Printed Circuit Design Notes for Capacitive Sensing with the CS0 Module

1. Introduction

Circuits with capacitive sense elements are affected in many ways by their environment. Packaging, sensor design, signal routing, power system design, and ambient conditions, among other factors, can change the response of capacitive sensors in different, sometimes unexpected, ways.

Techniques have been developed to enhance the responsiveness of capacitive sensors by increasing sensitivity and reducing noise. Failure to exercise care in the design of capacitive sensing applications will result in the unintended consequences of lower sensitivity and higher noise.

Employing the techniques described in this application note will help ensure that systems with capacitive sensing elements deliver optimal results. This note describes techniques used in the application of the Capacitance-Sensing (CS0) converter.

1.1. Key Points

This document includes:

- Effective patterns for buttons, sliders, and proximity sensors
- Shielding recommendations for noise suppression
- Routing recommendations to control unintended activation and reduce stray capacitance
- A design checklist to be used in addition to the design checklist in “AN203: C8051Fxxx Printed Circuit Board Design Notes”.

1.2. Related Documents

This application note is a supplement to AN203, which should be consulted regarding general design and printed circuit board techniques to use when building systems with Silicon Laboratories' mixed-signal microprocessors.

1.2.1. AN203: C8051Fxxx Printed Circuit Board Design Notes

AN203 is a general-purpose application note that describes techniques that must be employed for using digital microprocessor systems to process high-fidelity analog signals.

- Power and ground circuit design tips
- Analog and digital signal design recommendations with special tips for traces that require particular attention such as clock, voltage reference, and the reset signal traces
- Special requirements for designing systems in electrically-noisy environments
- Techniques for optimal design using multilayer boards
- A design checklist (which has been reproduced here in "Appendix—Design Checklist from AN203" on page 18).

AN203 should be consulted in detail during any review of systems designed with capacitive sensing elements.

1.2.2. AN376: Effects of ESD Protection Devices on Capacitive Sensing Performance

“AN376: Effects of ESD Protection Devices on Capacitive Sensing Performance” is a related application note providing specific recommendations for protecting capacitive sensing inputs from ESD damage. System-wide control of parasitic capacitance is discussed. It should be reviewed as part of the design process for any system in which capacitive sensing elements are employed.

- Methods of ESD protection, their operation and parasitic elements
- Applying ESD protection in capacitive sensing applications

2. Design of Buttons, Sliders, and Proximity Sensors

The CS0 module is primarily used for buttons, sliders, and proximity sensors. Using proven techniques for the design of printed circuit board patterns can make a huge difference in the performance of this converter.

2.1. Defining a "Good" Capacitance Sensor

An attractive feature of capacitive sensing elements is the almost limitless design options for these controls. There are also limitless ways to construct sensors that do not perform as desired. The development and analysis of electric field models is sufficiently complex as to be impractical during product development. Typical sensor design uses guidelines developed through proven application and sometimes field modeling.

All sensor designs benefit from bench testing. In the early stages of development, the effectiveness of different sensor shapes and types of covering materials can be evaluated by modifying existing boards.

In this application note, we demonstrate the use of a number of preferred patterns and discuss the reasons for their reliable performance. Other shapes with unusual characteristics are described both as a warning to new designers and as a way for more experienced designers to see how different design elements can add both good and bad characteristics to new sensor designs.

The sensor design goal is always to increase the "touch" signal over a given area while reducing noise. We increase signal by designing a sensor to give the maximum predictable capacitive response to the capacitive body we are sensing. We reduce noise by making the design suppress or ignore the many types of undesirable signals that may be encountered.

It should be expected that prototype testing will be required for any capacitance sensing design, regardless of whether field modeling is performed. Systems with capacitance sensors "see" environmental conditions as a proper extension of their operating state. The prototype evaluation and development process should include significant amounts of "real world" testing in the full range of anticipated environments and methods of use for the product.

2.2. Dynamic Range and Resolution

The untouched capacitance of a sensor should always be significantly less than the maximum input capacitance of the sensing circuit. It is not trivial to determine (before a circuit is constructed and tested) how much headroom must be reserved to allow for peak sensor performance. The amount of required headroom is a function of the levels of input noise in the system under test and the amount of capacitance increase resulting from the presence of a body.

Many elements make up dynamic range:

- Device internal capacitance
  - Capacitance due to internal routing, packaging, and board placement varies by device. Typically, the amount is 7 to 15 pF.
- Sensor configuration and signal routing
  - Determined by the size and shape of the sensor, the thickness and dielectric of the material overlaying the sensor, any surrounding sensors, and shields, the routing of the signal back to the device, and related shielding.
- Expected amount of noise
  - Noise filtering software can often benefit from added headroom, which allows a more accurate image of input noise.
  - Because noise into the converter is represented as an error in the capacitance level, we describe noise headroom in terms of the total capacitance error it can cause.
  - In high-noise environments, properly-designed sensors can benefit from 10 pF of additional headroom for accurate signal capture.
- Level of capacitance that a body will add when the sensor is touched
  - The presence of a body raises sensed capacitance, but the amount of dynamic range that must be reserved depends on whether the application must accurately characterize the level of touch (e.g. "pressure" sensing).
  - Different ways of touching a sensor (finger pad-versus-tip, large-versus-small hand size, damp-versus-dry finger) can deliver additional information from a sensor if 5 to 8 pF of extra headroom is provided.

Capacitive sensing circuits have a wide dynamic range to allow for large offset capacitances. In a system using the

CS0 module's lowest setting for dynamic range (60 pF), a target for total untouched capacitance of 45 pF would allow 15 pF of headroom for full-fidelity signal and noise analysis.

Consider the possibility of using a greater dynamic range (larger total range of measurable capacitance) if necessary. In CS0-based systems, the capacitive sensing system may be adjusted to provide greater dynamic range. This change is always made with an apparent decrease in resolution. In some applications, lost resolution has no real effect. You may find that the "lost" bits of resolution are describing tiny amounts of capacitance that are impossible to accurately sense due to uncontrolled noise in the system or in your application. In these cases, there will be no cost to real, usable resolution from increasing the dynamic range.

