

MSP430 Advanced Technical Conference 2006



Enabling Single Touch Capacitive Sensing with MSP430

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Agenda

- Overview of Single Touch Applications
- System-Level Careabouts
- MSP430 Implementations
- Keys, Sliders & Demos
- Summary

Applications of Touch Sensing

- **Alternative to mechanical switches**
 - Low cost
 - Longer life
- **Flexible user interface**
 - Simple buttons
 - Sliders
- **Adaptable**
- **Useful in...**
 - Consumer electronics
 - Appliances
 - Residential control
- **... and almost anywhere a switch is currently used**



Touch Sensing Overview

- **Different technologies**
 - Optical, Resistive, Capacitive, Strain,...
- **All detect change in system**
- **Optical**
 - Expensive
 - Complex system design
- **Resistive**
 - Require sensor material that changes R when touched
 - Relatively low cost, but is an additional element to the BOM
- **Capacitive**
 - Can be implemented on PCB directly
 - Flexible sensor size & shape
 - Cost is a function of the PCB and any externals needed

Capacitive Methods

- **Charge transfer technology**
 - Quantum Research Group patented solution
 - Fixed function ICs that measure charge transfer from one sensor C to another
 - Stimulus signal and measurement integrator
- **Capacitive measurement via ADC**
 - Stimulus signal impacts capacitive sensor element, resulting voltage is measured by ADC
 - ADI implementation using a 16-bit Sigma-Delta to perform C-to-Digital conversion
- **Relaxation Oscillator**
 - Creates oscillator dependent on sensor C variation & measures frequency
- **RC Charge/Discharge**
 - Using high frequency clock, times charge and/or discharge times for sensor element with varying C

MSP430 Capacitance Measurement

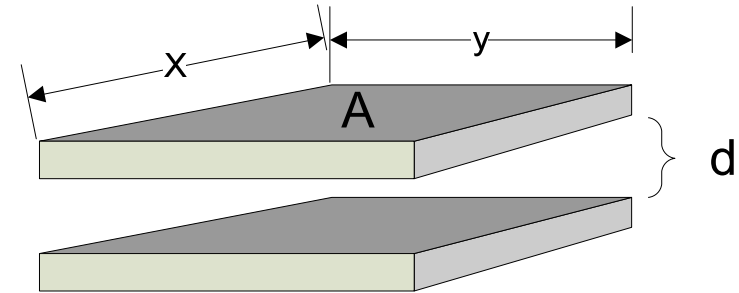
- **Change in capacitance due to physical proximity of a finger or other conductive object**
- **Method 1:**
 - Create oscillator dependent on capacitance of the sensing element
 - Measure freq change when sensor C is changed by touch
- **Method 2:**
 - Measure R-C charge/discharge where R is constant and the sensor element capacitance changes due to touch

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Capacitive Fundamentals

- **Base capacitance created by PCB mechanics**
- **Capacitance change due to changing parasitics**
 - Finger touch proximity (or conductive other source)
- **Minimize base capacitance**
 - Limit parasitics
 - Limit sensor size
- **Maximize impact of change**
 - Match sensor & finger areas for greatest delta-C
 - Minimize distance between sensor and finger
- **Sensitivity**



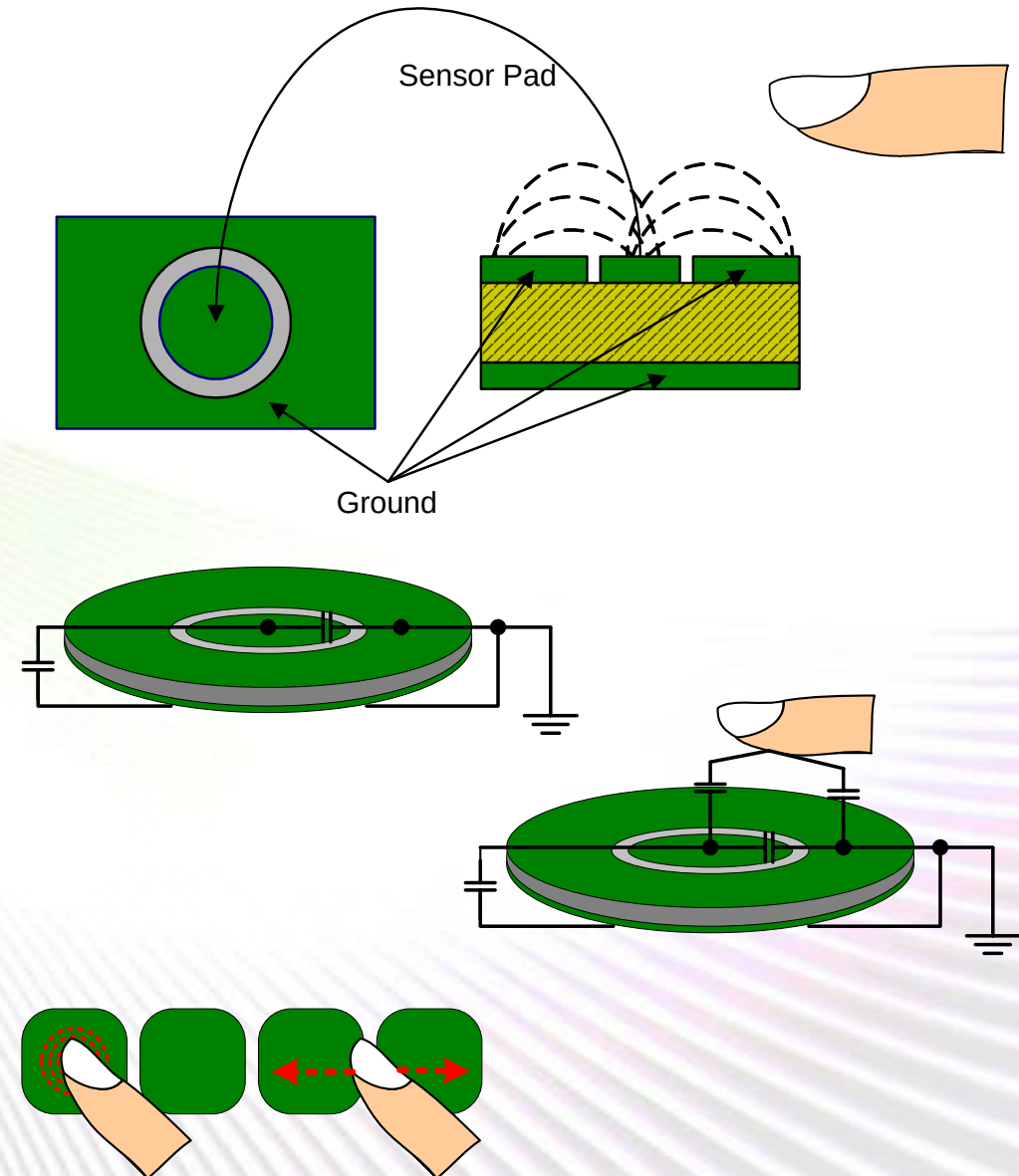
$$C = \frac{\epsilon_0 \epsilon_r A}{d}$$

