | 10 mm | 5 mm | 3 mm | >10 mm |

**(table continues...)**

**Table 4 (continued) Typical parameters for different use cases**

| Parameters | Touchovermetal (ToM) | Waterproof sensing | Force touch | Reed switch replacement |
|---|---|---|---|---|
| PCB Layers | 1 or 2 | 2 or 4 | 2 or 4 | 1 or 2 |
| Activation force | 3 Nm to 8 Nm | 4 Nm to 5 Nm | 5 Nm to 8 Nm for buttons | N/A |
| Other | Consumer grade EMI/EMC | Consumer grade EMI/EMC | Consumer grade EMI/EMC | Consumer grade EMI/EMC |
| Major challenges | Reliability, noise immunity, EMC | Low power, performance with small sensors, noise immunity (e.g., small motor, Bluetooth® LE), EMC | Low power, performance with small sensors, noise immunity (e.g., motor, Bluetooth® LE), EMC | Reliability, robustness, noise immunity (e.g., motor, Bluetooth® LE)<br>EMC |

## 2.3 Schematics and components selection

### 2.3.1 Schematics

#### 2.3.1.1 Inductive sensing

Figure 16 illustrates typical schematics for flyback inductive button sensor.

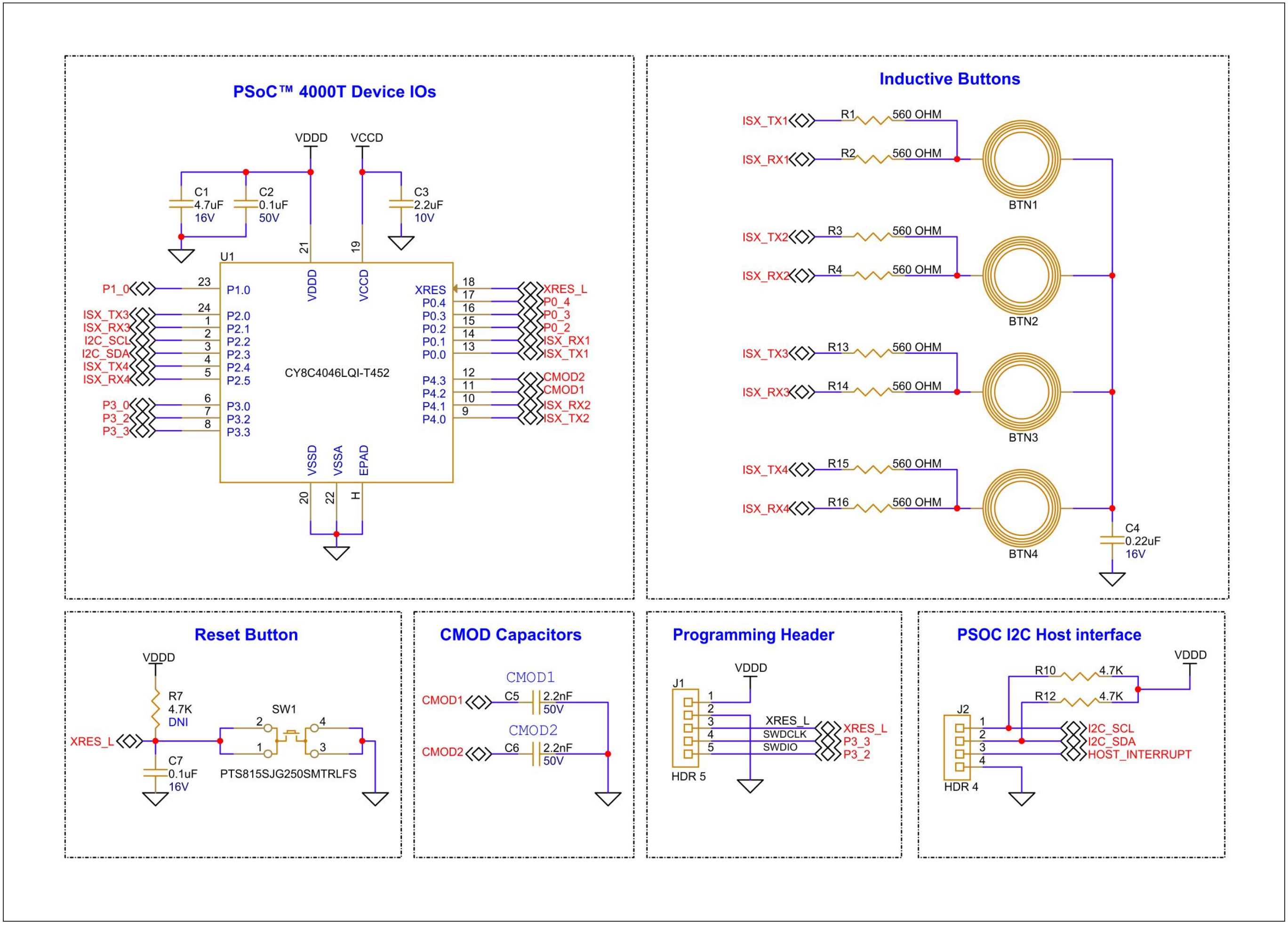


**Figure 16** Schematic for flyback inductive sensor connection

## 2.3.2 Component selection

### 2.3.2.1 $C_{Vref}$ selection

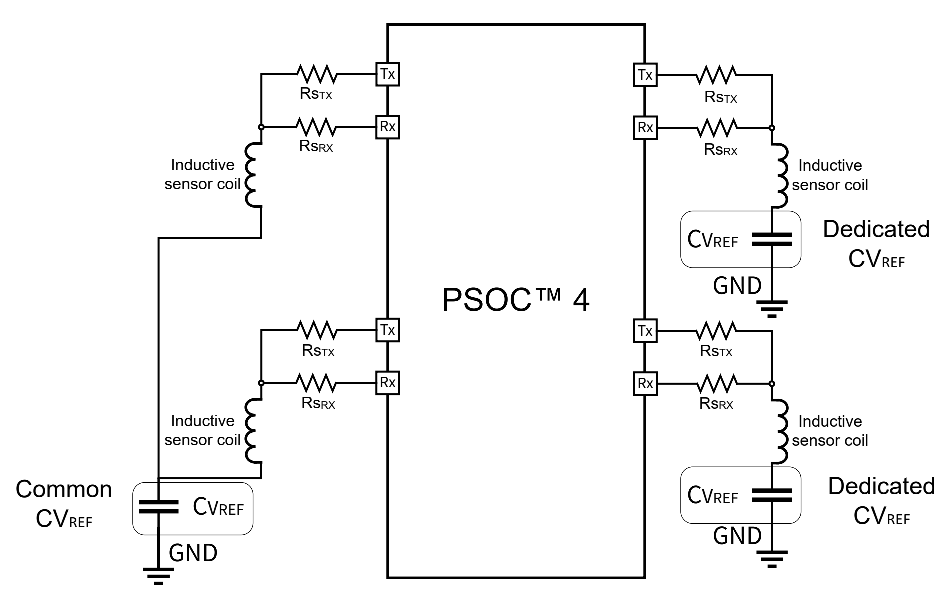


**Figure 17** **Flyback inductive sensing schematics**

$C_{Vref}$ represents the voltage reference capacitor for the sensor. It needs to provide a stable Vref value during the sensing operation. The required Vref is set by the PSOC™ device during initialization.

The recommended $C_{Vref}$ value is 220 nF.

**Common $C_{Vref}$ configuration**

A single common $C_{Vref}$ can essentially be connected multiple sensors in case the sensor properties are same/similar, for example, a four-button system, if all four sensor coils of the buttons are same inductance, a common $C_{Vref}$ can be used.

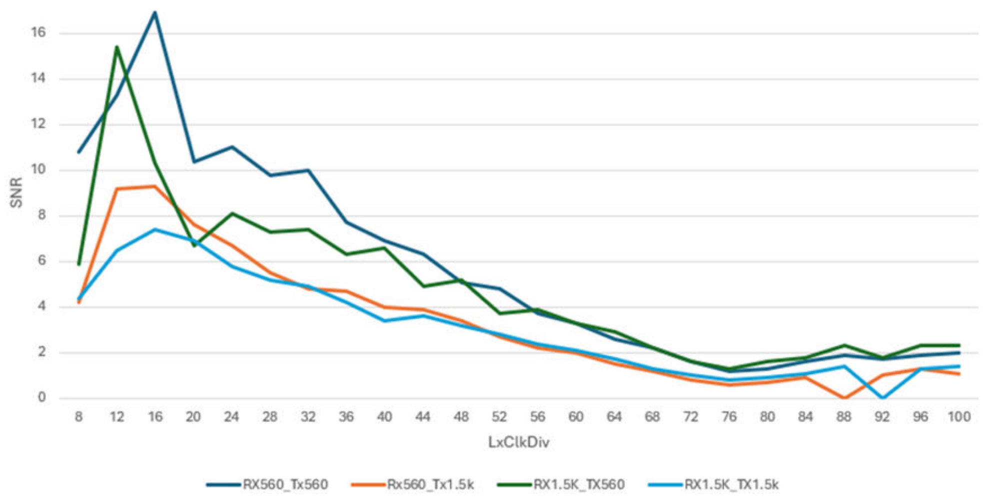
**Dedicated $C_{Vref}$ configuration**

If the sensor coils have different inductance values, because of sensor size, number of PCB layers etc., a dedicated $C_{Vref}$ is required for each sensor.

### 2.3.2.2 Sensor series resistance selection

Tx series resistance $RS_{TX}$ limits the sensor current and Rx series resistance $RS_{RX}$ limits the CVref (Cs) recharging current. The default recommended values are 560 Ω for both resistances.

Figure 18 shows the SNR for selection of sensor series resistance values.



13 mm sensor coil size, 2 layers, ~7 µH w/o target, 3 N force

**Figure 18** SNR vs LxClkDiv for different $RS_{RX}$ and $RS_{TX}$ resistors

## 2.3.2.3 External capacitors

MSCLP devices require an external capacitor for self-capacitance sensing. These external capacitors are connected between a dedicated GPIO pin and the ground. Recommended values of the external capacitors are as follows:

- $C_{MOD1}$ and $C_{MOD2}$ = 2.2 nF

### 2.3.2.3.1 External capacitors pin selection

The following table lists the recommended pins for $C_{MOD}$ capacitors for an ISX-based design.

**Table 5** Recommended pins for external capacitors

| Device | $C_{MOD1}$ | $C_{MOD2}$ |
|---|---|---|
| PSOC™ 4000T | P4[2] | P4[3] |
| PSOC™ 4100T Plus | Channel0: P4[0] | Channel0: P4[1] |
| | Channel1: P7[0] | Channel1: P7[1] |

To know more about pins that support external capacitors in PSOC™ devices, see the respective device datasheets.

## 2.3.2.4 Pin assignment

An effective method to reduce the interaction between sensor traces and communication or non-sensor traces is to isolate each by proper port/pin assignment. Figure 19 shows an ideal pin assignment that allows such isolation.

As much as possible, the PSOC™ 4 controller should be oriented such that there is no crossing of switching signals such as communication and LED lines with the sensing traces.

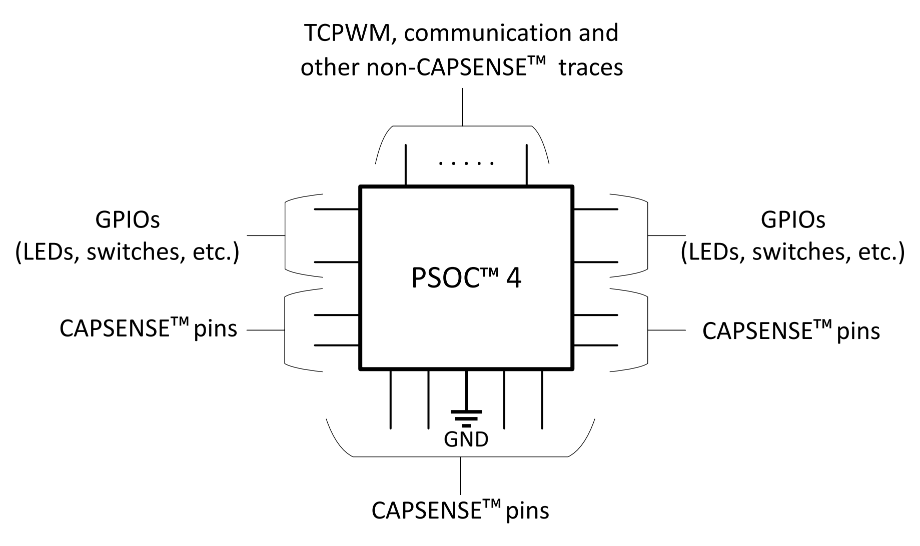
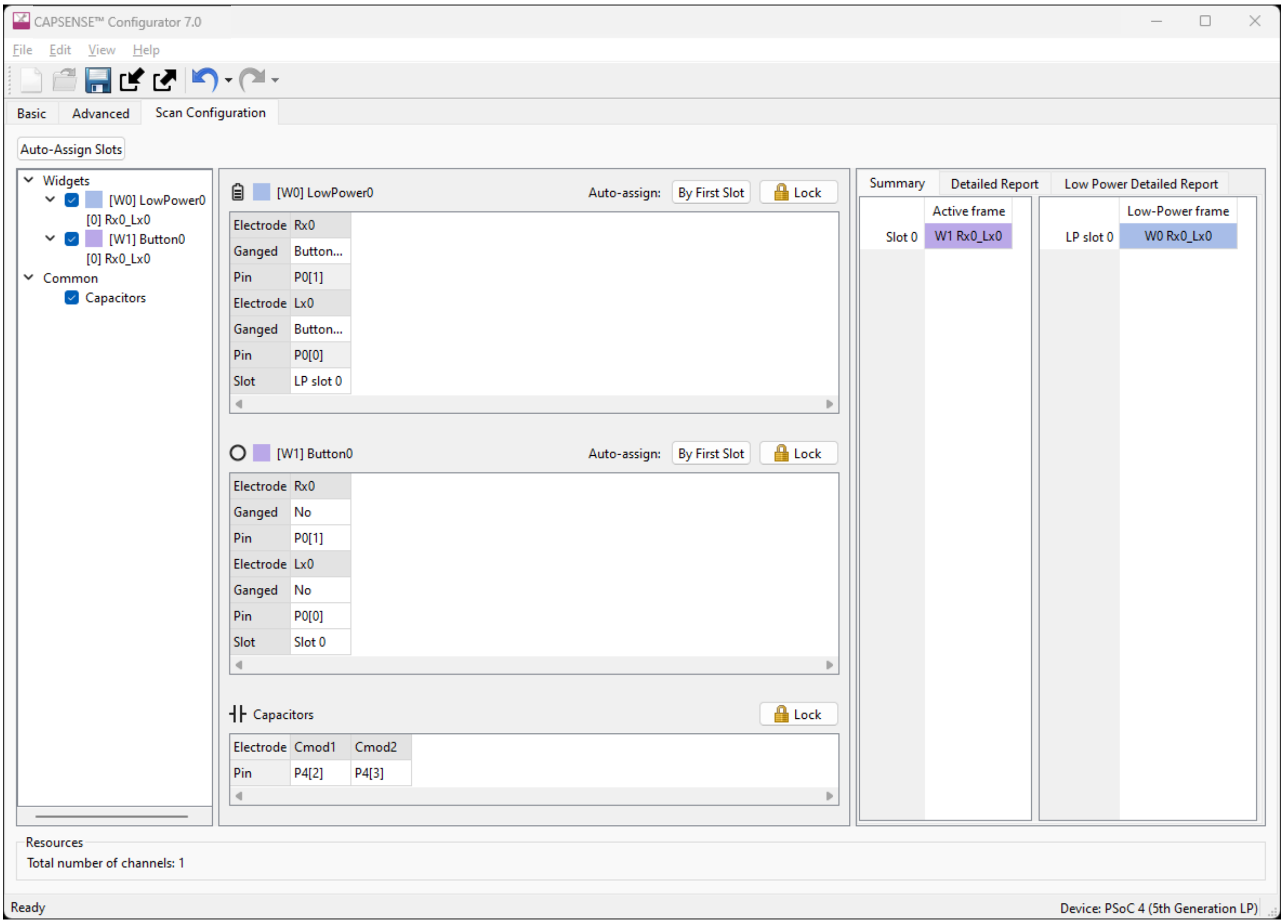


**Figure 19** **Recommended: Port isolation for communication, CAPSENSE™, and LEDs**

ModusToolbox™ CAPSENSE™ Configurator can be used for the pin assignment in the ISX design as shown in Figure 20.



[W0] LowPower0

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | Button... |
| Pin | P0[1] |
| Electrode | Lx0 |
| Ganged | Button... |
| Pin | P0[0] |
| Slot | LP slot 0 |

[W1] Button0

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | No |
| Pin | P0[1] |
| Electrode | Lx0 |
| Ganged | No |
| Pin | P0[0] |
| Slot | Slot 0 |

Capacitors

| | | |
|---|---|---|
| Electrode | Cmod1 | Cmod2 |
| Pin | P4[2] | P4[3] |

| | Active frame |
|---|---|
| Slot 0 | W1 Rx0_Lx0 |

| | Low-Power frame |
|---|---|
| LP slot 0 | W0 Rx0_Lx0 |

Resources
Total number of channels: 1

Ready
Device: PSoC 4 (5th Generation LP)

**Figure 20** **PSOC™ pin assignment with ModusToolbox™ CAPSENSE™ Configurator**

### 2.3.2.5 Tolerances/quality of discrete components

As ISX is a precision sensing technology, good tolerance components are recommended for the sensing circuit. Typically, 1% for resistors and 10% for capacitors are recommended.

### 2.3.2.6 Using connectors

In some use cases, use of the connector becomes necessary to connect sensors to PCB, for example, sensors can be designed on a flexible PCB and the PSOC™ device placed on the main PCB, in such scenarios a good quality sensor with low impedance and low contact resistance is recommended.

Note that the total trace length from PSOC™ device to sensor coil, including connectors should not exceed 100 mm.

### 2.3.3 Schematics and components checklist

This section lists the checks which should be done before finalizing the ISX design schematic. These recommendations are strongly recommended to optimize the performance.

The following table provides the checklist to verify your ISX schematic.

**Table 6** **Schematics and components checklist**

| Category | Recommendations |
|---|---|
| $C_{MOD}$ | 2.2 nF |
| $C_{Vref}$ | 220 nF |
| Sensor series resistance on input lines | 560 Ω resistance is recommended on Rx and Tx pins of the ISX sensor |
| Tolerances/quality of discrete components | 1% tolerance for resistors.<br>10% tolerance for capacitors |
| Using connectors | If needed, use low impedance and low contact resistance connectors<br>Trace length from the PSOC™ device to the sensor coil, including the connector should not exceed 100 mm |
| Sensor pin selection | If possible, avoid pins that are close to the GPIOs carrying switching/communication signals. Physically separate DC loads such as LEDs and I2C pins from the ISX pins by a full port wherever possible |

## 2.4 Sensor design and layout guidelines

The sensor layout plays a crucial role in achieving the required sensitivity and reliability of the detection. An inductive proximity/touch sensor can be constructed in various shapes, sizes, and using different materials depending on the application requirement. The basic objective during sensor layout design is to:

- Achieve high sensitivity
- Reliable detection
- Maximum sensing distance
- Optimum sensor inductance and minimum parasitic capacitance ($C_P$)

Major types of sensors for the most common applications are:

- Button sensor
- Proximity sensor
- Slider
- Rotary encoder

### 2.4.1 Supported sensor parameter range

A sensor coil, with a target present, should be designed to be within the range listed as given in the following table.

**Table 7** **Sensor design parameter supported range**

| Parameter | Minimum | Maximum |
|---|---|---|
| Effective sensor inductance | 0.1 µH | 200 µH |
| Series resistance | 0 Ω | 1000 Ω |
| Sensor parasitic capacitance | Check the following text | Check the following text |

- The maximum acceptable parasitic capacitance depends on the sensor inductance.

$$C_{p\_max}(pF) = \frac{L(uH)}{4R_{tx_{total}}^{2}}.10^{6}$$

**Equation 3** **Maximum parasitic capacitance based on inductance value**

- For instance, $R_{tx_{total}}$ = Rext + Rswitch = 560 Ω + 100 Ω and L(μH) = 20 μH
- Then in this case, the maximum acceptable parasitic capacitance is 10.81 pF for optimum performance.
- Higher parasitic capacitance (than the value given by the equation) can be supported at the cost of a reduction in the operating frequency. Note that in the $R_{tx_{total}}$ calculation, include the series resistance of the inductor for larger coil sizes
- Note that the bare sensor, without the target (metal), can have much larger inductance than the sensor with the target
- In general, larger coils with higher inductance (or higher coupling of magnetic field lines) provide higher sensitivity

## 2.4.2 Inductive sensor design

A long PCB trace on an FR4 or a flexible printed circuit (FPC) board can form an inductive button/proximity sensor. The trace can be a spiral as shown in the following figure. This is the simplest form of inductive sensor.

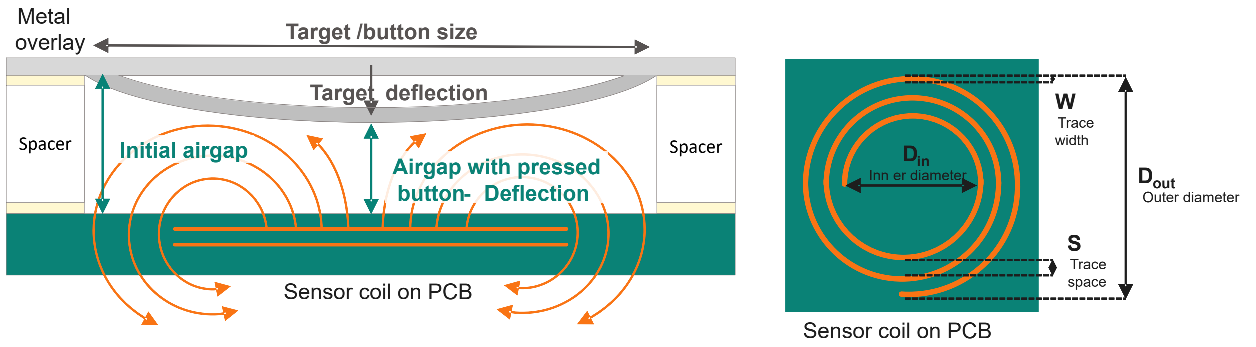


**Figure 21** **Simple inductive button sensor**

### Sensor parameters

For a given shape, the sensor coil is specified by the following parameters:

- n = The number of turns in a layer.
- nl = The number of layers
- w = The turn width.
- s = The turn spacing.
- Din = The inner diameter.
- Dout = The outer diameter. Usually, either Din or Dout needs to be specified; the other can be derived from other parameters.
- BtnSize = The size of the button, which is normally ≥ Dout

The sensor coil can span across two or four layers of the PCB to increase the value of inductance and sensitivity. For a simple button following parameters are recommended:

**Table 8 Layout recommendation for a simple ISX ToM button**

| Parameters | Recommendation |
|---|---|
| Button size | 15 mm to 30 mm |
| Sensor coil size | 12 mm to 23 mm (75% of button size) |
| Shape | Circular, rectangular, octagonal |
| PCB layers | 2, 4 |
| Trace width and spacing | 5 mils |
| Number of turns | 25-60 |
| Overlay material | Stainless steel (preferred for longer lifespan and good material strength)<br>Aluminum (slightly higher signal) |
| Overlay thickness | 0.5 mm to 0.8 mm |
| Overlay – sensor coil spacing | 0.3 mm to 4 mm |
| Recommended minimum SNR | 10 |

### 2.4.3 Sensor shapes

The shape of the inductive sensor is important because it determines the shape of the generated magnetic field and therefore the change in inductance in the presence of a target metal object. The following are common shapes of PCB and flex coils:

- **Circular coil:** Circular coils are generally used when sensing a target object that is moving orthogonal to the sensor plane, as Figure 21 shows. The illustration also highlights the optimal plane of movement of the target for a circular sensor.
- **Hexagonal or Octagonal coil:** Polygonal coils are designed to approximate circular coils in cases where a circular coil is difficult to manufacture.
- **Square coil:** Square coil provides optimal performance with respect to sensitivity in both horizontal and vertical directions.

See Figure 22 for an example of a hexagonal and square coil structure.

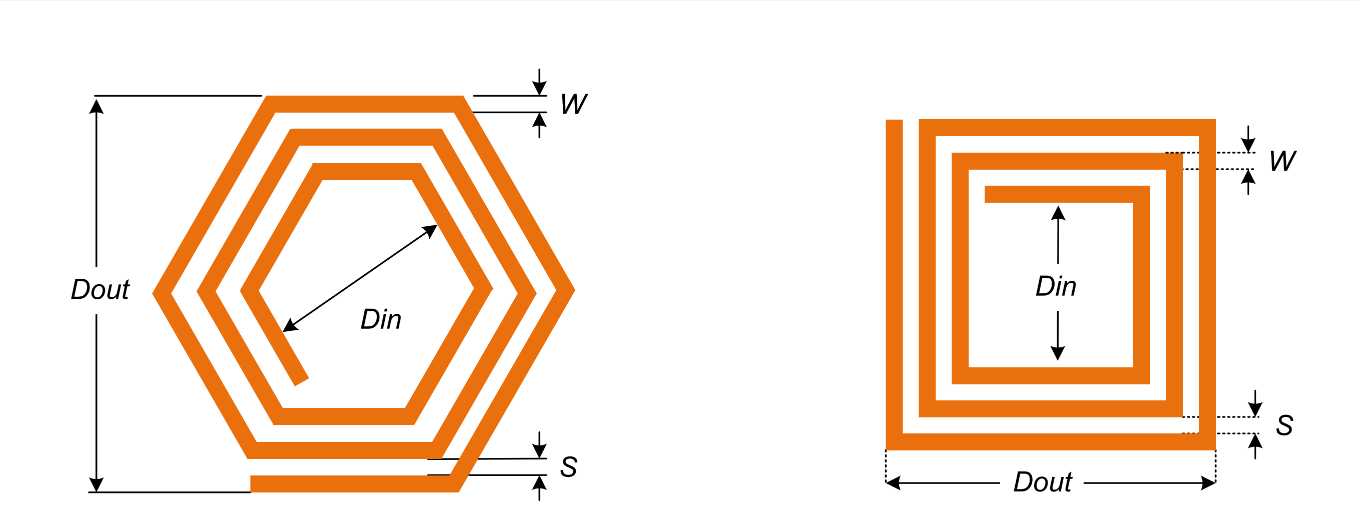


**Figure 22** Hexagonal coil and square coil examples

**Rectangular coil:** Rectangular coils can be used to detect movement along a preferred axis. Figure 23 shows an example of a rectangular coil with the axis for optimal detection of movement for this coil indicated in the diagram.

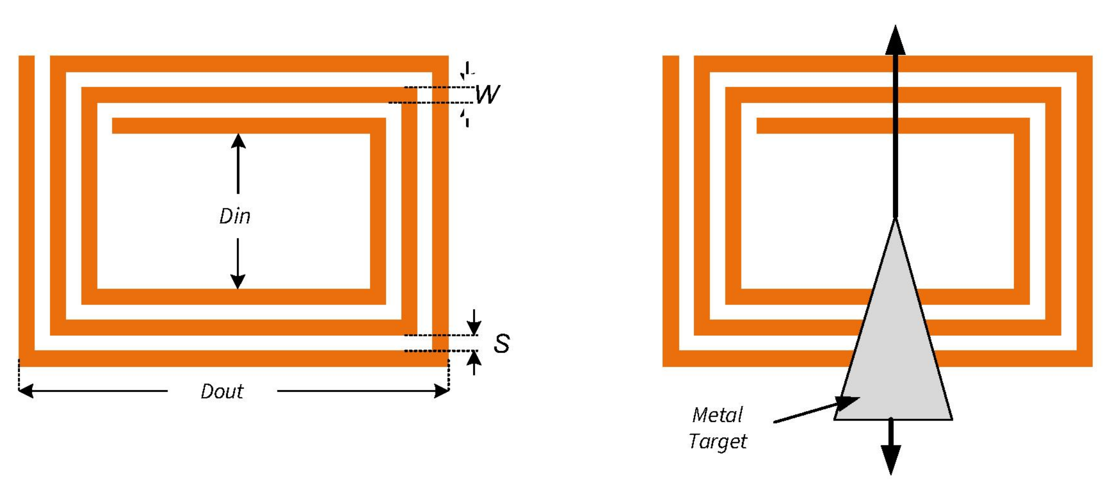


**Figure 23** Rectangular coil illustration showing the optimal plane of movement

***Note**:* *Non-circular coils have a higher series AC resistance ($R_S$) for the same inductance as of circular coil sensor.*

For touch-over-metal type of applications, the circular coil sensor performs better than a rounded square coil for the same button size as shown with the data in Figure 24. Rounded square coils are only recommended if there are constraints on the PCB design that do not allow circular coils.

