# AZD004

Overview of Azoteq Sensing Technologies

## Contents

## 1 Introduction

Capacitive sensing is in essence a highly accurate analog measurement process. Azoteq ProxSense® devices can be seen as Analog to Digital converters using Capacitive Sensing. Changes to capacitance in the order of picofarads to femtofarads can be detected with advanced digital signal processing. Azoteq sensors typically focus on very fine capacitance difference measurements. Absolute capacitance measurements are generally not required in most user interfaces and come with a range of challenges if required. Just by looking at Printed Circuit Board (PCB) tolerances, we should expect a difference in capacitance from one PCB to the next. Thus it is very useful to determine relative differences in capacitance.

ProxFusion® is an expansion of the analog measurement process used in ProxSense® (capacitive sensing) devices. With ProxFusion® analog structures, additional sensing capabilities are added. This includes HALL-effect sensing and inductive sensing (metal detection).

This document introduces charge transfer based capacitive sensing. It also covers a few fundamentals like current consumption, component choices, long term average (LTA) techniques, automatic calibration (ATI) and ProxFusion® technologies. For general capacitive sensing design guidelines please see application note AZD125.

## 2 The Charge-Transfer Method

Azoteq uses the charge transfer method to measure charge with its ProxFusion® and ProxSense® ICs. Using a simple analogy, charge, and capacitance are represented by a liquid and a container, represented in figure 2.1. The smaller container is the variable charge measured (sensing electrode) while the larger container is a fixed capacitance ($C_s$). The $C_s$ capacitor is internal to Azoteq ICs.

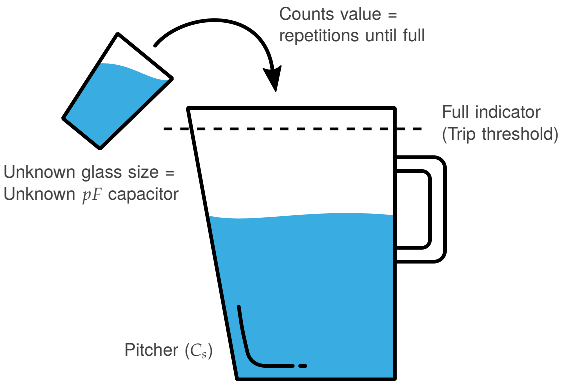


*Figure 2.1*

The smaller container is filled (charged) and then emptied (transferred) into the larger container. The number of times it takes to fill the larger container is representative of the volume (capacitance) of the smaller container. The amount of charge transfer cycles indicates the measured charge. This measured charge contains both the required measured capacitance, as well as an inherent "load" or "parasitic" system capacitance. The number of charge transfer cycles required to charge $C_s$ to a fixed reference voltage is referred to as *counts*. The period at which the small container is charged and discharged is known as the *conversion frequency*.

A typical capacitive sensing application requires the measurement of minute changes in capacitance. Compared to the typical "load" or "parasitic" system capacitance, these small changes are well below 1% of the total capacitance.

More information on the charge-transfer method and charge-transfer cycles can be found in application note AZD102.

## 3 Signal Conditioning

The basic charge transfer method has some challenges that need to be overcome:

- The range of the input capacitance is limited by the size of the internal sampling capacitor.
- A touch on the electrode could contribute to such a small percentage of the overall capacitance on the electrode that touch will be very difficult to detect.
- Measurement resolution is uncontrolled.

For these reasons, additional analog signal conditioning structures are integrated to allow for a wide range of input signals and focus the sensing "engine" on the area of interest (very small capacitive changes).

### 3.1 Resolution Control

The input charge is conditioned by the 2-stage analog circuit that ensures optimal resolution of the charge transfer system using a fixed internal capacitor for a wide range of applications. The first stage is called the Coarse Multiplier and conditions the charge in large intervals. The second stage is called the Fine Multiplier and conditions the charge in small intervals. See Figure 3.1 for visual representation.