<i>Material</i>	<i>Dielectric Constant (ϵ_r)</i>
Vacuum	1 (by definition)
Air	1.00054
Polyethylene	2.25
Paper	3.5
Pyrex glass	4.7
Rubber	7
Silicon	11.68

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Capacitive PCB Sensor

- Copper pour on PCB makes a good sensor element
- ~10-20mil spacing between sensor & adjacent elements
- Size pads to maximize finger overlap for max delta C
- Simple pads can also be good sliders
- For true sliders, sizing pads such that more than one is touched at a time helps determine position

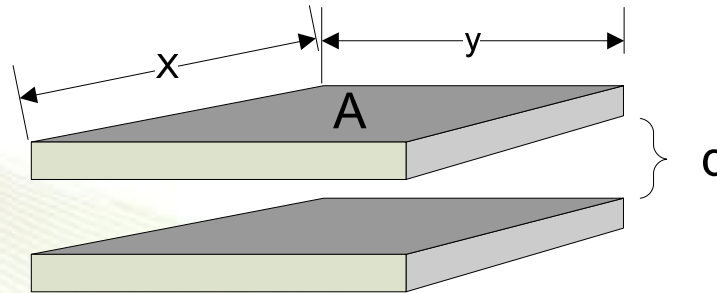


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PCB Thickness

- **Material and thickness matters**
 - Goal 1: Small base C
 - Goal 2: Stable base C

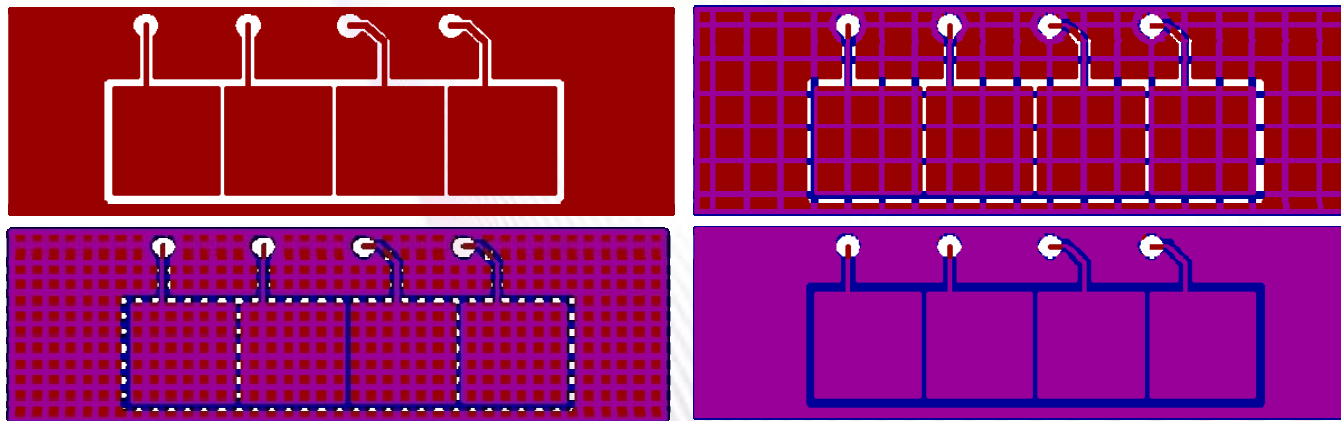
$$C = \frac{\epsilon_0 \epsilon_r A}{d}$$



- As d decreases, the base capacitance increase
- For a given sensor size and insulator thickness, the ΔC created by a touch is fairly constant
- This change is a smaller percentage of the base C as d goes down
- Thinner PCBs require more care in insulator selection and thickness

