Exhibit C
(Submitted Under Seal)

maXTouch Sensitivity Effects For Mobile Devices

1. Introduction

There is a growing acceptance of capacitive sensors in consumer devices. They allow the creation of very "cool" touch devices with intuitive user interfaces and smooth and fast responses to touch inputs.

Atmel's maXTouch™ devices address the need for high resolution XY sensing, coupled with the ability to also support touch keys.

The maXTouch devices offer a number of advantages in operation when compared to other competing technologies like resistive or optical sensors. For example, a capacitive sensor uses no moving parts and so is not subject to the wear-out problem of resistive sensors. In the case of maXTouch, the sensor can operate with a passive stylus and so the convenience of resistive stylus input is emulated without the downside of the mechanical fragility.

Multi-touch capability is also becoming more common, with XY touchscreens able to track several finger touches at the same time. This is the case with the mXT224 maXTouch chip, capable of tracking up to 10 touches simultaneously.

The sensitivity of any capacitive touchscreen, or any other capacitive touch sensor for that matter, relies on a number of physical factors that designers are often not aware of. Part of the initial "tuning" of a sensor requires that the designer picks a detection threshold to decide when touch is registered on the sensor.

This application note aims to highlight these factors and give some guidance on how to improve or mitigate the effects that changes in these factors can have on usability, and how to pick a "correct" detection threshold.

maXTouch Sensitivity Effects

Application Note QTAN0061

maXTouch™

10735BX–AT42–05/10

2. How Does Charge Transfer Work?

2.1 Introduction

This section describes the QMatrix™ technology, as this is the basis of the maXTouch touch sensor controllers. Understanding how QMatrix works will allow greater appreciation for some of the factors described in following sections.

Note: ***These factors are true for ALL methods of capacitive measurement, regardless of vendor.***

2.2 Summary Description

The following description is a brief description for those readers that want a quick summary.

- QMatrix measures the *mutual* coupling capacitance between a transmitter electrode X and a receiver electrode Y.
- An array of transmitters and receiver electrodes are arranged to form a grid to make a touchscreen. The grid creates an array of X-Y intersections or "nodes".
- The controller generates a "burst" of pulses on each X electrode in turn.
- Each pulse causes current to flow from X to Y because of the mutual capacitance.
- The current per pulse is integrated over time by a receiver connected to Y. It therefore measures charge because $Q = \int i.dt$.
- The charge measured is proportional to the mutual capacitance between X and Y.
- To improve measurement time there can be multiple integrators working in parallel, but it must be understood that X bursting is strictly sequential in nature and always one at a time, otherwise the unique measurement per X-Y intersection would be lost.
- Touching near an X-Y intersection influences the coupling capacitance.
- The touching object diverts charge away from the integrator, returning it to the touch controller chip via the touching finger, the person's hand, the body, and so on.
- This charge return path includes the "free space capacitance", Cf, of the device.
- Thinking of this capacitance as a lumped element is very misleading (but convenient) as it is spatially distributed in nature.
- The actual capacitance of the touch contact patch, Ct, is in series with Cf and hence the total capacitive influence from the touch is:

$$[(Ct \times Cf)/ (Ct + Cf)].$$

2.3 In-depth Description for the More Inquisitive Reader

2.3.1 Measurement Technique

The goal is to measure the coupling capacitance between a transmitter electrode X and a receiver electrode Y and to arrange for that coupling capacitance to change only when touched near the X-Y intersection (or "node").

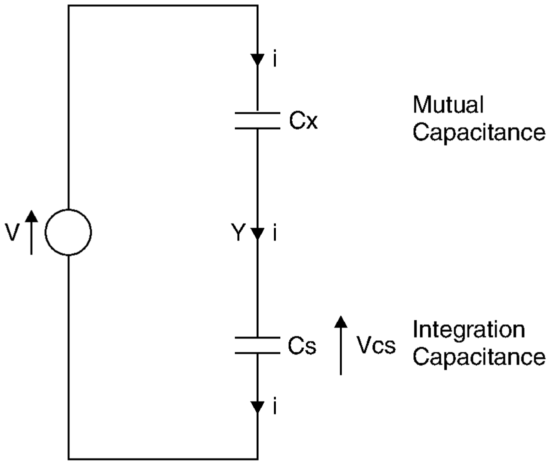
An array of coupling capacitances are formed by spatially distributing a grid of X and Y electrodes. The exact capacitance value of these X-Y nodes is not too important, but is typically a few pF, and is arranged to be quite closely matched for an entire touchscreen sensor (ideally better than ±10 percent for all nodes).