2.3. Buttons

Buttons should detect touch in a single location while ignoring capacitive bodies moving nearby. The simplest and most reliable finger touch sensor is a solid circle of metal, no larger than a fingertip:

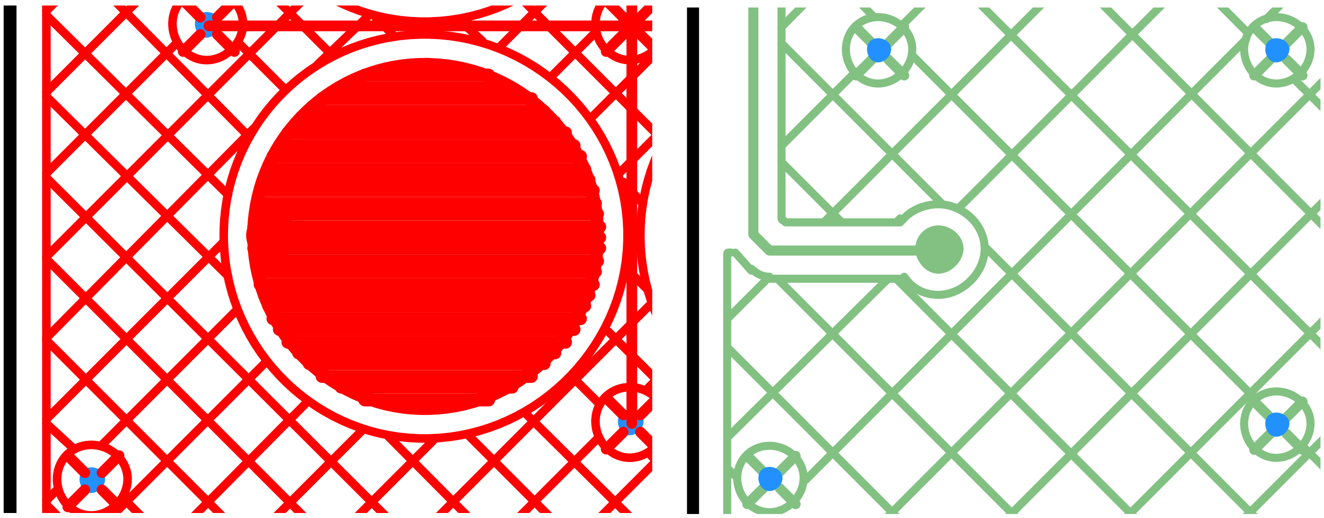


Figure 1. Circular Sensor (Top and Bottom Layer)

The operation of many other types of sensors can be better understood by examining what makes a circular sensor so effective.

The round shape is very well matched to the size of a fingertip's effective touch area, a circle 6 to 8 mm in diameter. Larger buttons can return more information about a finger including pressure and orientation (finger tip versus pad).

As the diameter of the button increases, its range increases: it begins to have more ability to sense movement at a distance. This is an important advantage in situations, such as the detection of gloved hands or sensing through thick cover panels. Larger buttons have the disadvantage that sensor pickup from unrelated nearby activity is also increased.

Slightly larger buttons offer the possibility of force detection. As the area above a sensor is pressed with more force, the fingertip flattens against the sensor, increasing the plate area and thus the effective capacitance of the touch. This can be used to provide a relative indication of contact pressure.

The area of the button is filled using a solid copper pour, maximizing the capacitive plate area of the sensor. This ensures high sensitivity when a finger's small capacitive plate is presented to the sensor.

On a two-or-more-layer printed circuit board (recommended):

- The area on the reverse side of the board behind the sensor should be filled with a hatched ground pattern (10% fill). Section “3.2.1. Electric Field Interference” describes the design of shields.
- On a multilayer printed circuit board, the board area behind the sensor should be blocked on all internal layers to prevent signal routing and plane pours in those locations.
- It is possible to route static signals (signals whose levels do not change while the capacitive converter is active) under the sensor, but the density of these routes should not exceed 10% fill.

- Switching signals, such as communication lines, clocks, and dimmable LEDs, should never be routed under capacitive sensors.
- Signal routing to other capacitive sensors may be located behind another sensor's pad, but this is not recommended due to the increased risk of false triggering for the other sensors.

Rows of buttons are implemented as either round buttons or square buttons.

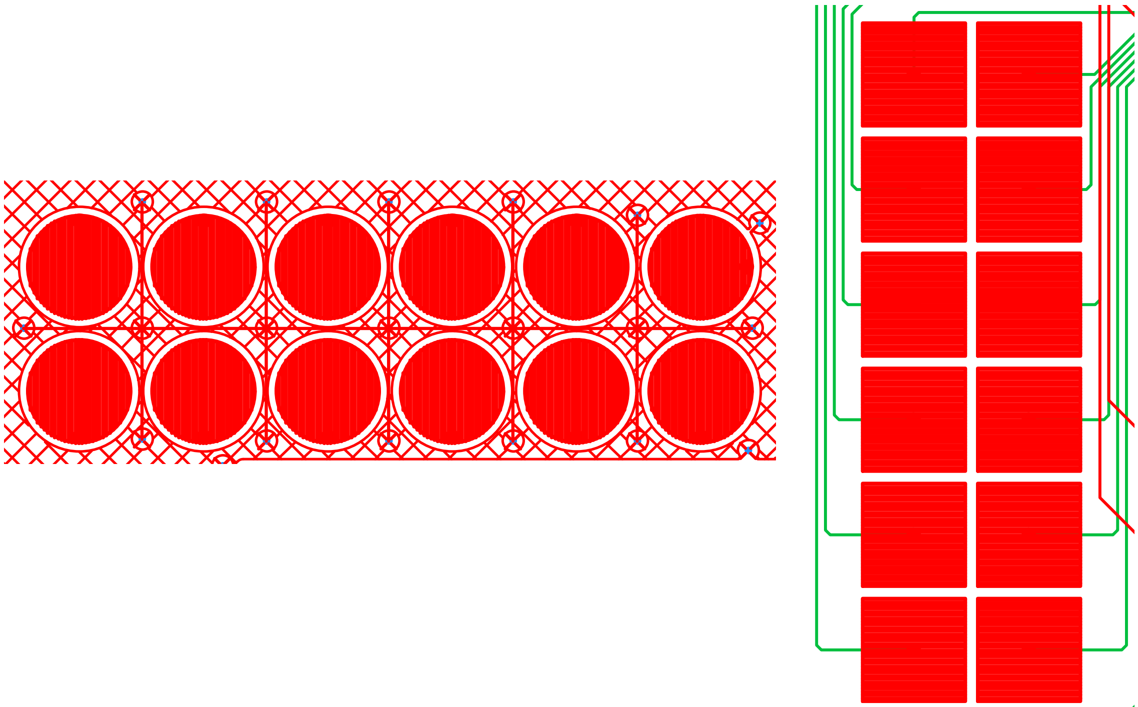


Figure 2. Button Arrays, Round and Square

Using round buttons reduces the risk of unintended activation, where a single finger might activate two buttons at the same time or cause the wrong button to be activated. The empty space surrounding round buttons causes no sensor return, reducing the risk that an off-center contact can cause erroneous activation. It is still possible to activate two neighboring round buttons by touching the closest point of shared contact, on the row's centerline exactly between the two buttons. Even at that location, the empty space between the round buttons causes a much lower response than a similar touch to the center of either button.

Square or rectangular buttons increase the amount of return signal in a given area. This gives additional information about proximity and off-center contacts.

In both cases, software techniques are used to determine which button is pressed if there is an increase in sensed capacitance from two neighboring sensors. If there is a desire to sense the simultaneous activation of two neighboring buttons, the isolation afforded by round buttons can deliver a less ambiguous indication that separate fingers are present at the two buttons. This is somewhat more difficult with neighboring square buttons, which could both present a strong return signal from a single body contact at any location on the boundary between buttons.