Layout & Grounding

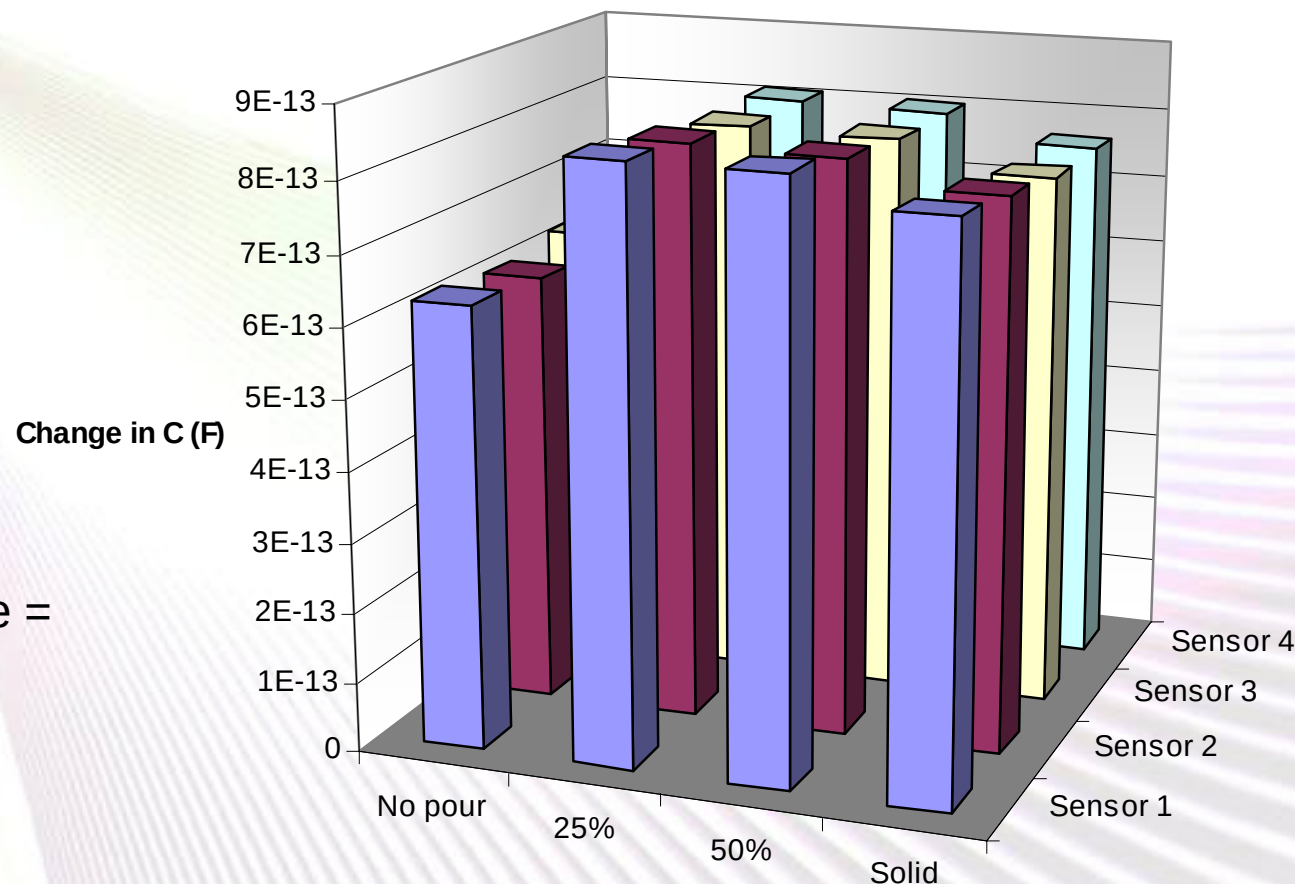
- Minimize noise & signal coupling with solid ground pour on sensor side of PCB
- Hatch pour underneath sensors if possible
 - Solid pour ok for noise, but increases base capacitance (larger A)
 - No pour has no increase in base capacitance but no noise benefits
 - A hatch of 50% is a good compromise



Sensors & Ground Influence

- Tradeoff between PCB ground pour under sensors and sensitivity
- No Pour
 - Low base C
 - Small delta C
- 25-75%
 - Base C increases
 - Larger delta C
- Solid Pour
 - Large base C
 - Harder to influence change = lower delta C

Delta C vs. Pour
(8x8mm sensor on 1.5mm FR4)



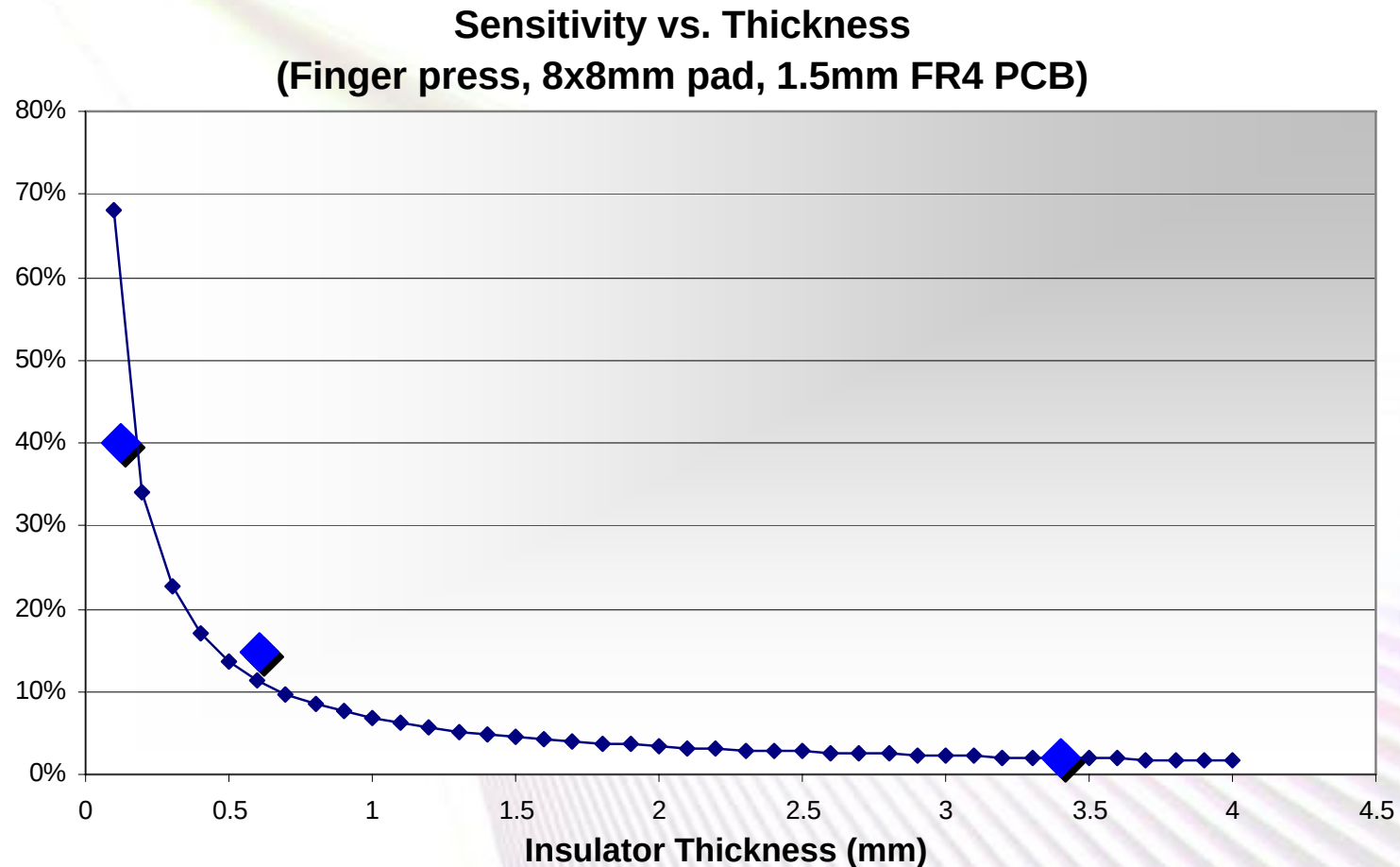
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Insulators & Assembly