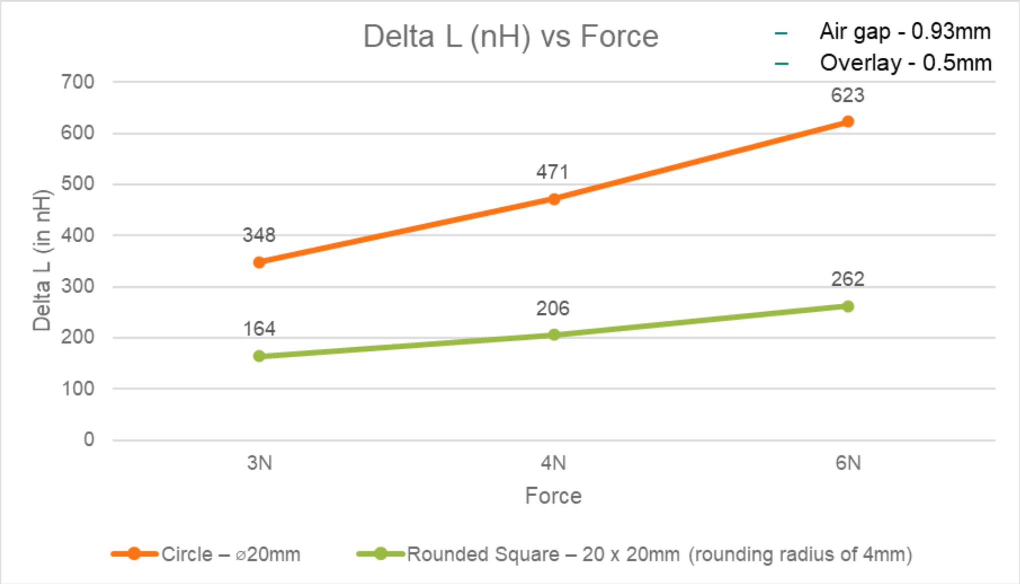


**Figure 24** Signal/delta L (nH) for two different coil shapes for 23 mm x 23 mm button

## 2.4.4 Sensor modeling

The inductance values L and series AC resistance, $R_S$ of the sensor need to be estimated for designing and the tuning of the sensors.

### 2.4.4.1 Sensor design – approximate equations

The following equations can be used to estimate the parameters of the inductor from the coil dimensions.

***Note**: These expressions are not as accurate as a field solver and are used for approximations only.*

The inductance of the coil can be estimated using the following expression derived from Simple Accurate Expressions for Planar Spiral Inductances 13.. Equation 4 and is based on a Current Sheet Approximation.

$$L_{gmd} = \frac{\mu_0 n^2 D_{avg} C_1}{2}\left(ln\left(\frac{C_2}{\rho}\right) + C_3\rho + C_4\rho^2\right)$$

**Equation 4** **Inductance of the coil equation**

- C1, C2, C3, C4 = Layout constant dependent on the shape of the coil. See Table 9.
- $D_{avg} = 0.5 \cdot (D_{out} + D_{in})$
- ρ = The fill factor = $(D_{out} - D_{in})/(D_{out} + D_{in})$
- $\mu_0$ = The permeability of free space, 4π x 10-7
- n = The number of turns

**Table 9** **Coefficients for current sheet method**

| Coil shape | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| Square | 1.27 | 2.07 | 0.18 | 0.13 |
| Hexagonal | 1.09 | 2.23 | 0.00 | 0.17 |
| Circle | 1.00 | 2.46 | 0.00 | 0.20 |

An expression to estimate the RS of a conductor due to the skin effect has been derived from High-Speed Digital Design: A Handbook of Black Magic 14.. This equation provides an estimate of the AC resistance of the inductor in ohms/inch. Table 10 shows some values for ρR (the relative resistivity of the coil material, compared to copper).

Note that the value of RS calculated in the following equation is the unit value. To get the total value of RS, the unit value needs to be multiplied by the length of the trace which can be measured from the PCB Design tool by making a sample coil of desired shape.

$$R_s = \frac{2.16x10^{-7} \cdot \sqrt{f\rho_R}}{2(w+d)}$$

**Equation 5** **$R_S$ estimation equation**

Where,

- w = trace width, inches
- d = trace height, inches
- f0 = frequency, Hz
- $\rho_R$ = relative resistivity, compared to copper = 1.00
- RS = AC resistance, ohms/inch

**Table 10** **Conductivity of different materials compared to copper**

| Metal | Resistivity (× 10-7 ohms inch) | Resistivity relative to copper |
|---|---|---|
| Copper | 6.7879 10 | 1.000 |
| Aluminum | 10.3606 | 1.526 |
| 304 SS | 302.847 | 44.616 |
| Titanium Alloy | 667.29 | 98.306 |

### 2.4.4.2 Sensor design – 2D/3D EM solver

An electromagnetic (EM) field solver tool such as from COMSOL or Maxwell can be used to get a complete electrical model of the inductor and understand its characteristics. Figure 25 shows an example of the coil modeling tool graphical outputs.

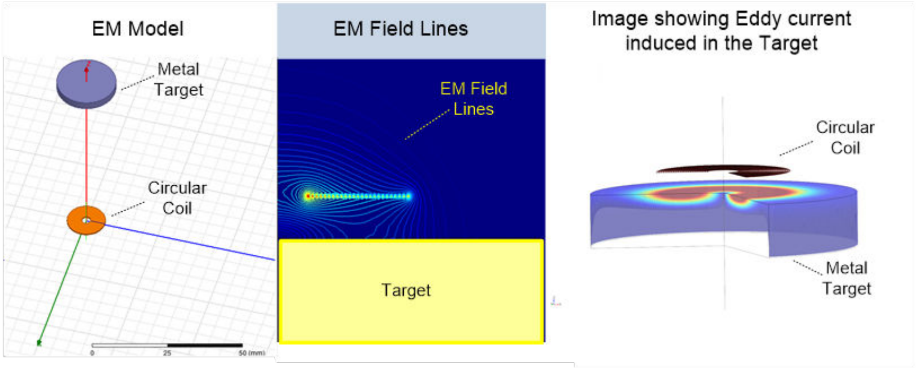


**Figure 25** Examples of output from an electromagnetic field solver (COMSOL)

### 2.4.5 Sensor size vs. sensing distance

The extent of the magnetic field is decided by the sensor physical dimensions; the outer diameter of the sensor, Dout, is the critical parameter. The ISX solution aims for sensing distances up to a coil diameter from the coil while maintaining the SNR at greater than or equal to 10:1. See Section Signal-to-noise ratio (SNR) for details.

For a button sensor with a metal overlay, the geometry of the inductive coil (circular or rectangular, for example) is one of the most important factors that affects the performance. For example, a circular button with 14-mm diameter will have more deflection of overlay than a button with 10-mm diameter. Figure 26 shows the comparison of a normalized signal for two different button diameters.

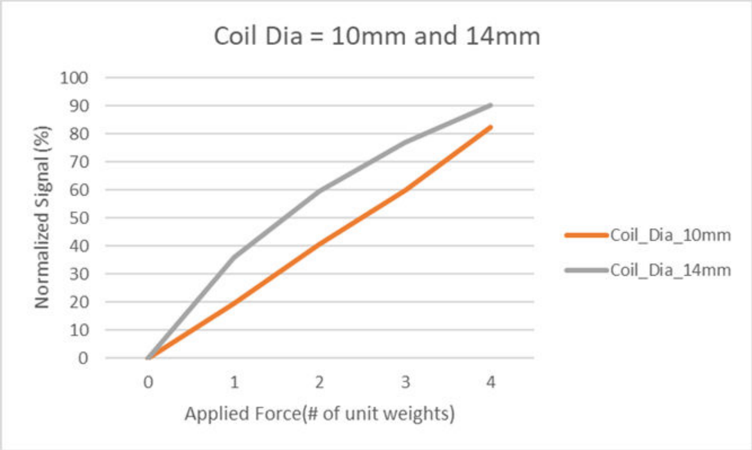


**Figure 26** Impact of coil diameter on normalized signal

If the metal target is near the coil, a small ratio of Din/Dout is optimal for the coil to give maximum change in inductance with distance. When the metal target is further away from the coil (Dout), the outer windings contribute most to the electromagnetic field and the windings near the center can be removed. Figure 27 shows the normalized change in inductance ($\Delta L/L$) as the metal target is moved away from the coil at the distances Dout and Dout/4 with different coil Din/Dout ratios.

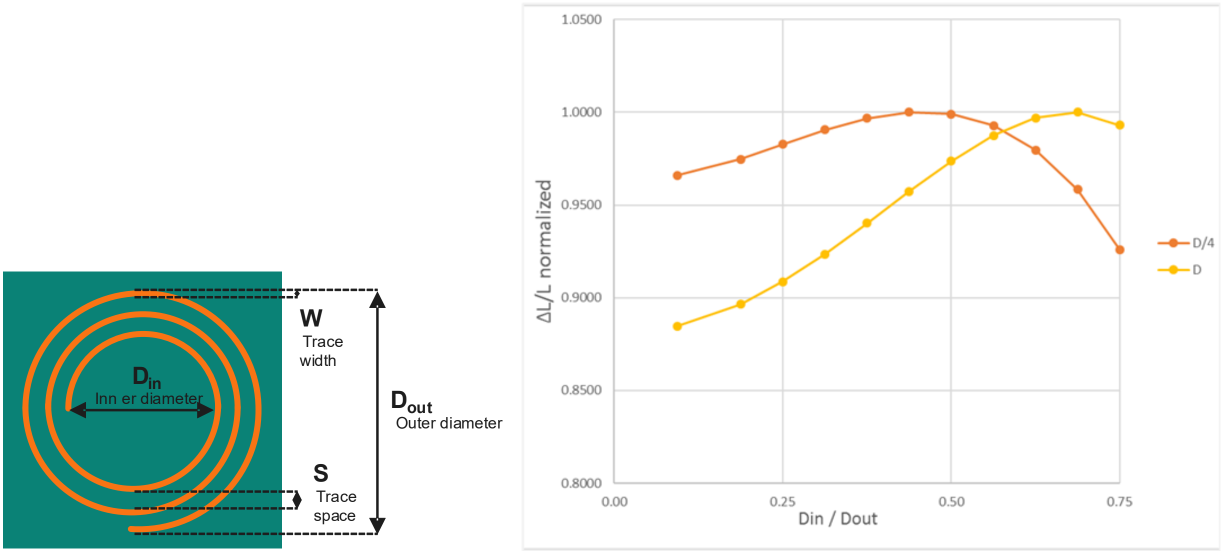


**Figure 27** **Normalized inductance Change (ΔL/L) vs. Din/Dout ratio for a 13-mm diameter coil for proximity applications**

**Note**: *This graph indicates ΔL/L for various loop sizes under lab conditions. The actual ΔL/L varies depending on the end-system environment.*

### 2.4.6 Number of turns and PCB layers in a sensor

In general, the higher the number of turns results in coupling with the metal, more the sensitivity. As shown in Equation 4, the inductance is dependent on the number of turns. The additional number of turns that can be incorporated with an increase in coil diameter can be found as follows:

$$Additional\ turns\ = \frac{\Delta Coil\ \ diameter}{Trace\ width + Trace\ thickness}$$

**Equation 6** **Additional turns obtained with an increase in coil diameter**

The number of turns in an equivalent size coil on PCB can be increased by reducing the trace width and spacing between the traces, for example, a 3.5 mil trace with 3.5 mil spacing can accommodate a greater number of turns than 5 mil trace with 5 mil spacing within same coil area.

Similarly, more the number of PCB layers, higher the inductance and resulting in higher sensitivity given the size of the sensor coil is <= 10 mm. For big sensors, increasing the turns in the upper layers of the PCB, increases sensitivity, as it results in more coupling with the metal. Increasing turns in the lower layers cannot have the same impact as the layers are further away from the metal. The size of the sensor coil, i.e., the diameter of the sensor has bigger impact on the sensitivity of the sensor than the number of layers as shown in Figure 28 and Figure 29.

In Figure 28, both scenarios can be considered as having an equivalent number of turns (20 turns in 1 layer, 10 turns each in 2 layers). The figure shows the higher sensitivity of the 16 mm coil on movement (deflection) of a metal target by around 0.3 mm at a 1 mm and 4 mm air gap.

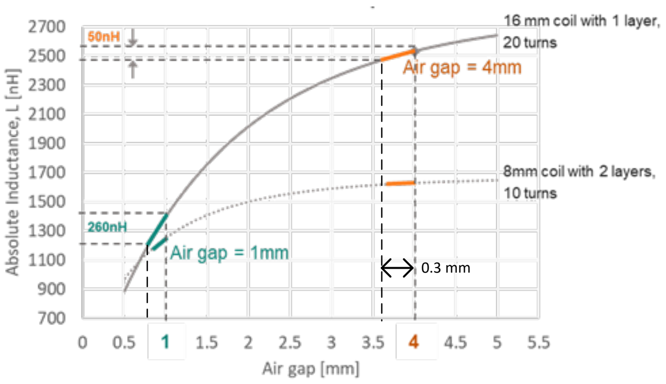


**Figure 28** Absolute inductance response for 1-layer and 2-layers sensor coils

Figure 29 follows from Figure 28. It shows the change in inductance versus the deflection (movement) of the metal target. The solid line corresponds to the 16 mm coil which is more sensitive than the 8 mm coil.

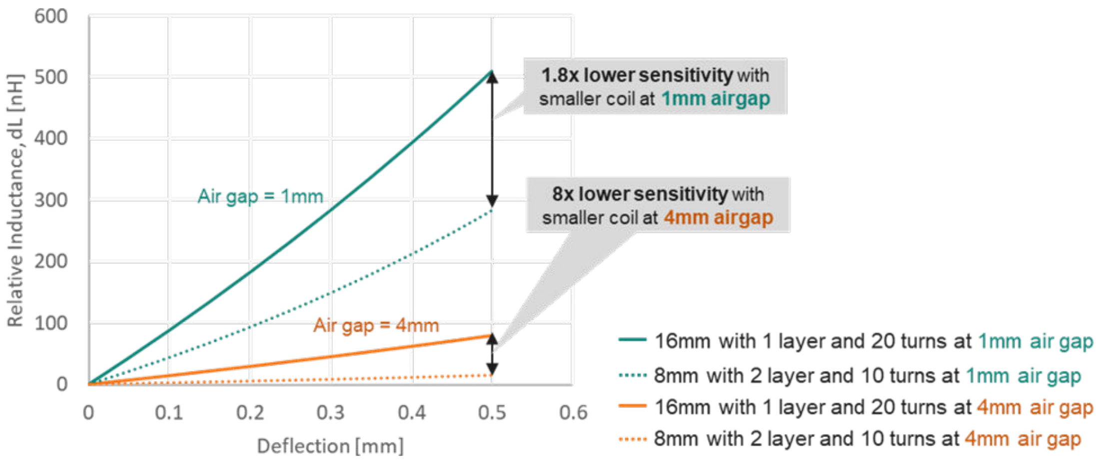


**Figure 29** Relative inductance change for 1-layer and 2-layers sensor coils

Figure 30 shows the impact of coil stack-up for a 20 mm coil (23 mm button). The more the coupling with the metal overlay, the higher the sensitivity of the coil. The coils exists in different layers of a four-layer PCB. The coil in the top two layers performs better than the coil in one and four layers. The coil in all four layers of the PCB has the highest change in inductance (highest sensitivity) for similar deflection of metal.

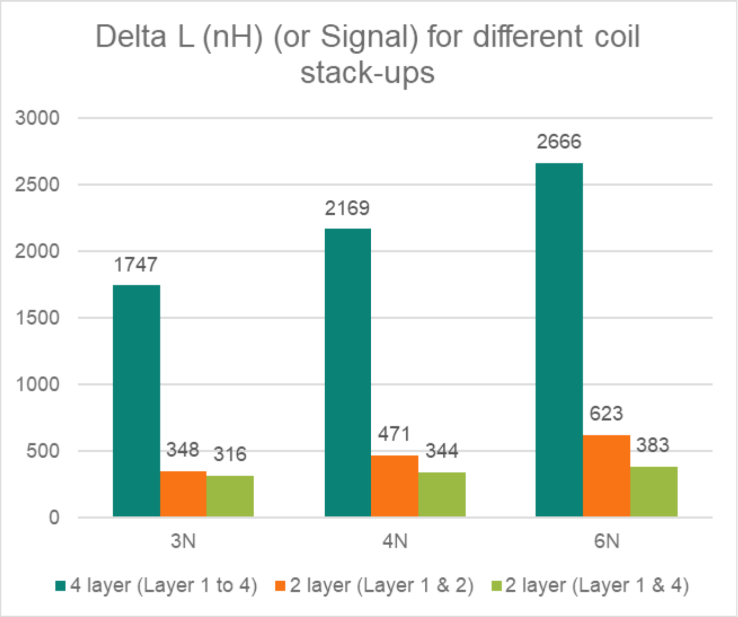


**Figure 30** **Signal (in terms of dL) for three different coil stack-ups**

The data is captured for a 20 mm coil (23 mm x 23 mm button) with a 0.93 mm spacer/air gap and 0.5 mm thick stainless steel overlay.

To get higher sensitivity, design the PCB to have the coil in all four layers of a four-layer PCB rather than the standard two-layer PCB design.

### 2.4.7 Layout considerations

This section highlights the layout considerations to be considered made during the physical design of an inductive sensing solution.

In general, consider the following guidelines while routing signals in inductive sensing solution PCB:

- Ensure that the current always flows in the same direction when making multilayer coils, so that the magnetic flux always adds up. Figure 36 illustrates this
- When the coil is designed to the minimal trace and space rules and then connected to the via ring, be careful with possible violations (over-etching or under-etching process) here. It is recommended to expand the trace width at connection to the via and avoid sharp angles, see Figure 37
- Place the Tx and Rx lines parallel to each other
- Make sure that the Rx lines are not near any digital toggling lines like communication traces and switching LED traces. See Figure 34
- Make sure that the Rx lines do not use the communications line port, for instance, the $I^2C$ or SWD ports as they may interfere with the signal. See Figure 19
- Minimize the trace length whenever possible. Long traces can pick up more noise than short traces. Long traces also add to parasitic capacitance ($C_P$)
- For etched or milled overlays, the Rx and Tx traces should not overlap with metal foot of the target. It is good to hide these traces in the inner layers of PCB

- Coil to coil spacing must be maintained to ensure that there is no crosstalk. Around 0.5 * Dout for ToM use cases and greater for proximity kind of applications
- LEDs and discreet components must be kept at least 0.5 * Dout from the coil edge

Figure 31 shows examples of good and bad sensor design layout.

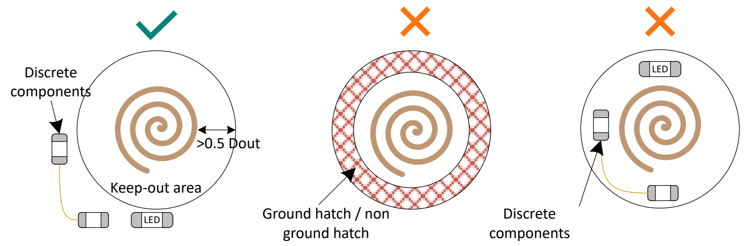


**Figure 31** **Good sensor layout design patterns**

Figure 32 shows the layout considerations for placement of bottom side of the sensor.

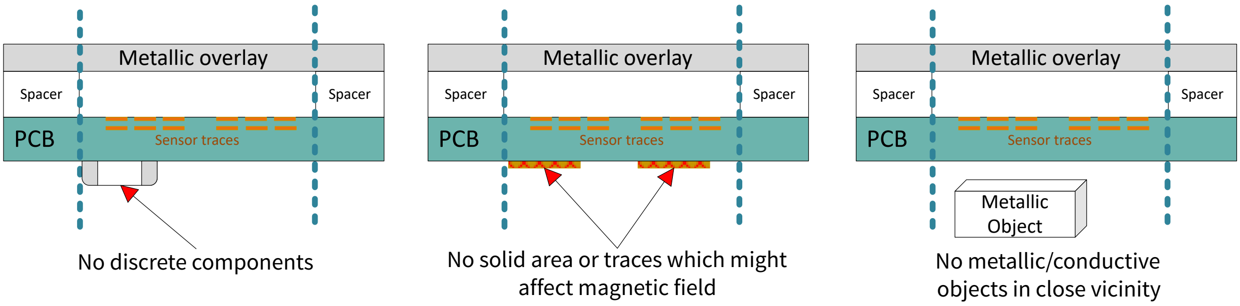


**Figure 32** **Layout considerations for bottom side of the sensor**

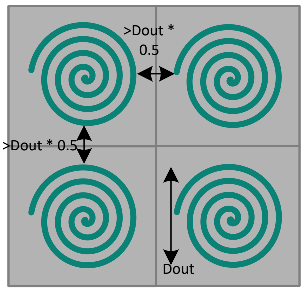


**Figure 33** **Coil-to-coil spacing for a four-button use case**

Route the sensor traces on the bottom layer of the PCB, so that the finger does not interact with the traces. Do not route traces directly under any sensor pad unless the trace is connected to that sensor.

Do not run traces too close to the switching signals or communication lines. Increasing the distance between the sensing traces and other signals increases the noise immunity. If it is necessary to cross communication lines with sensor pins, ensure that the intersection is at right angles as shown in the following figure.

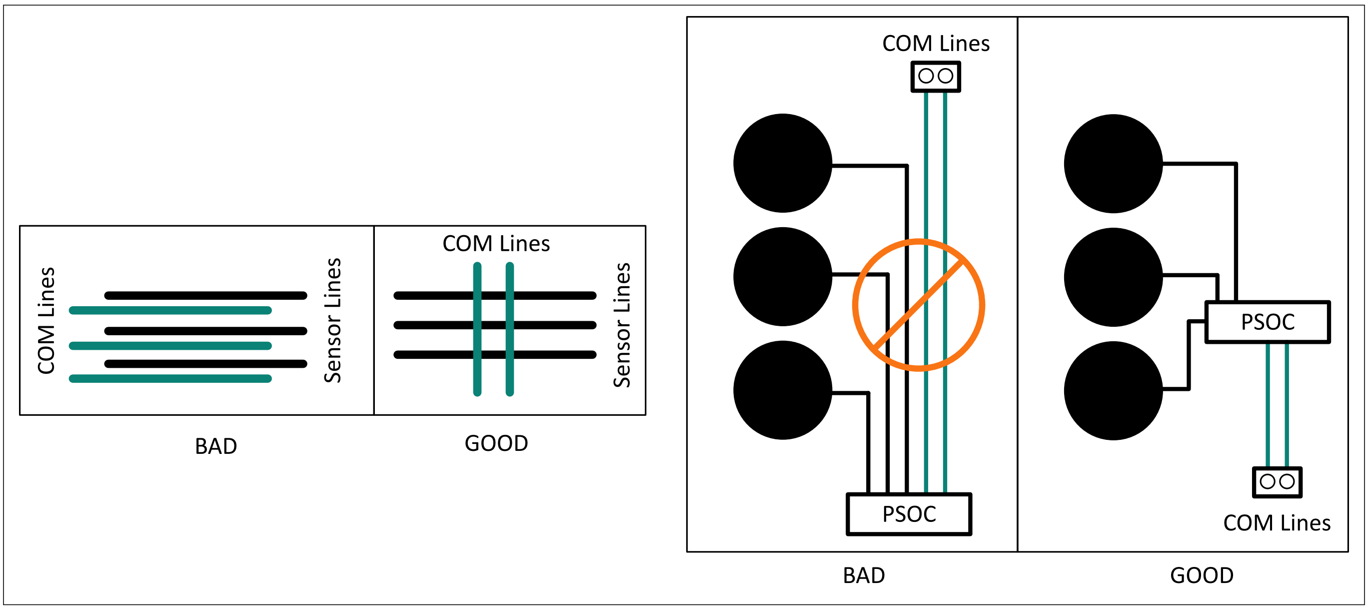


**Figure 34** Routing of the sensor and communication lines

### 2.4.7.1 Sensors with multiple PCB layers

For a given diameter of the coil, there is a maximum limit to the number of turns due to the minimum allowable space between traces. If additional inductance is needed on a PCB, a multi-layer inductor can be designed using multiple layers of the PCB.

The key consideration for multi-layer inductors is that the current flow on different layers is in the same direction so that it constructively adds to the EM field and does not destructively take from it. Spiral coils in each layer are usually connected in series magnetically and electrically. Figure 35 shows the connections for a coil in four layers in the PCB.

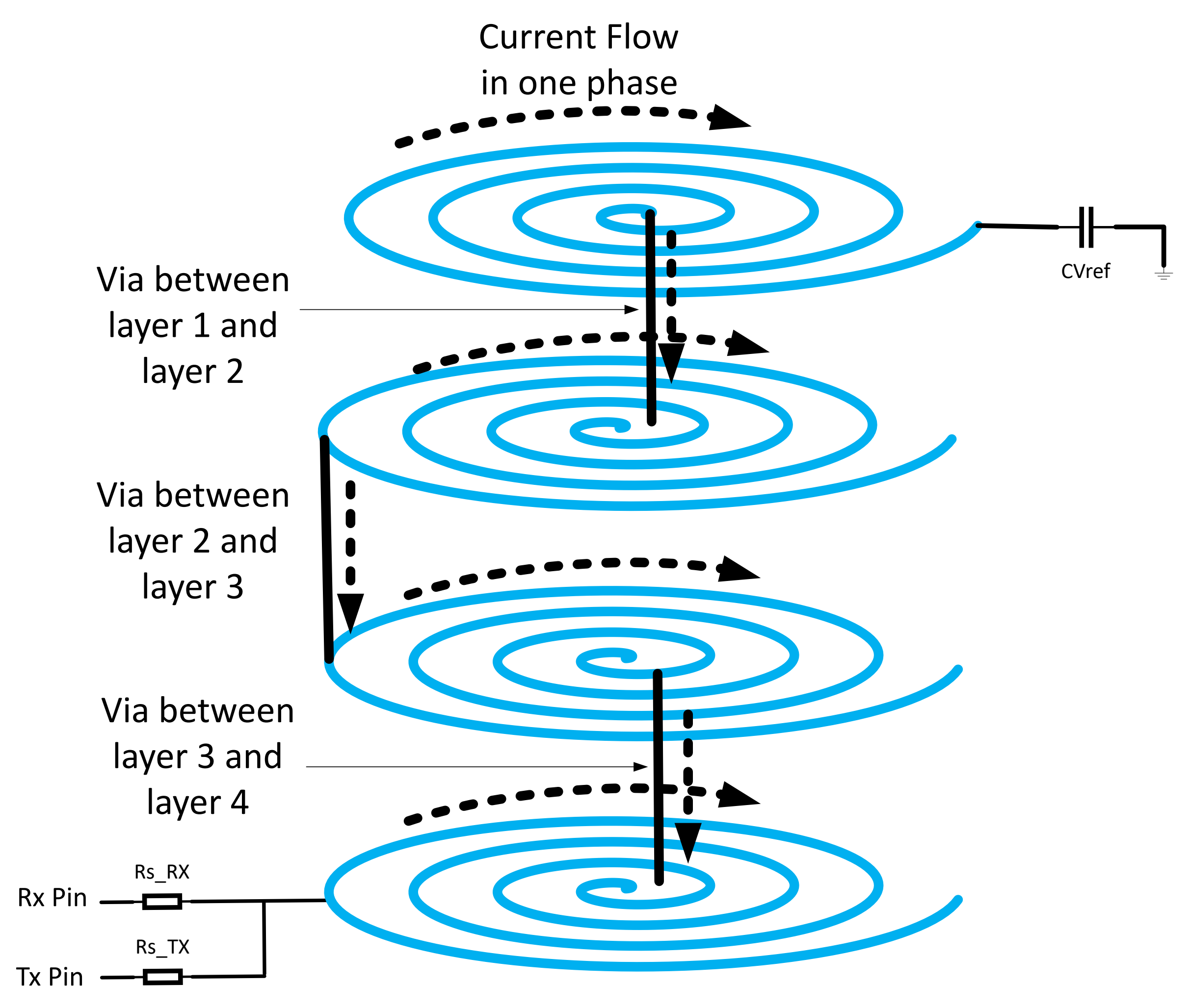


**Figure 35** **Different layers of the coil arranged to allow current flow to be in the same direction in each layer**

Figure 36 shows two-layer inductors in series with a flexible metal target above then coils. The rainbow colors indicate the voltage distribution on the coil turns.