Other shapes sometimes offer advantages, depending on the application. If the physical relationship between the sensor and capacitive body is well-defined, the sensor can be shaped to optimize performance.

A finger touch sensor that is always addressed from a front-and-center direction can employ buttons with an oval or fingerprint shape. In that case, the designer would be able to take advantage of an unusual aspect of the system's use to provide a best match for possible finger placements. This would increase the amount of signal that is received from expected contact while creating additional open space between sensors to minimize unintended pickup in nearby buttons.

Odd geometric shapes are seldom employed for buttons, but this is mostly due to practical considerations that favor the use of round and square buttons.

Interleaved sensor patterns have been used with other methods of capacitive sensing on single-layer boards when there is little or no cover material for the sensor. The disadvantages in this design illustrate what we are working to achieve when designing a sensor for CS0 applications.

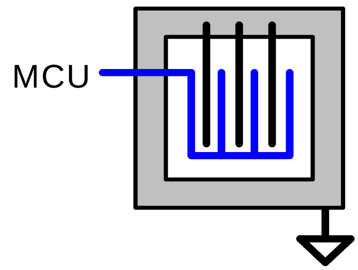


Figure 3. Interleaved Button, Not Recommended for CS0 Capacitive Sensing

The interleaved pattern forms a very long (but thin) parallel plate capacitor with large amounts of fringing capacitance. A body changes the capacitance at this sensor in two ways. There is a simple plate capacitance from half of the sensor's traces (those connected to the capacitive sensing circuit) to the approaching body's plate. Also, the body will disturb the portion of fringing capacitance due to electric fields passing through the air above the sensor. The body's dielectric (higher than that of air) will intercept a portion of this field, increasing the capacitance. This change in fringing capacitance is insignificant if a cover material is placed over the sensor. Most of the electric field generated in the interleaved sensor (parallel plate and fringing down into the PCB) performs no capacitance-sensing function.

Because the interleaved sensor provides little information per area and has a very high parasitic capacitance to ground, this pattern is ineffective for capacitive touch in CS0 applications and is not recommended.

2.4. Sliders

Sliders are sensor arrays that provide information about linear movement along a line or a curve. Sensor design issues are similar for all sliders, including wheel-style controls. The goal is to provide accurate position sensing along the array, often with a resolution that is higher than the number of channels in the array.

If the number of positions in the array is no greater than the number of channels in the array, the design is simple: Place the array elements immediately adjacent along the line and report position based on which sensor reports the greatest signal.

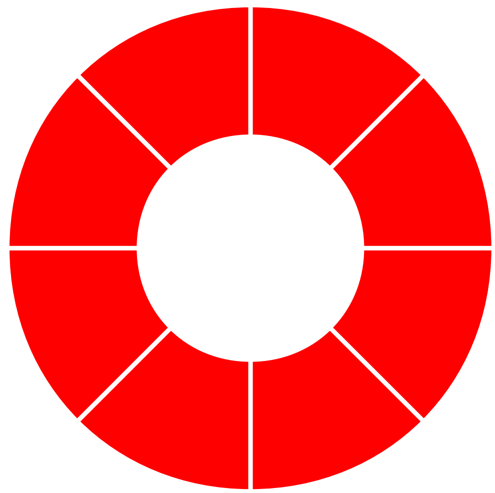


Figure 4. Click Wheel with Eight Segments (Each a 45° Segment of an Annulus)

Often, position information is required at a resolution greater than the number of channels in the sensor (e.g. a wheel control with 16 detents built with only four sensing channels). This level of detection is provided by overlapping sensors from different channels so that contact with the slider will affect sensors from both channels at the same time, but in an amount proportional to the location of the finger. The position can then be calculated based on the relative output of the sensor channels.

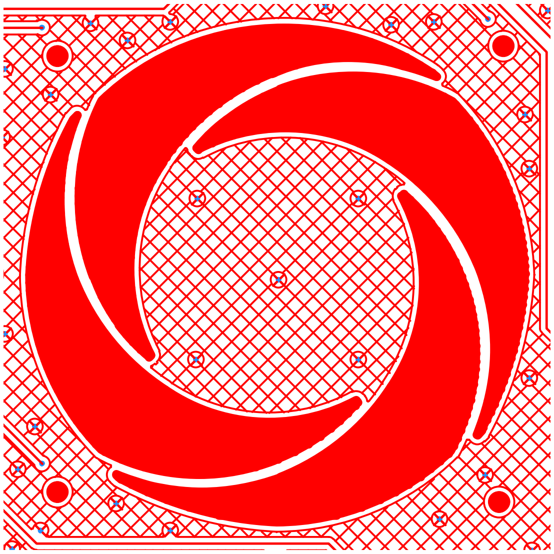


Figure 5. Simple Circular Slider Design

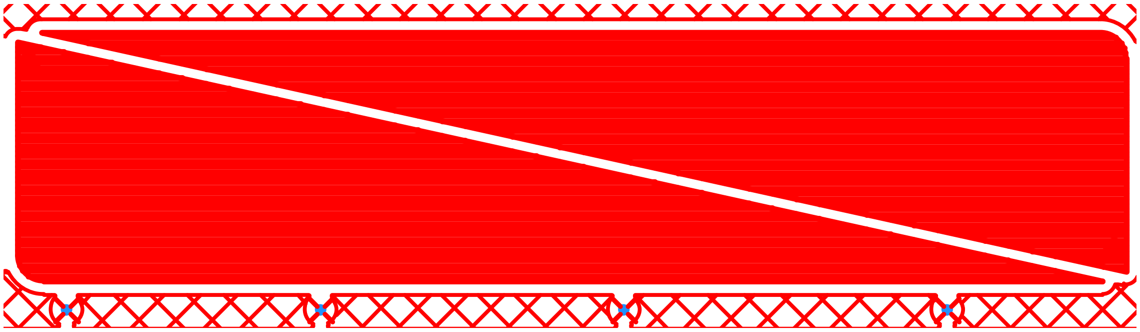


Figure 6. Simple Two-Element Slider Design

Many patterns have been used in the design of proportional sliders. When highly-accurate control is not required, a great variety of interleaving patterns will work with little complication. Accurate results require a uniform response from the slider which is only a function of the finger's position on the path of interest.

This slider provides a good user experience in an entertainment controller, but its absolute accuracy is poor because the relative response of the two sensors will change dramatically if the finger does not move in a straight line. This control is not used for absolute position encoding; it is used to detect relative speed and rough position, great value for a sensor that only requires two capacitance-sensing channels.

Figure 7. Straight-Line Slider with Eight Chevrons

To achieve higher-quality position sensing, more channels can be used. In this pattern, eight sensing channels are used to report position along the slider. Interpolation can be used to determine position with high resolution. Even in high-noise environments, where interpolation might be challenging, absolute location to one of fifteen points on this slider can be easily determined.