- **An insulator is usually needed between PCB and user**
- **Insulator material must be non-conductive**
- **Thin is better**
 - C is inversely proportional to the distance between the conductors
- **No air should be present between insulator and the sensors on the PCB**
 - C is proportional to the dielectric constant
- **Use adhesives to secure sensor and insulator**
 - Nonconductive adhesives, air-free
 - Those which tolerate temperature and humidity changes well are recommended

Insulator Spacing

- Achievable sensitivity is inversely proportional to insulator thickness



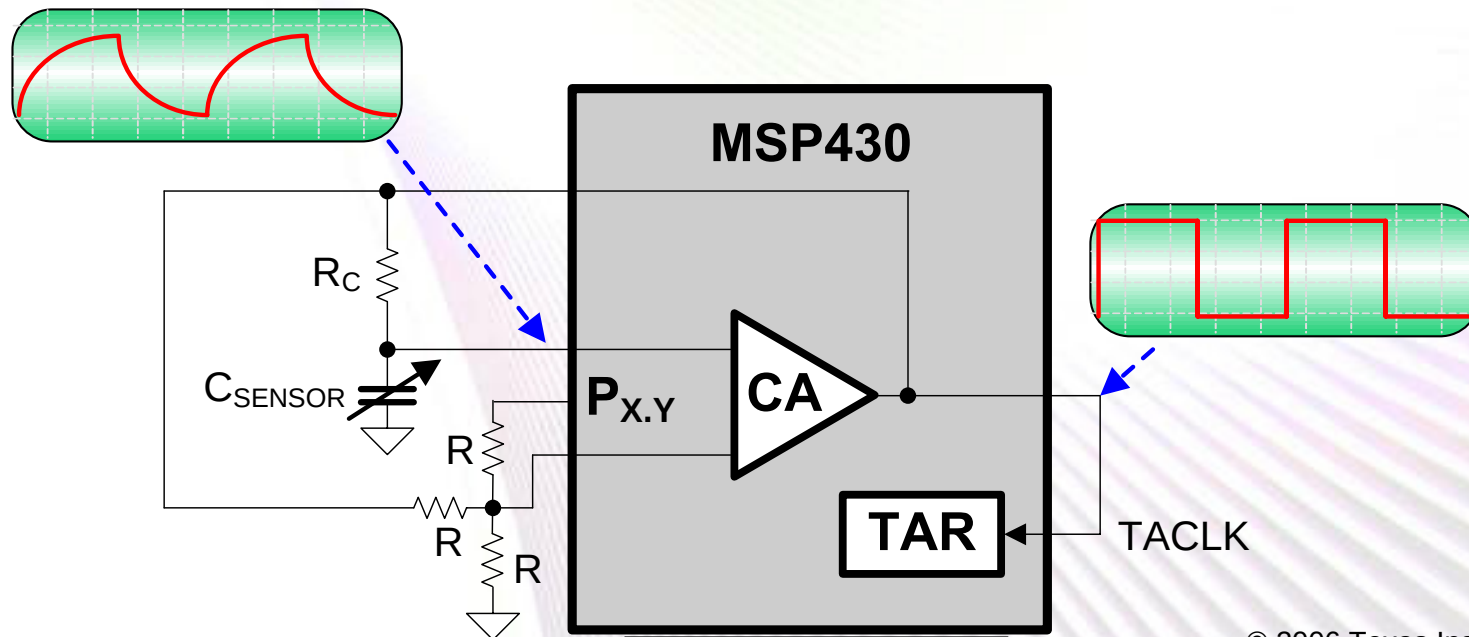
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RO System Overview

- Osc created using comparator with frequency a function of sensor capacitance
- Charge/discharge limits set by R's ($1/3 V_{cc}$ & $2/3 V_{cc}$)
- Freq is $1/[1.386 \times R_c \times C_{\text{sensor}}]$
- $\Delta C \Rightarrow \Delta f$