There are a limited number of ways to measure this mutual capacitance. The method described here is Atmel's patented charge-transfer method, as used in QMatrix.

Whilst there are numerous methods to measure a "self" capacitance, most of these techniques result in an unacceptable amount of touch sensitivity along the X electrode or along the Y electrode. That is, these methods tend to measure the sum of the self capacitance of X and Y electrodes **plus** the mutual capacitance from X to Y.

The basis of the QMatrix measurement is a voltage divider effect between the mutual capacitance Cx and a measurement capacitance Cs (see Figure 2-1). The capacitor Cs can be thought of as an integration capacitor, as it integrates the current flowing into it over time, producing a voltage across it, which can then be measured. The current which flows in Cs also flows through Cx by Kirchoff's Current Law (1) because they are in series.

Figure 2-1. Charge-transfer Method



Clearly the capacitive system being described is inherently AC-coupled. DC components play no part. However, any DC that builds up on the Cx capacitor must be neutralized, (2) otherwise it will prevent repeated integrations: current will only flow when a voltage difference is impressed across Cx.

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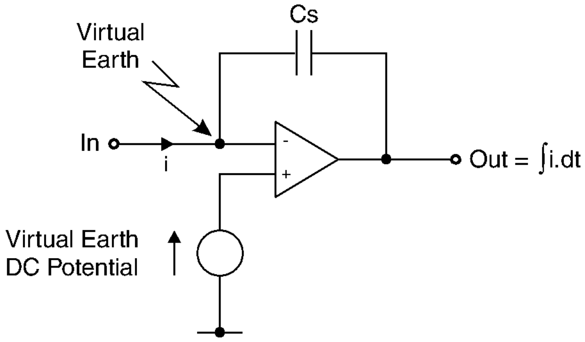
(1) The sum of the currents flowing into a node (junction) is equal to the sum of the currents out.

(2) Actually, the system can work very well with a fixed DC potential across Cx as long as the system is capable of driving a voltage difference across the Cx/Cs combination under all conditions.

The measurement cycle uses a voltage transition on the X electrode to force a voltage difference across the series connection of Cx and Cs. It is important to keep in mind **all** the voltage transitions in a capacitive system, as they are ultimately responsible for causing current to flow. They dictate which capacitances in the whole system are significant and should be factored into the overall measurement. Remember, too, that we want to measure *only* the spatially localized node capacitance, not the capacitance along X or Y electrodes (1).

The preferred configuration for Cs is a virtual earth integrator using an active op-amp (or similar) circuit (see Figure 2-2). This circuit has a very important characteristic: the action of the op-amp causes the Y electrode's potential (the integrator's input) to be actively held at a DC potential (2). This is known as a virtual earth integrator in recognition of the fact that, while the integrator input terminal appears to be a low impedance DC potential from the outside, it is in fact an active terminal and any current flowing into or out of the terminal can be manipulated around the op-amp's feedback path. As mentioned above, controlling voltage differences in the system allows us to control which capacitances we are actually measuring. So to have **no** net voltage change on the Y electrode renders the Y electrode *not* touch-sensitive; Cpy becomes unimportant to a first approximation (3).

Figure 2-2. Virtual Earth Integrator Using an Active Op-amp Circuit



Starting with a fully discharged system (that is, one in which all DC potentials in the sensor and integrators are at the same virtual earth potential), a rising potential is driven by the controller onto a single X electrode. This is done with a slew-rate-limited CMOS driver. This causes current to flow along X, through Cx, along Y and into the virtual earth, at which point it is integrated. After a settling period (typically a few microseconds), the integrator has settled to *almost* its ultimate voltage. Of course, theoretically, this settling profile is pseudo exponential and hence never actually reaches full charge.