Figure 8. Straight-Line Slider with Four Highly-Slanted Chevrons

As the number of channels decreases, the pattern must be changed to provide features that deliver signals to two or more sensors proportional to the location of a finger between the channels. Proportional response data allows location to be inferred by comparing the affected sense channels. Accurate interpolation depends on a slider whose design is certain to provide capacitance proportional to location, even if the finger is not tracking along the center of the slider.

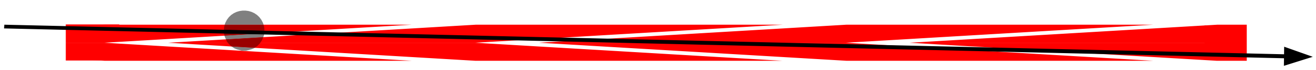


Figure 9. Fingertip Motion Over a Slider

When deciding on the shape of a slider, it is important to consider the size of a finger and its movement across the slider. The touch area from a fingertip may range from 3 to 10 mm in size. A finger pad can touch an area as large as 25 mm. In general, the more contact, the better; it is easy to measure response from several channels and find a "center of mass" where the center of the finger is probably located. If a small fingertip is used, the problem can be much harder to solve.

A small circular guide (4 mm diameter) can be used to evaluate how a slider design will work when a small finger passes over it at unexpected angles. Consider the first linear slider shown in Figure 7. A small fingertip touch can slide across most of the length of this shape without ever affecting the other side, or the finger can slide along the length of the separating line, providing a very consistent ratio of capacitance in both channels and very little information about position of the finger along the slider!

In the example above, the width of the slider is kept small, less than 8 mm. As a result, any path for a small fingertip across the length of the slider will provide proportional capacitance data to two or more channels at the same time.

Wider sensors can be built with the same resolution if the pattern ensures that a small finger cannot be missed when making proportional measurements.

The same principles apply if the proportional sensor is a round “click-wheel” style slider. The proper operation of proportional sensors depends on using shapes that provide information about movement in the direction of interest while ignoring motion in other directions.

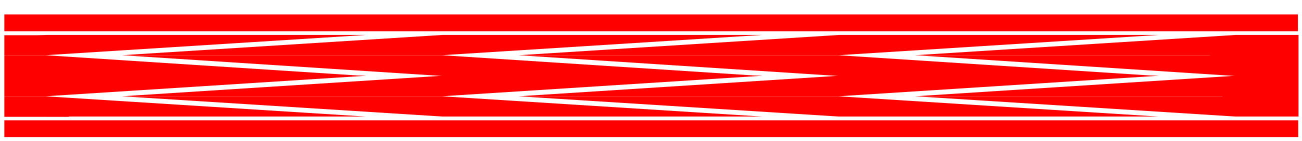


Figure 10. X-Y Controller Using Four-Element Slider with Two Side Channels

Unusual configurations can add substantial value. Here, six sensor channels provide position information in both the X and Y dimensions over a substantial area. This pattern, a one-dimensional slider with a side channel, can be repeated to make larger arrays capable of sensing multiple fingers using a limited number of discrete CS0 sensors. Wiring from the MCU to the sensing pads is done on the back side of the board using routing channels cut out of the backing ground plane. Routing distance under other sensors is minimized to the greatest extent possible.

2.5. Proximity Sensors

Any large area of solid copper pour can be used as a proximity sensor. The key is to maximize the return from the sensor. The larger the sensor, the greater its sensitivity will be. The metal sheet forming the proximity sensor does not have to be a single contiguous piece, but, if the sensor is split or cut to allow a signal to route through it, that open area will have much lower sensitivity than the neighboring solid-copper areas. As with all capacitance sensors, only a single contact and wire back to the MCU is required because capacitance sensing requires almost no current.

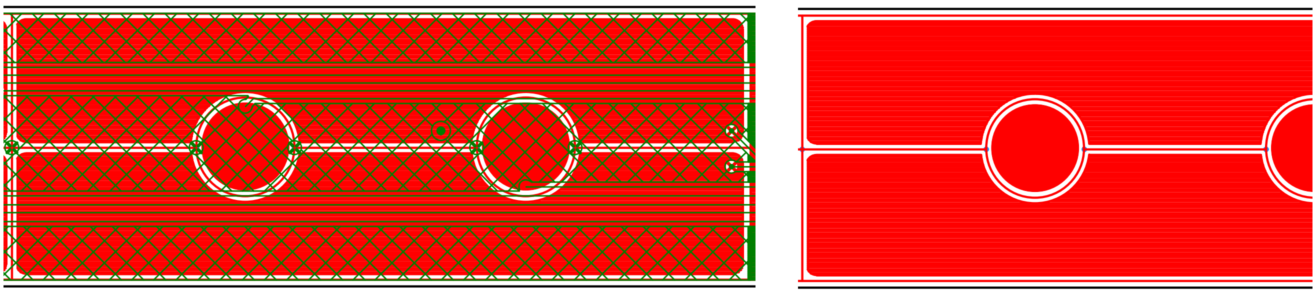


Figure 11. Use of the Hatched Ground Pattern Under Proximity Pads

Grounding the reverse side of a proximity sensor is important to reduce the pickup of radiated interference, but the ground pattern must be hatched with a very low copper density; a 10% hatch pattern is not too light because proximity sensors are so large that ground capacitance can be very large if a solid ground shield is used.

3. Printed Circuit Design to Reduce Noise

The converter connected to a capacitance sensor reads both a change in signal due to changing capacitance at the sensor and the many components that inject noise into the sensor.

3.1. Types of Unwanted Signals

- All sensors are vulnerable to pickup of radiating electric fields.
- Large amounts of energy from a user's body are coupled into the sensor through a finger's own capacitance.
- Coupling from the sensor and its wiring to circuits in the system that are switching can inject switching noise into the converter.
- Coupling from the shield ground to a sensor and its wiring can inject conducted ground noise into the converter.
- Sensors and their wiring can form loops that pick up magnetic field noise.
- Stray capacitance from bodies that are not intended to activate the sensor also creates unwanted signal.

Some noise can be removed by filtering in the converter and by digital processes, but the best policy by far is to design sensors without noise-capturing features.

3.2. Shielding for Noise Suppression

A capacitance sensor is a large metal plate operated with very little drive current, feeding into a sensitive, high-gain amplifier. It is very susceptible to noise pickup and there are many sources of noise in any practical application.

- The sensor pad and its routing traces convert electric fields in the environment into noise voltage for the converter.
- That essential element, capacitance from the user's finger to the sensor, couples environmental noise carried on a user's body directly into the converter's input.
- Every parasitic capacitance to a capacitive sensor and its routing is a potential coupling point for injecting switching noise.
- Ground shielding can result in coupling conductive ground noise into the converter input.

Building a design with proper shielding is essential. An unshielded system in the wrong environment will pick up levels of noise that are impossible to remove using practical numerical methods. As increasingly effective levels of shielding are applied, the levels of noise in a system drop to levels where modest processing is required, then little or no processing is needed. Well-designed systems deliver data with a high enough signal to noise ratio to allow sophisticated interpolation with limited processing, or simple detection with little or no processing.