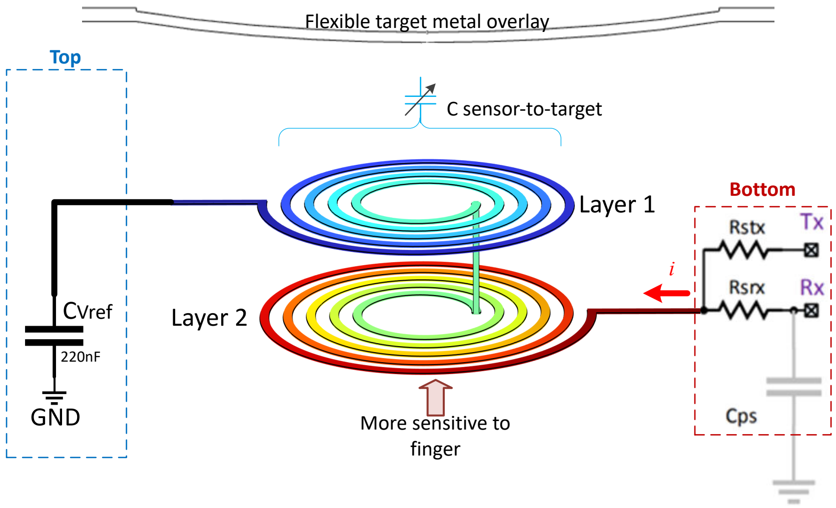


Figure 36 Two-layer inductors in a series configuration with a flexible metal target

In addition to magnetic field interaction, the coil and the target have parasitic capacitive coupling. In case the target (metallic overlay) is grounded, the coil-to-target capacitance adds to the total parasitic coupling of the coil to the ground.

In case the target (metallic overlay) is not connected to the PSOC™ 4 device ground, the parasitic capacitance creates a path to the noise from the environment (for instance, a finger-injected noise)

When the target (metallic overlay) moves, it changes the parasitic capacitance, which may contribute to the signal measured by PSOC™ 4. This capacitive signal may add up or partially cancel the pure indictive signal. Parasitic capacitive signal should be reduced for confident measurement of inductive signal. It is done by connecting the Tx feed to the bottom layers and the top layer to the $C_{V_{REF}}$ (reference) point.

In this case the top layer will be at a fraction of the Tx potential. The outer turns of the coil will be at about zero potential, consequently the charge generated by parasitic capacitance variation will be minimized.

Such a design would also reduce the electromagnetic emission.

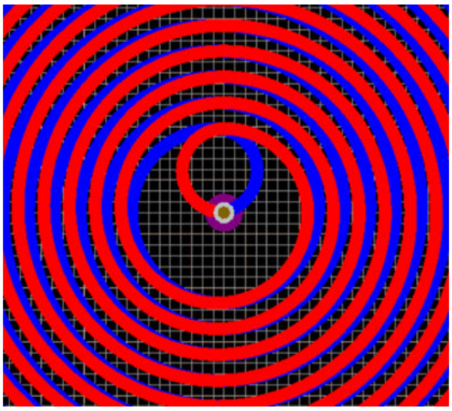


Figure 37 Via between spiral coils in two layers

Figure 37 shows the recommended via placement in multi-PCB layer sensor implementation.

### 2.4.7.2 Sensor series resistor placement

As shown in schematics, series resistors are required on Rx and Tx signal lines of each sensor. These sensors are recommended to be placed as close to the PSOC™ device as possible since the traces after the resistor (towards PSOC™) are very sensitive.

### 2.4.7.3 Clearance between sensors and ground

Solid grounds near the sensors reduce the inductance. If needed, it is recommended to use broken hatched or comb ground planes surrounding the sensor, that exclude formation of the eddy currents as shown in Figure 38.

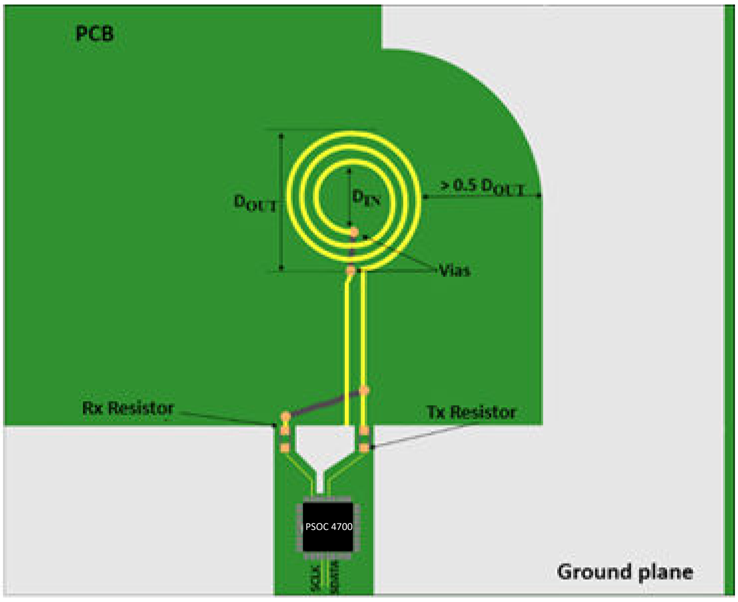


**Figure 38** Clearance between sensors and ground top side of PCB

Solid or hatch fill are strongly not recommended at the button area of sensor coil. If GND is needed for ESD protection add ground shape which does not affect the magnetic fields of the sensor coil as shown in Figure 31.

### 2.4.7.4 Trace clearances

Route the sensor traces as far from each other as possible, add ground trace in between if required.

### 2.4.7.5 Power and ground

- VDDIO noise could couple with the sensor through the IO, in case of excessive supply noise in the system, consider a regulator or a filter on the VDDD supply
- Make sure a low resistance ground plane to prevent any ground noise coupling into the sensor

### 2.4.7.6 LED placement and routing

When the LEDs are switched ON and OFF, the voltage transitions on the LED traces can create crosstalk in the inductive sensor lines, creating noisy sensor data. To prevent this crosstalk, the sensor lines and the LED traces must be isolated from each other as shown in Figure 34. LEDs and discreet components must be kept at least 0.5 * Dout from the coil edge for best performance.

LEDs can be mounted on the PCB and covered by the overlay with holes in it, or they can be separately exposed from the metal overlay. LED diffusers can be used for better electrical isolation by keeping the LEDs away from the coils.

The following figure shows the Keypad-4 and Keypad-2 expansion boards showcasing these two cases.

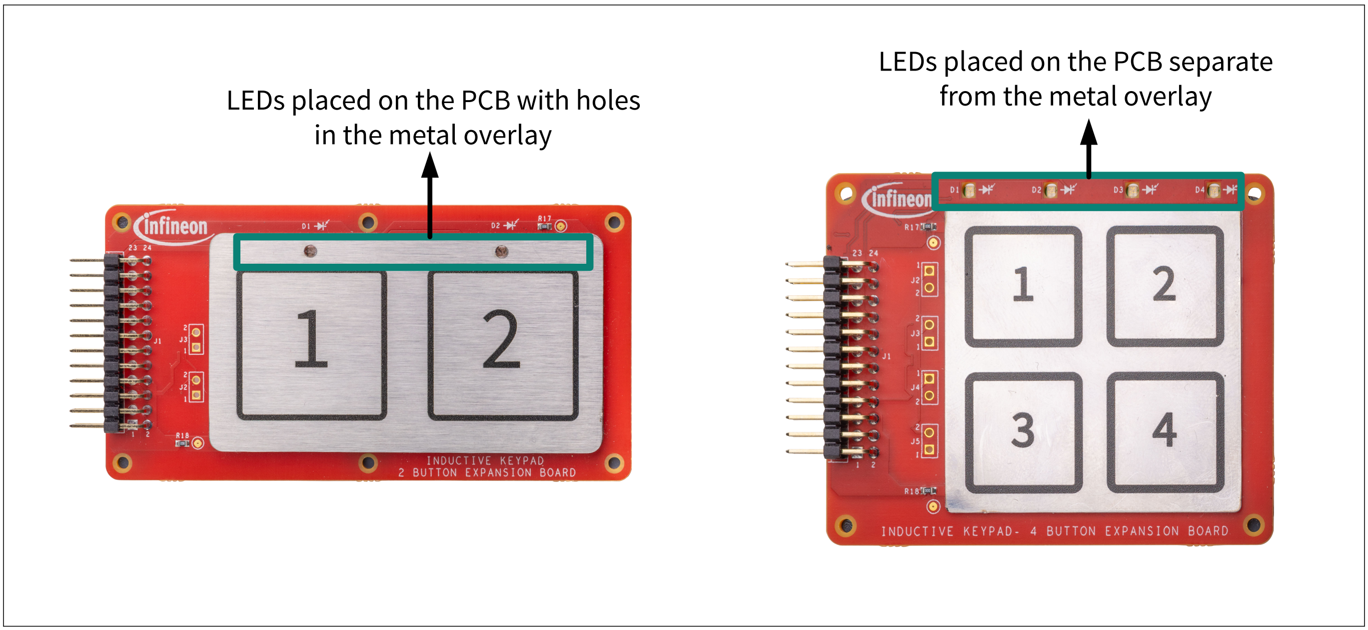


**Figure 39** **Different LED placements for ISX solutions**

Placement of LED at the center of the button is possible, but at the expense of inductive sensitivity. Button performance may degrade in such case.

## 2.4.8 Layout rule checklist

This section lists the checks which shall be done before finalizing the ISX design layout. These are strongly recommended to optimize the performance.

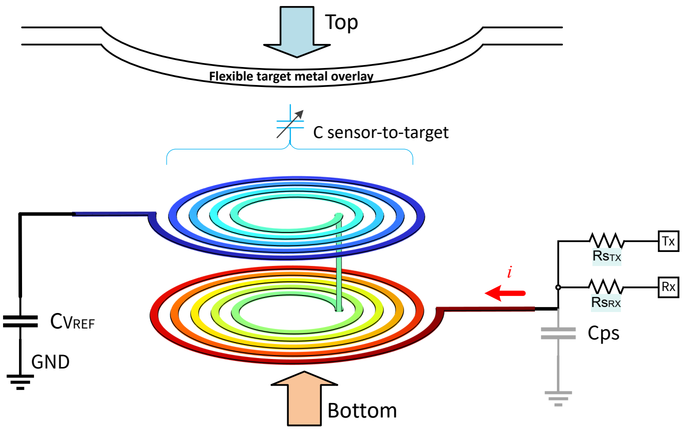
Table 11 provides the checklist to help verify your layout design.

**Table 11** **Layout checklist**

| Category | Parameter | Recommendation |
|---|---|---|
| Coil | Shape | Circle or rectangular with curved edges |
| | Size | 25 mm |
| | PCB layers | 2 or 4 |

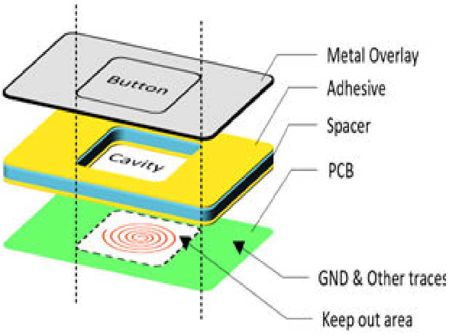
**(table continues...)**

**Table 11 (continued) Layout checklist**

| Category | Parameter | Recommendation |
|---|---|---|
| | Sensor routing |  <br>Must ensure that target/finger can only approach from top of the sensor (where the overlay is present) and not the bottom of the PCB.<br>The top is least sensitive to the finger where the bottom is sensitive to the finger. If you touch to the top surface (blue curve) sensitivity to the finger is <1% from proximity signal<br>From the bottom (orange curve) sensitivity strongly depends on the scanning frequency: The smaller the frequency the smaller the sensitivity<br>Connect Tx feed to the bottom layers and the top layer to the $C_{VREF}$ (reference) point |
| Overlay | Type | Aluminum, Stainless steel, or other conductive material as recommended in Table 12 with spacer |
| | Thickness | 0.25 mm– 0.5 mm (max.) thick, lower the thickness, better the deflection. Recommended deflection is 200 µm |
| Spacer | Type | Touch-over-metal use case overlay shall consist of nonmetallic spacer between coil and metal plate<br>Non-conductive non-magnetic material with zero magnetic permittivity |
| | Thickness | 0.1 mm – 5 mm (max.) thickness (based on sensor coil size) with cavities/openings over buttons to provide top metal overlay bending of 200 µm |
| Button | Cavity size | 133% of the coil size |
| Series resistors | Placement | Place the resistor as close to the PSOC™ device pin, within 10 mm |
| $C_{MOD}$ | Placement | Place the resistor as close to the PSOC™ device pin |
| Sensor traces | Width | Max. 7 mil. Use the minimum width possible with the PCB technology that you use |

**(table continues...)**

**Table 11** **(continued) Layout checklist**

| Category | Parameter | Recommendation |
|---|---|---|
| | Length | Max. 300 mm for standard (FR4) PCB, 50 mm for flex PCB |
| Sensor traces | Clearance to ground and other traces | Maximize |
| | Routing | Route on the opposite side of the sensor layer. Isolate from other traces. If any non-ISX trace crosses the ISX trace, ensure that intersection is orthogonal. Do not use sharp turns |
| Trace vias | Number of vias | Recommended maximum 2 since at least one via is required to route the traces on the opposite side of the sensor layer |
| | Hole size | 10 mils |
| Ground | – | No solid or hatch ground fill in the button area of the sensor coil. In case GND is at all needed for ESD protection, add ground shape which does not affect the magnetic field<br> <br>As shown in the schematics, series resistors are required on Rx and Tx signal lines of each sensor. These sensors are recommended to be placed as close to the PSOC™ device as possible, as the traces after the resistor (towards PSOC™) are very sensitive. For clearance between sensors and ground details, see Sensor series resistor placement |
| Other components | Placement | Do not place metal/conductive elements on the back side of the button close to coil. This decreases inductivity. See Layout considerations for more details |

## 2.5 Mechanical construction guidelines

The mechanical construction of an inductive sensor involves various aspects that need to be considered together that include:

- Sensor coil geometry (size, shape, layers)
- Overlay material properties (elasticity, conductivity)
- Overlay thickness
- Button cavity size
- Air gap (sensor to overlay spacing)

These guidelines are recommended to improve the performance of the inductive sensing design. This section helps to understand how changing a few mechanical configurations will affect the overall performance of the ISX button.

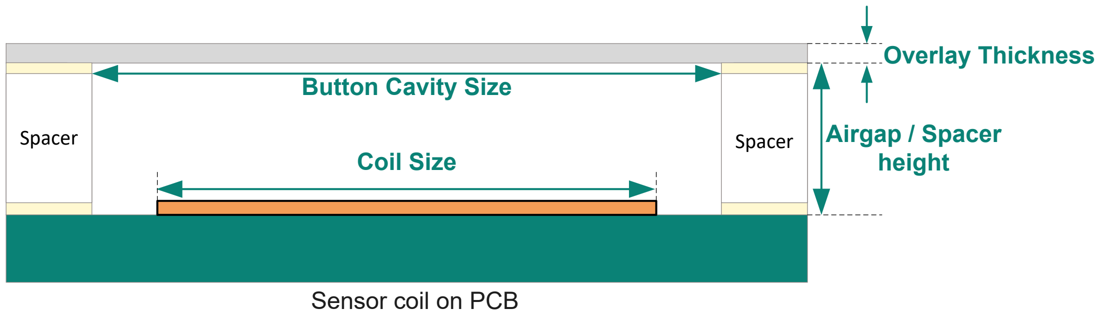


**Figure 40** **Mechanical construction of a touch-over-metal button**

When designing an end application, it is recommended to use the Sensor Designer tool, which simplifies the process of designing flyback inductive sensors and the mechanical stack-ups. For details on the tool, see Section Sensor Designer.

Touch-over-metal involves detecting the deflection of a metal overlay upon a touch. It uses a metal overlay separated from the sensor using a thin spacer or a metal overlay with an etched cavity as shown in Figure 41. The encasing of the product could also act as an overlay, providing a seamless design. When the metal is pressed, it deflects, and this deflection is detected by the sensor.

The deflection of the metal overlay obtained must be relative to the PCB that has the coil. The PCB must have appropriate support such that it does not deflect when the metal overlay is being pressed.

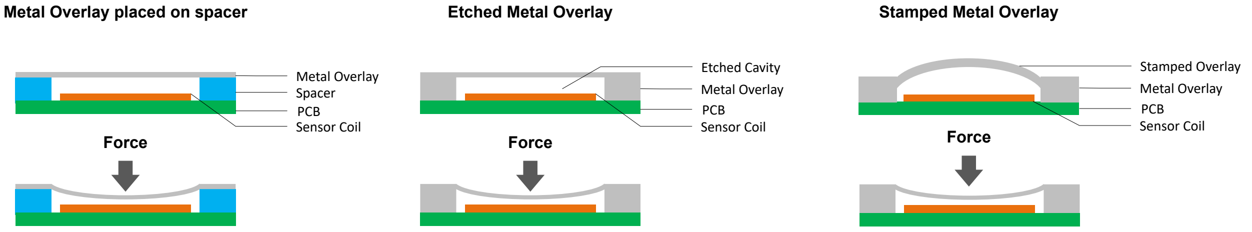


**Figure 41** **Arrangement of metal overlay for a typical touch button**

The etched metal overlay has metal surrounding the cavity and can produce lesser deflection when pressed. This can result in reduced sensitivity compared to an overlay on top of a non-conductive spacer.

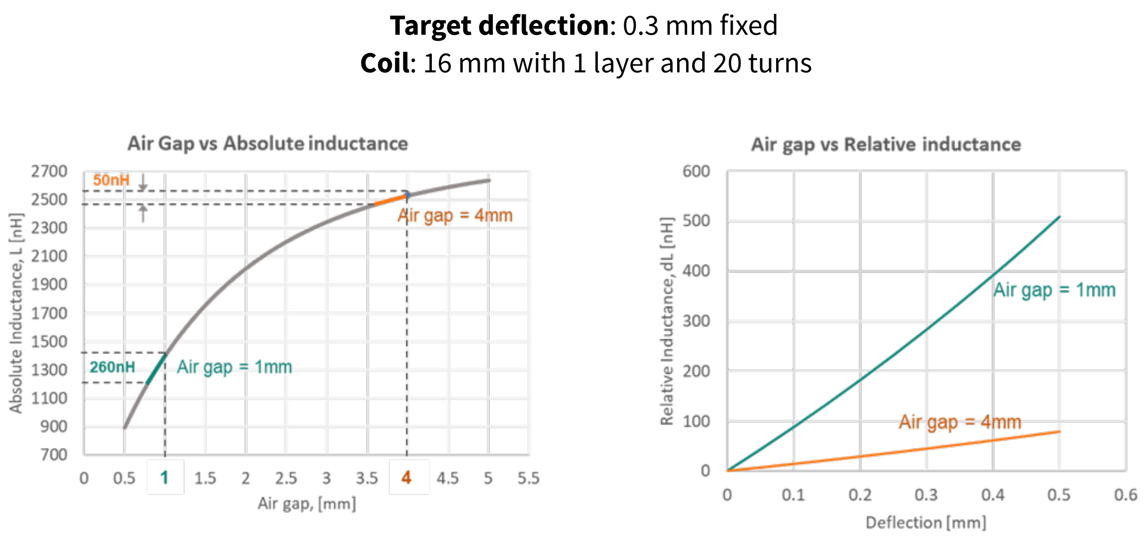
### 2.5.1 Air gap/spacing between sensor and overlay

The distance of separation between the sensor coil and the target is a major parameter that affects the performance of the ISX button.

As the air gap increases, the inductance of the coil also increases. This relative increase in inductance starts to flatten as the air gap approaches the diameter/diagonal of the sensor. For a given deflection, the measured change in inductance (dL signal) will decrease with increased distance.

Figure 42 compares L (absolute inductance) and dL (relative inductance) for 16 mm coils at air gaps of 1 mm and 4 mm.

Observe Figure 42, the sensitivity of a 16 mm coil is ~5x lower because of the larger air gap and lower diameter/air gap ratio. The dL is obtained by bringing the metal target closer to the coil (change in air gap).



**Target deflection**: 0.3 mm fixed
**Coil**: 16 mm with 1 layer and 20 turns

**Figure 42** **Air gap vs. absolute inductance (L) and relative inductance (dL)**

The sizes of the button considered are 3 mm wider than the coil, i.e., 19 mm overlay for a 16 mm coil.

As shown in Figure 43, for the same deflection, the SNR drops as the air gap/spacer height increases while keeping other parameters constant. If SNR needs to be increased, one option is to decrease the air gap while keeping the rest of the configuration as is.

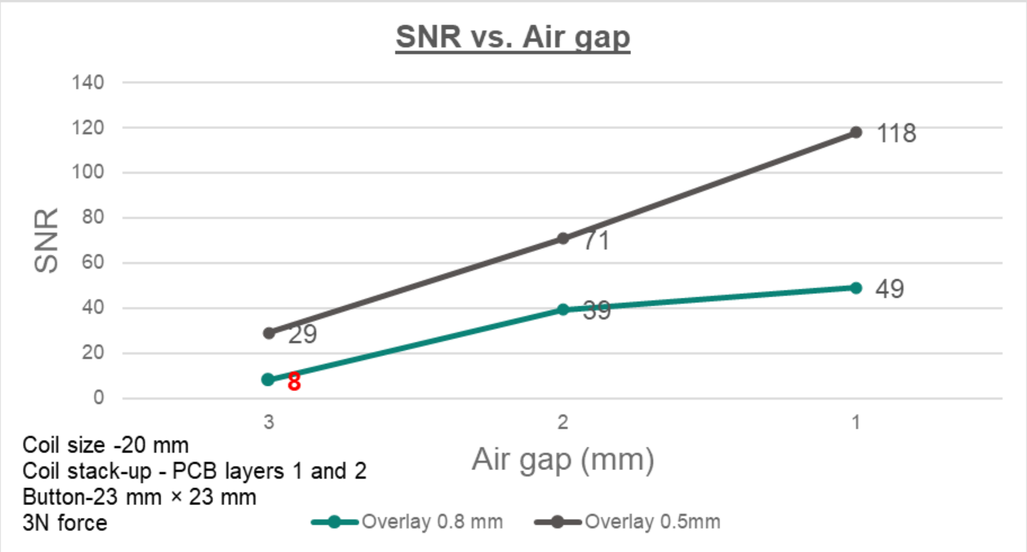


**Figure 43** **SNR vs. air gap/spacer height for a 20 mm coil (23 mm × 23 mm button) for two different stainless steel overlay thickness values**

For example, in the configuration shown in Figure 44, a stainless steel overlay with 0.8 mm air gap works well with air gaps up to 2 mm. With an air gap of 3 mm, the SNR drops under 10.

### 2.5.2 Button cavity size

For optimum performance, the button cavity (overlay) size must be 133% of the coil/sensor size.

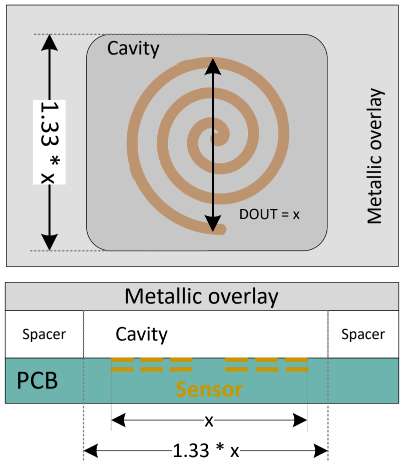
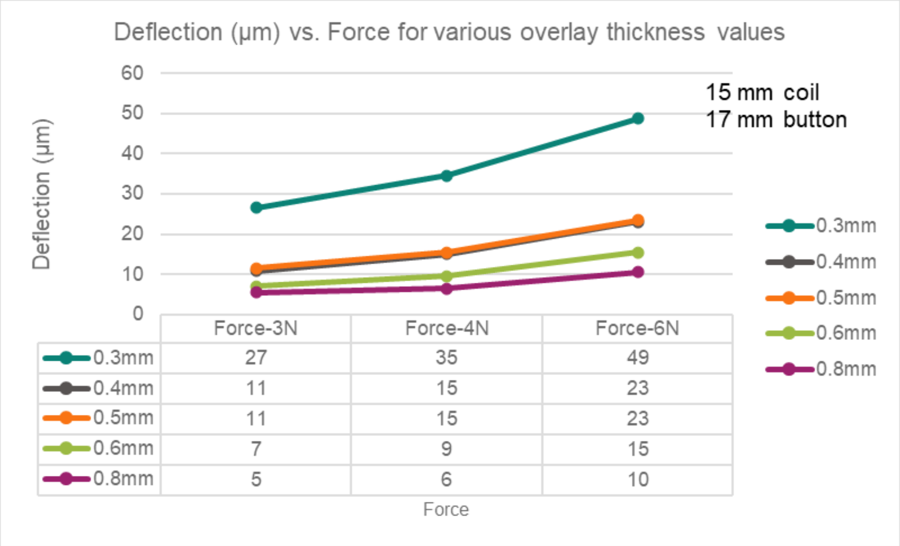
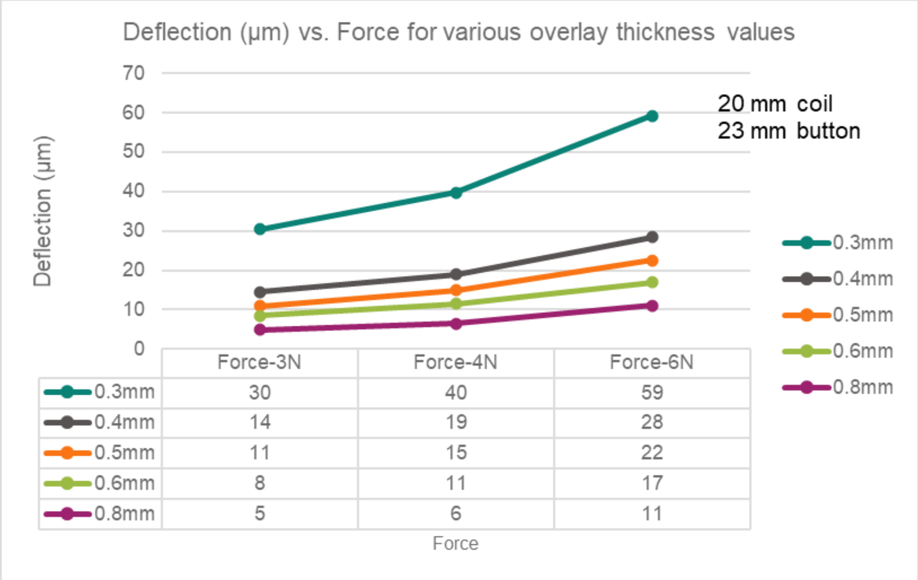


**Figure 44** **Button (overlay) vs. sensor coil size**

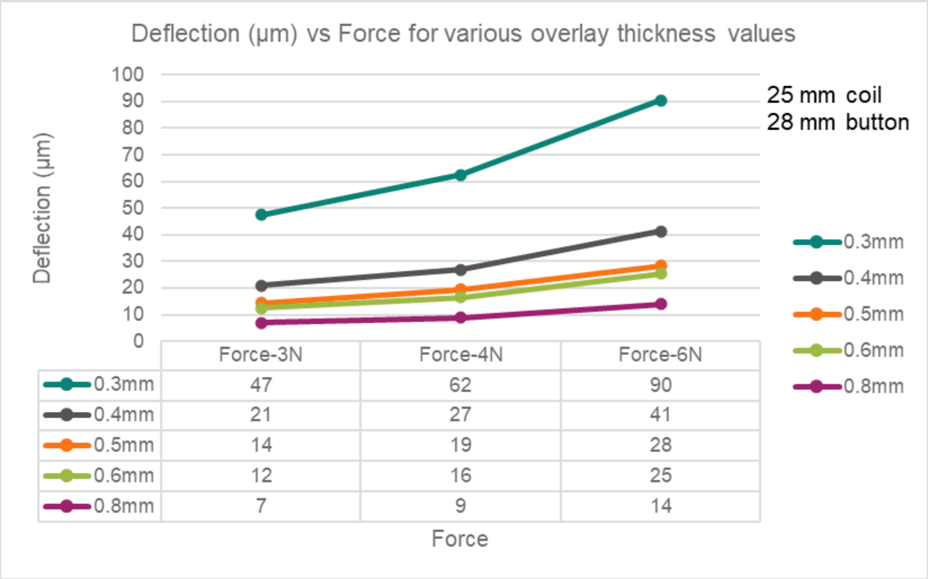
When the cavity size is larger, the deflection obtained in the metal for the same force is larger. Also, for thinner metals, the deflection is higher.



| | Force-3N | Force-4N | Force-6N |
|---|---|---|---|
| 0.3mm | 27 | 35 | 49 |
| 0.4mm | 11 | 15 | 23 |
| 0.5mm | 11 | 15 | 23 |
| 0.6mm | 7 | 9 | 15 |
| 0.8mm | 5 | 6 | 10 |



| | Force-3N | Force-4N | Force-6N |
|---|---|---|---|
| 0.3mm | 30 | 40 | 59 |
| 0.4mm | 14 | 19 | 28 |
| 0.5mm | 11 | 15 | 22 |
| 0.6mm | 8 | 11 | 17 |
| 0.8mm | 5 | 6 | 11 |



|  | Force-3N | Force-4N | Force-6N |
|---|---|---|---|
| 0.3mm | 47 | 62 | 90 |
| 0.4mm | 21 | 27 | 41 |
| 0.5mm | 14 | 19 | 28 |
| 0.6mm | 12 | 16 | 25 |
| 0.8mm | 7 | 9 | 14 |

**Figure 45** **Deflection values ( in µm) for different overlay thickness values and button (coil) sizes**

Figure 45 shows the deflection data for different coil (and button) sizes. In Figure 45, as the cavity size increases, the deflection increases. Also, thinner overlay materials have higher deflection. The deflection required for a particular configuration is dependent on other parameters such as air gap, coil size, etc.