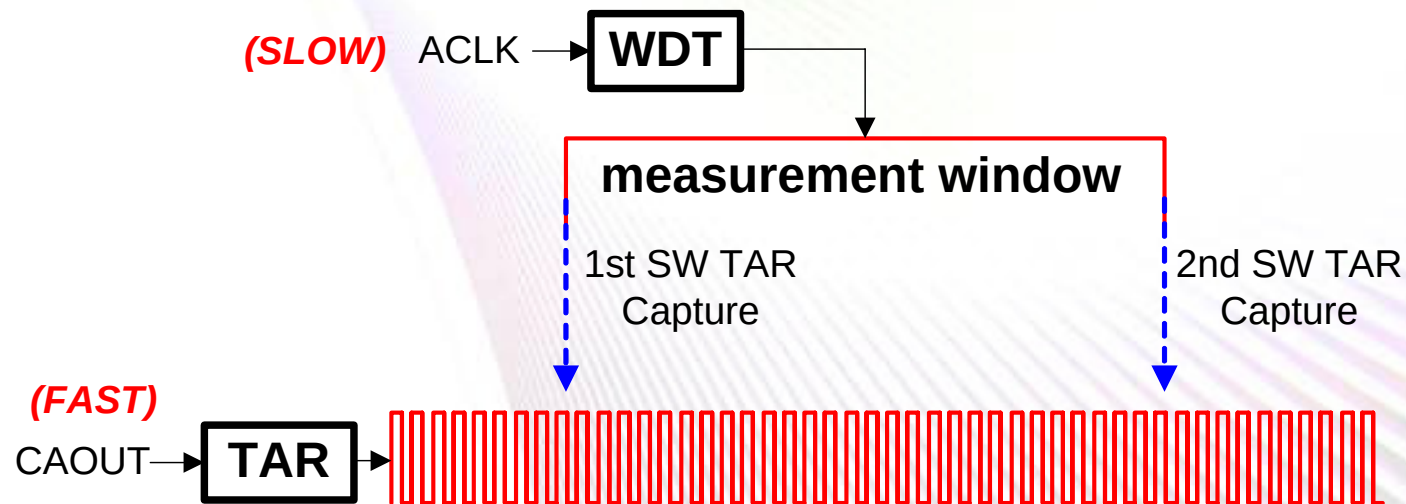


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RO Frequency Measurement

- Slow interrupt defines window for measurement
- Faster RO periods are counted via Timer_A
- CPU clock speed used to eliminate ISR s/w capture latency error

$$ACLK < RO\ Freq < CPU\ MCLK$$



Measurement Relationships

- Usable counts increase with measurement time
- Using VLO/64 for ACLK & DCO_cal/32768 for SMCLK
 - (100K R ~ 625kHz f_{RO})

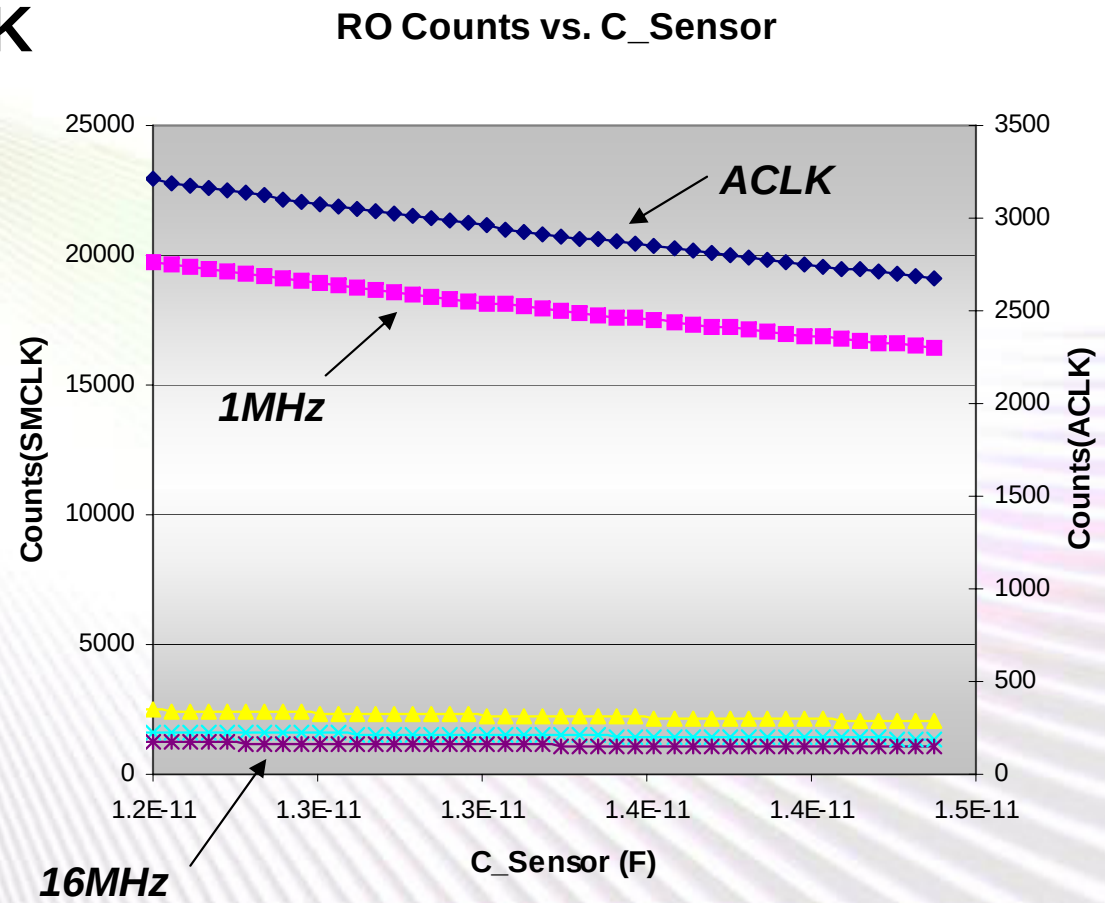
$$f_{RO} = \frac{1}{1.386 \times R \times C}, t_{RO} = \frac{1}{f_{RO}}$$

$$t_{window} = \frac{1}{f_{ACLK} / DIV_{ACLK} / DIV_{WDT}}$$

or...