Proper shielding is essential if a capacitive sensing system is expected to provide peak performance in low-power and sensitivity.

Shielding a system for optimal capacitive sensing performance starts *everywhere*. Trade-offs will become apparent, but there is no single element that can be completely ignored to the preference of another.

3.2.1. Electric Field Interference

The easiest source of interference to understand, and the simplest to protect against, is transmitted interference from electric fields.

Electric fields in the environment induce voltage in capacitive sensors and their routing to the CS0 converter. Proper ground shielding is used to reduce its effect. Each sensor must have a ground plane behind it, covering the entire area of the sensor. As with proximity sensors, the ground pattern need only be very lightly hatched: a 10% hatch pattern is not too light. Interconnect from a sensor to the CS0 converter should not be routed on the top of the board, and there should be a ground shield (30% hatch density) on some layer between the routing lines and the user.

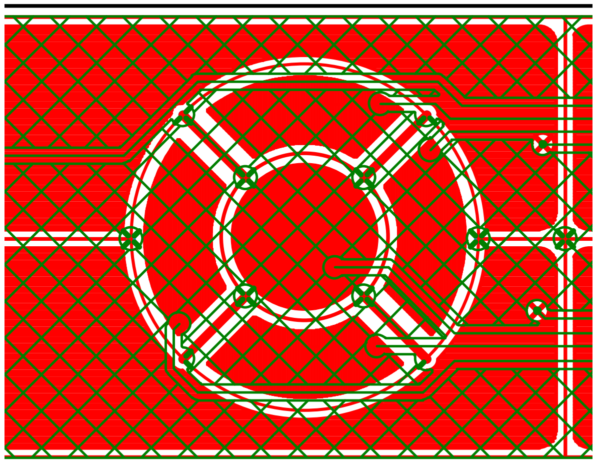


Figure 12. Bottom-Side Shielding for Sensors

Shielding on the back side of a board directly behind a sensor decreases the pickup of radiated interference by reducing the amount of voltage swing that an incident electric field can induce on a capacitance sensor.

Adding a ground shield to the board underneath a sensor pad limits the effect of incident electric fields as a function of the pad's proximity to the ground plane. This is why even a small ground wire behind a sensor pad has a significant effect in reducing radiated noise pickup.

3.2.2. Shielding from Finger Noise (Capacitance-Coupled Interference)

The user's body is an effective antenna for the pickup of radiated emissions. This noise is efficiently transferred from the user's body into the capacitance sensor through the same capacitor that is being used to sense their finger's presence. This interference is a significant source of CS0 input noise that is difficult to attenuate by shielding.

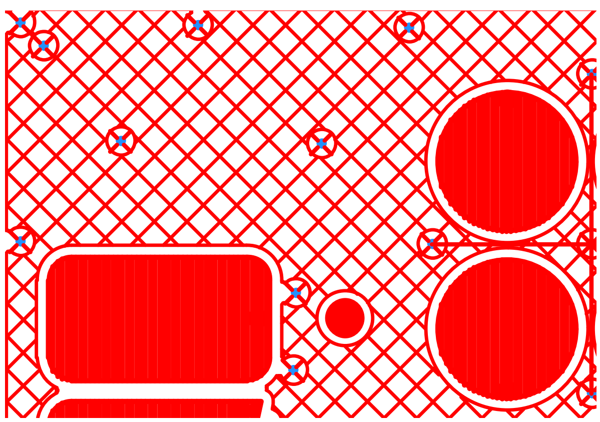


Figure 13. Top-Side Hatched Ground Shield

To reduce the amount of finger noise entering the system, all sensor pads must be surrounded with a ground shield, preferably a hatched ground (30% fill). All routing for sensors must be located beneath a ground shield and not underneath any other sensor pads.

The front ground shield protects other circuit elements from finger-coupled noise. It also provides a voltage divider and shunt to ground for a portion of the noise.

3.2.3. Shielding from System Switching Noise

Output port pin switching (LEDs and serial communications) can affect capacitive sensing. The CS0 converter will wait to complete a conversion whenever an output pin is switching. In cases where LED dimming and high-speed serial communications are being performed in the MCU, the CS0 conversion rate will decrease.

There is generally no restriction for multi-layer boards in routing capacitance sensor lines on layers adjacent to power and ground planes, but they should not be routed directly under or parallel to any high-frequency clock lines, communications lines, or LEDs with dimming control without the protection of a shield ground between the traces. Where necessary, sensor lines should cross switching lines at right angles.

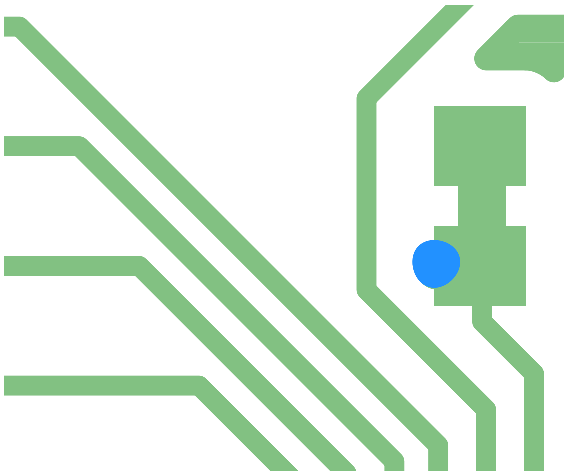


Figure 14. Routing to Avoid Current-Carrying Vias

Double minimum spacing should be maintained between sensor lines and vias that carry signal switching noise to power or ground planes.

As with other mixed-signal systems, ground planes for analog and digital systems should be split and combined at a single point with appropriate filtering. Digital logic should always be separately and sufficiently decoupled before connection to power and ground planes used by capacitive sensing systems.

3.2.4. Routing to Reduce Coupling Capacitance

A capacitance sensor for a finger is usually designed to be so sensitive that it can measure tiny changes in capacitance (small fractions of a picofarad) though it is possible for a finger's touch to change the converter's output by more than 10 pF. Because the range of the CS0 converter is large (the minimum range is about 60 pF, maximum range is much greater), it might seem that reducing the untouched (bulk) capacitance in a sensor is unimportant. This is not the case; because sensors with larger amounts of untouched capacitance are more susceptible to noise, they operate more slowly and deliver less resolution.

For the CS0 converter, measurement range and precision have an inversely proportional relationship. Using a larger range means that each bit represents more capacitance, thus precision is reduced.

A capacitance sensor feeds into a sensitive, high-gain amplifier. For this reason, it is very susceptible to noise pickup from other traces on the printed circuit board. Although we will use ground shielding to minimize pickup from other signal traces, this has the unintended effect of creating a large amount of coupling capacitance from the board ground to the capacitance sensor's input. Conducted noise on the board ground will thus be effectively coupled into the CS0 input.

For all of these reasons, it is important to reduce coupling capacitance as much as possible while maintaining the ground shielding required for control of pickup from other noise sources.

The simplest way to reduce coupling capacitance is to place the CS0 converter as close to the capacitance sensor as possible. Shorter traces will always have less coupling to ground.