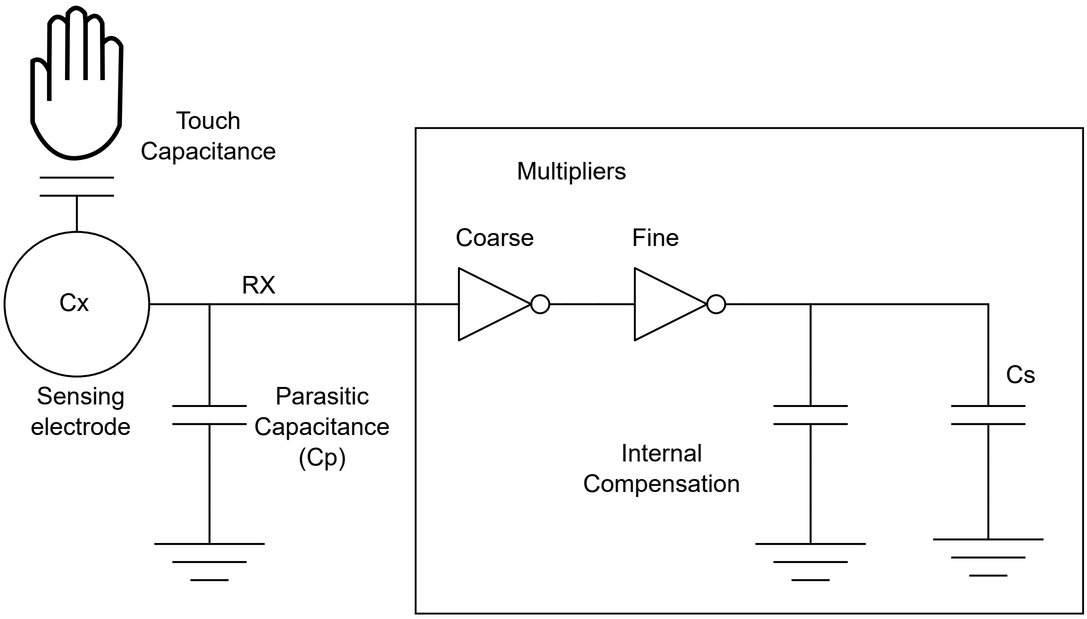


*Figure 3.1: ProxSense® IC's charge transfer overview*

These 2 Multipliers are adjusted until a certain value is reached. This value is called Base value. "Base value" is a term used to evaluate the charge transfer count of the 2-stage analog front-end. Base values typically range between 75 and 200.

### 3.2 Offset subtraction

Offset subtraction refers to the Internal Compensation on the IC. In a certain way, this can be seen as subtracting the DC component from a signal that has a DC and AC component and we are mainly interested in the AC component. By removing a part of the signal, we will need more charge cycles to reach the threshold of our internal sampling capacitor $C_s$.

The "Compensation value" is related to an adjustable capacitor bank that is used to remove a capacitive offset. The "Target value" is the number of charge transfers required to fill the Cs capacitor after charge has been deducted via the compensation capacitance bank. This Compensation value is adjusted until the Target value is reached. Target values are always larger than Base values. For small compensation values, a small part of the signal is removed (thus the sensor will have little sensitivity) and thus a defined touch event might not be detected. For large compensation values, a large part of the signal is removed (thus the sensor will have much sensitivity) and thus a defined touch event might easily be detected. Large compensation values can also result in false touches due to noise that couples into the system being amplified, thus this should be chosen carefully.

## 3.3 ATI intro

ATI (Automatic Tuning Implementation) uses an advanced signal processing algorithm to optimize the hardware sensing circuits.

The advantages of ATI include:

- Increased sensitivity
- Automatic sensitivity adjustment
- Minimal "tuning" of components, settings, or layouts to achieve optimum sensitivity, which enables easier integration into new designs
- Excellent proximity detection
- No external components or programming required to adjust the sensitivity
- Consistent sensitivity to changing environmental conditions

**Base value:** The Base value is the desired number of charge transfer cycles required to fill the internal reference capacitor. This is done by only using the multipliers, thus without any compensation.

**Target value:** The Target value represents the number of charge cycles needed to charge the internal reference capacitor with compensation added. This is done with both the multipliers and the internal compensation.

## 3.4 ATI stages

The ATI routine focuses on two stages of signal conditioning. For the first step, the multipliers are automatically chosen to reach the ATI base value. In the second step, a compensation value is automatically chosen to reach the ATI target value.

## 4 Power Modes

Power modes relate to the current consumption of the device. An MCU is required to switch the analog circuit and runs at a certain clock frequency. When this MCU is ON it consumes current and when it is in sleep mode it consumes much less current. Thus to achieve low current consumption the MCU must be ON for short periods of time and in sleep mode for long periods of time. Some applications (such as battery-operated devices) may require a low current consumption.

One way of lowering the average current consumption is to perform charge cycles with longer periods of time in between. See Figure 4.1 showing charge cycles spaced apart on a timeline.