### 2.5.3 Overlay selection

In an ISX design, the overlay material and thickness play a key role in the deflection and inductance change produced. This determines the overall sensitivity of the button.

#### 2.5.3.1 Overlay material selection

The overlay material is selected based on the application requirements by analyzing the mechanical, electrical, and magnetic properties and finding the right balance.

Materials such as stainless steel and aluminum can be used.

Stainless steel is more durable and has a longer life span. It can withstand more force than aluminum before deforming permanently due to its higher yield strength. This makes it ideal for touch-over-metal (ToM) kind of applications.

Aluminum has more conductivity and less Young’s modulus compared to other commonly used metals which makes it suitable for inductive sensing applications (ideal in case of proximity sensing/reed switch applications using Al as a metal target).

##### 2.5.3.1.1 Overlay material mechanical properties

The amount of deflection for the given force at a distance depends on the elasticity of the target material. The Young’s modulus of the material is the measure of elasticity of the material. Materials with a lower Young’s modulus are more flexible. Copper, aluminum (AL6061-T6), and stainless steel (SS304) are the commonly available materials that can be used as the target materials. The following table shows the mechanical properties of different overlay materials. These are generic values; vendors can provide the exact specifications for the material used.

**Table 12** **Properties of commonly used materials as overlay**

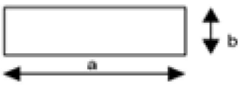
| Overlay material | Young's modulus [Gpa] (Lower is better) | Elastic limit (yield strength) [MPa] |
|---|---|---|
| Copper | 130 | 33–70 |
| Aluminum (AL6061-T6) | 68.9 | 20 |
| Stainless steel (SS304) | 200 | 520 |
| Regular steel | 200 | 100–1650 |
| Phosphor bronze | 110 | 200 |
| Titanium | 105 | 225–830 |
| Ferrite | Not flexible | Not flexible |

Overlay thickness is one of the factors that affect the deflection of the target for the applied force. The target with lesser thickness deflects more for the given force.

Beyond the elastic limit (yield strength), the permanent deformation of the material occurs. Therefore, the selected material should withstand the maximum pressure/force from expected finger size without deforming permanently.

The center-point deflection for thin membrane with fixed edges as explained in 15. and 16. can be defined by Equation 7 as:

For metal sheet



$$w_0 = \frac{\alpha \cdot q \cdot b^4}{E \cdot t^3}, where\ q = \frac{F}{A}$$

**Equation 7** **Empirical formula for thin membrane with fixed edges**

Where,

- $w_0$ = center-point deflection (mm)
- t = Target sheet thickness (mm)
- b = Rectangle short side length
- E = Young's modulus
- F = Force applied (N)
- A = Area of the button (m2)
- $\alpha$ = Coefficient equal to 0.0138 for a = b and fixed edges

### 2.5.3.1.2 Overlay material electrical properties

The change in the inductance of the sensor for a given target deflection depends on the conductivity of the target material as well. The material with higher conductivity has more induced eddy current on the surface of the target and it causes more change in the sensor inductance for the given deflection of the target.

The following table shows the electrical properties of different overlay materials. These are generic values and vendors can provide the exact specifications for the material used.

**Table 13** **Properties of commonly used materials as overlay**

| Overlay material | Electrical conductivity (S/m)(Higher the better) |
|---|---|
| Copper | $59.77 \times 10^6$ |
| Aluminum (AL6061-T6) | $36.9 \times 10^6$ |
| Stainless steel (SS304) | $1.67 \times 10^6$ |
| Regular steel | $2 \times 10^6$ |
| Phosphor bronze | $8.97 \times 10^6$ |
| Titanium | $2.4 \times 10^6$ |
| Ferrite | $10^{-5}$ |

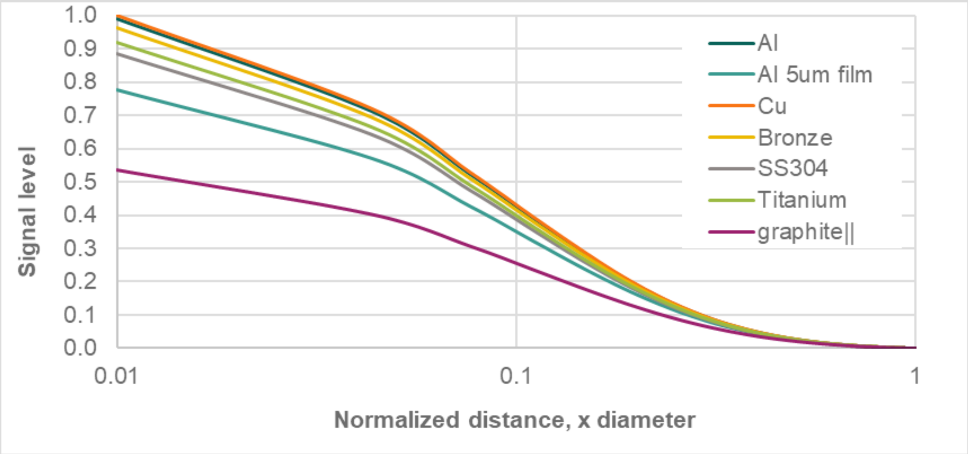


**Figure 46** **Electrical conductivity of metal as function of signal level and distance/diameter**

### 2.5.3.1.3 Overlay material magnetic properties

**Opposing effect of ferromagnetic and conductive materials**

Magnetic flux at 1 MHz is rejected by conductive objects. The higher the conductivity and size of the object, the more the eddy current generated to reject the primary magnetic flux. Materials with magnetic permeability (mu) >1, especially ferromagnetic materials are known to concentrate the magnetic field and therefore, increase the inductance of the coil.

Ferromagnetic materials (with high magnetic permeability) will have an additive effect on the sensor coil inductance, which is not desirable in the current scheme. The effective signal from eddy current and the effect of high magnetic permeability will cancel each other at the operating frequency of MSCLP. This is why the response of regular steel will be worse than SS304. Materials with lower permeability are desirable.

When the target is ferromagnetic and conductive, such as nickel or steel, there are two opposing phenomena. The magnetic field is concentrated due to ferromagnetic properties and is being rejected because of the eddy currents.

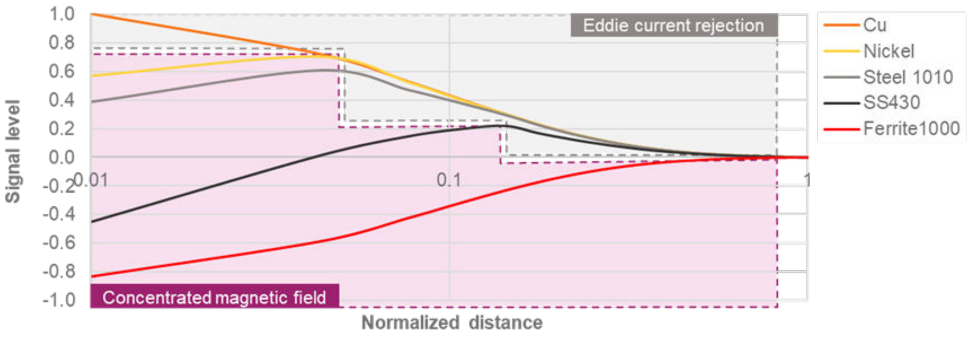


**Figure 47** Properties of ferromagnetic materials as function of signal level and distance

**Table 14** Properties of commonly used materials as overlay

| Overlay material | Relative magnetic permeability(Lower the better) |
|---|---|
| Copper | 0.999994 |
| Aluminum (AL6061-T6) | 1.000022 |
| Stainless steel (SS304) | 1.01–1.05 |
| Regular steel | 200–1000 |
| Phosphor bronze | 1.005 |
| Titanium | 1.00005 |
| Ferrite | 10–20 000 |

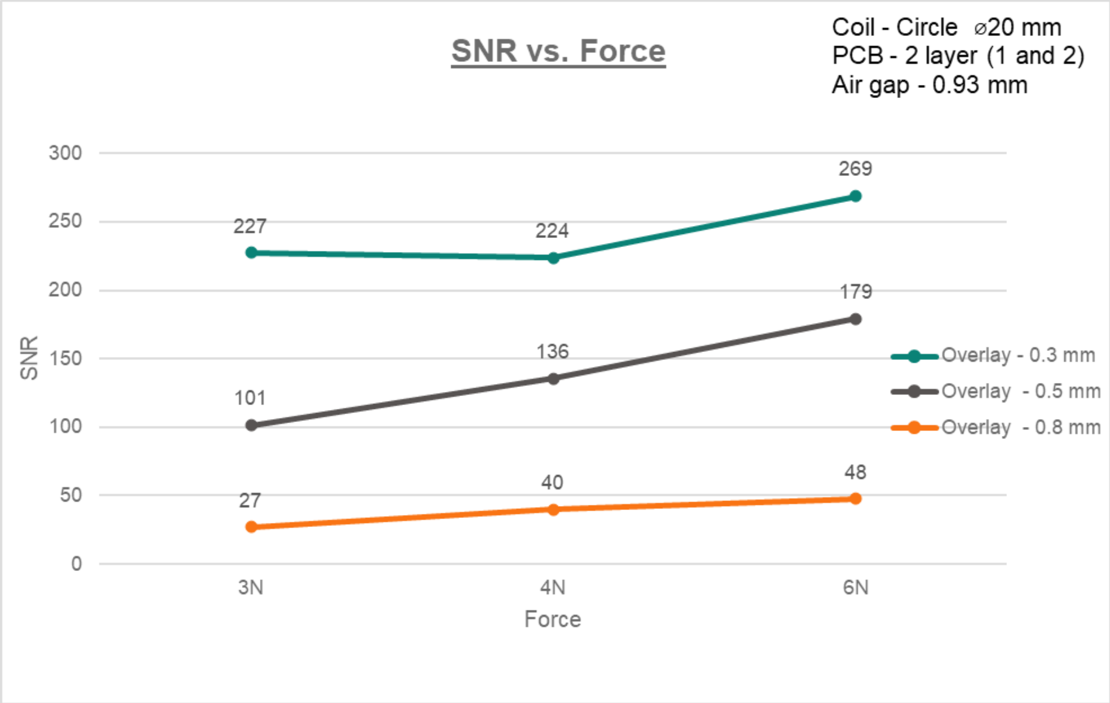
Table 15 shows the magnetic properties of different overlay materials. These are generic values, vendors can provide the exact specifications for the material used.

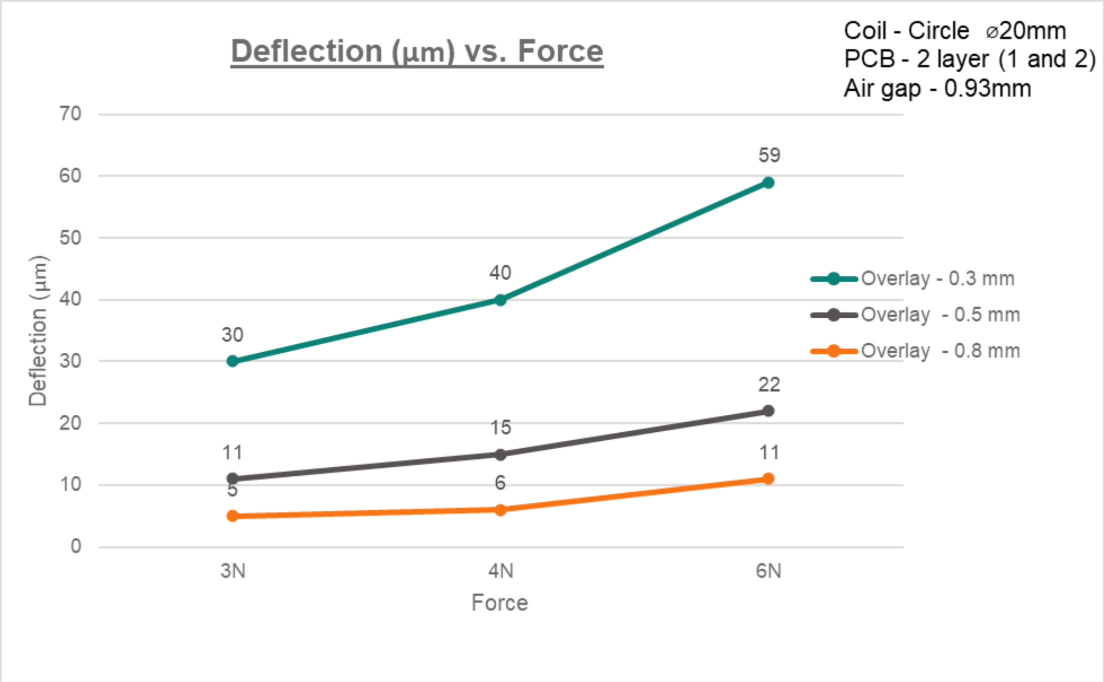
### 2.5.3.2 Overlay thickness

The deflection of the metal used as an overlay depends on the material properties and metal thickness. Thinner metals are deflected more easily. The more the deflection, the higher the change in the effective inductance and the higher the signal obtained. Therefore, the sensitivity drops with an increase in the overlay thickness. SNR can be increased by decreasing the metal thickness while keeping other parameters constant. However, the metal should not be so thin as it gets completely deformed when pressed.

Figure 48 shows the data for different overlay thickness values of stainless steel. The graphs are for a 20 mm coil (23 mm × 23 mm button) in 1, 2 layers of a four-layer PCB with a 0.93 mm spacer/air gap between the metal and the PCB. The three curves represent different overlay thickness values. The X-axis for all three curves show the force with which the button is being pressed.

***Note**: The setup used for capturing this data has been optimally tuned for the 0.5 mm overlay thickness.*


SNR vs. Force
Coil - Circle ⌀20 mm
PCB - 2 layer (1 and 2)
Air gap - 0.93 mm
SNR
300
250
200
150
100
50
0
227
224
269
179
136
101
48
40
27
3N
4N
6N
Force
Overlay - 0.3 mm
Overlay - 0.5 mm
Overlay - 0.8 mm


Deflection (µm) vs. Force
Coil - Circle ⌀20mm
PCB - 2 layer (1 and 2)
Air gap - 0.93mm
Deflection (µm)
70
60
50
40
30
20
10
0
59
40
30
22
15
11
11
6
5
3N
4N
6N
Force
Overlay - 0.3 mm
Overlay - 0.5 mm
Overlay - 0.8 mm

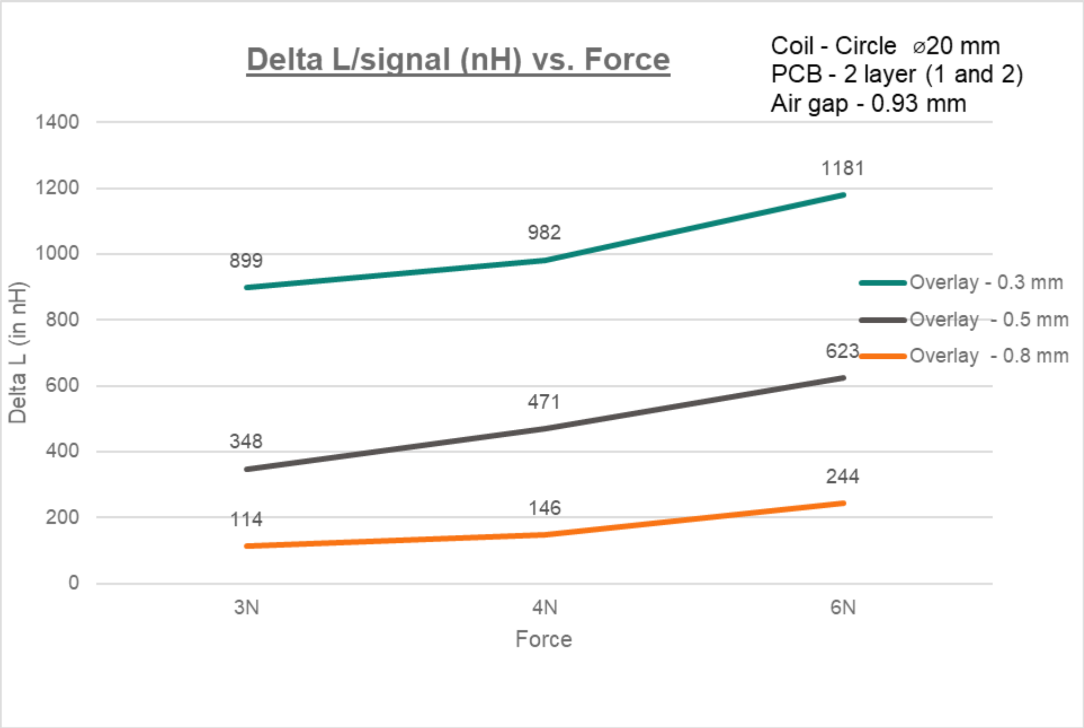


**Figure 48** **SNR, deflection (µm), and signal (nH) data for different overlay thicknesses of stainless steel**

Observe the SNR curve in Figure 48, for a 0.93 mm air gap and 20 mm coil, the SNR is sufficiently high (>10) for all three overlay thickness values: 0.3 mm, 0.5 mm, and 0.8 mm. Additionally, the deflection and signal curves show clearly that thinner materials are deflected more for the same pressing force which in turn results in a larger signal (or delta L).

### 2.5.3.3 Overlay warpage

In touch over metal buttons, consistent usage of the buttons can cause overlay warpage over time which in turn affects the button performance. The following strategies can help mitigate this behavior.

- Having larger buttons
- Choosing the overlay material such that its maximum elasticity is not exceeded when subjected to button presses.
- Construction of cavity in such a way, that it prevents the excessive deformation of the overlay when high force is applied.

### 2.5.3.4 Grounded or floating overlay

In inductive sensing applications, the metal overlay can be connected to ground or kept floating based on the system conditions. A grounded overlay can provide ESD immunity and will have lesser parasitic capacitive coupling with a hand/finger nearby as compared to a floating overlay.

Flyback-based inductive sensing works with both floating and grounded metal overlays. In the LC resonance-based method the capacitive coupling can cause false triggers.

### 2.5.4 Isolation of buttons

In a multi-button system, the mechanical disturbance from the adjacent button can cause a false trigger on the given button. To minimize the mechanical disturbance caused by the adjacent buttons, it is particularly important to provide proper isolation between the buttons.

Also, see the section Mechanical crosstalk.

The cross sensitivity is dependent on the factors as given in the following table.

**Table 15 Effect of materials used in system on overlay lift-off/deflection crosstalk**

| Parameter | Relationship/effect | Recommendation |
|---|---|---|
| Overlay thickness | Higher the thickness, more the movement/lift-off of overlay on nearby buttons | Thin overlay is recommended. However, ensure that the overlay is not so thin as it gets deformed permanently |
| Spacer material | Elastic spacer material will allow the overlay to move in a wider region than the button being pressed. | Use rigid overlay which will limit the movement of overlay on adjacent buttons |
| Adhesive material/thickness | Elastic adhesive material will allow the overlay to move in a wider region than the button being pressed, weak adhesive will have similar effect | Use rigid and firm adhesive which will limit the movement of overlay on adjacent buttons. 3M acrylic adhesives provide strong and consistent bonding. Thinner adhesive layers can be used when there is minimum surface irregularity |
| Grooves on overlay | Grooves on overlay/corrugated overlay help add flexibility to the overlay making it possible to deflect the required area with smaller pressure and avoid impact to adjacent buttons/area | Use grooves on the button borderline as deep as possible |
| Coil to coil spacing | The coil spacing determines the crosstalk between adjacent coils | Coil to coil spacing must be 0.5 * Dout or more. For spacing between two coils of different sizes, consider the Dout of the larger coil |

An example 4-button system is shown in Figure 49.

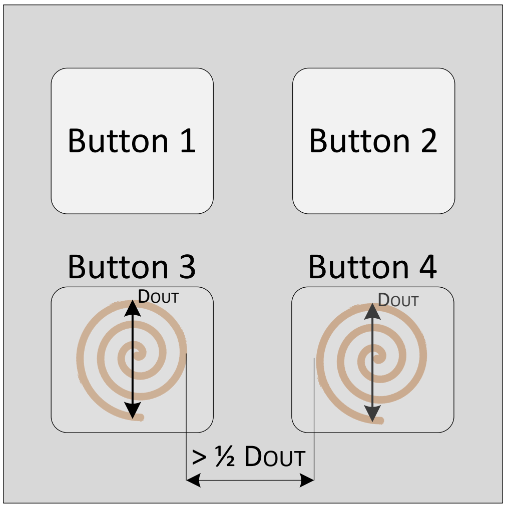


**Figure 49** 4-button system

The cross-sensitivity matrix of buttons for the given multi-button system can be used to tune the finger threshold of a given button in firmware to avoid the false trigger caused by adjacent buttons. The cross-sensitivity matrix as shown in Table 16 provides the probability of the given button to get false triggered by the adjacent buttons.

$$\text{Probability of a button false triggered by adjacent button} = \frac{Interference\ signal\ from\ adjacent\ button}{Finger\ threshold\ of\ given\ button}$$

**Equation 8** Probability of a button false triggered by an adjacent button

**Table 16** Cross-sensitivity matrix for a 4-button system with 0.5 mm overlay thickness, 0.25 mm spacer thickness, and 14 mm sensor outer diameter and ~7 mm spacing between buttons

| Button | By BTN1 | By BTN2 | By BTN3 | By BTN4 |
|---|---|---|---|---|
| False trigger probability of **BTN1** | – | 0.33 | 0.18 | 0 |
| False trigger probability of **BTN2** | 0.58 | – | 0 | 0.4 |
| False trigger probability of **BTN3** | 0.19 | 0 | – | 0.36 |
| False trigger probability of **BTN4** | 0 | 0.36 | 0.58 | – |

The following techniques can be used to provide proper mechanical isolation between the buttons:

- A groove around the button.
- Use of a thin metal target/overlay.
- Separate adjacent coils at least by a distance more than half the coil diameter.
- Proper tuning (see the Tuning the inductive-sensing solution section for more information).

## 2.6 System design considerations

When designing inductive sensing technology in an application, it is important to remember that the ISX system exists within a larger framework. Careful attention to every level of detail from PCB layout to user interface to end-use operating environment will enable robust and reliable system performance.

## 2.6.1 EMI/EMC considerations

### 2.6.1.1 Series resistors on digital communications lines

Communication lines, such as I2C and SPI, can have long traces that act as antennae. They benefit from the addition of series resistance; 330 Ω is the recommended value as shown in Figure 50. The recommended pull-up resistor value for I2C communication lines is 4.7 kΩ. If a series resistor of value greater than 330 Ω is placed in series with these lines, the VIL and VIH voltage levels may fall out of specifications, while 330 Ω will not affect $I^2C$ operation as the VIL level remains within the I2C specification limit of 0.3 VDD when PSOC™ outputs a "LOW".

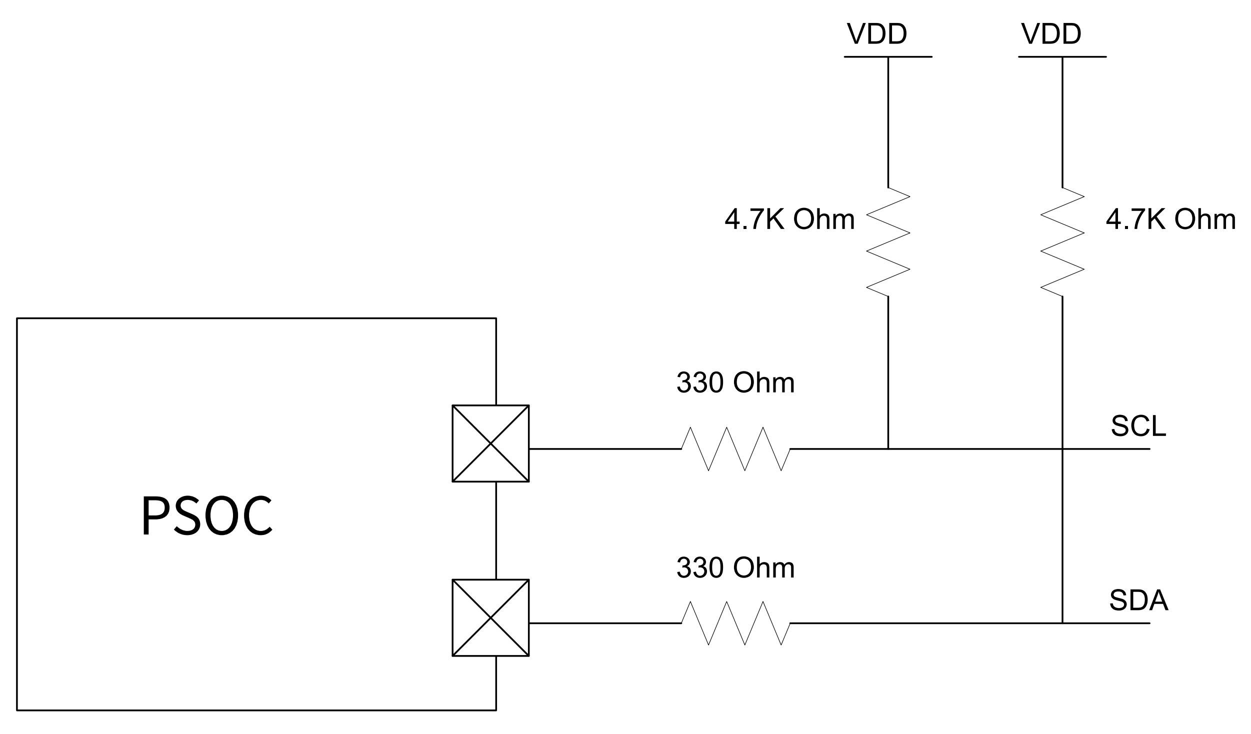


**Figure 50** **Series resistors on communication lines**

### 2.6.1.2 Current loops

Another important layout consideration is to minimize the return path for currents. This is important as the current flows in loops. Unless there is a proper return path for high-speed signals, the return current will flow through a longer return path forming a larger loop, thus leading to increased emissions and interference.

If you isolate any ground hatch and ground fill around the device, the sensor-switching current may take a longer return path. The sensors are switched at a high frequency, so the long return current may cause EMC issues. It is recommended to use a single ground fill to minimize the length of such a return path and any subsequent emissions.

### 2.6.1.3 Use of spread spectrum sense clock

Since the ISX technique does not use resonance frequency operation, a spread spectrum excitation frequency can be used for the sensor. This reduces the effective emission compared to resonance frequency inductive sensing techniques. The following figure shows a comparison of emissions between resonance frequency inductive sensing techniques and ISX technique.

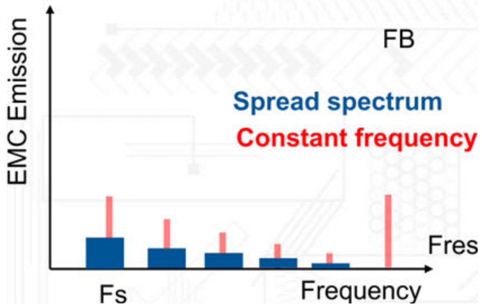


**Figure 51** **EMI for typical inductive sensor with constant and SS frequency**

## 2.7 Firmware design guidelines

After the proximity sensor layout is ready, the next step is to implement the firmware. This section describes the guidelines for the firmware and configuration of the ISX system parameters.

To learn more about using ModusToolbox™ to create a CAPSENSE™ project, see the PSOC™ 4: MSCLP CAPSENSE™ low-power proximity tuning code example.

### 2.7.1 Configuring the type of widgets

PSOC™ devices with fifth-generation MSCLP offer two types of widgets configurations: active and low-power widgets.