When ground traces are used to shield longer routing to capacitance sensors, doubling the minimum spacing between traces will reduce ground capacitance while maintaining sufficient shielding.

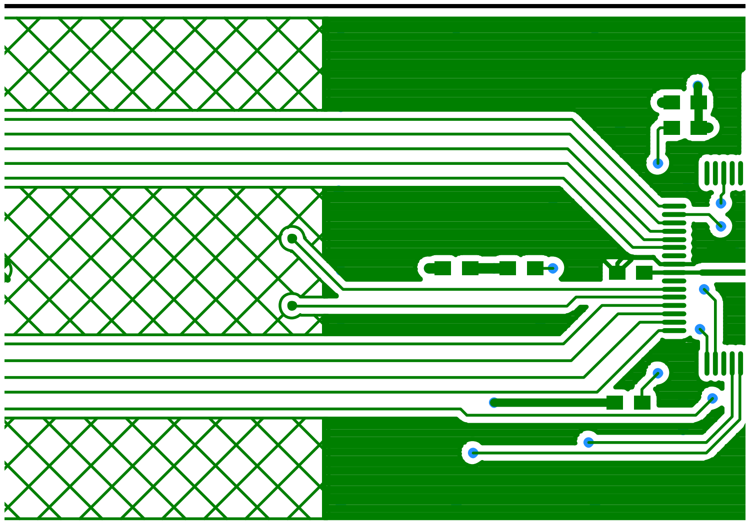


Figure 15. Routing for Longer Capacitive Sensing Lines

In most cases where longer routing to capacitance sensors is required, there will be multiple sensor lines being routed. These lines can be laid adjacent at minimum spacing to reduce routing space. If electric field radiation in the system is found to be a problem for lines in such a group, using active control to ground alternating adjacent lines will reduce noise for other lines in the group.

Techniques for routing signals near possible ESD sources or other high-energy noise sources in any electronic system should be observed in products using capacitive sensing circuits, but care should be taken to minimize the amount of bulk capacitance added to the lines being routed. Although a length of RG-179 coaxial cable might seem to provide ideal protection for routing signals to a distant capacitance sensor, its conductor-to-shield capacitance of 68 pF/m can quickly add enough bulk capacitance to make remote sensing difficult.

3.2.5. Magnetic Fields

When employing capacitive sensors in applications where strong magnetic field noise with higher frequency (Fo > 5 kHz) oscillation is known to exist, designs should also be checked to eliminate circuit loops in which a magnetic field could induce a noise current. The use of the other shielding techniques discussed here should minimize this risk by eliminating vectors through which a magnetic field could effectively influence current flow in sensor loops.

3.3. Routing to Prevent Unintended Sensor Activation

All portions of printed circuit routing between a capacitance sensor and the CS0 module are electrically active as part of the capacitance sensor. Small buttons, for example, are likely to have much more surface area in routing metal than in their sensor pad. The high responsiveness of capacitance sensors means that careful routing is required for printed circuit traces connecting sensors to the CS0 module.

Unintended activation can occur if a sensor route is close to another sensor pad. Because the effect of a finger on a touch sensor can range from less than a picofarad to more than 10 pF, a firm finger press that is slightly off-center on one sensor can activate another sensor just by landing on a nearby signal route.

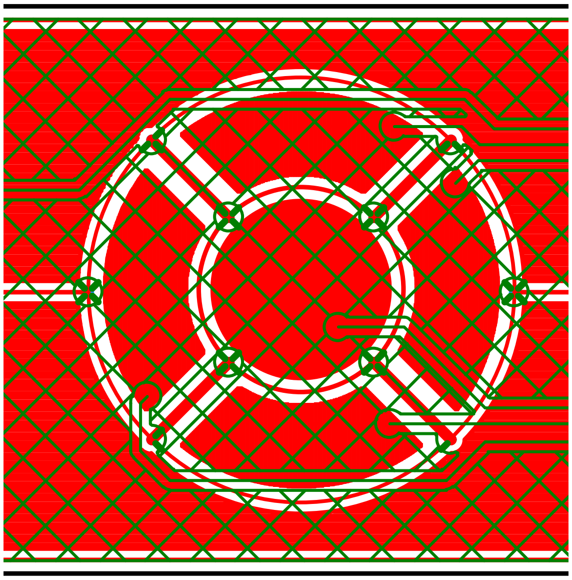


Figure 16. Sensor Lines Routed Another Touch Sense Pad

The best method for avoiding unintended activation is to surround all sensor pads with a hatched ground (30% fill) and place all routing for sensor pads on the bottom side of the board and not underneath any other sensor pads. The hatched ground on the top layer of the board reduces the effect that a misplaced finger will have on other circuit elements. Using the bottom side of the board for sensor routing ensures that they are separated from a misplaced finger by additional distance and a shield ground mesh.

Packaging considerations are also important in understanding and preventing unintended activation of capacitance sensors.

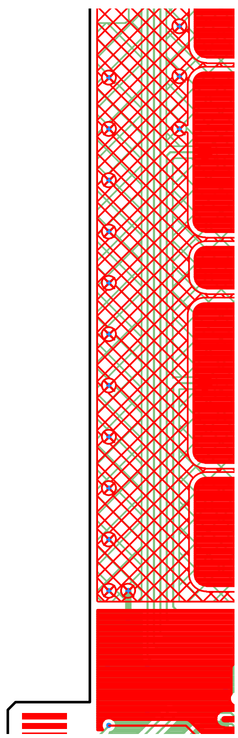


Figure 17. Sensor Line: Watch for Unintended Touch Points on Board Edge

In this product, a problem was found after packaging when the device was picked up by hand near the top and bottom of the board. The capacitance from multiple fingers to the traces on the sides of the board was sufficient to activate the capacitance sensors. One solution to this problem would have been to reduce the sensitivity of the sensors so that they would not respond to the unintended touch.

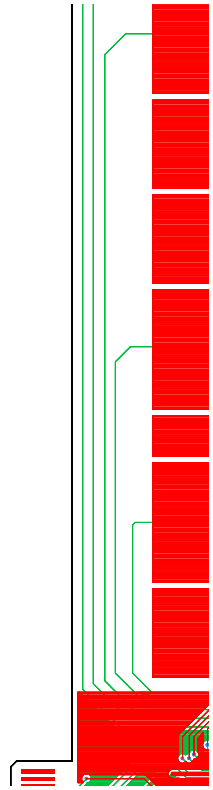


Figure 18. Sensor Line, Preferred Routing Method

An effective solution was to move the signal lines away from the edge of the board as much as possible and to reduce sensitivity slightly for the affected channel. The answer might have been different if the box was intended for laptop use (close proximity to a large mass that must be completely ignored) or an unusual configuration.

3.4. Environmental Noise

Capacitance measurements are greatly affected by the environment in which the system is operated. Capacitance sensors are so sensitive to humidity that they are often used for just that purpose. Even changes in temperature and air pressure, to the extent that they affect humidity, will change capacitance measurements.