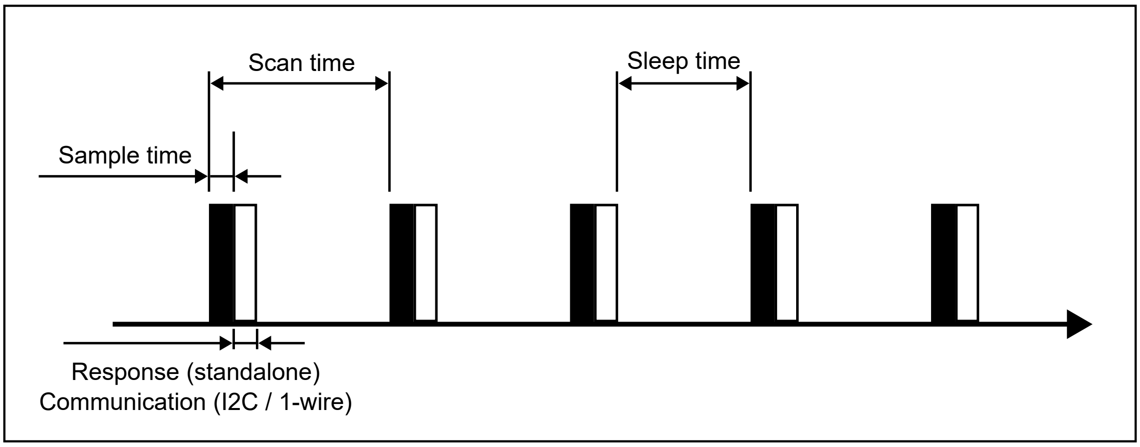


*Figure 4.1: Sample-, scan-, sleep- and communication time diagram*

Performing charge cycles consumes current due to the MCU being ON. By spacing charge cycles further apart would lead to lower average current consumption.

Charge cycles spaced too far apart would lead to sluggish (slow response rate) behavior.

This gives a trade-off between current consumption and response rate. The wider apart the charge cycles are performed, the lower the current consumption and the slower the response rate. The closer the charge cycles are performed, the higher the current consumption and the faster the response rate.

One way of having low current consumption and a fast response rate is by having different power modes and intelligently switching between them. This can be achieved by increasing the time between charge cycles when no difference in capacitance is measured. And by decreasing this time between charge cycles when a difference in capacitance is measured.

A typical use here could entail moving to a lower current consumption mode when no change in capacitance is detected for a certain time. When a change in capacitance is detected move to a higher current consumption mode with a faster response rate.

## 4.1 ULP

ULP (Ultra Low Power) focuses on sensing the least amount of time in order to keep the current consumption as low as possible. See Figure 4.2. NP (Normal Power), LP (Low Power), and ULP (Ultra Low Power) are shown. In NP all channels are sensed in quick sucsession. In LP all channels are sensed with longer pauses in between. In ULP only one channel is sensed with long pauses in between and all the channels are sensed periodically at a very slow rate.

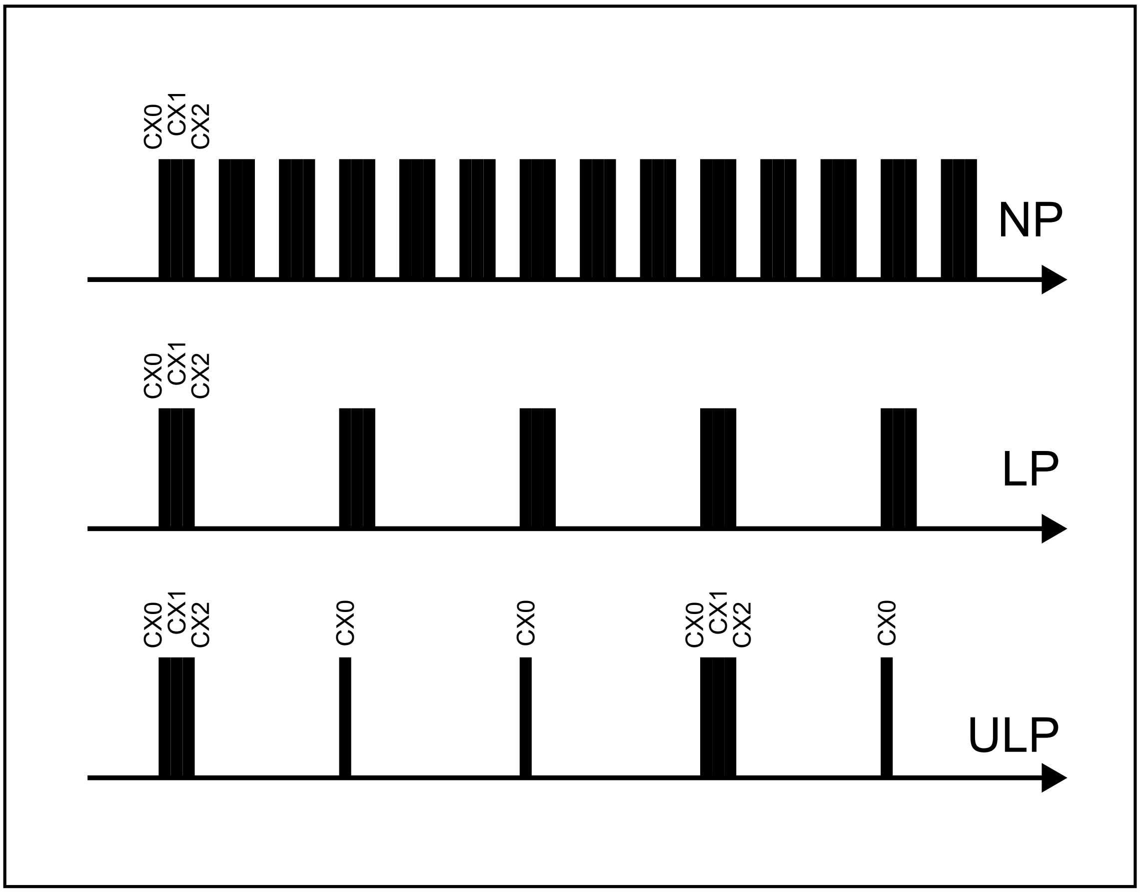


*Figure 4.2: Power Modes Comparison*

# 5 EMC

## 5.1 Introduction

In most sensing applications there exist a distance between the IC and the electrode from a few mm to tens of mm's. Measuring in the picofarad and femtofarad range, noise can couple into the system between the electrode and IC. This noise can influence the sensor and give false detections, resulting in faulty behavior.