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1. As doing so makes the system non-multi-touch capable, or at best, highly compromised multi-touch.
2. Except for the time when the op-amp is settling when some charge diverts momentarily into the Y electrode capacitance Cpy. However, after allowing an appropriate settling time the op-amp "pulls" the charge back out of Cpy to restore the Y electrode's voltage accurately to the virtual earth potential.
3. In fact Cpy affects the settling time of the charge integration. Larger Cpy slows it down. Current flowing down the Y electrode can divert into Cpy if the voltage on Y is allowed to rise. No integrator is perfect and hence this voltage rise is inevitable, albeit transient in nature. A well designed integrator can restore this voltage back to the virtual earth's DC potential rapidly by pulling the charge in Cpy back out again, into Cs, so negating the momentary voltage rise on the Y electrode. If Cpy changes due to touch, it can be seen that this causes a small settling timing change, but not a measurement change, *if* sufficient settling time is allowed.

A good design rule is to ensure that a settling time of at least three sensor time-constants is allowed and ideally five time-constants. The latter represents 99.7 percent of full charge. The time-constant here is the total X-to-Y "delay" caused by the various resistances and capacitances in the system (Rpx, Cpx, Cx, Cpy, Rpy, plus others). Calculation of the RC time constant for a particular sensor design is done using proprietary Atmel tools. (1).

So now we have an amount of voltage at the output of the integrator that is proportional to Cx only. (2)

We could stop and measure this voltage if we choose, and use this as our measurement. Alternatively we could disconnect the integrator from Y, assert the virtual earth potential to *both* sides of Cx to "reset" it (hence returning X to its starting potential), and then reconnect the integrator and make a second rising edge on X. By superposition, this will cause another equal amount of charge to integrate. It also has the useful side effect that the integrator output voltage gets larger, and hence increases SNR (3) for the ensuing integrator measurement (all other things being equal). It also has a useful "averaging" effect, helping to dilute the effects of transient noise.

With the right integrator configuration, it is also possible to integrate charge using both the rising and falling edges on X. This is a very efficient method in terms of time.

It is also highly advantageous to have multiple integrators working in parallel. In this way we can reduce the overall measurement time for the nodes distributed along a single X electrode.

Lastly we should consider what happens to the "other" non-pulsed X electrodes. To be able to measure each node uniquely we must, of course, apply pulses to only one X electrode at a time. So X electrodes are driven in a sequential, one-at-a-time, manner. The non-driven electrodes are usually clamped to GND for noise suppression reasons.

Actually, from an AC point of view, and from a charge-transfer point of view, even if the non-pulsed X electrodes were "floated" they would in reality tend to look substantially low-impedance to system GND.

2.3.2 Single Touch Influence

With QMatrix measurement, we are explicitly measuring the coupling capacitance Cx between X and Y. It is clear that the current flow through Cx is what we are measuring (the time integral of the current to be precise). The physical nature of Cx is the spatial arrangement of the X and Y electrodes where they cross. Electric field couples from X into Y by design, and hence current flows through this node when the X voltage is transitioned.

Any current supplied by the X driver that returns to GND directly (and hence back to the controller chip), and not via Cx, has no impact on the measurements. This current flow is associated with the parasitic capacitance on X called Cpx (see Figure 2-3 on page 6). At least part of this capacitance comes from electric field emanating from the pulsed X electrode and coupling into its neighboring X electrodes. It is unavoidable and quite normal.

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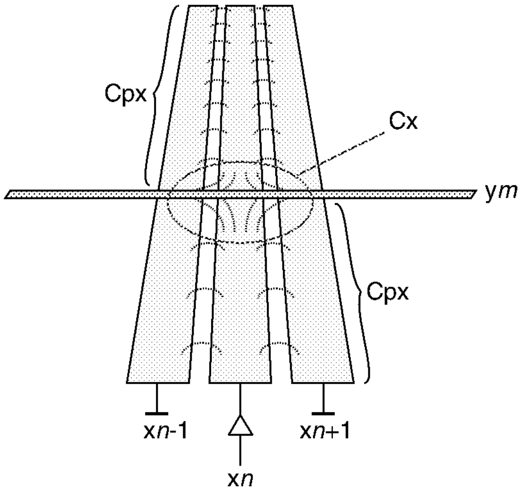
1. Some vendors will report simple "rule of thumb" computations for maximum resistance, capacitance, and so on. Be wary of such over simplifications; they can be very misleading and create marginal designs.
2. We have discussed Cpy in terms of touch sensitivity, but not Cpx. It is easy to see that Cpx does not feature in the overall measurement because it only (marginally) affects the voltage rise-time of the X electrode and not the voltage level. If there *is* X electrode touch sensitivity, it implies the settling time is drastically too small and the system is badly flawed.
3. SNR = Signal-to-Noise Ratio, a measure of the ability of a system to resolve small changes in the input variable.