Environmental noise due to electrical interference varies dramatically between different locations. It is common to find ambient RF noise levels that vary more than an order of magnitude within a single building, and by a factor of more than a hundred between two locations in a city.

Different users carry different amounts of radiated noise on their bodies. Not necessarily due to clothing or body size, a sensor will pick up maximum noise levels that vary by more than a factor of two between two different people in identical physical locations.

The spectrum of electrical interference varies across locations. Some characteristics are commonly seen, even as level vary. Noise that is synchronous to the power line frequency (50/60 Hz) is common and strong. The total amount of energy is relatively low between 1 kHz and 100 kHz, where most switching power supplies do not operate in order to protect audio signal paths. A substantial increase is seen above 100 kHz and below the 500 kHz limit where radiated signal limits become more strict. Radiated interference and capacitance-coupled interference measured at the same time at the same location are very similar in spectrum. This is to be expected, since the body is transferring noise via coupling that it picks up from the same environment.

Because all of these noise sources affect the performance of capacitive sensors, the development process for systems with capacitive sensors should include testing in a variety of settings that are representative of the range of environments in which they will be used.

4. Printed Circuit Design Checklist For Capacitance Sensing with the CS0 Module

4.1. Sensor Design

- ☐Sensors are large enough to respond to the movement of a hand at a distance, through a plastic cover, and, if necessary, a glove.
- ☐The thickness and composition of the cover material has been chosen and their effect on sensitivity has been evaluated using test structures.
- ☐Solid copper pour is used to fill the shape.
- ☐Slider designs have been checked for off-axis operation using a 4 mm circular guide.

4.2. Shielding from Electric Field Interference

- ☐The entire area behind each sensor is filled with a 10%-fill hatched ground.
- ☐If static signals are routed in the touch-sensitive area between a sensor and its background, the density of these routes does not exceed 10% fill.

4.3. Shielding from Finger Noise

- ☐Connections from sensors to the CS0 converter are not routed on the top of the board.
- ☐On the top layer, the area around each sensor that is not occupied by another sensor is filled with a ground shield of not less than 30% hatch density to a distance of not less than 2 mm (more is better).
- ☐All wiring between sensors and the CS0 converter is shielded from the user with a ground shield of not less than 30% hatch density.

4.4. Shielding from System Switching Noise

- ☐Any layers between the sensor and its background do not use the touch-sensitive area between these features for signal routing, power plane, or ground plane pours.
- ☐Switching signals, such as communication lines, clocks, and dimmable LEDs, are not routed under or near sensors.

4.5. Reduction of Coupling Capacitance

- ☐The CS0 converter is as close to the capacitance sensor as possible, and they are connected with short traces.
- ☐Ground shield spacing to capacitance sensor routing is double the minimum space between traces.
- ☐Bulk capacitance of shielded cabling that might be used to route sensor lines in a system has been accounted for.

4.6. Preventing Unintended Sensor Activation

- ☐Lines connecting to other capacitive sensors are not located in the touch-sensitive area between a sensor and its background.
- ☐Wiring between sensors and the CS0 converter is shielded from the user with a ground shield of not less than 30% hatch density.
- ☐Unshielded connections from sensors to the CS0 converter are not routed near any area that can be affected by unintended touch by the user's hand or body, or near any other capacitive body (metal door, tabletop, etc.).

4.7. Magnetic Fields

- ☐Requirements for protection from strong magnetic fields with higher frequency (Fo > 5 kHz) oscillation have been reviewed.
- ☐If necessary, the design has been checked to eliminate circuit loops in which such a magnetic field could induce an oscillating noise signal.

4.8. Ground

- ☐Separate the analog ground plane from the digital ground plane to decrease capacitance sensing noise.
- ☐Separate ground planes should be connected in only one location, usually close to the power supply.
- ☐Isolate the PCB's ground plane from noisy systems' ground circuits.

4.9. PCB Testing

- ☐A plan is in place to test your PCB design using prototype boards.
- ☐Comprehensive environmental test plans include electrical noise, weather, and human-factor elements.

4.10. General Guidelines

- ☐Total capacitance on each sensor is calculated to be within the allowable range, including capacitance internal to the CS0 device, plus required headroom.
- ☐“AN203: C8051Fxxx Printed Circuit Board Design Notes” checklist has been completed.
- ☐“AN376: Effects of ESD Protection Devices on Capacitive Sensing Performance” has been consulted regarding application-specific ESD protection issues.
- ☐Keep capacitive sensing signals and digital signals as far apart from each other as possible.
- ☐Avoid routing capacitive sensing signals and digital traces perpendicular to each other.
- ☐Trace length should always be minimized.

Appendix—Design Checklist from AN203

In order to make special note of the importance of the application of AN203 guidance in capacitive sensing applications, the design checklist from that document is reproduced here in its complete form. Use of this checklist will not supplant careful study of AN203.

Design Checklist

PCB Testing

- ☐ Test your PCB design using prototype boards.
- ☐ Add jumpers that can connect traces and planes on prototype boards to aid testing of ground plane connections, power supply nets, etc.
- ☐ Design with a place to add bypass capacitors so that different capacitances can be tested in order to find the optimal value.

Power Supply Circuit

- ☐ Filter the output of dc-dc converters by adding bypass capacitance to the converter's output.
- ☐ Add a large bulk capacitor at the voltage regulator's output that can provide current for local capacitors and ensure regulator stability.
- ☐ Place bulk capacitors as close to the voltage regulator output as possible.
- ☐ The large bulk capacitor's capacitance should be 10 to 100 times as large as local IC decoupling capacitors.
- ☐ Tantalum and electrolytic capacitors work well as bulk decoupling capacitors.
- ☐ Add a second capacitor an order of magnitude or two smaller in capacitance relative to the large bulk capacitor to help filter high-frequency noise.
- ☐ Place a local capacitance as close as possible to the power supply pin of each IC.
- ☐ The side of the local capacitor that connects to ground should be placed as close to the IC's ground pin as possible in order to minimize the loop area between the cap and the power and ground pins.
- ☐ Add a filter, such as an L-C filter or an R-C filter, to the power supply circuit.
- ☐ Filter the analog voltage supply using a series inductance, either in the form of a ferrite bead or a 2 Ω wire-wound resister.

Ground

- ☐ Design using a ground plane instead of traces connecting components to ground.
- ☐ The ground plane should cover as much of the board as possible, including the spaces between devices, traces, and the area underneath the mixed-signal MCU.
- ☐ Separating the analog ground plane from the digital ground plane improves analog performance.
- ☐ Separate ground planes should be connected in only one location, usually close to the power supply.
- ☐ Connecting separate ground planes near the microcontroller instead of the power supply can sometimes improve analog performance.
- ☐ If possible, place the mixed-signal MCU over the analog ground plane. Otherwise, try to place the device so that the analog-related pins reside over the analog ground plane.
- ☐ An analog component should not be placed between a digital component and the power supply.
- ☐ Be mindful of return current paths for all components.
- ☐ If possible, each component should have a straight-line return path in the solid ground plane to the power supply ground.
- ☐ Isolate the PCB's ground plane from noisy systems' ground circuits.