## 5.2 Relevant Standards

There are many EMC standards and the most popular EMC standards will be introduced below.

EMC mainly has two concerns:

- Does the device cause other devices to malfunction ? (Does it radiate too much EMC ?)
- Does the device malfunction due to lack of protection against received electromagnetic energy ? (Is it immune to predefined levels of EMC ?)

For the first question, emissions are measured to determine the energy radiated into the space around the device. Capacitive sensing emissions are typically in the nW to $\mu$W range and thus compliance should not be a problem. For more detail on this, please see AZD085 on the Azoteq website.

For the second question much more care needs to be taken. Capacitive sensing circuits are very sensitive. Interfering sources can couple into these circuits and thus thorough testing is advised. Main focus should be on noise sources which result in capacitive currents flowing to earth, thus focus on common mode EMC tests.

Typical noise sources can be:

- lightning
- power supply voltage fluctuations
- 50Hz or 60Hz magnetic fields
- arcing due to breaks in inductive circuits
- radio transmitters
- electrostatic discharges
- switch mode power supplies

For more detail on this, please see AZD085 on the Azoteq website.

## 5.3 Sync

By synchronizing on certain events we can perform charge cycles at less noisy intervals. A typical example would be if the device is connected to mains power which gives 50Hz or 60Hz frequencies. The system noise is least when the mains power crosses the zero line. This zero-line crossing we call zero-cross (ZC). Thus synchronization on this ZC will get less noise than when performing charge cycles at any other moment in time.

# 6 Capacitive components

Capacitive component miniaturization has a significant impact on certain electrical parameters. For certain capacitor roles in the Azoteq sensing circuit, the capacitor capacity, physical size and tolerance needs to be carefully considered.

## 6.1 Component Choices

It is important to carefully consider the minimum capacity constraints of $\mu$F-range reservoir capacitors on power supply inputs ($V_{DD}$) and regulator outputs ($V_{REG}$). These will be sensitive to derating and tolerance. In addition, inductive sensing circuits will be specifically sensitive to component tolerances.

## 6.2 Derating

The derating of critical power supply capacitors (in the $\mu$F range) should be taken into account. The typical derating of various capacitors are shown in Figure 6.1.

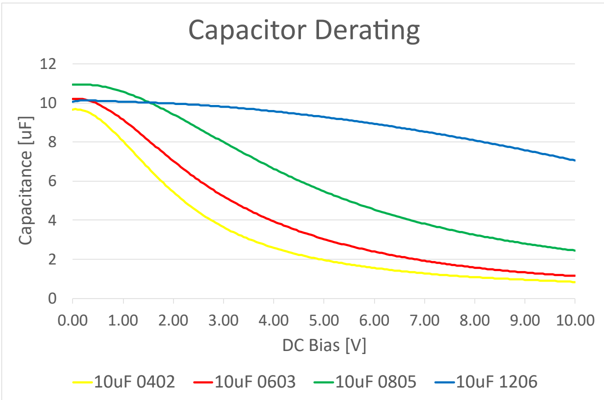


*Figure 6.1: Capacitance variation vs. DC voltage for selected 10uF capacitors*

This means that the 4 Capacitors which should be 10uF each, behave differently when biased at a certain voltage. Let's take for instance the mark at 3.3V, where Azoteq ICs can operate at. For 1206 component size, the 10uF capacitor is still very close to the 10uF value and should operate sufficiently. 0805 component size change to just below 8uF, more than 20% lower than the wanted value. 0603 component size just keeps on going lower to just below 6uF, which is 40% lower than wanted. And lastly, 0402 component size which sits at just below 4uF, less than half of the wanted value.

This shows that a 10uF 1206 capacitor operated at 3.3V will function as a 10uF capacitor. To conserve board space 0402 size might be considered, then the 10uF capacitor will function like a 4uF capacitor which is unwanted.

For 1uF capacitors, the same phenomenon can be seen.