$$t_{window} = \frac{1}{f_{DCO} / DIV_{SMCLK} / DIV_{WDT}}$$

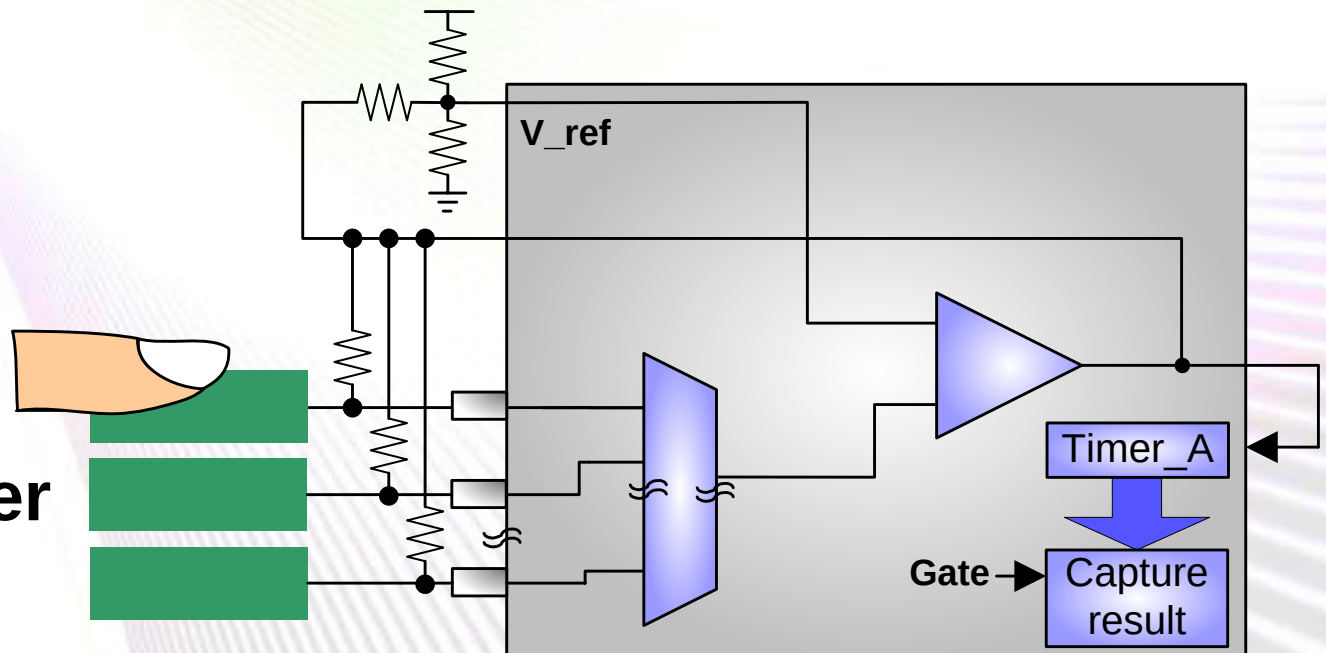
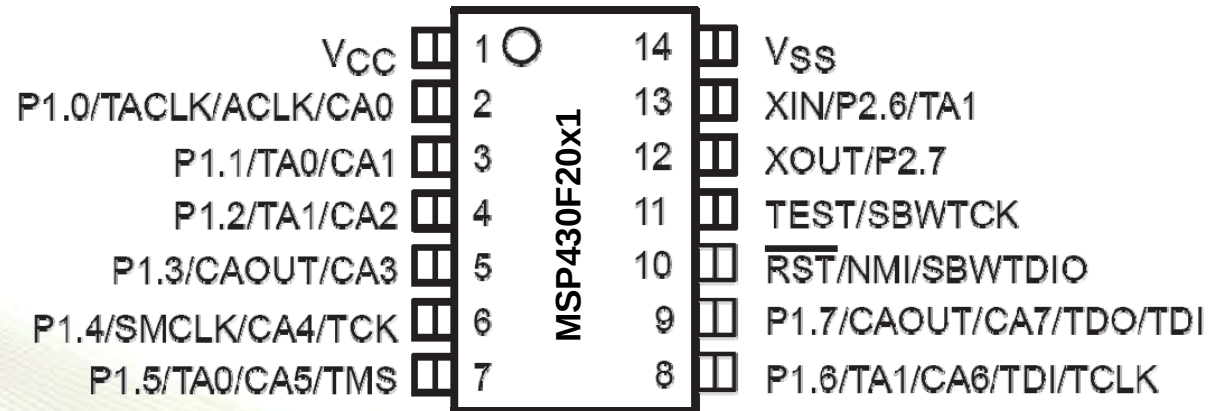
$$counts = \frac{t_{window}}{t_{RO}}$$