Figure 2-3. Parasitic Capacitance (Cpx)

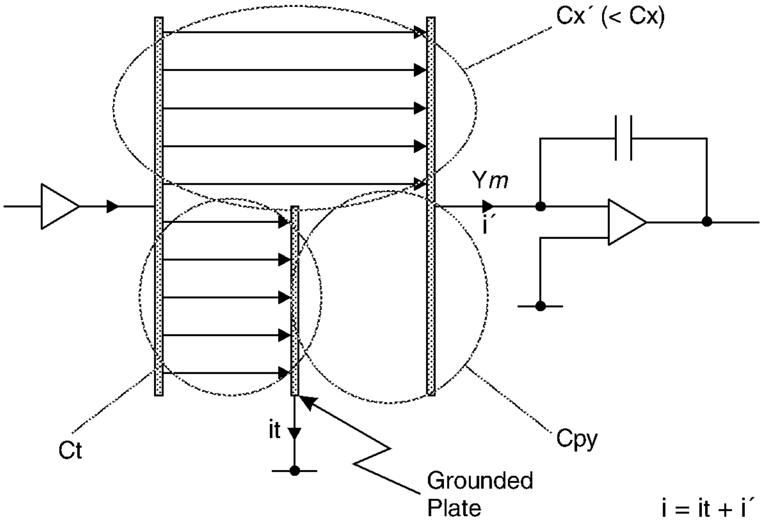


So what happens when we touch an X-Y node? The real answer is quite complex, but let us build the picture up in stages.

Simply put, the touching finger interrupts the coupling from X and Y, and diverts charge away from the integrator input, so that the charge travels through the touch, and couples back to the GND pin of the controller via the body (so obeying Kirchoff's Current Law). However, this explanation too simplistic. How exactly does this work? Furthermore, why does the touch divert charge anyway: surely Cx is fixed by the design of the sensor and its value does not change?

Thinking about electric fields can help us here. If we consider the field distribution between X and Y, and imagine what happens if we place a grounded (1) metal plate, t, in this field then we start to postulate that perhaps Cx might actually reduce because a part of the X to Y coupling region is removed from Cx and instead is formed between X and t. Think of this as the touch capacitance, Ct (see Figure 2-4).

Figure 2-4. Touch Capacitance (Ct)



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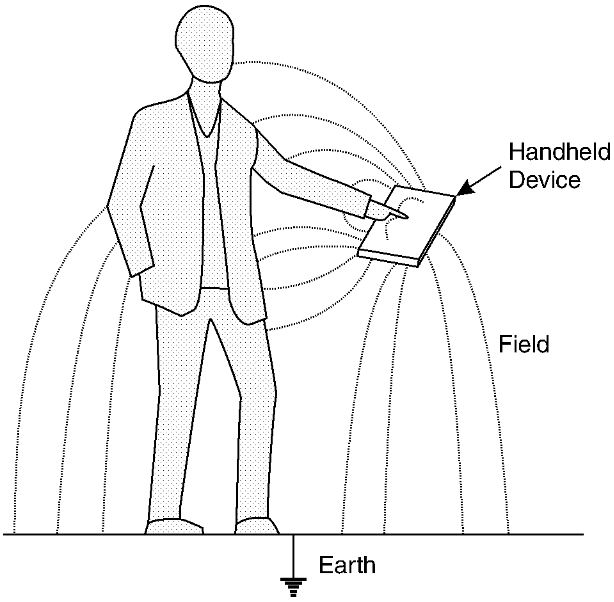
(1) By grounded we mean connected to GND, that is the device's 0V power rail; not the same as Earth.

The touch acts to “split-off” part of Cx to become Ct, with balance of Cx becoming Cx'. From the Y electrode’s point of view, there is also a new capacitor formed from t to Y. But the plate t is grounded and so it cannot introduce any charge. This capacitance appears as an additional amount of Cpy. As we have already said, we are not too worried about Cpy.

So, if we now take the next step and imagine that the touching finger is the equivalent of the plate, we can easily explain the change in Cx caused by touching. However, a normal touch is *not* grounded, and furthermore, a normal touch has a moderate bulk resistance. So a finger touch looks like a poor AC-coupled approximation to the grounded metal plate.