General Guidelines

- ☐ Keep analog and digital signals as far apart from each other as possible.
- ☐ Avoid routing analog and digital traces perpendicular to each other.
- ☐ Trace width should remain constant throughout the length of the trace.
- ☐ Turns in traces should be routed using two 45 degree turns instead of one 90 degree turn.
- ☐ Trace length should always be minimized.
- ☐ Use vias only when absolutely necessary.
- ☐ Avoid the use of vias when routing high-frequency signals.
- ☐ Follow the "3W Rule", which states that the distance between adjacent traces should be equal to two trace widths when routing signals close to each other.
- ☐ Keep traces less than 100 cm to minimize reflections.

Special Considerations

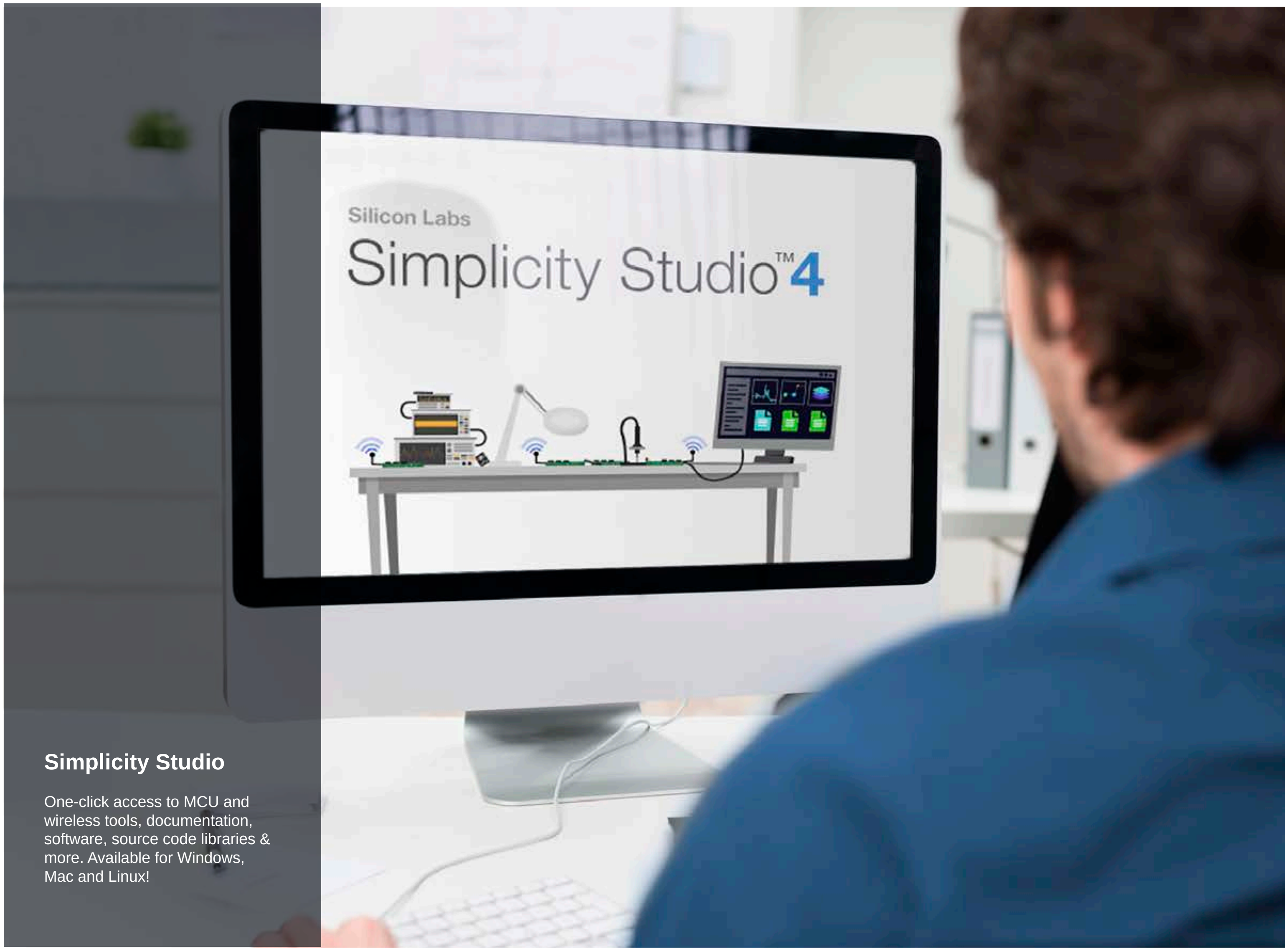
- Connect unused I/O pins to ground, and configure them as open drain with weak pull-ups disabled. Alternatively, leave them unconnected and drive them to logic low.
- Connect unused analog signals directly to analog ground.
- Connect unused op-amp's non-inverting (+) input to ground and the inverting input (–) to the op-amp output.
- When possible, use the microcontroller's internal oscillator.
- If an external oscillator must be used, consider using a "canned" CMOS oscillator that has its own power supply, ground, and amplifier if the system will be used in an electronically-noisy environment.
- Place the external oscillator as close as possible to the microcontroller.
- Keep the reset signal's trace length as short as possible.
- Add a decoupling capacitance of 1 µF and an external pull-up resistor of 1–10 kΩ between VDD and the reset pin.
- Never leave the reset signal floating in noisy environments.
- Keep the trace length of the VDD monitor signal as short as possible, and route this trace as far as possible from electrically-noisy signal traces.
- Place a parallel capacitance of 4.7 µF and 0.1 µF close to the voltage reference pins.
- See "AN124: Pin Sharing Techniques for the C2 Interface" for details concerning C2 interface layout techniques.
- If the C2 interface pins, C2DAT and C2CK, will not be used in the design, treat them as the normal port pin and reset pin, respectively.
- Keep JTAG traces as short as possible.
- Either galvanically isolate JTAG ground from off-board equipment or make sure that the PCB and the off-board equipment share a common ground.
- Add a 3–5 kΩ pull-up resistor to the JTAG interface's TCK pin to reduce susceptibility to EMI.
- In noisy systems, add pull-down or pull-up resistors to every JTAG signal.
- Place small series resistance on JTAG traces that are routed to external connectors.

Isolation And Protection

- Isolate PCB circuits from external systems by galvanic isolation, filtering, or circuits with transorbs or diodes.
- Diodes can be used when a PCB's signal trace interfaces with an external component with dissimilar power and ground voltage supply levels.
- Use a series resistance on the signal trace in conjunction with the diode.

Multilayer Designs

- Design using a power plane instead of traces routed from the power supply.
- Connect split analog and digital ground layers at just one point.
- High-speed digital traces should not jump layers because these signals radiate the most noise from vias.
- Place all signal layers adjacent to image planes.
- Place higher speed and critical trace layers adjacent to ground layers and not power layers.



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