### 2.7.1.1 Active widgets

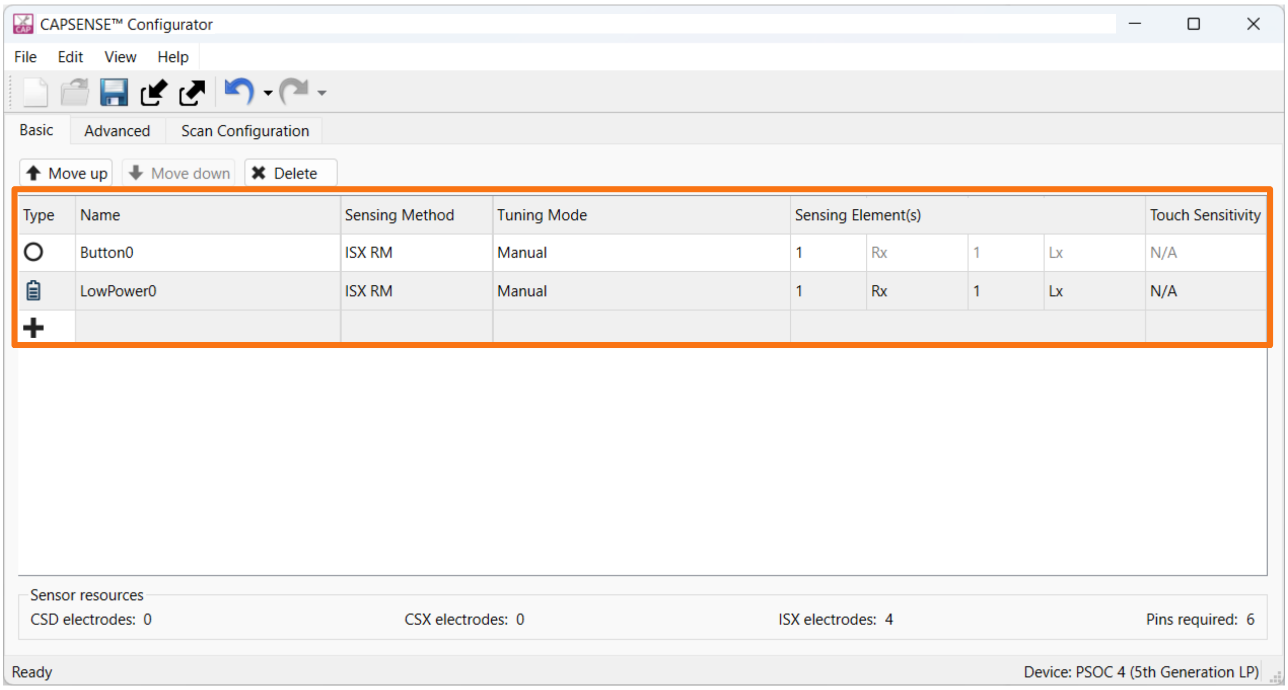
Active widgets are the regular widgets scanned during the active mode of the CPU and cannot be scanned during the sleep mode. All the widget types available in CAPSENSE™ Configurator are by default active widget types, except for the low-power widgets offered by the fifth-generation CAPSENSE™ devices.

### 2.7.1.2 Low-power widgets

PSOC™ devices offer multiple power modes such as Active, Sleep, Deep Sleep, etc. Devices with fifth-generation CAPSENSE™ offer the capability to keep the CAPSENSE™ peripheral active even in Deep Sleep mode. This capability can be implemented using a widget type called “Low-Power Widget”. These widgets are scanned and processed without any CPU intervention in Deep Sleep mode; they can act as a wake-up source for the device.

Widgets such as buttons, ganged sensors, and proximity sensors can be configured as low-power widgets (see Figure 52) to enable wake-on-touch/wake-on-approach functionality.

***Note**:* *If a widget is configured as a low-power widget for normal operation in active mode, they need to be additionally configured as an active widget as well.*



| Type | Name | Sensing Method | Tuning Mode | Sensing Element(s) | | | | Touch Sensitivity |
|---|---|---|---|---|---|---|---|---|
| ○ | Button0 | ISX RM | Manual | 1 | Rx | 1 | Lx | N/A |
| 🔋 | LowPower0 | ISX RM | Manual | 1 | Rx | 1 | Lx | N/A |
| + | | | | | | | | |

Sensor resources
CSD electrodes: 0
CSX electrodes: 0
ISX electrodes: 4
Pins required: 6

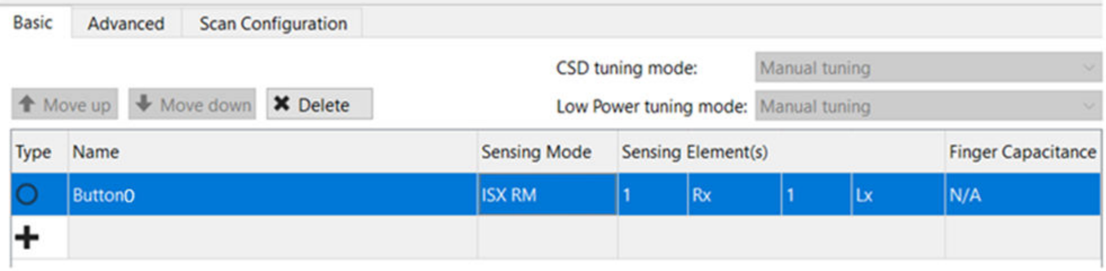
Ready
Device: PSOC 4 (5th Generation LP)

**Figure 52** **Adding a widget using CAPSENSE™ Configurator in ModusToolbox™**

### 2.7.1.3 Adding ISX widgets to the design

**Adding the ISX button**

The ISX widget can be added to the design as shown in the following figure.



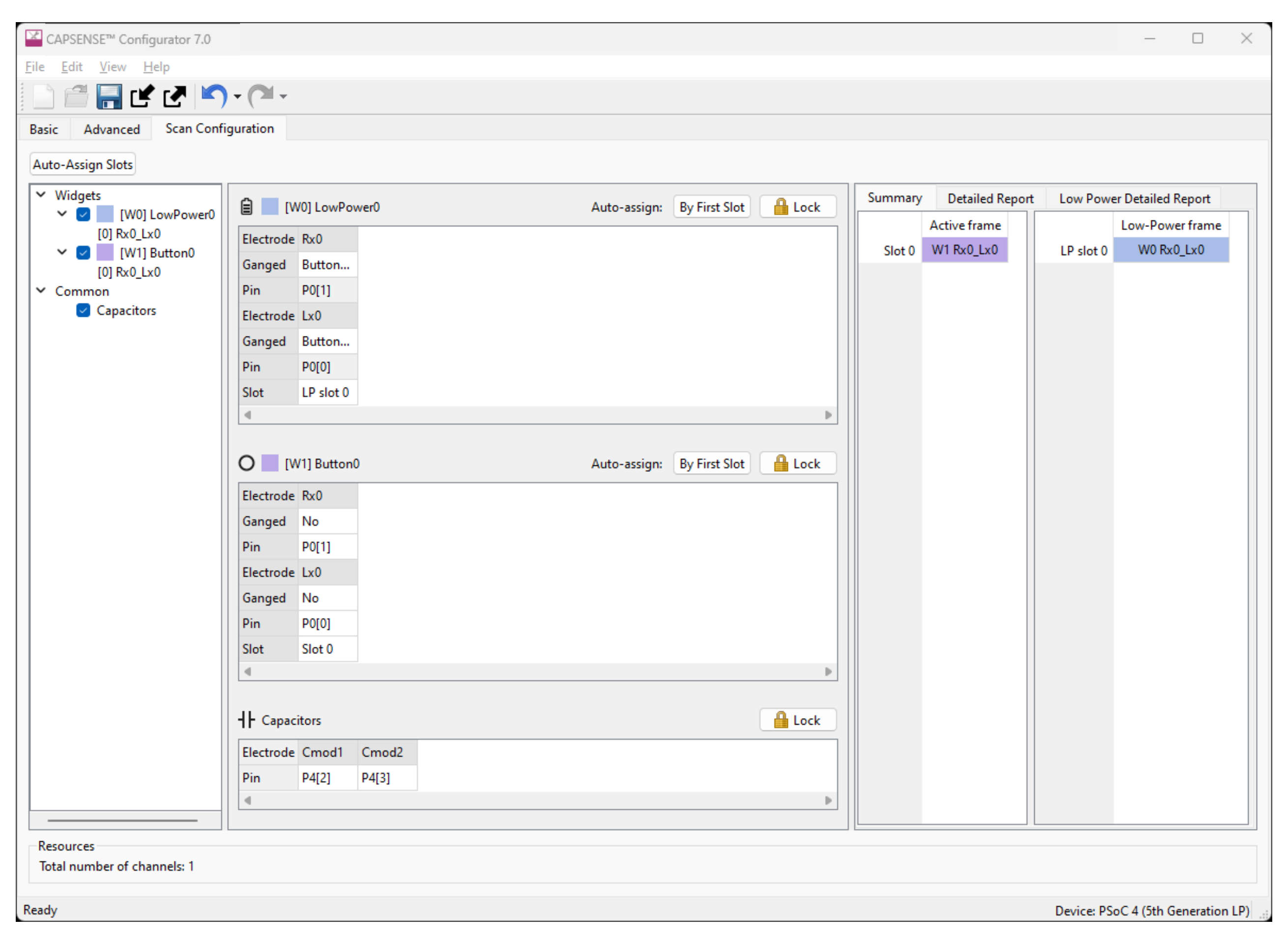
CSD tuning mode: Manual tuning
Low Power tuning mode: Manual tuning

| Type | Name | Sensing Mode | Sensing Element(s) | | | | Finger Capacitance |
|---|---|---|---|---|---|---|---|
| ○ | Button0 | ISX RM | 1 | Rx | 1 | Lx | N/A |
| + | | | | | | | |

**Figure 53** **Adding ISX button to the design**

### 2.7.1.4 Scan configuration

Scan configuration defines the distribution of the sensors, make ganged connection, pin assignments, and scan slots assignments for each sensor channel.



[W0] LowPower0

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | Button... |
| Pin | P0[1] |
| Electrode | Lx0 |
| Ganged | Button... |
| Pin | P0[0] |
| Slot | LP slot 0 |

[W1] Button0

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | No |
| Pin | P0[1] |
| Electrode | Lx0 |
| Ganged | No |
| Pin | P0[0] |
| Slot | Slot 0 |

Capacitors

| | | |
|---|---|---|
| Electrode | Cmod1 | Cmod2 |
| Pin | P4[2] | P4[3] |

| | Active frame |
|---|---|
| Slot 0 | W1 Rx0_Lx0 |

| | Low-Power frame |
|---|---|
| LP slot 0 | W0 Rx0_Lx0 |

Resources

Total number of channels: 1

Ready

Device: PSoC 4 (5th Generation LP)

**Figure 54** **CAPSENSE™ Configurator - Scan Configuration**

Channel and slots for the sensors can be assigned using the **Scan Configuration** tab in CAPSENSE™ Configurator. See the CAPSENSE™ Configurator user guide for more details.

### 2.7.2 Force-touch (detecting different levels of force)

In some applications, it is desirable to have detection of different levels of force. In such cases, the sensor can be tuned to detect the minimum amount of force that needs to be detected. After tuning, thresholds can be set to detect different force levels by observing the signal levels corresponding to each force level (Figure 56 shows the different signals corresponding to force levels). Custom thresholds can be set to detect 5 N and 6 N forces in the firmware. The finger threshold parameter in the CAPSENSE™ configuration is set according to the signal obtained by the 3 N force (the minimum force expected to be detected in this case).

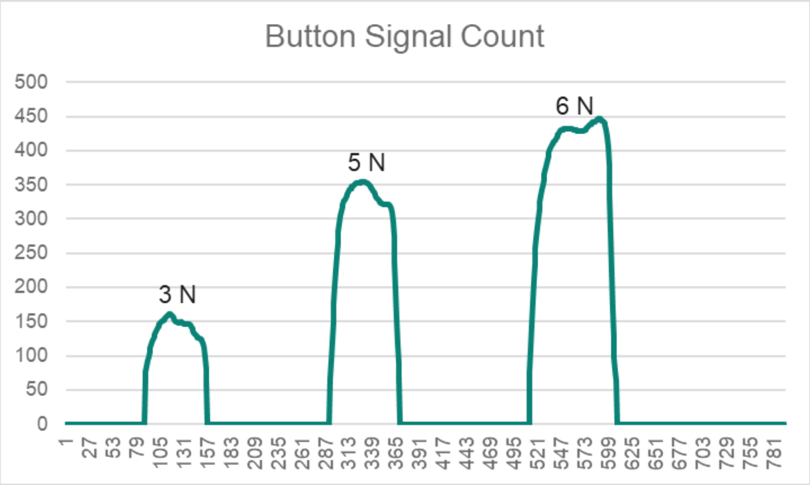


**Figure 55** Signal levels corresponding to different force levels

## 2.8 Filters

Proximity sensors are susceptible to noise because of their large sensor area and high sensitivity setting. Filters help to greatly reduce the noise in the raw count, therefore, improving the SNR and the response time. A higher SNR implies a large proximity-sensing distance and reliable sensing.

The CAPSENSE™ ecosystem features the following types of filters:

- Hardware filters
- Software filters

Based on what these filters are applied for. They are further classified as:

- Raw count filters
- Baseline filters

As the baseline is used as a reference for calculating the signal, it needs to be more stable than the raw count. Therefore, a separate filter needs to be applied for the baseline than that of the raw count.

Additionally, as the CAPSENSE™ widgets can be configured as active or low power, the ecosystem offers separate filters for these types of widgets.

Table 17 shows an overview of the filters offered by the CAPSENSE™ ecosystem.

**Table 17** Filters offered by CAPSENSE™ ecosystem

| Implementation | Filter application | Filter type | Active widget | Low-power widget |
|---|---|---|---|---|
| Hardware | Raw count filter | CIC2 | Yes | Yes |
| | | HW-IIR | Yes | Yes |
| Software | Raw count filter | SW-IIR | Yes | – |
| | | Average | Yes | – |
| | | Median | Yes | – |
| | Baseline filter | SW-IIR | Yes | – |

**(table continues...)**

**Table 17** **(continued) Filters offered by CAPSENSE™ ecosystem**

| Implementation | Filter application | Filter type | Active widget | Low-power widget |
|---|---|---|---|---|
| | | SW-IIR fast | – | Yes |
| | | SW-IIR slow | – | Yes |

The following sections describe how to use and configure these filters effectively for proximity-sensing applications.

### 2.8.1 Hardware filters

The PSOC™ devices with fifth-generation MSCLP architecture feature two types of hardware raw count filters:

- Cascaded integrator-comb 2 (CIC2) filter
- First-order hardware IIR filter

This section describes these filters and their configuration in more detail.

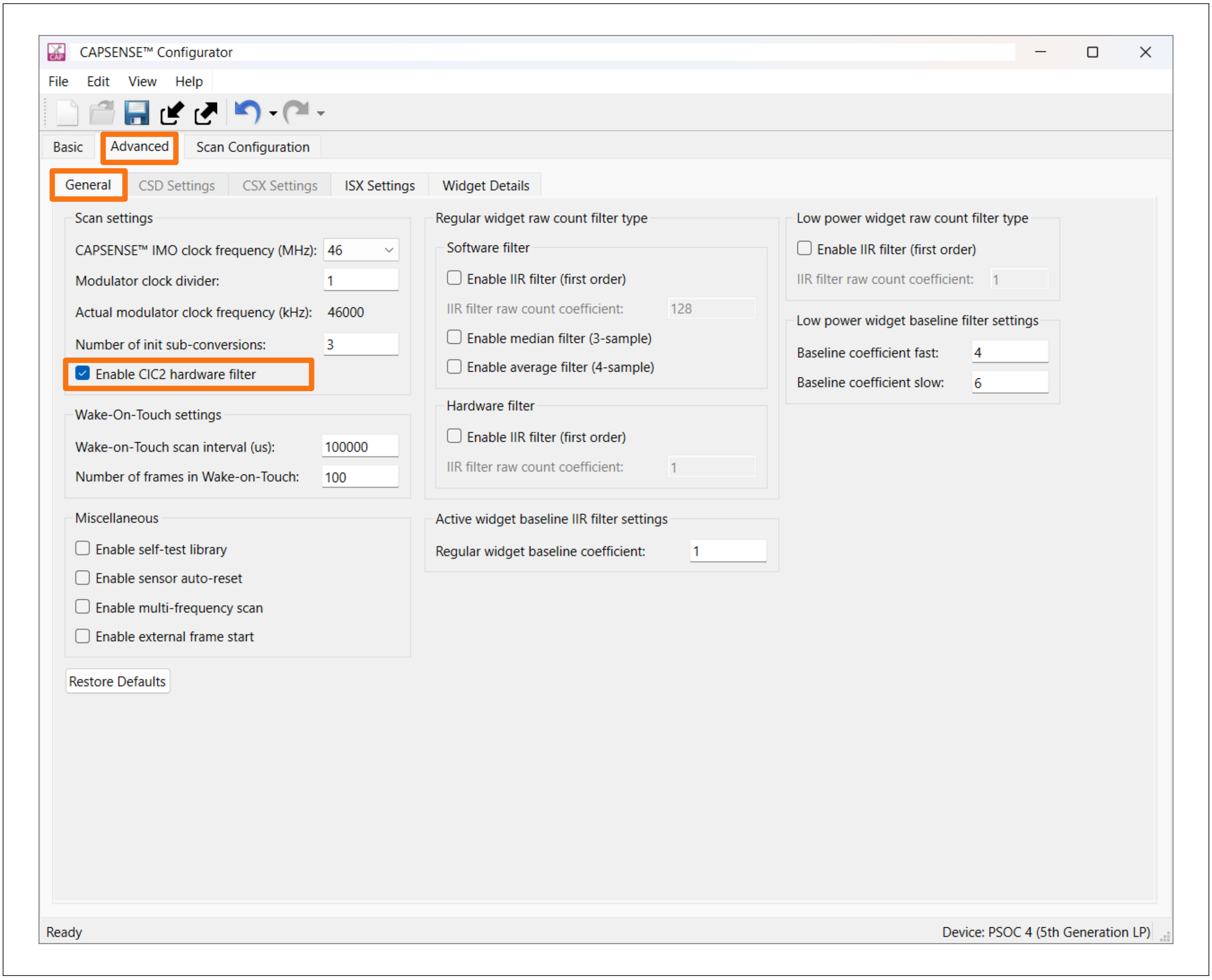
#### 2.8.1.1 Cascaded integrator-comb 2 (CIC2) filter

It is a second-order digital low-pass (decimation) filter for delta-sigma converters. It provides a higher resolution and then the SNR for a given scan period.

The CIC2 filter receives the output of the CAPSENSE™ analog front-end, which is a delta-sigma convertor. This filter is a combination of a moving average low-pass filter and a down-sampler. This filter is also known as a decimator. It provides a significant improvement in SNR when used along with an IIR filter.

**Enabling CIC2 filter**

The following figure shows how the CIC2 filter can be enabled in the **Advanced** tab of CAPSENSE™ Configurator in ModusToolbox™.



Scan settings

CAPSENSE™ IMO clock frequency (MHz): 46

Modulator clock divider: 1

Actual modulator clock frequency (kHz): 46000

Number of init sub-conversions: 3

☑ Enable CIC2 hardware filter

Wake-On-Touch settings

Wake-on-Touch scan interval (us): 100000

Number of frames in Wake-on-Touch: 100

Miscellaneous

☐ Enable self-test library

☐ Enable sensor auto-reset

☐ Enable multi-frequency scan

☐ Enable external frame start

Regular widget raw count filter type

Software filter

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 128

☐ Enable median filter (3-sample)

☐ Enable average filter (4-sample)

Hardware filter

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 1

Active widget baseline IIR filter settings

Regular widget baseline coefficient: 1

Low power widget raw count filter type

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 1

Low power widget baseline filter settings

Baseline coefficient fast: 4

Baseline coefficient slow: 6

Device: PSOC 4 (5th Generation LP)

**Figure 56** **Enabling CIC2 filter**

Table 18 describes the parameter that can be tuned for CIC2 filter.

**Table 18** **CIC2 Parameters to be tuned**

| Parameter | Description |
|---|---|
| CIC2 accumulator shift | The CIC 2 accumulator shift sets the right shift value applied to the CIC2 accumulator to form raw counts when the CIC2 filter is enabled. |
| Decimation rate | Sets the configurable decimation rate when the CIC2 filter is enabled. |

See the AN85951 – PSOC™ 4 and PSOC™ 6 MCU CAPSENSE™ design guide for more details.

### 2.8.1.2 First-order hardware IIR filter

This filter is used to filter raw counts of sensors (both Active widgets and Low-power widgets). The input to this filter is:

- Output of CIC2 filter when CIC2 is enabled
- Output of the CAPSENSE™ analog front-end when the CIC2 filter is disabled

Equation 9 represents the instantaneous output raw count of the filter:

$$RawCount = \frac{1}{2^{iirRCcoef}} RawCount_{Current} + \left(1 - \frac{1}{2^{iirRCcoef}}\right) RawCount_{Previous}$$

**Equation 9** **Hardware IIR filter raw count equation**

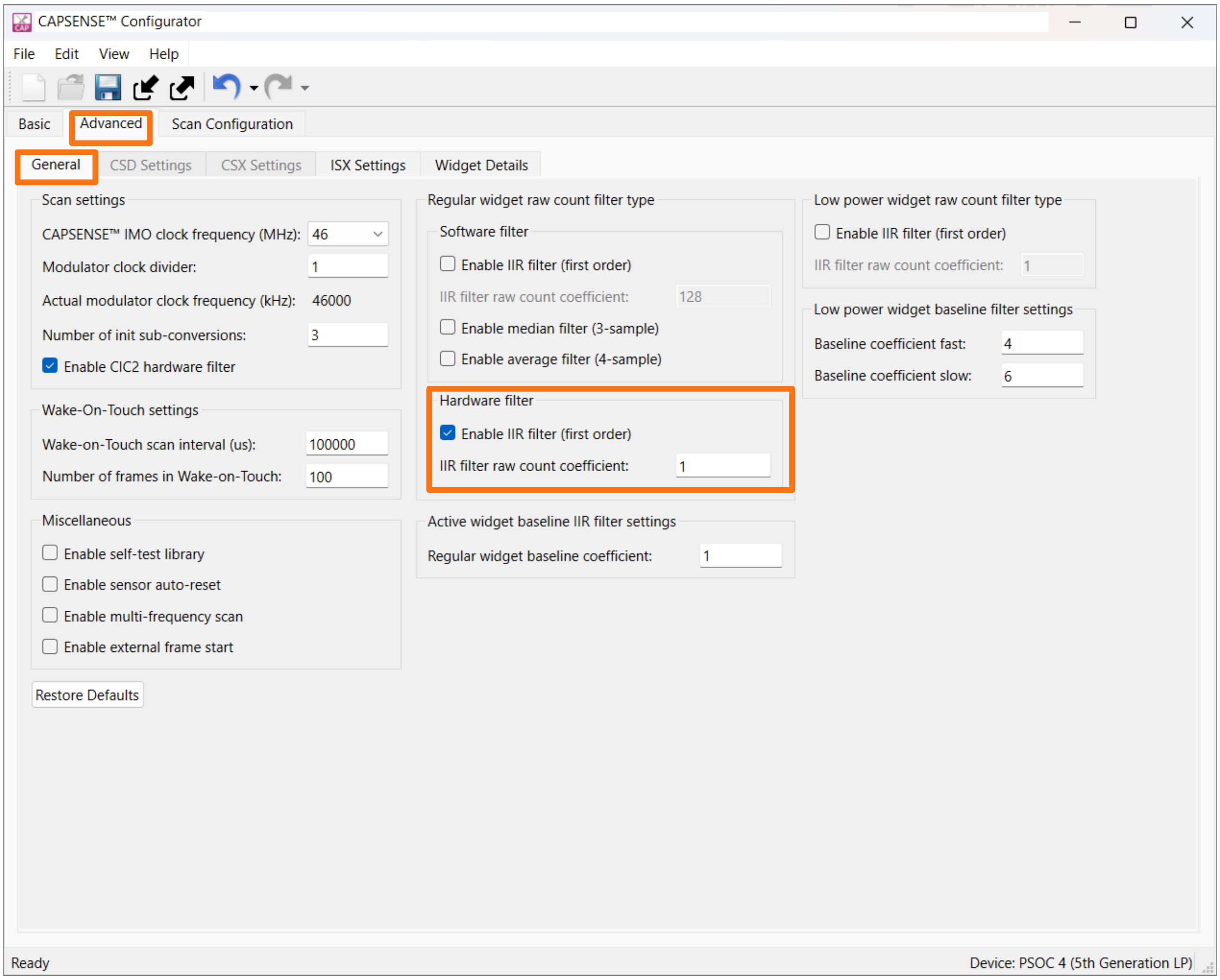
Where,

iirRCcoef = IIR filter raw count coefficient.

The valid range is 1 to 8; a low coefficient means lower filtering, but a faster response time

**Enabling hardware IIR filter**

The following figure shows how the hardware IIR filter can be enabled in the **Advanced** tab of CAPSENSE™ Configurator in ModusToolbox™.



Scan settings

CAPSENSE™ IMO clock frequency (MHz): 46

Modulator clock divider: 1

Actual modulator clock frequency (kHz): 46000

Number of init sub-conversions: 3

☑ Enable CIC2 hardware filter

Wake-On-Touch settings

Wake-on-Touch scan interval (us): 100000

Number of frames in Wake-on-Touch: 100

Miscellaneous

☐ Enable self-test library

☐ Enable sensor auto-reset

☐ Enable multi-frequency scan

☐ Enable external frame start

Regular widget raw count filter type

Software filter

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 128

☐ Enable median filter (3-sample)

☐ Enable average filter (4-sample)

Hardware filter

☑ Enable IIR filter (first order)

IIR filter raw count coefficient: 1

Active widget baseline IIR filter settings

Regular widget baseline coefficient: 1

Low power widget raw count filter type

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 1

Low power widget baseline filter settings

Baseline coefficient fast: 4

Baseline coefficient slow: 6

Ready

Device: PSOC 4 (5th Generation LP)

**Figure 57** **Enabling the hardware IIR filter**

## 2.8.2 Software filters

The CAPSENSE™ ecosystem's middleware library offers the following types of software filters:

- Raw count filters
    - Average

  - First-order IIR
  - Median
- Baseline filters
  - First-order IIR for active widgets
  - Slow baseline IIR filter for Low power widgets
  - Fast baseline IIR filter for Low power widgets

For more information on the details of software filters, see the “Software filtering” section of the Getting started with CAPSENSE™.

**Software IIR filter**

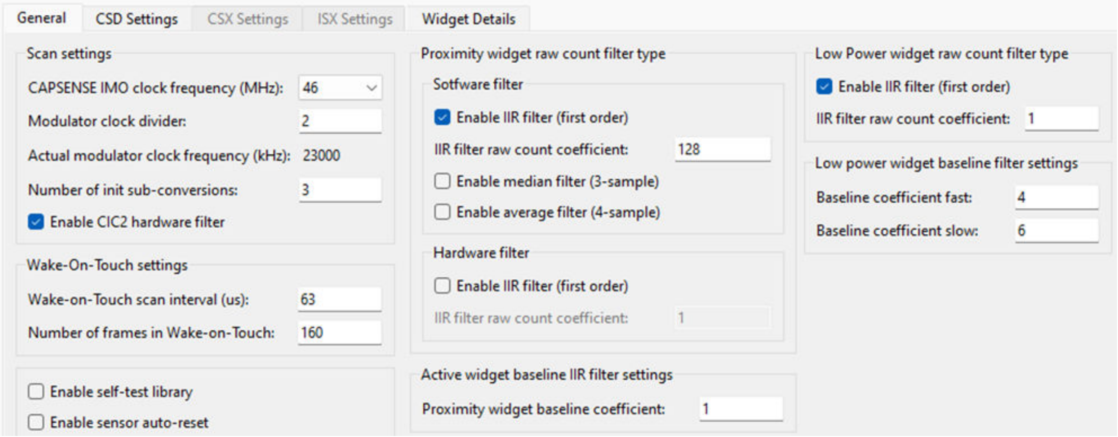
All the software IIR filters offered by CAPSENSE™ middleware are implemented with the following equation:

$$Output = \left(\frac{Coefficient}{256} \times input\right) + \left(\frac{256 - Coefficient}{256} \times previous\ \ output\right)$$

**Equation 10 Software IIR filter equation**

**Adding software filters to the project**

The required software filters can be added to the ModusToolbox™ project from the **Advanced** tab of CAPSENSE™ Configurator as shown in the following figure.