So how – or more accurately where – does the current return to the controller through a touching finger? The answer to the “where” is: from every part of the touch and touching body to a greater or lesser extent (see Figure 2-5). The answer to the “how” is: capacitively – no surprise there!

Figure 2-5. Current Return Paths



If we are not careful, it is possible to get overcomplicated at this point. To avoid this, it is helpful to think about Ct, and importantly, the entire touchscreen and device’s coupling with “free space”, Cfd. (1) We then assume that the body of the touch has its own coupling with “free space”, Cfb. See Figure 2-6 on page 8 for a summary.

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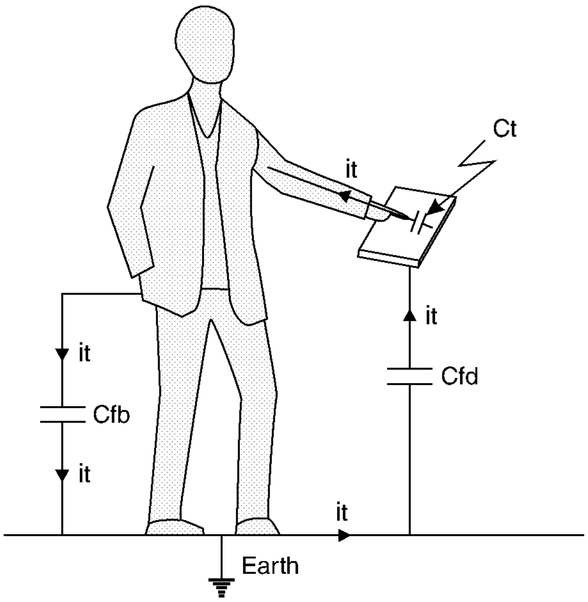
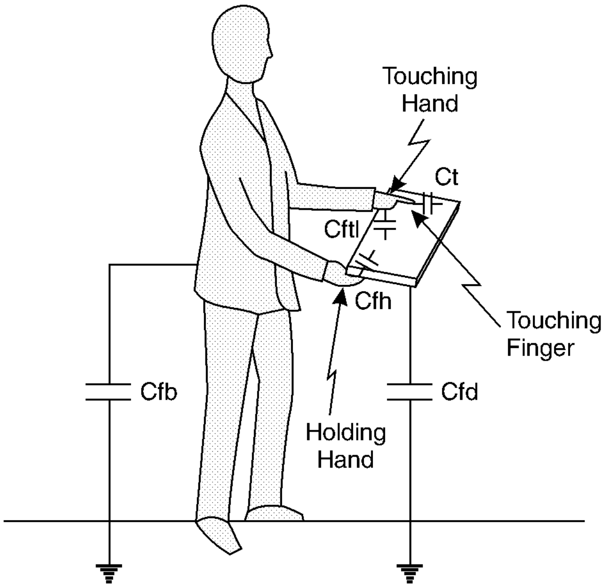
1. Free-space coupling is notionally equivalent to the combined coupling to Earth, that is the surrounding physical environment: floor, walls, tables, chairs and so on.

Figure 2-6. "Free Space" Capacitance Model



The "free space" capacitance model gives as a useful lumped approximation for what happens as an overall picture. However, it is not so useful when trying to understand the behavior for mobile devices that are hand-held. For this we need the model shown in Figure 2-7.

Figure 2-7. "Free Space" Capacitance Model With Handheld Devices



This model takes account of the local return path around the touch Cftl, the overall lumped return paths, Cfb and Cfd, and lastly the extra return path formed by the device being held in-hand, Cfh.

The important relationship to understand is that the touch capacitance caused by a finger's contact patch, Ct, is *always* reduced because it must use a return path that is a combination of the above mentioned capacitances. If we denote the effective touch capacitance as Cte, then:

$$Cte = Ct \# (Cftl // (Cfb \# Cfd) // Cfh)$$

where:
\# means in series with
// means in parallel with

(A quick reminder: capacitors in parallel increase total capacitance, capacitors in series reduce total capacitance.)

If we make the assumption that Cfb is much larger than Cfd,(1) then this equation simplifies to:

$$Cte = Ct \# (Cftl + Cfd + Cfh)$$

So, as can be seen, the reduction in Ct is reduced if Cfh is made large, the other two terms in the parallel connection being rather hard to influence.