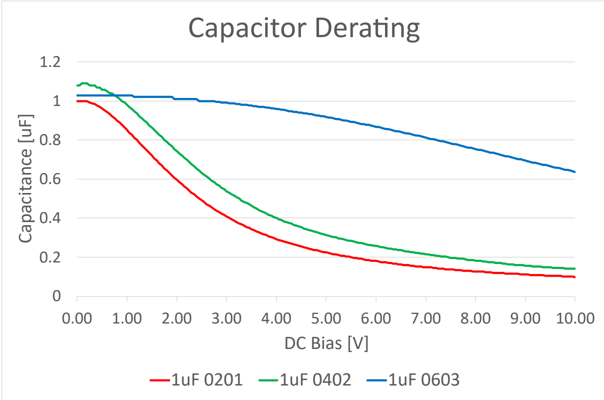


*Figure 6.2: Capacitance variation vs. DC voltage for selected 1uF capacitors*

At 3.3V the 0603 capacitor behaves very closely to a 1uF capacitor, as wanted. The 0402 capacitor is close to 0.5uF which is half of the wanted value. Lastly, the 0201 capacitor is at about 0.3uF which is very much lower than wanted.

Capacitors should be chosen with derating and datasheet limits in mind. For Azoteq capacitive sensing devices, this mainly applies to $V_{REG}$ and $V_{DD}$ requirements.

# 7 Azoteq Sensing Technologies

## 7.1 Self-capacitive Sensing

*Surface* or *self-capacitance* technology makes use of the parallel plate capacitor theory where

$C = \frac{\epsilon_r \epsilon_o A}{d}$.

The capacitance is measured between the electrode and the earth and is dependent on the surface area $A$ of the electrode and approaching conductive object, as-well-as the distance $d$ between them.

- As a finger (conductive object) approaches the electrode the distance $(d)$ between the electrode and the earth decreases, effectively increasing the capacitance $(C)$.
- $Q = CV$. As $C$ increases, the charge $(Q)$ per transfer increases too.
- This will decrease the number of transfers required to charge the reference capacitor $C_s$ to a fixed voltage. Therefore counts go down when touching self-capacitance applications.

Typically, self-capacitive technology operates at a conversion frequency of around 250kHz.

Figure 7.1 shows an equivalent circuit model for a typical self-capacitive application. [1]

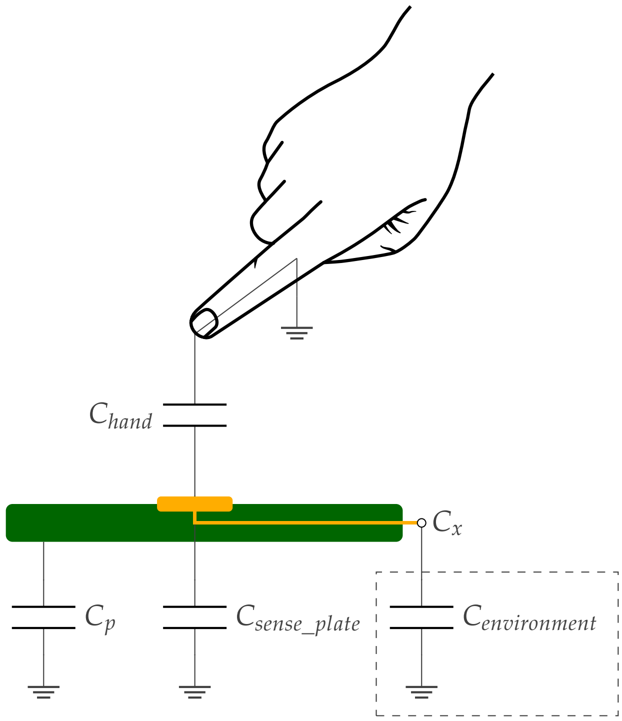


*Figure 7.1: Self Capacitance Circuit*

$C_p$ is the parasitic capacitance. See section 9 for more information on parasitic capacitance. $C_{sense\_plate}$ is the capacitance between the electrode and ground. Together $C_p$ and $C_{sense\_plate}$ make up $C_{environment}$. It is this capacitance, along with $C_{hand}$, that is seen at the $C_x$ pin.

[1] Approximation of reality

## 7.2 Mutual Capacitive Sensing

Electrically charged conductive objects close to one another will form an E-field. *Mutual capacitive* technology measures the change in capacitive coupling between *two* electrodes. The coupling between the electrodes is called mutual capacitance ($C_m$) and the electrodes are called the transmitter ($CT_x$) and receiver ($CR_x$). Figure 7.2 shows the capacitance $C_m$ between the electrodes and the parasitic capacitances associated with each electrode.

- As a finger (conductive object) approaches the electrodes couple more with the finger and effectively "steal" some of the charges. This causes the capacitance $C_m$ between the electrodes to decrease.
- $Q = CV$. As $C_m$ decreases, the charge ($Q$) per transfer will decrease too.
- This will increase the number of transfers required to charge the reference capacitor $C_s$ to a fixed voltage. Therefore counts go up when touching mutual-capacitive applications.