Scan settings
CAPSENSE IMO clock frequency (MHz): 46
Modulator clock divider: 2
Actual modulator clock frequency (kHz): 23000
Number of init sub-conversions: 3
☑ Enable CIC2 hardware filter

Wake-On-Touch settings
Wake-on-Touch scan interval (us): 63
Number of frames in Wake-on-Touch: 160

☐ Enable self-test library
☐ Enable sensor auto-reset

Proximity widget raw count filter type
Software filter
☑ Enable IIR filter (first order)
IIR filter raw count coefficient: 128
☐ Enable median filter (3-sample)
☐ Enable average filter (4-sample)
Hardware filter
☐ Enable IIR filter (first order)
IIR filter raw count coefficient: 1

Active widget baseline IIR filter settings
Proximity widget baseline coefficient: 1

Low Power widget raw count filter type
☑ Enable IIR filter (first order)
IIR filter raw count coefficient: 1

Low power widget baseline filter settings
Baseline coefficient fast: 4
Baseline coefficient slow: 6

**Figure 58 Adding software filters to the project**

### 2.8.2.1 Software raw count filters

Three types of raw count filters are offered by CAPSENSE™ middleware which can be configured using the CAPSENSE™ Configurator tool. Table 19 describes these filters, their applications, and respective tunable parameters.

**Table 19** **Software raw count filters offered by CAPSENSE™**

| Type | Description | Application | Tuning parameter |
|---|---|---|---|
| Average | Simple moving average filter of 4 samples length.<br>Consumes 6 bytes of RAM per each sensor to store a previous raw count (filter history) | Periodic noise (e.g., noise from AC mains) | None |
| IIR | Similar to a simple RC filter, a software IIR filter with tunable IIR co-efficient.<br>Consumes 2 bytes of RAM per each sensor to store a previous raw count (filter history) | High-frequency white noise (1/f noise) | IIR co-efficient – Lower the co-efficient, higher filtering effect; The valid range: 1-128 |
| Median | Similar to a moving average filter, a nonlinear filter that computes the median input value from a buffer of size 3<br>Consumes 4 bytes of RAM per each sensor to store a previous raw count (filter history) | Noise spikes from motors and switching power supplies | None |

If multiple filters are enabled, the execution order is as follows:

1. Median filter
2. IIR filter
3. Average filter

### 2.8.2.2 Software baseline filters

As the baseline is used as a reference for calculating the signal, it needs to be more stable than the raw count. Therefore, separate filters are offered in CAPSENSE™ middleware, which can be configured using the CAPSENSE™ Configurator tool.

**Table 20** **Software baseline filters offered by CAPSENSE™ ecosystem**

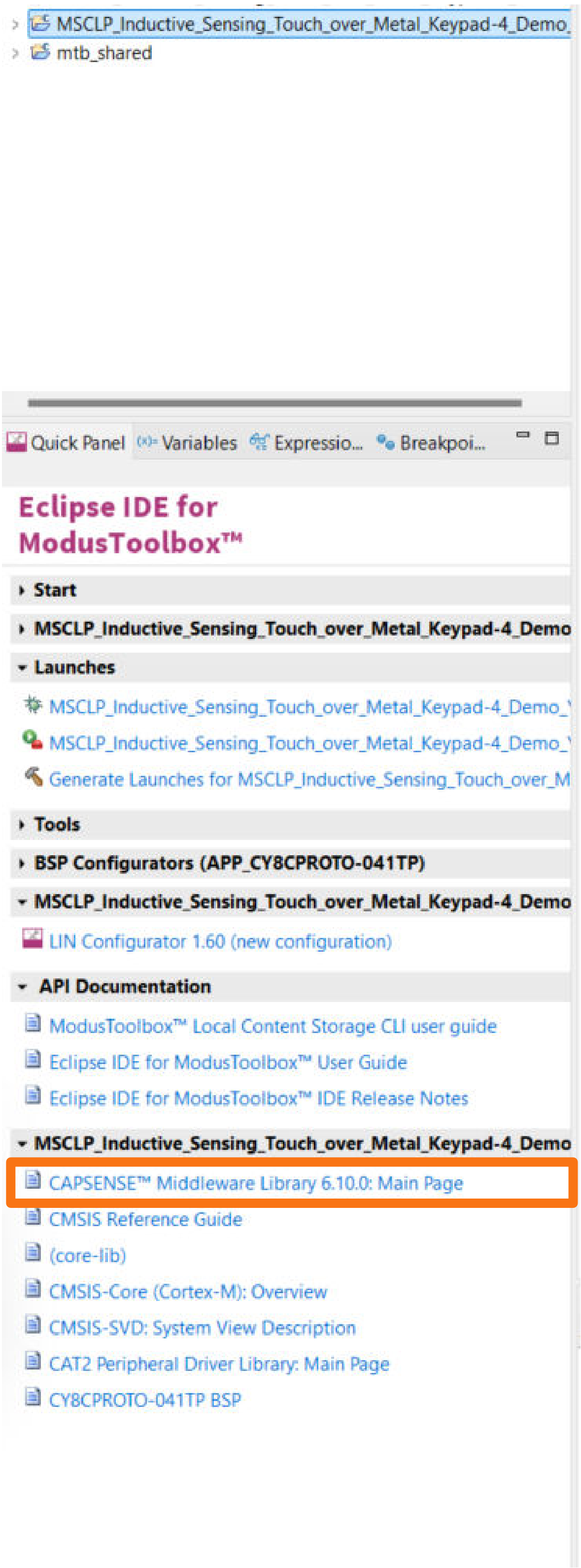
| Type | Description | Application | Tuning parameter |
|---|---|---|---|
| First-order IIR for active widgets | A software IIR filter with tunable IIR co-efficient | High-frequency noise | IIR co-efficient – Lower the co-efficient, higher filtering effect: The valid range: 1–255 |
| Slow baseline filter | IIR filter coefficient for slow changing baseline (Low power widget only) | High-frequency white noise | IIR co-efficient – Lower the co-efficient, higher filtering effect; The valid range: 1–15 |
| Fast baseline filter | IIR filter coefficient for fast changing baseline (Low power widget only) | High-frequency white noise | |

## 2.9 Middleware library and APIs

Infineon provides a middleware library for CAPSENSE™ products and solutions which can be used to implement the features mentioned in the Firmware design guidelines section.

See the CAPSENSE™ middleware library help document available in the ModusToolbox™ Quick panel as shown in the following figure.

**Figure 59** **CAPSENSE™ middleware library help document in the ModusToolbox™**



MSCLP_Inductive_Sensing_Touch_over_Metal_Keypad-4_Demo_
mtb_shared

Quick Panel | Variables | Expressio... | Breakpoi...

Eclipse IDE for ModusToolbox™

Start
MSCLP_Inductive_Sensing_Touch_over_Metal_Keypad-4_Demo
Launches
- MSCLP_Inductive_Sensing_Touch_over_Metal_Keypad-4_Demo_
- MSCLP_Inductive_Sensing_Touch_over_Metal_Keypad-4_Demo_
- Generate Launches for MSCLP_Inductive_Sensing_Touch_over_M

Tools
BSP Configurators (APP_CY8CPROTO-041TP)
MSCLP_Inductive_Sensing_Touch_over_Metal_Keypad-4_Demo
- LIN Configurator 1.60 (new configuration)

API Documentation
- ModusToolbox™ Local Content Storage CLI user guide
- Eclipse IDE for ModusToolbox™ User Guide
- Eclipse IDE for ModusToolbox™ IDE Release Notes

MSCLP_Inductive_Sensing_Touch_over_Metal_Keypad-4_Demo
- CAPSENSE™ Middleware Library 6.10.0: Main Page
- CMSIS Reference Guide
- (core-lib)
- CMSIS-Core (Cortex-M): Overview
- CMSIS-SVD: System View Description
- CAT2 Peripheral Driver Library: Main Page
- CY8CPROTO-041TP BSP

The PSOC™ 4: MSCLP ISX keypad-4 demo code example available on GitHub can serve as an excellent starting point to learn how to use Infineon’s CAPSENSE™ middleware library and respective APIs.

# 3 Tuning the inductive-sensing solution

After the sensor layout and firmware are ready, the next step is to tune the parameters for the ISX sensor to achieve optimum performance.

The change in inductance caused by a target object at a distance from the sensor is in tens of nH. To detect such a small change, the ISX circuitry must be tuned for high sensitivity, and the threshold parameters should be set to the optimum values. The process of setting these parameters for an optimum sensor performance is called “tuning”. This section describes how to tune the parameters in ModusToolbox™ for a sensor to achieve optimum performance.

This tuning guide is created based on existing knowledge and can be revised after acquiring new information on the flyback inductive sensing method.

## 3.1 Signal-to-noise ratio (SNR)

Before tuning the capacitive sensor for optimal sensing, it is important to understand the concept of SNR and how to calculate it.

As a thumb rule, an SNR of ≥ 10:1 is required for reliable sensing in inductive-sensing use cases. Higher the SNR, the higher the sensitivity that can be achieved.

**Calculating SNR**

The first step in measuring SNR is to monitor the raw count for each sensor with OFF and ON scenarios.

- OFF scenario is where the buttons is not pressed, or the metal target object is not present in the proximity of the sensor.
- ON scenario is where the button is pressed, or the metal target object is present, and this is detected by the sensor. At least 3000 samples each are recommended to be logged to measure the SNR.

Another factor to consider is how the signal is produced. The worst-case ON and OFF scenarios should be used when measuring SNR.

For a touch-over-metal (ToM) button, SNR can be calculated for the least amount of force (deflecting the metal overlay) that is expected to trigger the button. If the system is designed to sense the presence of a metallic target in proximity, then measure the SNR with the presence of the target at the farthest required distance from the sensor.

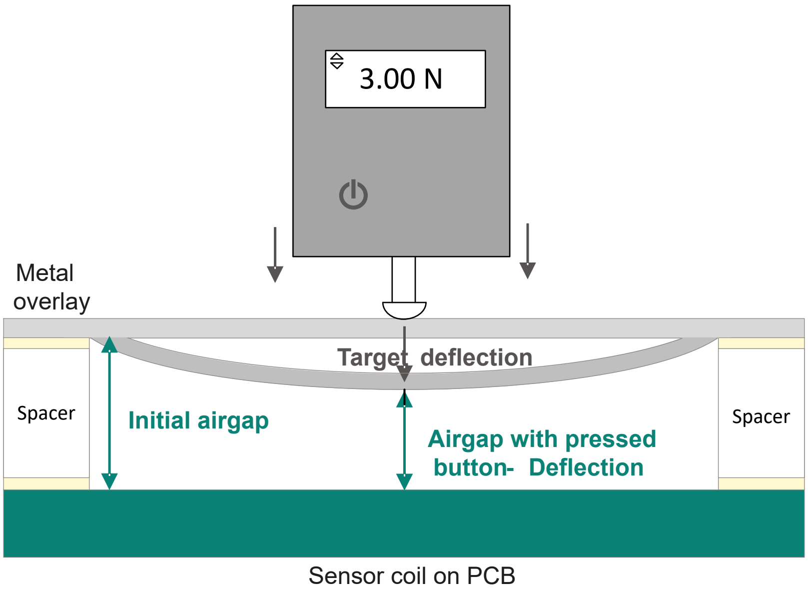


**Figure 60** Use a force gauge (also called force meter) to deflect the metal target with the minimum required force while measuring SNR

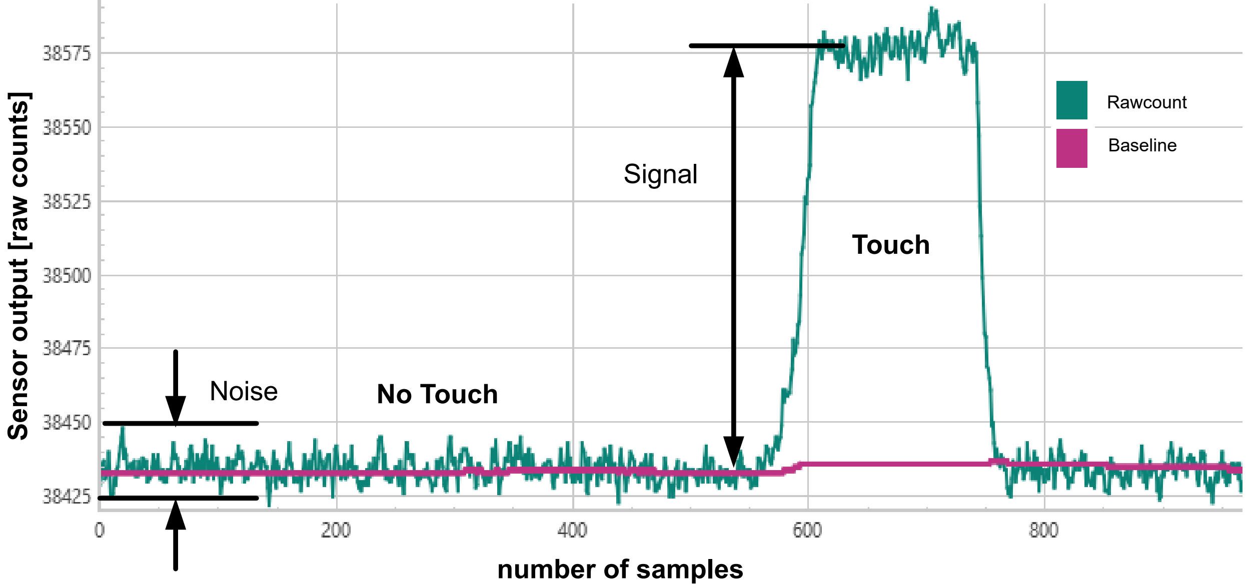


**Figure 61** ISX sensor signal and noise

As an example of measuring SNR, consider the raw count waveform in Figure 61, with the calculations mentioned in the following table:

**Table 21** **Parameters to calculate SNR**

| Parameters | Value |
|---|---|
| Minimum raw count without a target in the proximity | 2850 counts |
| Maximum raw count without a target in the proximity | 2880 counts |
| Average raw count without a target in the proximity (baseline) | 2865 counts |
| Average raw count with a target in the proximity | 3110 counts |
| Diff Count (Signal) | 3110 – 2865 = 245 counts |
| Noise count | 2880 – 2850 = 30 counts |
| SNR | **245:30 = 8.2:1** |

**Using ModusToolbox™ for tuning and SNR measurement**

See the PSOC™ 4: MSCLP inductive sensing touch-over-metal keypad-4 demo and PSOC™ 4: MSCLP inductive sensing touch-over-metal keypad-2 code example for details on tuning and measuring SNR using the CAPSENSE™ Configurator and CAPSENSE™ Tuner tools.

## 3.2 ISX SmartSense (Beta version)

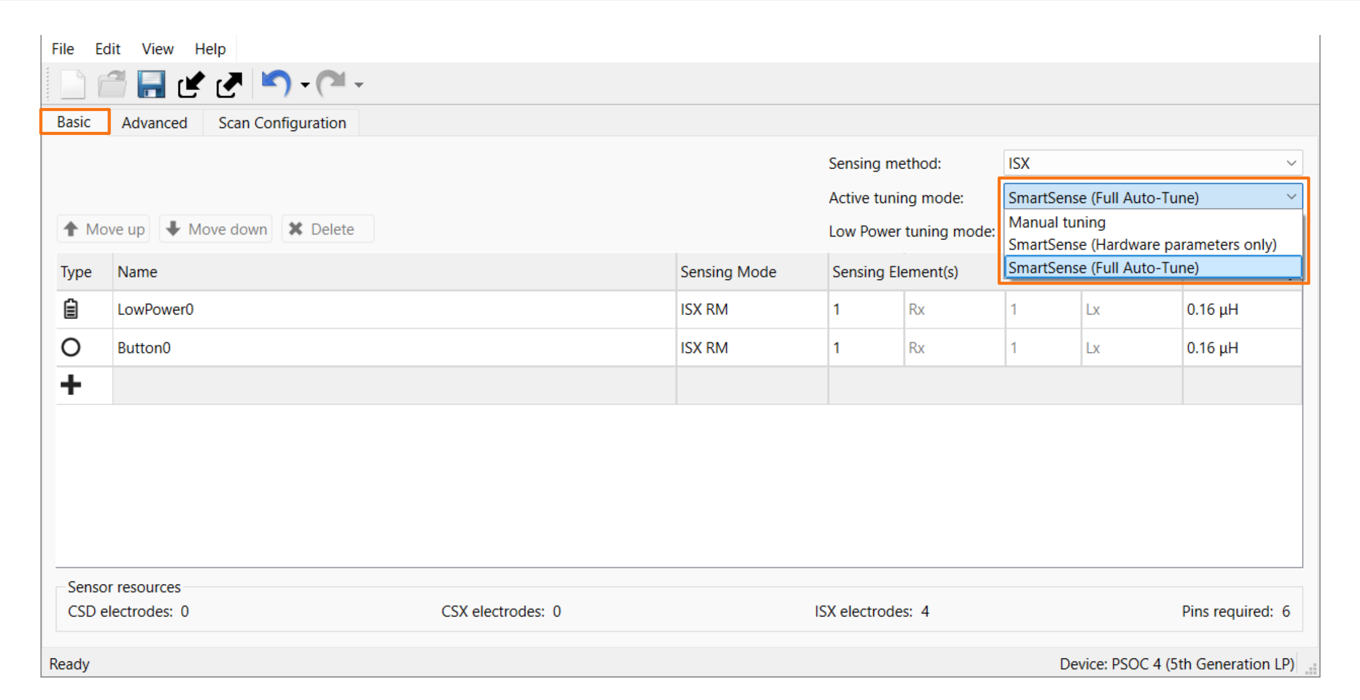
ISX SmartSense helps you to get the basic tuning parameters and acts as a starting point for tuning a particular configuration.

SmartSense has two modes:

**Full auto-tune:** In this mode, the middleware sets both the hardware and the threshold parameters. This mode is not available for low-power widgets.

**Hardware parameters:** In this mode, the middleware sets the hardware parameters only and you must set the threshold parameters.

To enable SmartSense, change the tuning method in the CAPSENSE™ Configurator as shown in the figure below. Touch sensitivity is the minimum sensitivity for which the configuration is tuned.



Sensing method: ISX

Active tuning mode: SmartSense (Full Auto-Tune)

Low Power tuning mode:

| Type | Name | Sensing Mode | Sensing Element(s) | | | | |
|---|---|---|---|---|---|---|---|
| | LowPower0 | ISX RM | 1 | Rx | 1 | Lx | 0.16 µH |
| ○ | Button0 | ISX RM | 1 | Rx | 1 | Lx | 0.16 µH |
| + | | | | | | | |

Sensor resources
CSD electrodes: 0
CSX electrodes: 0
ISX electrodes: 4
Pins required: 6

Ready
Device: PSOC 4 (5th Generation LP)

**Figure 62** Enabling SmartSense in the CAPSENSE™ configurator

For more information regarding SmartSense, see the PSOC™ 4: MSCLP inductive sensing touch-over-metal keypad-4 demo code example.

## 3.3 Manual tuning flow

The tuning procedure for the inductive sensors can be explained in the following stages:

1. Set the initial parameters.
2. Measure the sensor inductance and set the sense clock frequency (Lx).
3. Set CDAC and dither parameters.
4. Fine-tune for the required SNR, power, and refresh rate.
5. Tune the threshold parameters.

Figure 63 shows the high-level steps for tuning an ISX sensor.

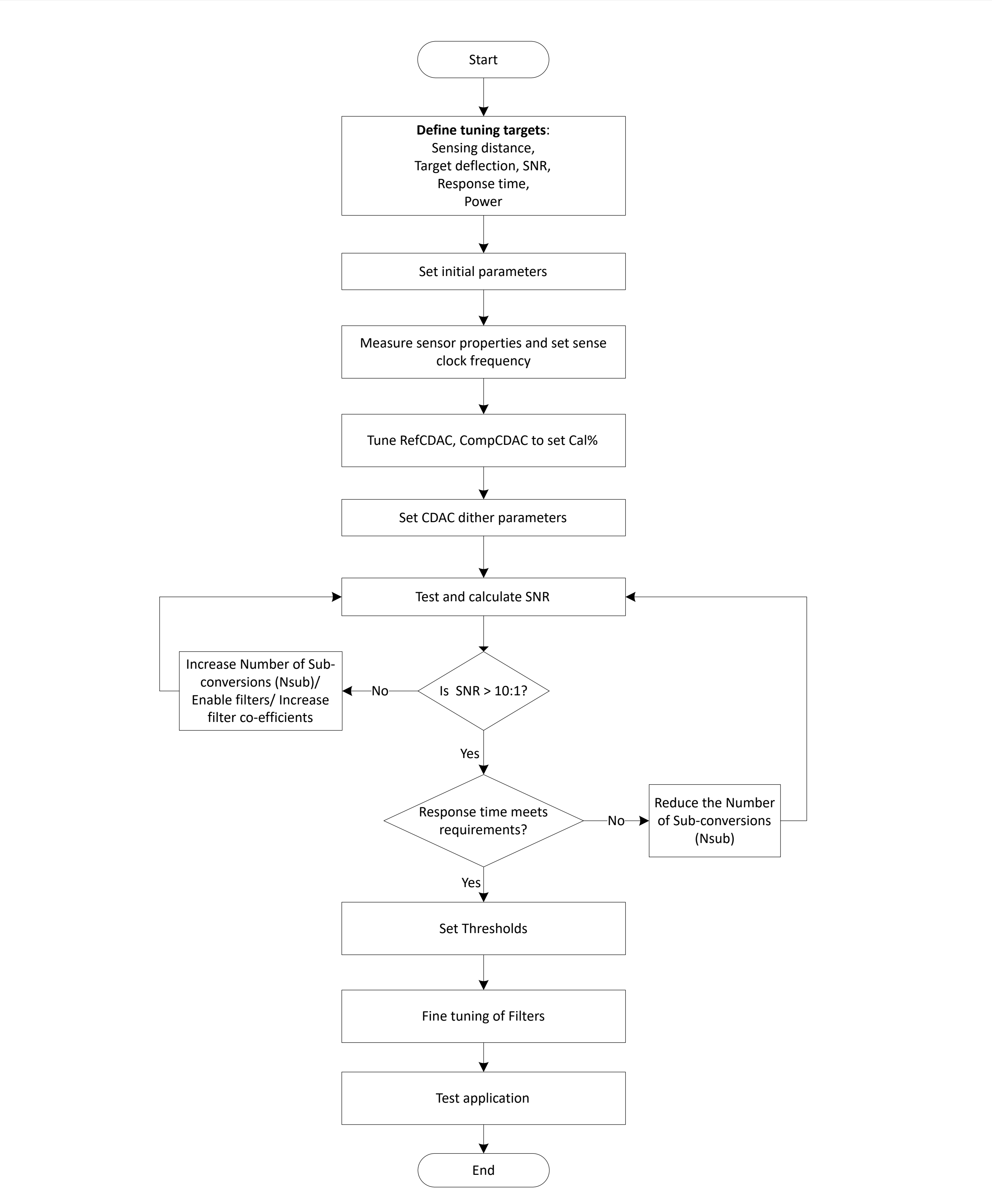


**Figure 63** High-level steps for tuning an inductive sensor

### Parameters to be tuned

CAPSENSE™ ecosystem provides great flexibility to support different types of CAPSENSE™ touch and proximity sensing applications. The following sections list proximity sensing parameters available in ModusToolbox™ along with their recommended values.

### 3.3.1 Set initial parameters

- Lx clock divider: 200
- Clock source: Direct (default)
- Number of sub-conversions: 300
- Other parameters leave as default
- ISX raw count calibration percentage to 40%

### 3.3.2 Setting the Lx clock divider

The Lx clock divider should be configured such that the pulse width of the sense clock is long enough to allow the sensor inductance to accumulate its energy completely while preventing prolonged charging which will waste scan time.

1. Find the expected or approximate value of the Lx clock divider using the following equation.

$$Lx\ Clock\ Div = \frac{Ntau \times Nphases \times Fmod(Mhz) \times L(uH)}{Rext + Rswitch + Rinductor} + Settling\ Shift$$

$$Lx\ Clock\ Div = \frac{3 \times 4 \times 46 \times L(uH)}{(560 + 100)} + 8$$

$$Lx\ Clock\ Div = 4 \times round\left(\frac{27.6}{4}\right)$$

$$Lx\ Clock\ Div = 28$$

$$\left(if\ this\ value\ is\ less\ than\ 8,\ set\ the\ LxClk\ Div\ to\ 8\right)$$

**Equation 11 Lx clock divider approximation**

Where,

- **Lx clock divider**: Approximate value is obtained (Should be divisible by 4 to ensure all four scan phases have equal durations)
- **Ntau**: Settling constant. Set to 3 by default
- **Nphases**: Number of scan phases. Set to 4
- **Fmod (MHz)**: Modulator clock frequency in MHz. In this example, the frequency is 46 MHz

- **L(µH)**: Obtain the inductance value using an LCR meter. For the buttons in this example, the value is around 34 µH
- **Rext**: Tx resistor in series. 560 ohms in the kit
- **Rswitch**: Internal switch resistance. The default value can be set as 100 ohms
- **Rinductor**: This value can be obtained using the LCR meter while obtaining the inductance value. Include when the sensor is larger and can contribute to the total resistance value significantly
- **Settling shift**: Provide a shift to consider actual settling time. The default value is 8. Change this based on oscilloscope observations

***Note**: This equation serves solely as the starting point for finding the actual Lx clock divider value using the oscilloscope as explained in further sections. It is not recommended to set the Lx clock divider exactly as given by this equation.*

Set this Lx clock divider value in the CAPSENSE™ configurator and program the device

2. Probe the Rstx resistor and observe the waveforms at both CH4 and CH3 as shown in the following figure

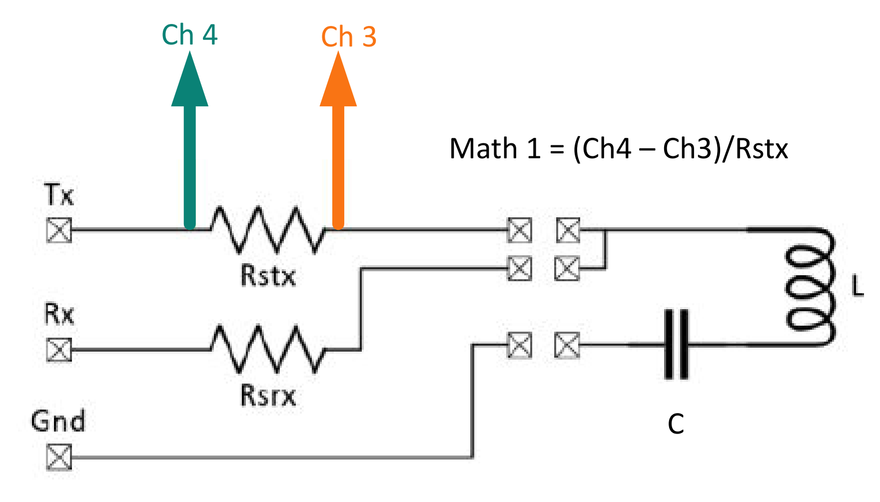


**Figure 64** **Oscilloscope probe setup to measure Lx clock divider**

3. Perform a math function on the oscilloscope to calculate the approximate current passing through the resistor

$$M1 = \frac{Ch4 - Ch3}{Rstx} \sim current\ through\ the\ Rstx\ resistor$$

**Equation 12** **M1 waveform equation**

- If the charging/discharging phases are too short, increase the Lx clock divider in steps of 4 until the sensor is charging/discharging completely in both phases. See the following figure for more information

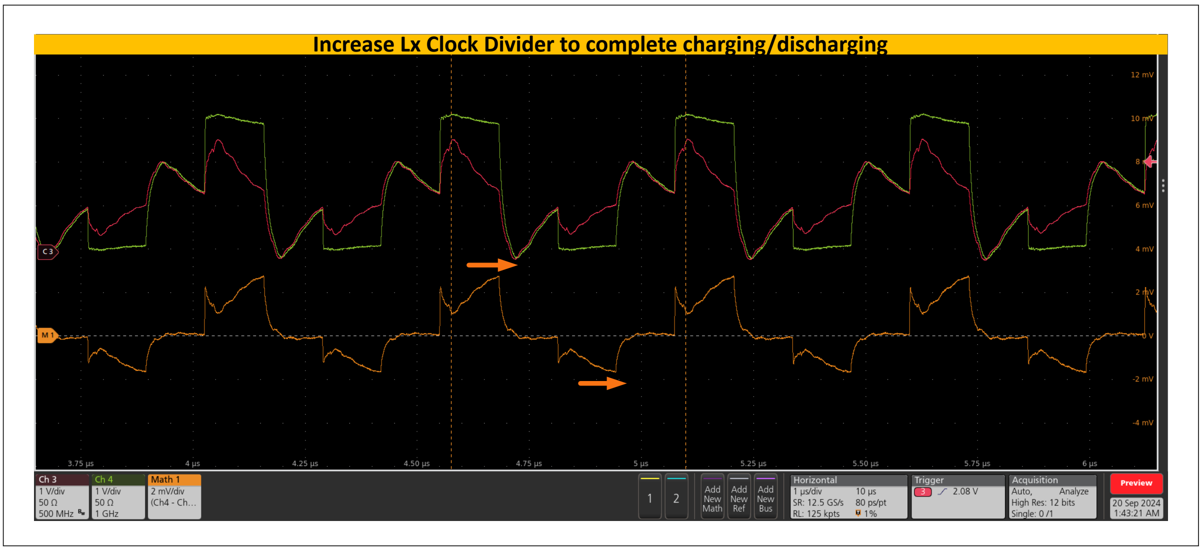


**Figure 65** Improper charge cycle of a sensor with incomplete charging/discharging

- If the charging/discharging phases are prolonged, start decreasing the Lx clock divider value by 4 such that current through Rstx becomes constant (Figure 66). It means that the inductor has accumulated its energy (transient processes are finished)