2.3.3 Multi-touch Influence

As we saw in Section 2.3.2, the return path situation is complex enough with single touch; so what happens when we apply two touches? The return path situation stays unaltered:

- There is still a local return path contribution for each touch.
- There is still a free-space coupling effect overall.
- There is still a hand-held return path effect overall.

BUT...
the second touch (Ct_2) acts as a new return path
AND...
it tends to retransmit X from one touch to the other:

$$Cte\_1 = Ct\_1 \# (Cftl\_1 + Cfd + Cfh + Ct\_2)$$

The equation shown here is only part of the picture due to the retransmission effect mentioned above.

The extra return path from the second touch **does** mean that each of the two touches get stronger than one alone, but the effect can appear to be swamped by the retransmission effect, as described in the following text.

With reference to Figure 2-8 on page 10, imagine that the touches are #1 and #2, with the lower touch being #1. For example, touch #1 is over node (X1,Y1) and touch #2 is over (X4,Y5). When the sequential X scan reaches the X1 row that is "underneath" touch #1, the X1 electrode is burst and all other X electrodes are held at GND. The touch diverts some of the charge from the X-Y coupling under the finger. But also, the finger now looks like a weak X line driver because it is capacitively coupled to X1. So touch #1 picks up the X1 burst.

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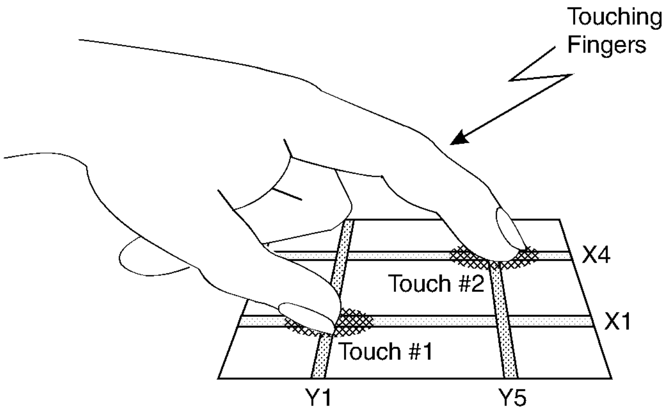
[1] Which it normally is if the product is substantially smaller than the person touching it.

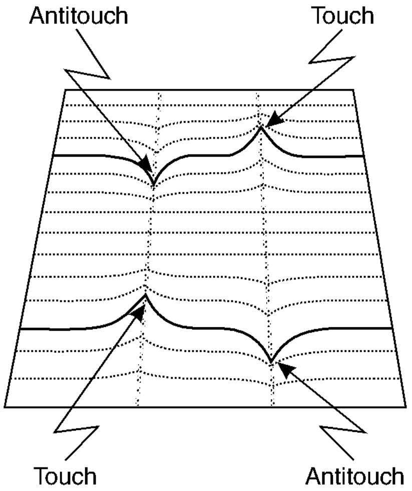
Figure 2-8. Local Return Path With Multi-touch



The conductivity of a hand is quite good, so the X_1 burst appears at the tip of the finger which is numbered touch #2. Touch #2 is capacitively coupled to the Y5 electrode that it is physically above and so it "injects" some charge into this Y5 receiver. The effect is to cause the measurement on the X1Y5 node to raise artificially: that is, the signal goes towards antitouch (1). Remember that when we burst X1 we collect the node measurements for X1Y0, X1Y1... up to X1Y*m*. We are not expecting any signal on X1Y5 because there is no touch above it, and yet we see antitouch there because of a second touch over the Y5 column elsewhere on the sensor.

If the two touches are over the same column, the effect of the increased return path is more than offset by this antitouch effect and the two touch "peaks" reduce in size as a result (see Figure 2-9).