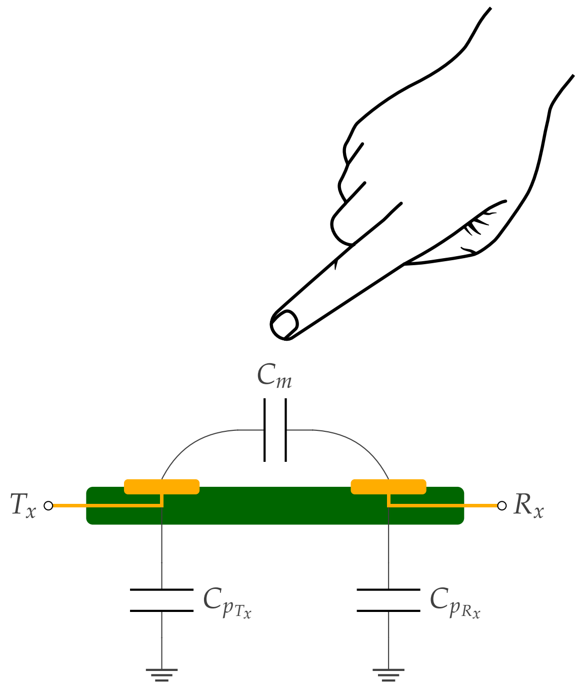


*Figure 7.2: Mutual Capacitance Circuit*

This explanation assumes that the finger is strongly coupled to the earth. In applications where the approaching conductive object is floating, $C_m$ is typically found to increase. However, for a typical touch application, the user will be closely coupled to earth.

A typical mutual-capacitive application operates at a conversion frequency of around 1MHz.

Mutual-capacitive technology can be used in single-capacitive button applications as well as in keypads and trackpads. It is suited to these applications because the sensing electrodes are tightly coupled to one another and therefore multiple electrodes can be placed close to one another with minimal inter-electrode interference.

The term *projected-capacitance* is sometimes used instead of *mutual-capacitance*.

## 7.3 Resonant Inductive Sensing

By placing a capacitor and inductor in parallel as shown in figure 7.3, an *LC tank* is formed. This circuit has a resonant frequency $f_{res}$. The resonant frequency is dependent on the value of the inductor and capacitor. Thus, by keeping the capacitor $C$ fixed, a change in the inductance $L$ can be detected by measuring a shift in the resonant frequency. This is done by driving the $T_x$ node close to the resonant frequency and measuring the amplitude of $V_{tank}$.

When a metal object approaches the inductor, eddy currents are formed in the object. This causes the frequency response of the *LC Tank* to shift and results in a decrease in the amplitude of $V_{tank}$. Azoteq's ProxFusion® and ProxSense® ICs drive the $T_x$ node and measure the amplitude of $V_{tank}$ at the $R_x$ node to measure the change in the inductance $L$. In this way, the presence of a metal object near the inductor can be detected.

Typical applications for inductive sensors include waterproof snap-dome buttons and metal flex force sensors.

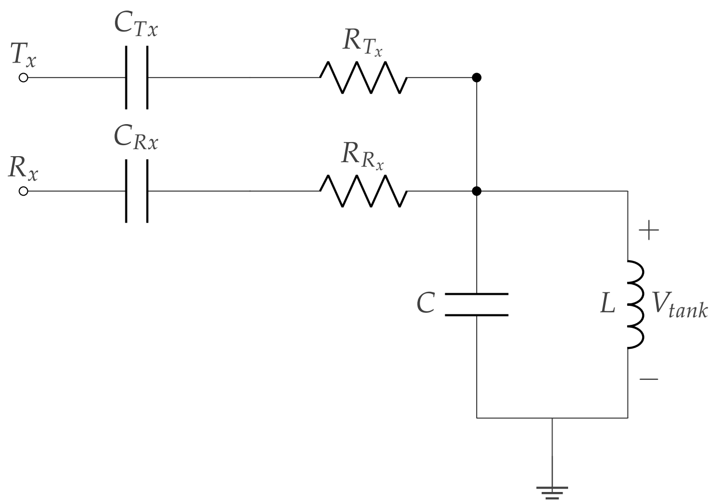


*Figure 7.3: LC Tank Circuit for Inductive Sensing Mode 1*

For more details on this sensing method please refer to AZD115.

## 7.4 Hall Effect Sensing

The Hall Effect is a phenomenon where charge carriers can be deflected in the presence of a magnetic field. Azoteq's hall sensing ICs use this phenomenon in combination with our ProxFusion® Technology to measure magnetic field strength using dedicated *Hall Plate* areas within the IC.

Information regarding the amplitude of a magnetic field can be used to create magnetic switches. By placing these sensing areas on the edges of the IC it is possible to calculate field differentials which are used to determine the orientation of discrete magnets within range of the IC.

Hall effect sensors can be used for contactless switches and to measure angular position. Typical applications include mouse wheels and earbud docking detection.

For more details on this sensing method please refer to AZD127.

## 8 LTA Overview

A touch or proximity event is recorded if the current counts and a reference value differ by more than a set threshold. In an absolute measurement the reference value is fixed. When using relative sensing, the reference value is dynamically updated. Azoteq ICs make use of relative sensing which enables them to detect small changes in the measured signal.