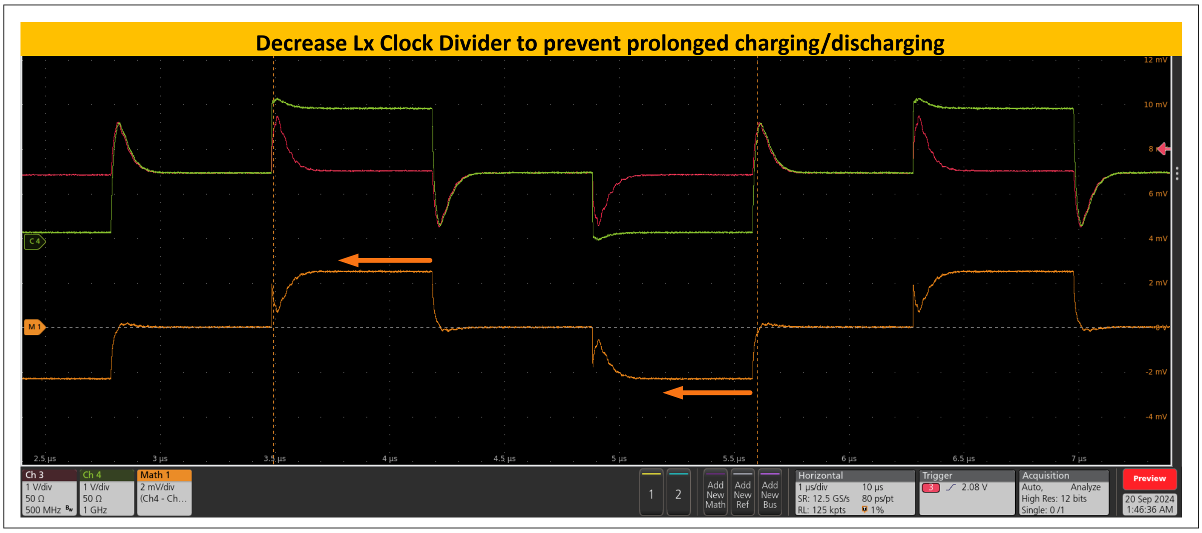
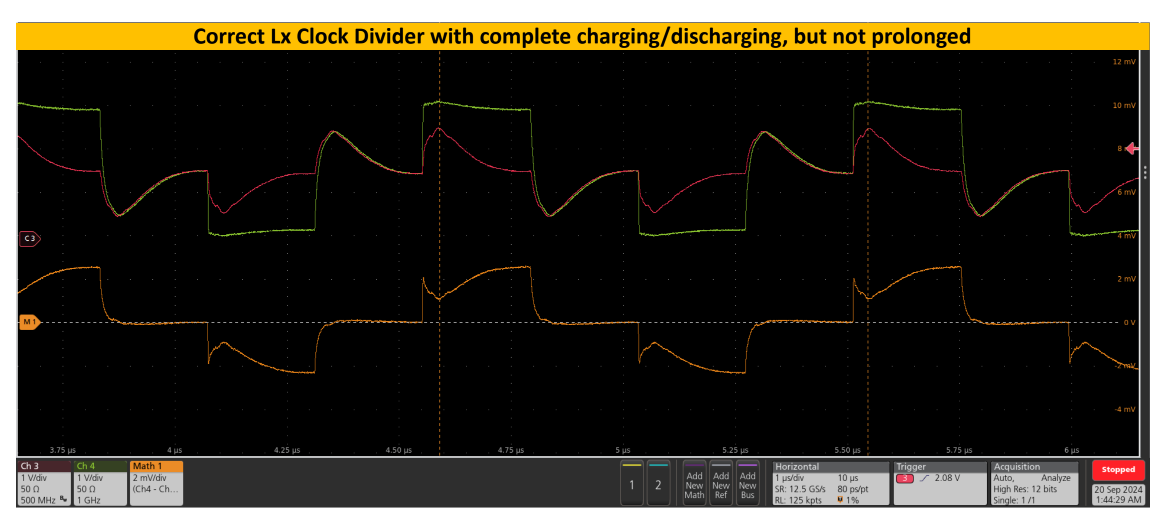


**Figure 66** Improper charge cycle of a sensor showing prolonged charging/ discharging

The following figure shows the cases where both conditions are met such that the inductor charges/ discharges completely however, it does not have prolonged cycles.



Correct Lx Clock Divider with complete charging/discharging, but not prolonged

Ch 3
1 V/div
50 Ω
500 MHz

Ch 4
1 V/div
50 Ω
1 GHz

Math 1
2 mV/div
(Ch4 - Ch…

Horizontal
1 µs/div 10 µs
SR: 12.5 GS/s 80 ps/pt
RL: 125 kpts 1%

Trigger
3 2.08 V

Acquisition
Auto, Analyze
High Res: 12 bits
Single: 1 /1

Stopped
20 Sep 2024
1:44:29 AM

**Figure 67** **Proper charge cycle of a sensor**

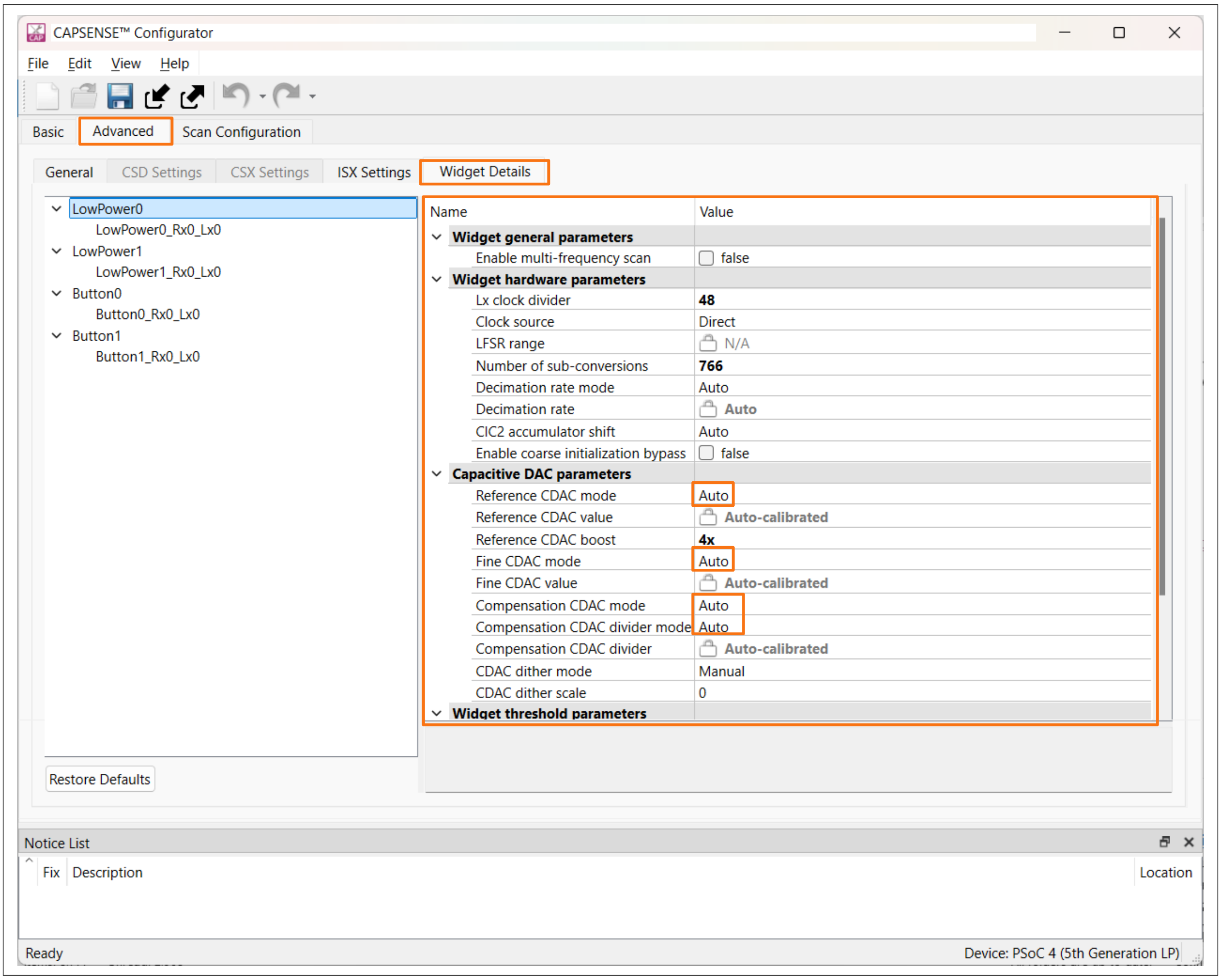
As the Tx phase width selection step is limited to the Fmod period, it might not be possible to select the optimal value of LxClkDiv. In this case, choose a divider value closer to the start of constant current.

When there are multiple sensors in a widget, choose the maximum LxClkDiv value obtained among these sensors.

When unclear, it is better to increase the LxClkDiv and have a slightly prolonged charging/discharging cycle as compared to incomplete charging/discharging.

### 3.3.3 Setting RefCDAC and CompCDAC

The reference and compensation CAPDAC values can be set to auto mode in the configurator as shown in the following figure. The middleware will calculate the values based on the raw count calibration percentage set in the CAPSENSE™ Configurator. It is recommended that the compensation CDAC is always enabled.



| Name | Value |
|---|---|
| **Widget general parameters** | |
| Enable multi-frequency scan | ☐ false |
| **Widget hardware parameters** | |
| Lx clock divider | **48** |
| Clock source | Direct |
| LFSR range | N/A |
| Number of sub-conversions | **766** |
| Decimation rate mode | Auto |
| Decimation rate | **Auto** |
| CIC2 accumulator shift | Auto |
| Enable coarse initialization bypass | ☐ false |
| **Capacitive DAC parameters** | |
| Reference CDAC mode | Auto |
| Reference CDAC value | **Auto-calibrated** |
| Reference CDAC boost | **4x** |
| Fine CDAC mode | Auto |
| Fine CDAC value | **Auto-calibrated** |
| Compensation CDAC mode | Auto |
| Compensation CDAC divider mode | Auto |
| Compensation CDAC divider | **Auto-calibrated** |
| CDAC dither mode | Manual |
| CDAC dither scale | 0 |
| **Widget threshold parameters** | |

**Figure 68** **Setting CAPDAC values to Auto in the CAPSENSE™ configurator**

***Note**: To increase sensitivity, RefCDAC boost can be enabled.*

### 3.3.4 Number of sub-conversions

**Calculate the number of sub-conversions and resolution**

Use the following equation to find the Nsub based on the scan time and the LxClkDiv obtained previously.

$$NumOfSubConv = floor\left(\frac{ScanTime(us) \times Fmod(MHz)}{LxClkDiv}\right)$$

**Equation 13** **$N_{SUB}$ equation**

i.e., LxClkDiv = 24 , Fmod = 46 MHz and Scan Time = 800 µs : $N_{SUB}$ = 1533

Alternatively, Nsub can be set based on the SNR requirements. Increase the Nsub to obtain higher SNR, which will come at the cost of an increase in scan time.

**Calculate resolution (max raw count) with the following equation**

$$Resolution\ (MaxRawCount) = ScanTime(us) \times Fmod(MHz)$$

**Equation 14** **Resolution (max raw count) equation**

i.e., for scan time equal to 800 μs and Fmod equal to 46 MHz: 36800 raw counts

***Note**: The resolution should not be greater than 65535 (maximum raw count value supported (16 bits, *CIC2 disabled)). Therefore, maximum scan time is limited. i.e., for Fmod = 46 MHz, maximum scan time is 1424 μs. If longer scan time is needed – sample averaging can be used.*

Set the obtained Lx clock divider and number of sub-conversions in the CAPSENSE™ Tuner.

### 3.3.5 Setting the CDAC dither scale

As the input inductance changes, the raw counts should change linearly. However, there are regions where the inductance does not change linearly, which are called flat-spots. Dithering helps reduce these flat-spots by adding white noise that moves the conversion point around the flat region. The CDAC dither value can be set based on the following table.

**Table 22** **CDAC dither scale recommendation**

| Sensor inductance range | Dither scale value |
|---|---|
| 0 nH to 140 nH | 6 |
| 140 nH to 232 nH | 5 |
| 232 nH to 465 nH | 4 |
| 465 nH to 1.4 μH | 3 |
| 1.4 μH to 2.3 μH | 2 |
| 2.3 μH to 4.6 μH | 1 |
| >4.6 μH | 0 |

### 3.3.6 Calculate init sub-conversions

To calculate the number of init sub-conversions, set this value in the CAPSENSE™ Configurator. Build and reprogram the chip if this value is different from the initial value (3):

$$Number\ of\ init\ \ sub\ conversions\ = ceiling\left(\frac{C_{\mathrm{mod}} \times V_{OS}}{VDDA\ \times\ LxClkDiv\ \times C_{ref}\ \times\ (1 - Bal\ \%)}\right) + 1$$

**Equation 15** **Recalculating $N_{SUB}$**

Where,

CMOD = Modulator capacitor

VOS = Comparator offset voltage (3 mV)

Bal% = Raw count calibration percentage

LxClkDiv = Lx clock divider

Cref = Reference capacitance

Cref = RefCDACCode * Clsb

RefCDACCode = Reference CDAC value

Clsb = 8.86 fF

$$e.g., Number\ \ of\ init\ \ sub\, conversions\ = ceiling\left(\frac{2.2\times 10^{-9}\times 3\times 10^{-3}}{3.3\times 24\times 60\times 8.86\times 10^{-15}\times (1-0.1)}\right)+1=2$$

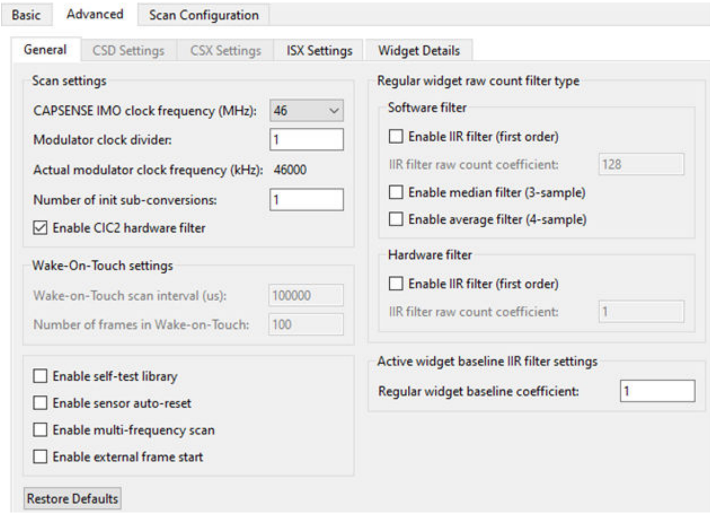
**Equation 16** **Example of $N_{SUB}$ calculation**

### 3.3.7 Post tuning (filters)

1. Enable filters (CAPSENSE™ Configurator, a reprogram is required):
    a. Enable hardware IIR filter to eliminate high-frequency noise. Set the filter coefficient value to 1. Higher values of coefficient provide better noise suppression but also slow down the touch response and need to be adjusted based on the requirements
    b. Enable average filter (moving average) to eliminate periodic noise (i.e., noise from AC mains), if present
    c. Enable median filter to eliminate spike noise (i.e., motors and switching power supplies), if present
    d. Enable CIC2 filter to increase resolution (recommended to enable this by default). Set decimation rate to the maximal allowable value and leave CIC2 accumulator shift value to Auto (widget hardware parameters)
2. Measure SNR using the SNR Measurement tool in CAPSENSE™Tuner to verify filters efficiency

### 3.3.8 Parameters: Descriptions and recommendations table

#### 3.3.8.1 General tab parameters



Scan settings

CAPSENSE IMO clock frequency (MHz): 46

Modulator clock divider: 1

Actual modulator clock frequency (kHz): 46000

Number of init sub-conversions: 1

☑ Enable CIC2 hardware filter

Wake-On-Touch settings

Wake-on-Touch scan interval (us): 100000

Number of frames in Wake-on-Touch: 100

☐ Enable self-test library

☐ Enable sensor auto-reset

☐ Enable multi-frequency scan

☐ Enable external frame start

Regular widget raw count filter type

Software filter

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 128

☐ Enable median filter (3-sample)

☐ Enable average filter (4-sample)

Hardware filter

☐ Enable IIR filter (first order)

IIR filter raw count coefficient: 1

Active widget baseline IIR filter settings

Regular widget baseline coefficient: 1

**Figure 69** **General tab**

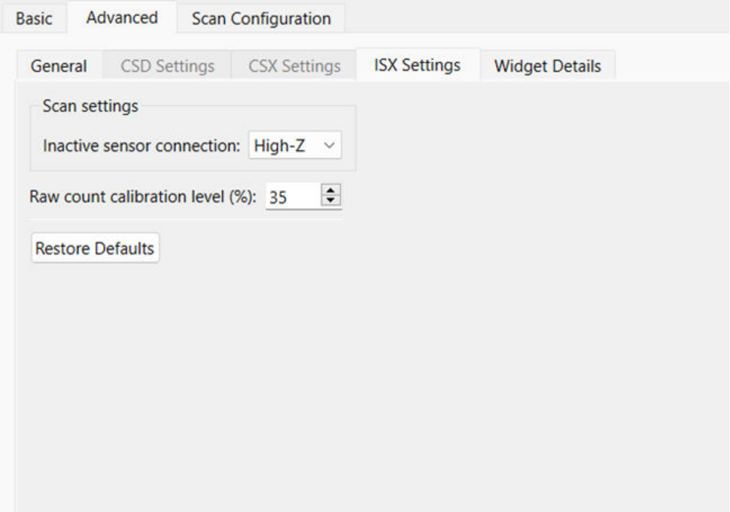
**Table 23 Scan settings parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| IMO clock frequency | Frequency of clock used as source for the CAPSENSE™ peripheral | Keep it default i.e., 46 MHz (PSOC™ 4000T,PSOC™ 4100T Plus) |
| Modulator clock divider | Divider value used to divide system clock; the resulting clock then used as clock for Inductance to digital modulation | Use a slower modulator clock to reduce peak-to-peak noise in raw counts if required |
| Number of init sub-conversions | Selects the number of initialization sub-conversions at the start of the scan. This part of scan is intended to ensure proper initialization of MSCLP hardware and does not perform the raw count measurement | This parameter should be set after complete tuning. Initial value can be set to 3 |
| Enable CIC2 hardware filter | The cascaded integrator-comb 2 (CIC2) filter is a second-order digital low-pass (decimation) filter for delta-sigma converters. See CIC2 filter section for details | Should be turned on to scale the resolution and for the best performance |
| Enable sensor auto-reset | When enabled, the baseline is always updated and when disabled, the baseline is updated only when the difference between the baseline and raw count is less than the noise threshold. When enabled, the feature prevents the sensors from permanently turning on when the raw count accidentally rises due to a large power supply voltage fluctuation or other spurious conditions | For most cases turned off. Can be turned on in specific conditions (harsh environment) |
| Enable self-test library | Not used | – |
| Enable multi-frequency scan (MFS) | Not used | – |
| Enable external frame start | Not used | – |
| Enable (software) IIR filter | Enables the software IIR filter (see Filters section for details) | Can be turned on depending on the noise level after tuning. The average filter (moving window) is recommended to be turned on. Hardware IIR filter is preferable over the software IIR filter |
| Enable median filter (3-sample) | Enables the non-linear median filter (see Filters section for details) | (See Filters section for details) |
| Enable average filter (4-sample) | Enables the finite-impulse response filter (no feedback) with equally weighted coefficients (see Filters section for details) | (See Filters section for details) |

**(table continues...)**

**Table 23** **(continued) Scan settings parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| Enable (Hardware) IIR filter | Enables the hardware IIR filter (see Filters section for details) | (See Filters section for details) |



Inactive sensor connection: High-Z

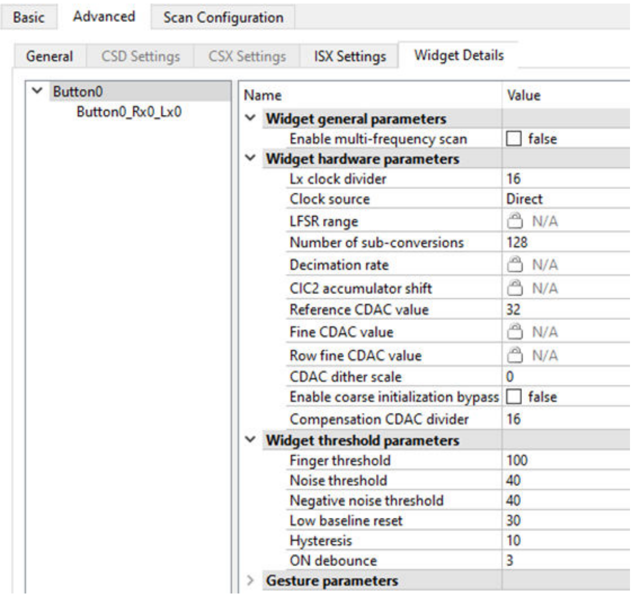
Raw count calibration level (%): 35

**Figure 70** **ISX Settings tab**

**Table 24** **ISX Settings tab parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| Raw count calibration level (%) | The target raw count calibration % to which the raw counts are calibrated on enabling auto-calibration. It should be set such that the raw counts do not saturate during ISX sensor operation. | 40% by default |
| Inactive sensor connection | The state of the ISX sensor when it is not being scanned | High-Z by default |

### 3.3.8.2 Widget Details tab parameters



| Name | Value |
|---|---|
| **Widget general parameters** | |
| Enable multi-frequency scan | ☐ false |
| **Widget hardware parameters** | |
| Lx clock divider | 16 |
| Clock source | Direct |
| LFSR range | N/A |
| Number of sub-conversions | 128 |
| Decimation rate | N/A |
| CIC2 accumulator shift | N/A |
| Reference CDAC value | 32 |
| Fine CDAC value | N/A |
| Row fine CDAC value | N/A |
| CDAC dither scale | 0 |
| Enable coarse initialization bypass | ☐ false |
| Compensation CDAC divider | 16 |
| **Widget threshold parameters** | |
| Finger threshold | 100 |
| Noise threshold | 40 |
| Negative noise threshold | 40 |
| Low baseline reset | 30 |
| Hysteresis | 10 |
| ON debounce | 3 |
| **Gesture parameters** | |

**Figure 71** Widget Details tab

**Table 25** Widget Details parameters

| Parameter | Description | Recommended values |
|---|---|---|
| Enable multi-frequency scan | Not used | – |
| Clock source | Source of the clock to be used for ISX<br>There are three sources available:<br>• Direct<br>• SSC<br>• PRS | Keep it default i.e., Direct. (SSC/PRS – not implemented/not tested). |
| Lx clock divider | Divider to the system clock (IMO clock frequency); the resulting clock is used to drive the sensor<br>$F_s = \frac{F_{\text{mod}}}{LxClkDiv}$<br>Value must be multiple of 4<br>The range of valid values: 8-4096 | Lx clock divider can be set as per guidelines in Section Setting the Lx clock divider. |
| LSFR range | Not used. | – |
| Number of sub conversions (NSUB) | See Section Number of sub-conversions for details | See Section Number of sub-conversions for details |
| Decimation rate (CIC2) (5th Gen CAPSENSE™) | See Section Cascaded integrator-comb 2 (CIC2) filter for details | See Section Cascaded integrator-comb 2 (CIC2) filter for details |

**(table continues...)**

**Table 25** **(continued) Widget Details parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| CIC2 accumulator shift (5th Gen CAPSENSE™) | See Section Cascaded integrator-comb 2 (CIC2) filter for details | See Section Cascaded integrator-comb 2 (CIC2) filter for details |
| Reference CDAC | Cref is used as gain, the lower it is the higher the response/sensitivity we will observe for the same changes in charge<br>The range of valid values: 0-255 | Set to Auto |
| Reference CDAC Boost | Divides the actual Reference CDAC value to increase sensitivity | Recommended to “Disable”. Use it to achieve higher sensitivity only after trying other available options |
| Fine CDAC value | Not used | – |
| Row fine CDAC value | Not used | – |
| Enabling compensation CDAC | The compensation constant amount of inductance from the sensor to increase the sensitivity, which allows for higher gain setting for ΔL conversion (lower reference CDAC value)<br>The range of valid values: 0–255 | Set to Auto |
| Compensation CDAC value | The compensation constant amount of inductance from the sensor to increase the sensitivity, which allows for higher gain setting for ΔL conversion (lower reference CDAC value)<br>The range of valid values: 0–255 | Set to Auto |
| Compensation CDAC divider | Divider to ‘Lx clock divider’, which decides the number of times the compensation CDAC is used ($K_{comp}$) within a single sense clock period.<br>$K_{comp} = \frac{Sense\ Clock\ Divider}{Comp\ \ CDAC\ Divider}$<br>Auto calibrated when ‘CDAC auto calibration’ is enabled<br>With increase in the inductance value for the sensor, higher charge is produced. To compensate that, larger value of Comp CDAC is needed, thus smaller value of Comp CDAC Clock divider<br>The value range is [3 to 4095] | Set to Auto |

**(table continues...)**

**Table 25 (continued) Widget Details parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| CDAC dither scale | Sets the CDAC dither value. As the sensor inductance is swept, the raw count should increase linearly with inductance. There are regions where the raw count does not change linearly with input inductance these are called flat-spots. Dithering helps to reduce flat-spots using a dither CDAC. The dither CDAC adds white noise that moves the conversion point around the flat region<br>The value range is [0–6]. Higher values mean lower dithering | Set the value depending on the sensor inductance as explained in Section Setting the CDAC dither scale |
| Course Initialization bypass | Enables skipping the coarse initialization and thus, the scan refresh rate increases | Disabled |

### 3.3.8.3 Widget threshold parameters

**Table 26 Widget threshold parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| Finger threshold | The finger threshold parameter is used along with the hysteresis parameter to determine the sensor state as follows:<br>**ON** = Signal > (Finger Threshold + Hysteresis)<br>**OFF** = Signal ≤ (Finger Threshold – Hysteresis)<br>Note that “Signal” in the above equations refers to: Signal = Raw Count – Baseline | 80 percent of signal when sensor is touched |
| Noise threshold | Sets a signal limit below which a signal is considered as noise. Raw count limit above which the baseline is not updated<br>In other words, the baseline remains constant as long as the raw count is > baseline + noise threshold, unless Enable sensor auto-reset is selected | 30 percent of signal. Because most of the proximity solutions, speed of human hand movement is slower to control algorithm, keep this threshold as low as possible, except when liquid tolerance is required |

**(table continues...)**

**Table 26 (continued) Widget threshold parameters**

| Parameter | Description | Recommended values |
|---|---|---|
| Negative noise threshold | Raw count limit below which the baseline is not updated for the number of samples specified by the low baseline reset parameter<br>The negative noise threshold ensures that the baseline does not fall low because of any high-amplitude repeated negative-noise spikes on a raw count caused by different noise sources such as ESD events<br>The baseline is not updated for the number of samples specified by the Low baseline reset parameter | 40 percent of signal |
| Low baseline reset | If a finger is placed on the sensor during a device startup, the baseline gets initialized to a high raw count value at a startup. When the finger is removed, the raw count falls to a lower value. In this case, the baseline should track low raw counts. The Low Baseline Reset parameter helps handle this event. It resets the baseline to a low raw count value when the number of low samples reaches the low baseline reset number | Keep it default, i.e., 30 |
| Hysteresis | Value used in addition to thresholds as mentioned below, to prevent the sensor status output from toggling due to system noise<br>Sensor state is reported:<br>• **ON** = Difference Count > Threshold + Hysteresis<br>• **OFF** = Difference Count < Threshold – Hysteresis<br>Hysteresis is not available for the low power widget | 10 percent of signal |
| ON debounce | This parameter indicates the number of consecutive scans during which a sensor must be active to generate an ON state from the system. Debounce ensures that high-frequency, high-amplitude noise does not cause false detection | 3 |

The design tuning parameters can be tuned from CAPSENSE™ Configurator in ModusToolbox™.