Figure 2-9. Touch and Antitouch Effects When Two Touches are Over The Same Column



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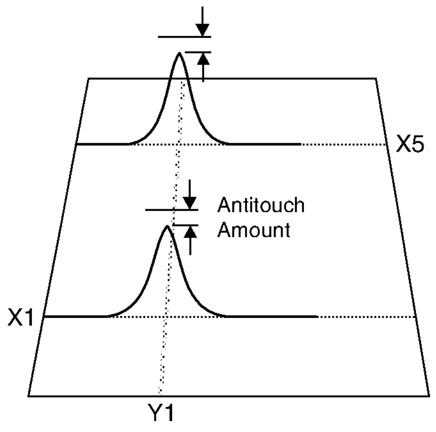
(1) A touch normally diverts charge away and so the measurement gets smaller – towards touch.

The same is true if the two touches are along the same row (see Figure 2-10).

Figure 2-10. Touch and Antitouch Effects When Two Touches are Along The Same Row



Both peaks are lower because they share the same Y

With three or more touches, or very large touches that cover more than one or two nodes, the effects become a superposition of all the touch and antitouch contributions. The situation rapidly becomes complex.

If the device has a good return path, these effects are usually too small to care about.

3. Factors That Affect Sensitivity

3.1 Introduction

As was described in Section 2, there are multiple return paths that allow charge diverted by a touch to return to the touch controller (which it must).

We can think of these return paths as discrete/lumped capacitors to help the discussion, but of course they are really spatially distributed in nature. Keep this in mind in the following discussions.

For a single touch, the lumped returns paths are (see Figure 2-7 on page 8):

- Local return path around the touching finger, Cftl
- The device's free space coupling to Earth, Cfd (1)
- An extra hand-held return path, Cfh

All three of these paths work in parallel and hence they all add an amount to the overall return path "strength".

The stronger the return path, the easier it is for the charge to get back to the controller chip, and so the stronger the touch signal looks good.

This means the touch sensitivity changes as these paths change.

So what affects these return path components? The answers are in the following sections.

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1. There is also the free space return path to Earth of the person touching but this is assumed to be an order of magnitude (at least) larger than the device's return path and hence becomes insignificant.

3.2 Local Touch Return Path – Cftl

This depends on:

- **The size of the touch**

  A larger touch will tend to overlap with neighboring grounded electrodes and so improves the local return path. However, it also tends to accentuate the X retransmit antitouch effect, and so tends to come out overall rather neutral.

  The return path of this type also tends to increase for a touch where the finger is at a shallow angle to the sensor because more of the hand participates in the return path.

- **The spacing of the electrodes**

  If the electrodes are more tightly packed, then, in effect, a given touch will look larger because it overlaps more neighboring electrodes, improving the local return path. The same comment applies to the antitouch effect.

There is little we can do about the local return path because it depends on the nature of the touch, and electrode spacing. For very widely-spaced electrodes (say >10 mm) there may be a loss of sensitivity or an unacceptably non-uniformity of sensitivity especially when the device is not "tethered" (see Section 3.3)

3.3 Device Free Space Coupling – Cfd

This depends on:

- **The physical device size**

  Small devices have poor coupling to Earth. Think of the device as one plate of a capacitor, and Earth as the other. Smaller device = weaker return path.

- **The device's construction**

  If the device is made mainly of non-conductive parts and has only a very small conductive chassis or PCB, then the free space coupling can be weak. The careful placement of exposed conductive casework, decorations, and the such like, can help the return path. However, this may present other problems, such as a gross sensitivity increase when the device is held in the hand.

- **Whether the device is "tethered"**

  This is a *major* factor. If you connect ("tether") a battery powered device using a cable to, say, a wall charger or a PC's USB port, there will be a significant improvement in Cfd and so the touch will be more sensitive. In fact, connecting anything conductive to the device will improve Cfd (normally there is some spatial effect, but this is beyond the scope of this document). So attaching, for example, a USB cable alone (that is, one that is not even plugged into a PC), will improve Cfd. If there are no extra contributors to Cfd, we call the device "floating".

  This effect is the second most common reason for a perceived sensitivity shift between "on-charge" and "off-charge". While charging, the device will feel more sensitive.

  It is impossible to put precise figures around the change that will be observed, but expect to see a 10 – 20 percent increase in sensitivity when tethered, due to this effect.

- **The physical location of the device**

  Taking into account the previous point, and if we assume that the device is not tethered, placing the "floating" device on a wooden table and touching it with a single finger will show a different sensitivity to when doing the same on a metal table. Cfd massively increases in this latter case, due to the close coupling with the conductive desk, and hence touch sensitivity goes up.