### 8.1 Long Term Average (LTA)

The dynamically updated reference value is known as the Long Term Average (LTA). The LTA is a channel-specific filtered average of the measured counts. It allows ProxSense® and ProxFusion® ICs to intelligently track slow changes in the external environment.

A touch or proximity event is recorded if the current count's value and the LTA differ by more than a configurable threshold. During such an event, the LTA filter is halted for a maximum time of $T_{HALT}$. During this time the value of the LTA is frozen. If a touch or proximity event lasts longer than $T_{HALT}$, then the system will re-calibrate (re-ATI) and the LTA is adjusted to match the new calibration. Upon exiting a touch or proximity event the LTA filter is unfrozen and the LTA value is once again continuously updated.

If an object or a hand comes into proximity with the sensor the current sample is affected. If the objected is not removed after a set time (adjustable) the LTA is typically adjusted to equal the current samples. The sensor is now calibrated to the new environmental condition and can register proximities to the same level of accuracy (sensitivity) as before the object was introduced to the environment.

When the current samples drift slowly towards a proximity threshold, the LTA reference will slowly adjust according to the filter characteristics defined. The LTA is also capable of readjusting upwards (away from the proximity threshold) as soon as the object causing the interference is removed (as the current sample will move up). Typically a different adjustment speed is chosen according to the direction of the change in current samples compared to the LTA. Typically the LTA adjusts at a different speed when the current samples are above the LTA, than when below the LTA.

As an example, see Figure 8.1. The Couns value is represented by the blue line. The LTA value is represented by the red line. The Delta value is represented by the green line. The Delta is the difference between the Counts and LTA value. When the difference between Counts and LTA value is small, such as at areas A and C, the LTA follows the Counts value. When the difference between Counts and LTA value is big, such as at area B, the LTA Halts and does not follow the Counts value.