### 3.3.8.4 Tuning verification

This section explains how to be confident that the system is tuned correctly and works as expected. In general, this post-tuning procedure is redundant if all steps in the tuning procedures are done correctly.

After the complete tuning, the last step is to verify that the system is working as expected. If tuning was done carefully as described in the previous sections, the system should work properly.

There are two steps to verify that the system is working as expected:

1. Verify that the raw counts are changing due to changes in the inductance and there is no saturation
2. Convert obtained raw counts to the inductance and compare it to one measured with an LCR meter

The first step includes testing the sensor with the target:

- In case of force application:
  - Press the button and check whether the raw count level increases

- In the case of proximity application:
  - Move the target towards the sensor and check whether the raw count level increases
- Check that saturation is not occurring in any case

The second step includes converting raw counts to the inductance, measuring sensor inductance with an LCR meter, and comparing both values:

1. Convert the raw counts to the inductance using the following equation:

$$L(uH) = 2 \times R^2 \left( CompCDACCode \cdot \frac{LxClkDiv}{CompCDACDiv} + \frac{MaxRawcounts - RawCounts}{MaxRawcounts} \cdot \frac{\mathrm{Re}\, fCDACCode}{2} \cdot LxClkDiv \right) \cdot 8.864 \cdot 10^{-9}$$

**Equation 17** **Raw counts to the inductance equation**

Where,

- R ≈ Rext + Rint ≈ 560 + 120 ohm
  - For larger inductance values add Rinductance (coil resistance) for more accuracy. R ≈ Rext+Rint+Rinductance
- Resolution = Max Raw Counts = LxClkDiv x NumOfSubConv. If CIC2 filter is enabled, CIC2 resolution (max. raw count) should be used
- This equation works for inductances larger than 5 µH. For smaller inductances, the equation provides an overestimation of the actual value
- Equation accuracy is limited to CDACs mismatch and resistance variation. Note that the LxClkDiv value will affect the obtained inductance due to transition processes not included in the equation

2. Compare this value with one obtained with an LCR meter
3. If $|Lcalc - Lmeasured|$ is less than 2-5 µH, the system works as expected (only when Rinductance is included in the equation)

# 4 Performance and reliability

When designing robust and reliable real-world applications of inductive sensing at a mass scale, there are certain challenges which need to be considered. This application note attempts to address the most significant challenges as described in the following sections.

## 4.1 Power supply transient noise

It is preferred to have an LDO regulator in the system to reduce the impact of power supply transients at all frequencies.

In case significant noise (>20% of the actual signal) is observed on the signal due to power supply variations, the following decision tree shall be followed to select a mitigation:

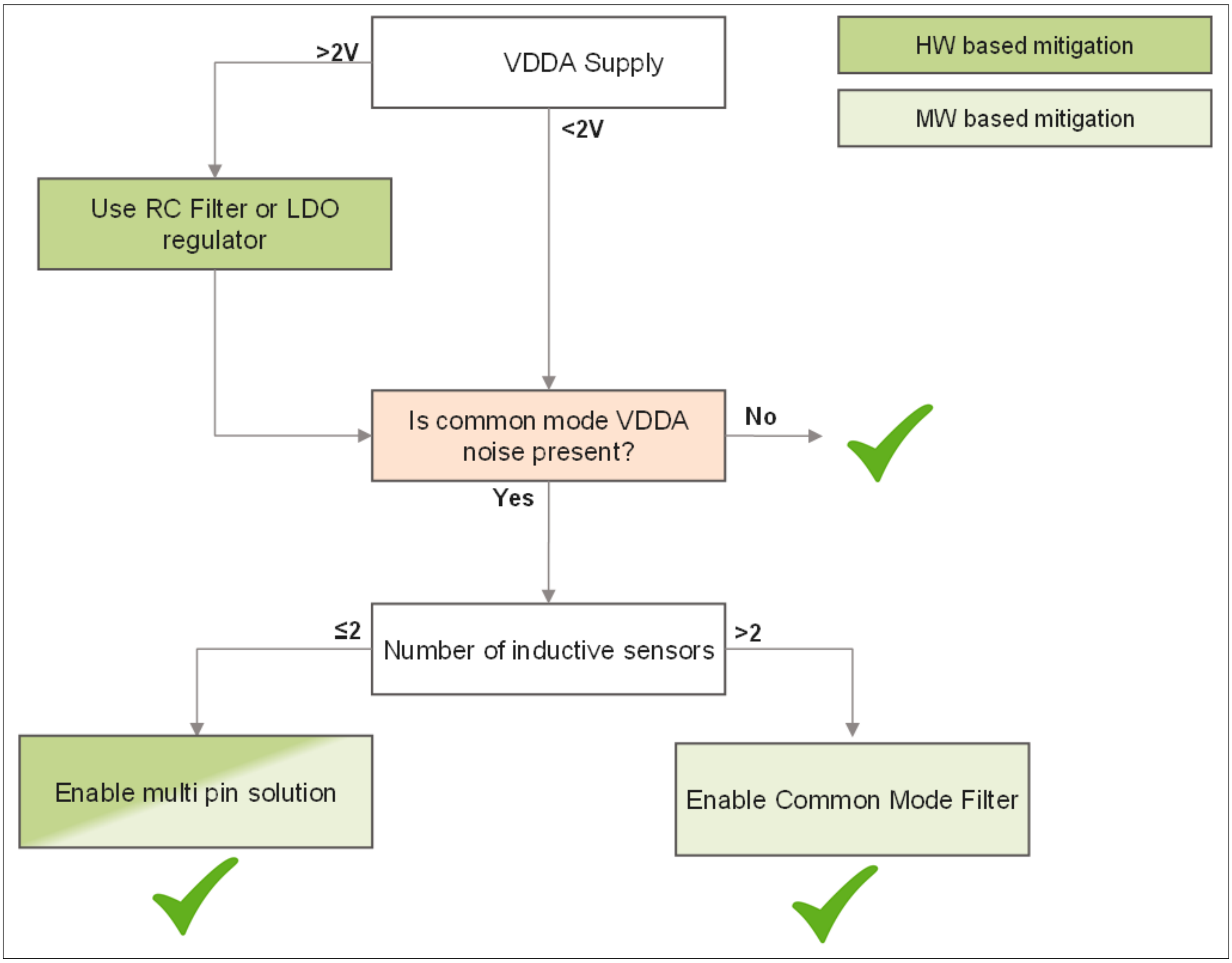


**Figure 72** Power supply noise mitigation decision tree

**Table 27** **Mitigation options based on the PST noise frequency**

| Frequency range of noise | Preferred mitigation option |
|---|---|
| 0–30 Hz | CMF(Common mode filter)<br>LDO (requires hardware)<br>Multi-pin configuration (requires hardware configuration) |
| 30 Hz – 1/Tscan | LDO (requires hardware)<br>Multi-pin configuration (requires hardware configuration)<br>(CMF is not recommended for this frequency range) |
| >1/Tscan | Less impact of power supply transients post the cut-off frequency. |

Where,

$$\mathrm{Tscan} = \frac{\mathrm{LxClkDiv} \times \mathrm{Nsub}}{\mathrm{Fmod}}$$

Tscan = Scan time

LxClkDiv = Lx clock divider

Nsub= Number of sub-conversions

Fmod = Modulation clock frequency (46 MHz by default)

It is recommended to keep the IIR filter enabled by default. RC filters and samples averaging also help mitigate the noise.

### 4.1.1 Linear regulator

The easiest way to suppress the power supply noise is to use a good linear regulator with high PSSR. The following are a few options with 3.3 V as output which can be used.

**Table 28** **Suggested linear regulators**

| MPN | Manufacturer | PSRR | Iq (µA) |
|---|---|---|---|
| TLV74033PDBVR | Texas Instruments | 67 dB ~ 32 dB (100 Hz ~ 1 MHz) | 80 |
| TLV74133PDBVR | Texas Instruments | 70 dB ~ 55 dB (100 Hz ~ 1 MHz) | 50 |
| TLV74333PDBVR | Texas Instruments | 68 dB ~ 28 dB (100 Hz ~ 100 kHz) | 60 |
| AP2120N-3.3TRG1 | Diodes Incorporated | 65 dB (1 kHz) | 50 |
| TPS7A0233PDBVR | Texas Instruments | 55 dB (1 kHz) | 0.6 |
| TPS7A0333PDQNR3 | Texas Instruments | 55 dB (1 kHz) | 0.3 |
| TCR3UF33A,LM(CT | Texas Instruments | 70 dB (1 kHz) | 0.68 |

### 4.1.2 Multi-pin configuration

If the noise in the sensor signal due to power supply variation reaches beyond 20% of the actual signal, a multi-pin sensor configuration can be used as shown in Figure 73.

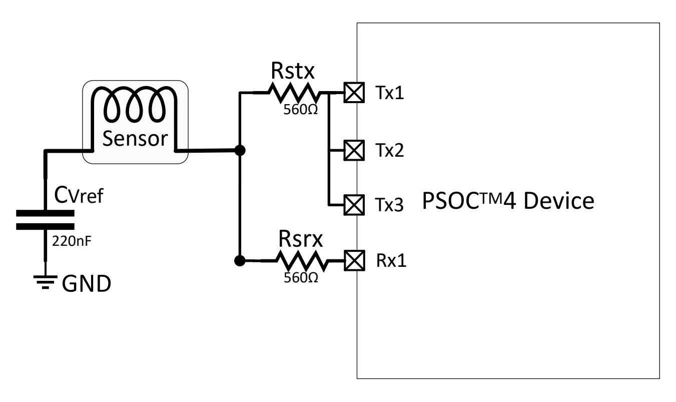
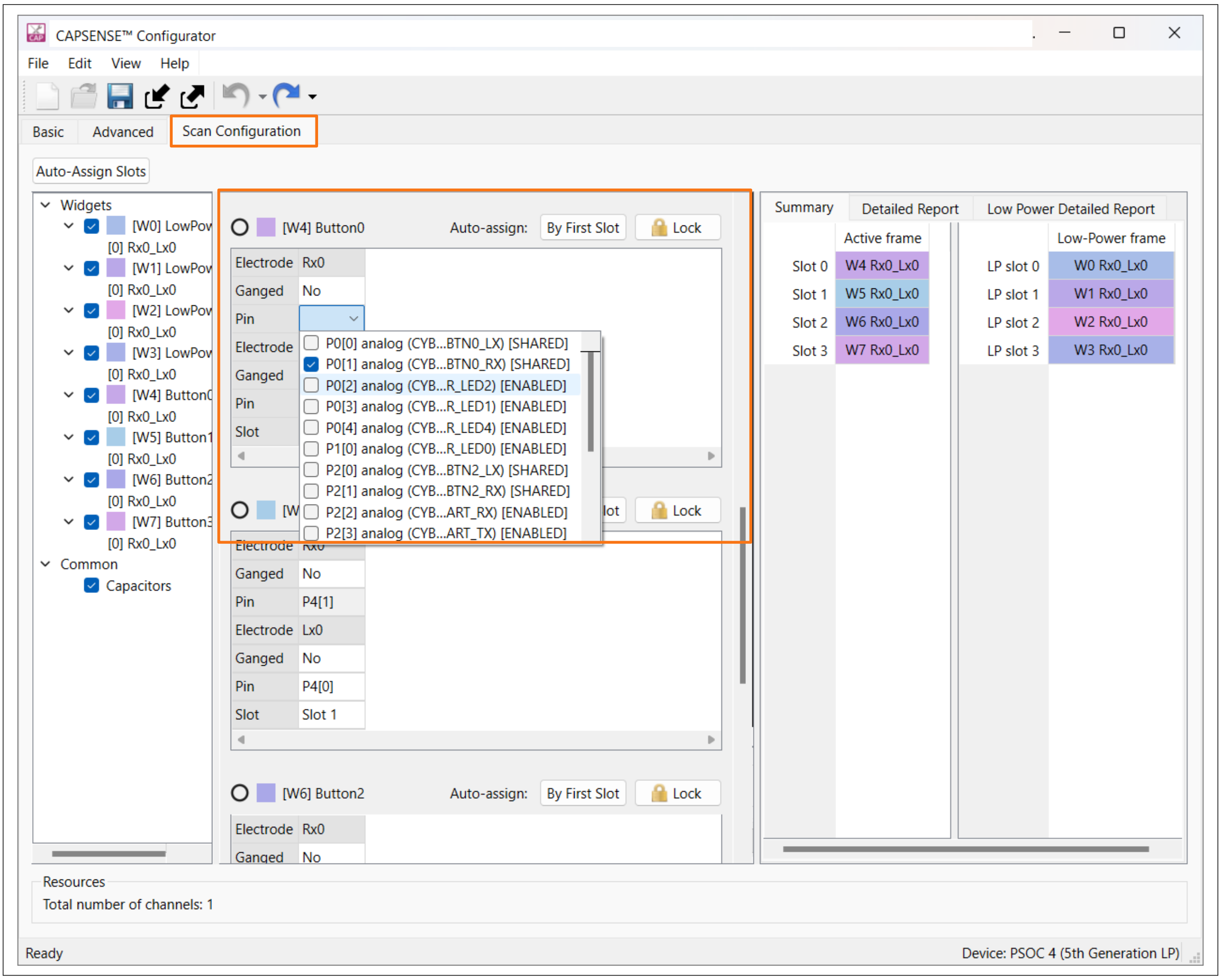


**Figure 73** Multi-pin sensor configuration

To enable this feature, the sensor should be connected as shown in the figure above. Using three Tx pins and one Rx pin gives better results than using two Tx pins and two Rx pins.

When selecting the pins in the CAPSENSE™ Configurator, follow the Figure 74. In the scan configuration, click on the “Pin” tab corresponding to the respective sensor button. Select the three Tx pins (Tx1, Tx2, and Tx3) and the Rx pin(Rx1) in the dropdown.



Widgets
- ☑ [W0] LowPow
  - [0] Rx0_Lx0
- ☑ [W1] LowPow
  - [0] Rx0_Lx0
- ☑ [W2] LowPow
  - [0] Rx0_Lx0
- ☑ [W3] LowPow
  - [0] Rx0_Lx0
- ☑ [W4] Button0
  - [0] Rx0_Lx0
- ☑ [W5] Button1
  - [0] Rx0_Lx0
- ☑ [W6] Button2
  - [0] Rx0_Lx0
- ☑ [W7] Button3
  - [0] Rx0_Lx0

Common
- ☑ Capacitors

○ [W4] Button0

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | No |
| Pin | |
| Electrode | |
| Ganged | |
| Pin | |
| Slot | |

- ☐ P0[0] analog (CYB...BTN0_LX) [SHARED]
- ☑ P0[1] analog (CYB...BTN0_RX) [SHARED]
- ☐ P0[2] analog (CYB...R_LED2) [ENABLED]
- ☐ P0[3] analog (CYB...R_LED1) [ENABLED]
- ☐ P0[4] analog (CYB...R_LED4) [ENABLED]
- ☐ P1[0] analog (CYB...R_LED0) [ENABLED]
- ☐ P2[0] analog (CYB...BTN2_LX) [SHARED]
- ☐ P2[1] analog (CYB...BTN2_RX) [SHARED]
- ☐ P2[2] analog (CYB...ART_RX) [ENABLED]
- ☐ P2[3] analog (CYB...ART_TX) [ENABLED]

○ [W

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | No |
| Pin | P4[1] |
| Electrode | Lx0 |
| Ganged | No |
| Pin | P4[0] |
| Slot | Slot 1 |

○ [W6] Button2

| | |
|---|---|
| Electrode | Rx0 |
| Ganged | No |

| | Active frame |
|---|---|
| Slot 0 | W4 Rx0_Lx0 |
| Slot 1 | W5 Rx0_Lx0 |
| Slot 2 | W6 Rx0_Lx0 |
| Slot 3 | W7 Rx0_Lx0 |

| | Low-Power frame |
|---|---|
| LP slot 0 | W0 Rx0_Lx0 |
| LP slot 1 | W1 Rx0_Lx0 |
| LP slot 2 | W2 Rx0_Lx0 |
| LP slot 3 | W3 Rx0_Lx0 |

Total number of channels: 1

Device: PSOC 4 (5th Generation LP)

**Figure 74** **Multi-pin configuration in the CAPSENSE™ Configurator**

In multi-pin configuration, as multiple pins are connected, the effective internal resistance will be lesser (the internal resistance of the pins in parallel). Use this lower resistance value in equations, such as the Lx clock divider calculation.

Multi-pin configuration also helps with temperature-related raw-count drift.

***Note****:* *When using multi-pin configuration, it is not recommended to use the same pin for different sensors.*

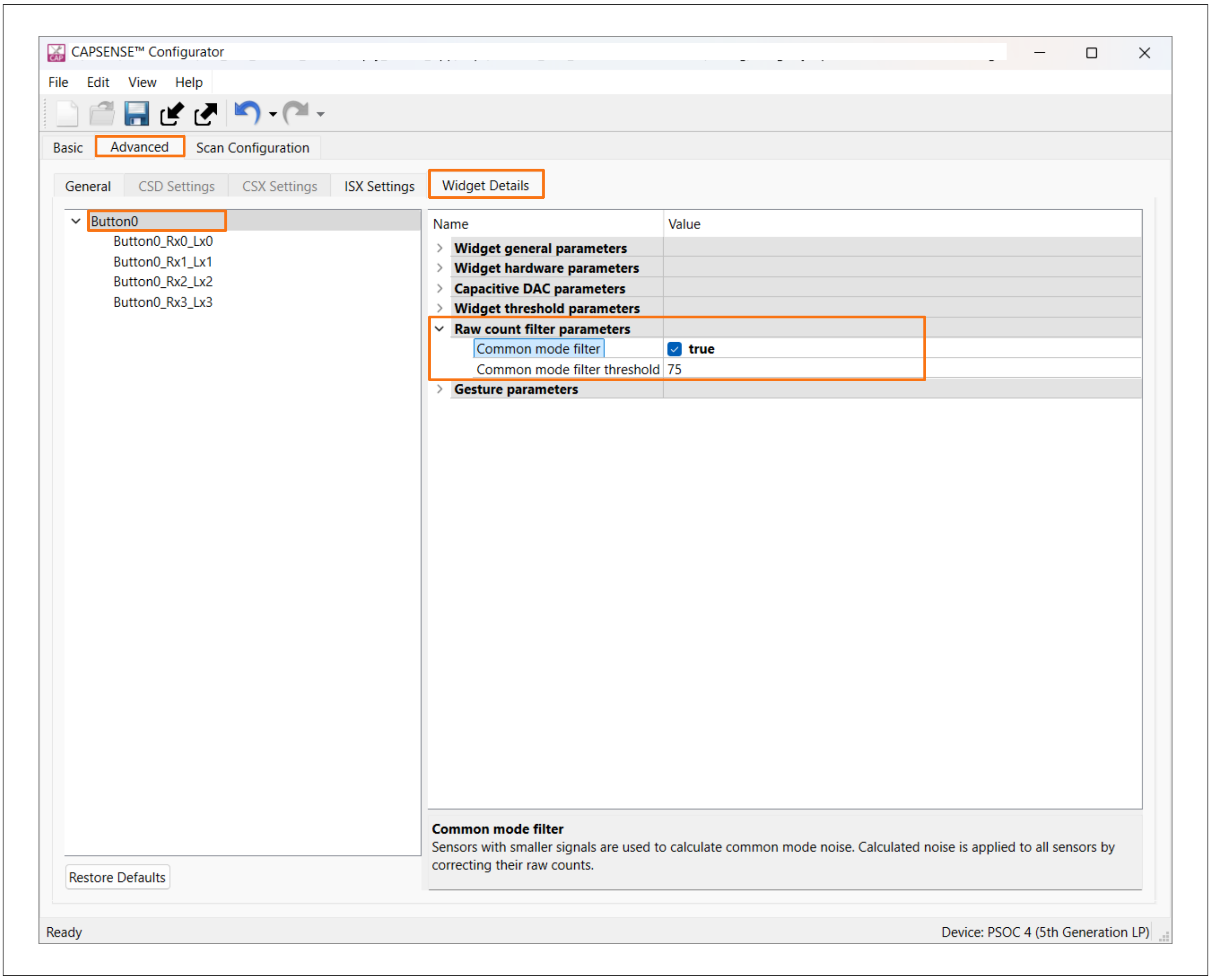
### 4.1.3 Common mode noise filter (CMF)

A common mode filter can be used to suppress common mode noises present in the system. The filter can only be applied when there are more than two sensors present in a widget[1].

The common mode filter can be enabled in the CAPSENSE™ Configurator by going to the **Widget Details** tab under **Advanced**.

---

[1] Currently available only for widgets with more than two sensors.



| Name | Value |
|---|---|
| Common mode filter | ☑ true |
| Common mode filter threshold | 75 |

**Common mode filter**
Sensors with smaller signals are used to calculate common mode noise. Calculated noise is applied to all sensors by correcting their raw counts.

**Figure 75** Enabling the CMF (common mode filter) in the CAPSENSE™ Configurator

The **Common mode filter threshold** is the signal threshold up to which the signal obtained is considered as common mode noise and included in the common mode noise calculation. It helps distinguish between the common mode noise and the actual touch signal.

The recommended value if large common mode noise is expected: 75% of the touch signal (maximum possible value). The maximum common mode noise must be below this value otherwise the noise will not be removed.

The recommended value if large common mode noise is not expected: 40% of the touch signal (same as noise threshold)

The maximum value is 75% of touch signal considering that the finger threshold is at 80% of the signal. Going beyond this value will result in improper CMF operation.

It is recommended to enable the median filter along with the common mode filter.

***Note**:* *The common mode filter removes/suppresses common mode noise that is caused by temperature changes. Due to this, the baseline algorithm will not track the temperature changes. Hence, the common mode filter threshold should be set such that it handles the maximum expected raw count shift caused by temperature changes.*

## 4.2 Raw count drift

Temperature drift can lead to slow raw count drift. In case the raw count drift is significant, a multi-pin configuration, or common mode filter (CMF) can be used to mitigate the raw count drift.

## 4.3 Crosstalk

Two types of crosstalk can occur in systems with more than one inductive sensor as described in this section.

### 4.3.1 Electrical crosstalk

Capacitive coupling between adjacent traces/components and sensors can contribute to crosstalk, i.e., unwanted signal being introduced in the sensor. Any nearby floating electrodes can also contribute to crosstalk. Rx lines/traces are more sensitive to crosstalk and higher on the sensors tuned for higher sensitivity.

**Mitigation**

- Route the sensor traces as far from each other as possible, add ground trace in between if required.
- Must be handled through appropriate tuning.
- Sensors need to have dedicated $C_{Vref}$ capacitors.

### 4.3.2 Mechanical crosstalk

The pressure on a button can have some impact on adjacent buttons as the overlay used is a single unit as shown in the following figure. For thinner overlays, the impact is so small that it is not noticeable, however for thicker overlays (e.g. stainless steel with thickness > 0.4 mm and button size =<25 mm), it can produce mechanical crosstalk resulting in signal on the adjacent sensor.

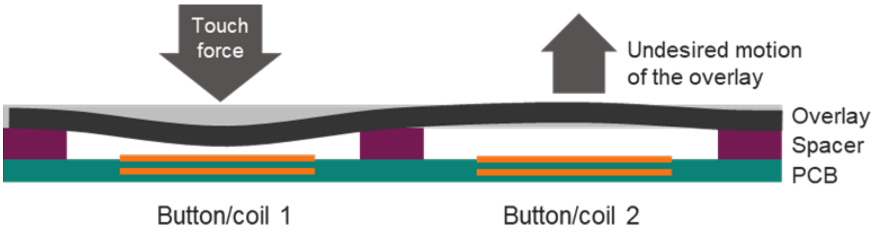


**Figure 76** Mechanical crosstalk in 2 button setup

To avoid the mechanical crosstalk in adjacent buttons, the following actions are recommended as shown in Figure 77:

- Strong and stiff spacer between the PCB and overlay
- Strong adhesive/epoxy
- Grooves on the button boundary or corrugated overlay surface

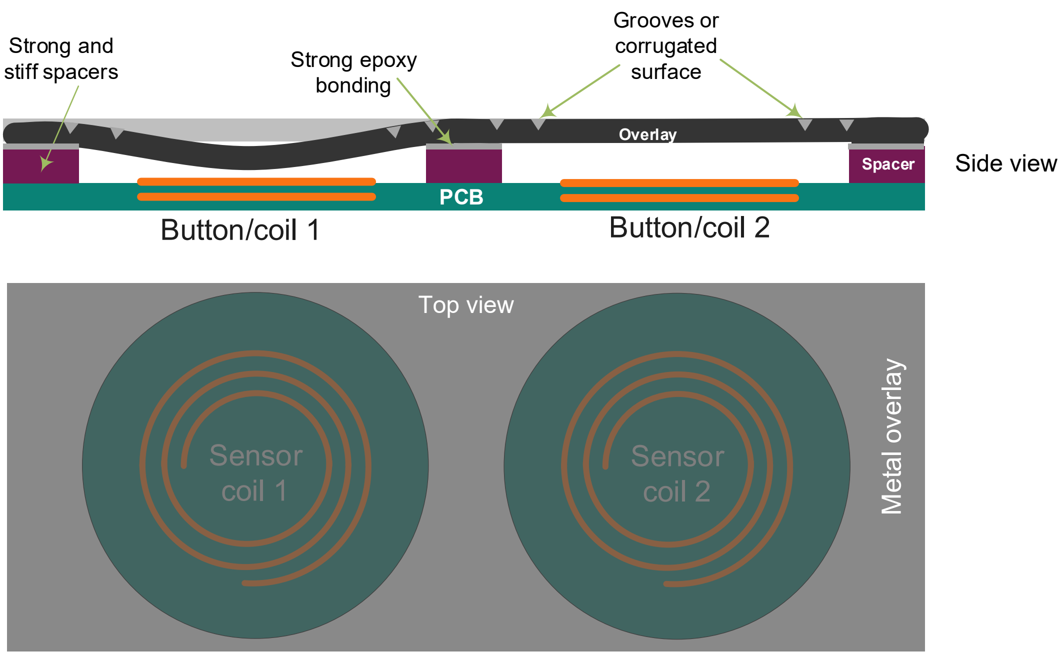


**Figure 77** Mechanical decoupling measures to avoid undesired motion

For more information, see Section Overlay thickness.

# 5 Troubleshooting tips and techniques

See the Tuning debug FAQs section of the AN85951 – PSOC™ 4 and PSOC™ 6 MCU CAPSENSE™ design guide for troubleshooting and debugging.

# References

### Application notes

[1] AN85951 - PSOC™ 4 and PSOC™ 6 MCU CAPSENSE™ design guide
[2] AN79953 - Getting started with PSOC™ 4 MCU
[3] AN234231 - PSOC™ 4 CAPSENSE™ ultra-low-power capacitive sensing techniques
[4] AN86233 - PSOC™ 4 MCU low-power modes and power reduction techniques

### Code examples

[5] PSOC™ 4: MSCLP CAPSENSE™ low-power proximity
[6] PSOC™ 4: MSCLP CAPSENSE™ liquid-tolerant proximity-sensing
[7] PSOC™ 4: MSCLP CAPSENSE™ low power
[8] PSOC™ 4: MSCLP robust low-power liquid-tolerant CAPSENSE™

### Other resources

[9] CAPSENSE™ webpage
[10] ModusToolbox™ webpage
[11] ModusToolbox™ software help on GitHub
[12] PSOC™ 4 CAPSENSE™ Component datasheet

### External references

[13] Mohan, S. “Simple Accurate Expressions for Planar Spiral Inductances” in IEEE Journal of Solid State Circuits, vol. 34, no. 10, (Oct. 1999): pp 1419-1424
[14] Howard Johnson, Martin Graham. “High-Speed Digital Design: A Handbook of Black Magic”
[15] Theory of Plates and Shells (2nd Edition) – Timoshenko & S. Woinowsky-Krieger
[16] Simplified Equations: Loaded Flat Plates

# Revision history

| Document revision | Date | Description of changes |
|---|---|---|
| ** | 2024-12-10 | Initial release |
| *A | 2025-02-13 | Updated Layout considerations and Overlay selection sections<br>Updated Figure 31, Figure 40, and Figure 62 |
| *B | 2025-03-11 | Added sections LED placement and routing and Overlay warpage. Updated section Sensor Designer |
| *C | 2025-04-03 | Template update<br>Updated figures<br>Added sections CY8CPROTO-041TP PSOC™ 4100T Plus CAPSENSE™ Prototyping kit and Capacitive and inductive sensing buttons example |

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