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Complete RO System

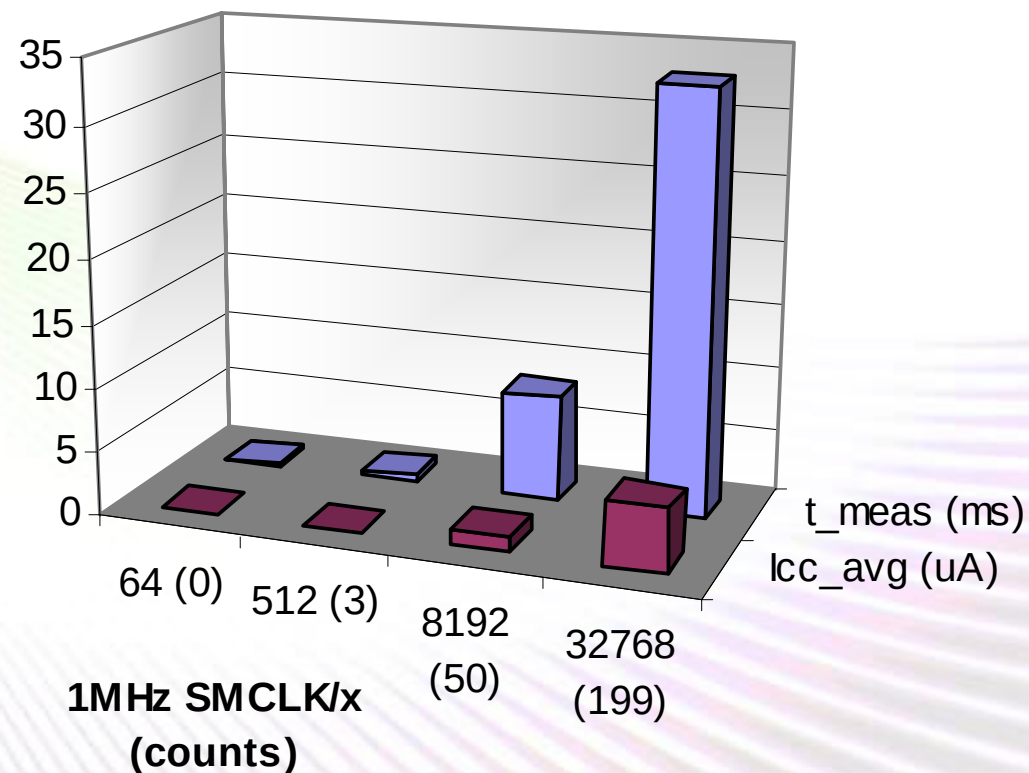
- Requires **Comp_A+** (needs mux input for multiple sensors)
- One external R per sensor, three for reference feedback
- External connection to TACLK
- Power Vref ladder via port pin for ULP



RO Current Consumption

- Longer t_{measure} = more counts
- Also means higher average I_{CC}
 - DCO: ~85uA @ 1MHz
 - Comp_A+: ~45uA
 - CA Vref: $V_{\text{CC}}/(1.5R)$ (for 100k R's, ~20uA)
- Define t_{measure} for adequate counts for application
 - Bigger delta C, smaller t_{measure} can be used
 - Design to fewest counts needed for lowest current

Current & Measurement Time vs.
Measurement Window (1% C_delta)