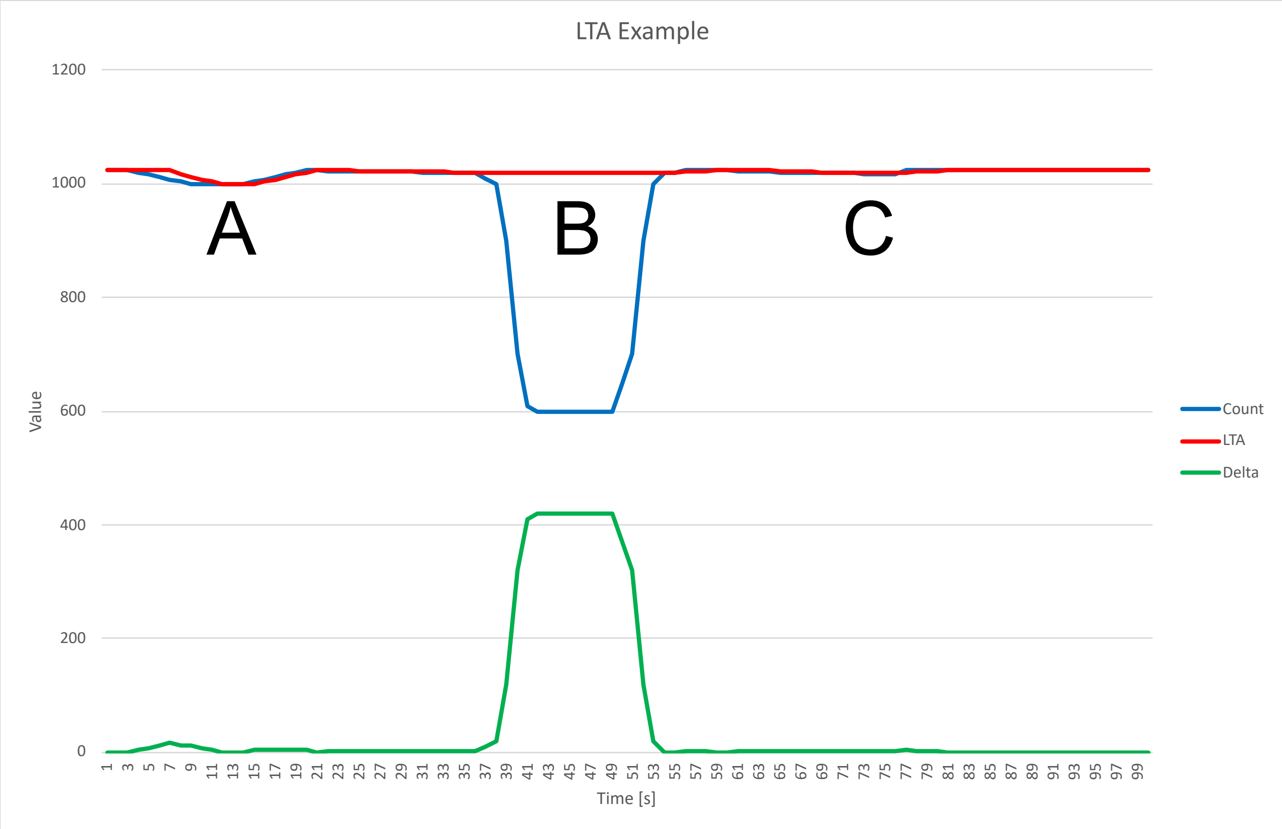


*Figure 8.1: LTA follow Counts example for small variations*

## 9 Parasitic Capacitance

In any capacitive application, there exists some parasitic capacitance $C_p$ to ground. This parasitic capacitance hurts the sensitivity of the measurement. The unwanted capacitance is caused by coupling to or between ground pours, PCB traces, and other metals near the sensor.

To understand why parasitic capacitance negatively affects sensitivity, it is important to note that Azoteq ICs make use of a *relative* measurement. A large parasitic capacitance results in a small relative change in the total measured capacitance.

In a self-capacitive example application, a user interacting with the sense electrode causes an increase in the measured capacitance of 1pF. In one design, the parasitic capacitance is high and contributes 100pF to the total capacitance. In another design, the parasitic capacitance is only 10pF.

- In the first design, the measured capacitance increases from 100pF to 101pF. There is a 1% increase in capacitance.
- In the second design, the measured capacitance increases from 10pF to 11pF. There is a 10% increase in capacitance.

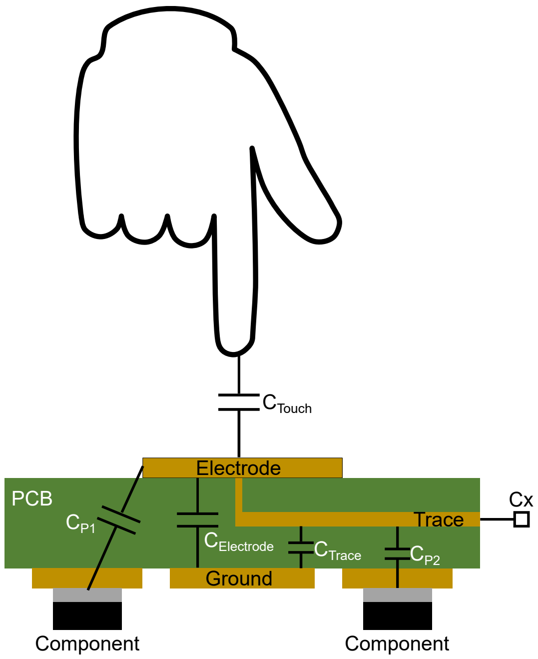


*Figure 9.1: Parasitic Capacitance example*

The second design will be much more sensitive because, for the same user interaction, there is a much greater relative increase in the measured capacitance. It is therefore important to reduce the parasitic capacitance as much as possible.

## 10 Automatic Tuning Implementation (ATI) Overview

ProxSense® and ProxFusion® IC's feature market-leading Automatic Tuning Implementation (ATI) technology, incorporated to ensure increased sensitivity and ease of implementation into new designs. The ATI feature uses an advanced signal processing algorithm to optimize the hardware sensing circuits.

The advantages of ATI include:

- Increased sensitivity
- Automatic sensitivity adjustment for various sensing electrodes
- Minimal tuning of components, settings, or layouts needed to achieve optimum sensitivity, which enables easier integration into new designs
- Excellent proximity detection
- No external components or programming required to adjust the sensitivity
- Consistent sensitivity to changing environmental conditions

### 10.1 ATI in Capacitive Applications

In capacitive applications, ATI compensates for the following:

- The parasitic capacitance $C_p$
- Changes in capacitance caused by the environment (temperature and humidity)
- Variations in the electrode layout and routing
- Changes in the overlay thickness or type of overlay used
- PCB type (FR4/FPC)

### 10.2 ATI in Inductive Applications

In inductive applications, ATI compensates for the following:

- Changes in capacitance caused by the environment (temperature and humidity)
- Variations in the TX/RX coils during manufacturing
- Variations in the coil layout and routing
- Changes in the overlay thickness or type of overlay used
- PCB type (FR4/FPC)

### 10.3 ATI in Hall-Effect Applications

In hall-effect applications, ATI compensates for the following:

- Magnetic field variation
- Changes in environmental temperature
- Variations in mechanical implementation

## 10.4 Conclusion

One of the biggest challenges sensor designers must deal with is dynamically designing solutions used in a variety of applications, while maintaining optimum performance. The ATI algorithm allows product developers to design sensing electrodes, trackpads, and inductive sensors rapidly and easily. The ATI algorithm's benefit is the advantage that the sensors will have similar performance, even over variations such as manufacturing tolerances or environmental conditions. Azoteq offers a full range ProxSense® and ProxFusion® IC's that integrates the ATI algorithm in a variety of packages that can be used in self-capacitive, mutual capacitive, and inductive sensing.

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