Larger devices exhibit less sensitivity shift than smaller devices, because Cfd is already large. Devices that are small and predominantly plastic with small internal conductive parts, can exhibit very low Cfd. Therefore sensitivity changes more dramatically between tethered and non-tethered situations, and depending on physical location.

3.4 Hand Held Coupling – Cfh

This depends on:

- **Whether the device is being held or not**

  Clearly this depends on the mode of use of the device. It is common to expect a mobile phone for example, to be operated with a gripping hand in 99 percent of use cases. But it also might be touched while it is resting on a wooden desk. This would require a slightly harder touch to activate because it is just about the weakest combination of return paths imaginable.

  It is impossible to put precise maths around the change that will be observed, but expect to see a 10 – 20 percent increase in sensitivity when hand-held due to this effect.

It might appear tempting to actually expose *grounded* metal parts on the device that make electrical contact with the gripping hand. This would effectively short-circuit Cfh when hand-held and so lead to a near-perfect return path.

But this also accentuates the *difference* in sensitivity experienced between in-hand and on-desk; so it is probably not a great idea. To be clear, this only applies if the metal parts are *grounded*; if they are floating then the situation is basically the same as a normal hand-held return path.

4. Conclusions

Capacitive sensing, of all varieties, relies on return paths that are somewhat vague and hard to imagine. But they *are* real and essential to close the capacitive circuit with the person touching the device.

The sum of return paths in a capacitive system defines how strong a given touch, Ct, looks to the controller chip. Ct is in series with this sum of return paths, and capacitors in series *always* have a net smaller overall capacitance.

☞ **Changes in the return path *will* manifest themselves as changes in sensitivity to touch. This is absolutely normal, and inevitable.**

The primary return path components to consider are:

- **The free-space device return path, Cfd**

  This is affected by physical attributes of the device, such as size and case material conductivity. Cfd is also affected by whether the device is battery powered (and hence “floating”), or is connected to a charger or PC (which improves Cfd).

- **The hand-held return path, Cfh**

  This depends on the use case of the device. When in-hand, the coupling through Cfh improves and increases sensitivity. Operating the same device at arm’s length on a wooden desk, or in a car cradle-mount (for example) will show reduced sensitivity.

☞ **As can be seen, these natural variations of capacitive sensors mean that sensitivity thresholds need to be set in the context of possible variations that are 30 – 40 percent under extreme cases.**

☞ **There is no perfect setting. It is normally best to pick a threshold that is “correct” (1) when the device is hand-held and not tethered, and then accept, for example, a slight drop in sensitivity when on a table or a slight increase when charging.**

☞ **Remember, sensitivity can be context dependent and in certain conditions the threshold can be adjusted on-the-fly; the threshold setting does not have to be an “all or nothing” affair. For example, if you know when a handheld device is tethered or not (by detecting the presence of a charger or USB cable, say), then the threshold can be adjusted accordingly.**

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1. By correct, we mean that a touch is actively registered for a light, vertical finger tip touch on the sensor using a typical adult index finger with a contact patch of around 3 mm in diameter. This is NOT the same as using a flat test target with 3 mm diameter because of the fringe fields and local return path effects described. In this case the target would be more like 5 mm in diameter, depending on construction.

Appendix A. List of Terms

Cf	The total “free space” capacitance; that is, the charge’s return path to Earth.
Cfb	“Free space” capacitance of the user’s body; that is, the return path from the user’s whole body to Earth and not just the hand.
Cfd	“Free space” capacitance of the device to Earth; that is, the return path from the handheld device to Earth.
Cfh	“Free space” capacitance of the user’s hand to the device; that is, the return path from the holding hand to the device.
Cftl	“Free space” capacitance local to the touching finger; that is, the local return path from the area immediately around the touching finger to the device.
Cp	Parasitic capacitance in the circuit; that is, unintentional, additional capacitance on a circuit.
Cpx	Parasitic capacitance on X.
Cpy	Parasitic capacitance on Y.
Cs	The sampling (integration) capacitance in a mutual-capacitance (QMatrix) circuit. The Cs capacitor integrates the current flowing into it over time, thereby producing a voltage across it that can then be measured.
Ct	The capacitance of the touch contact patch; that is, the capacitance at the point of touch.
Cx	The capacitance formed between the X line and a neighboring Y line receiver electrode in a mutual-capacitance (QMatrix) circuit,

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