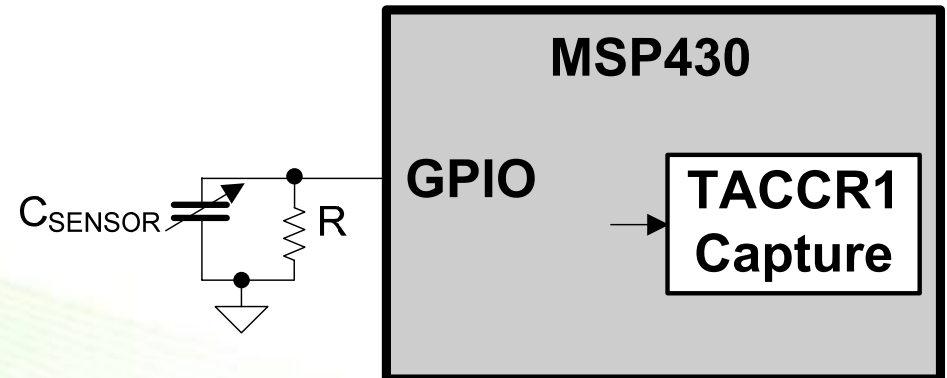


RO Tradeoffs

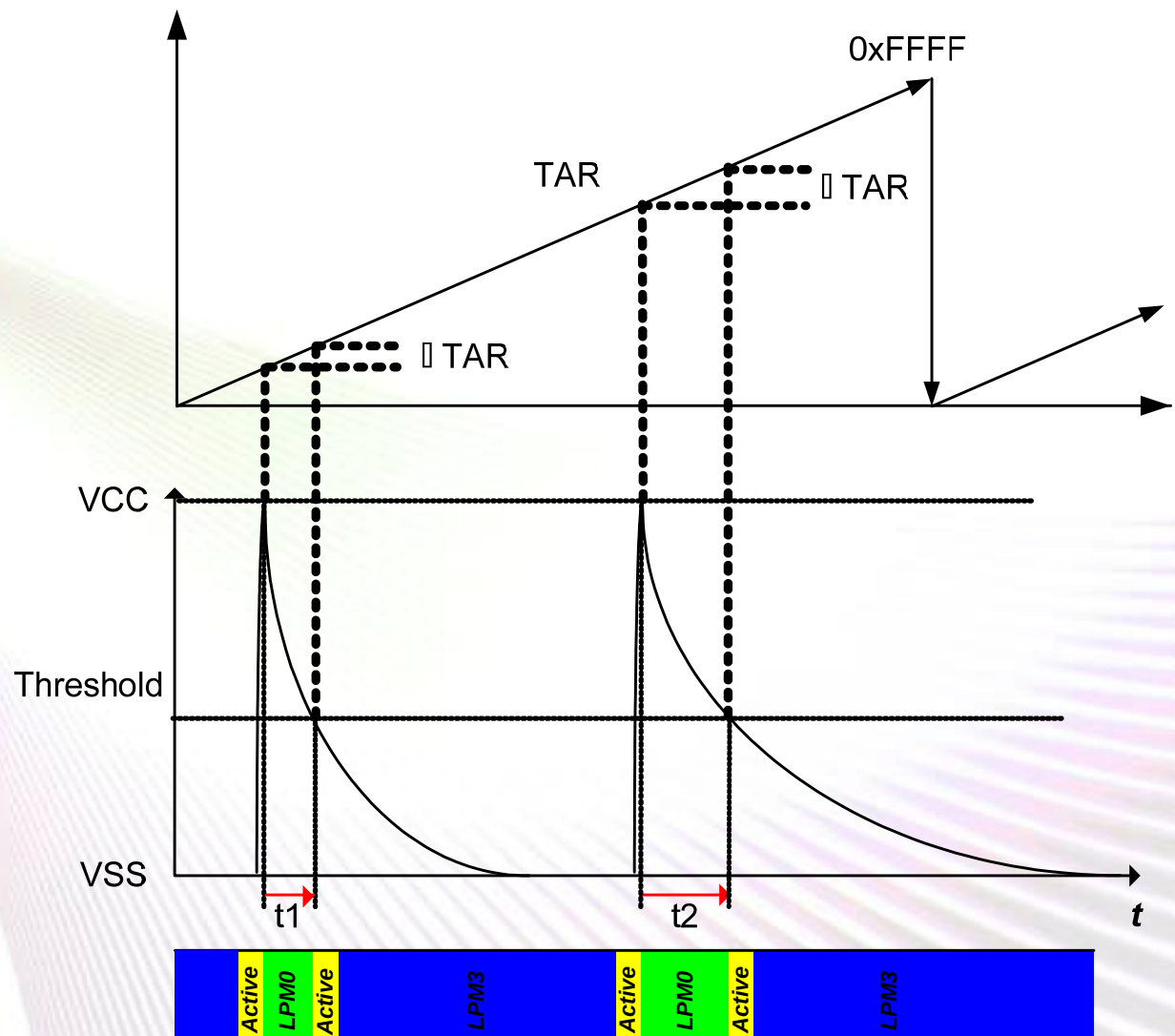
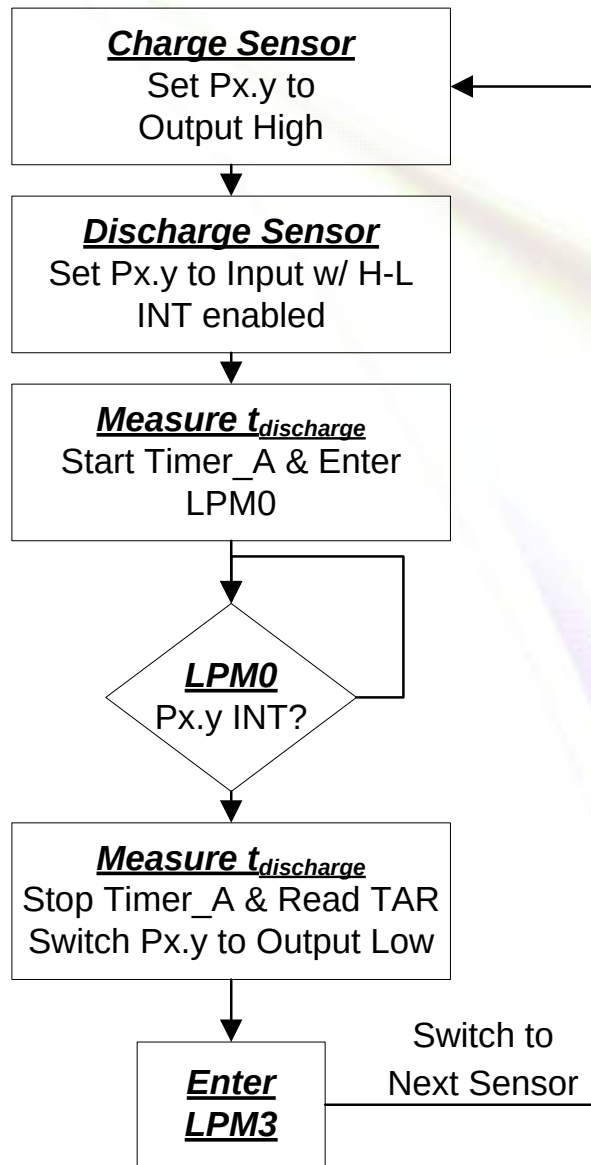
- Needs Comp_A+ input mux for multiple sensors
- Sensors used limited by usable CA+ mux inputs
- External R's needed to setup CA+ reference
- External CAOUT to TACLK required
- Good noise immunity: freq vs. voltage
- Programmable measurement time
- No high speed clock needed
- Measurement time dependent influenced by Vcc & Temp (VLO & DCO)

RC System Overview

- RC discharge time measured using interrupt on GPIO
- P1.x/P2.x GPIOs used
- Port pin used to charge sensor cap and measure discharge time
 - GPIO = Output high (charge C)
 - GPIO = Input (discharge C)
 - GPIO INT on low threshold
- Timer_A used to measure discharge time of C_sensor



RO Measurement Cycle



Measurement Relationships

- Usable counts increase with increased reference clock
- Using **ACLK = VLO** & **SMCLK = DCO_cal**
 - 5.1Mohm R

$$V(t_{rc}) = V_{cc} \times e^{\frac{-t}{RC}}, V(t_{rc}) = V_{cc} \times [1 - e^{\frac{-t}{RC}}]$$

$$V_{IT-} = V_{cc} \times e^{\frac{-t_{\text{discharge}}}{RC}}, V_{IT+} = V_{cc} \times [1 - e^{\frac{-t_{\text{charge}}}{RC}}]$$

$$V_{IT-} = 0.4 \times V_{cc}, V_{IT+} = 0.6 \times V_{cc}$$

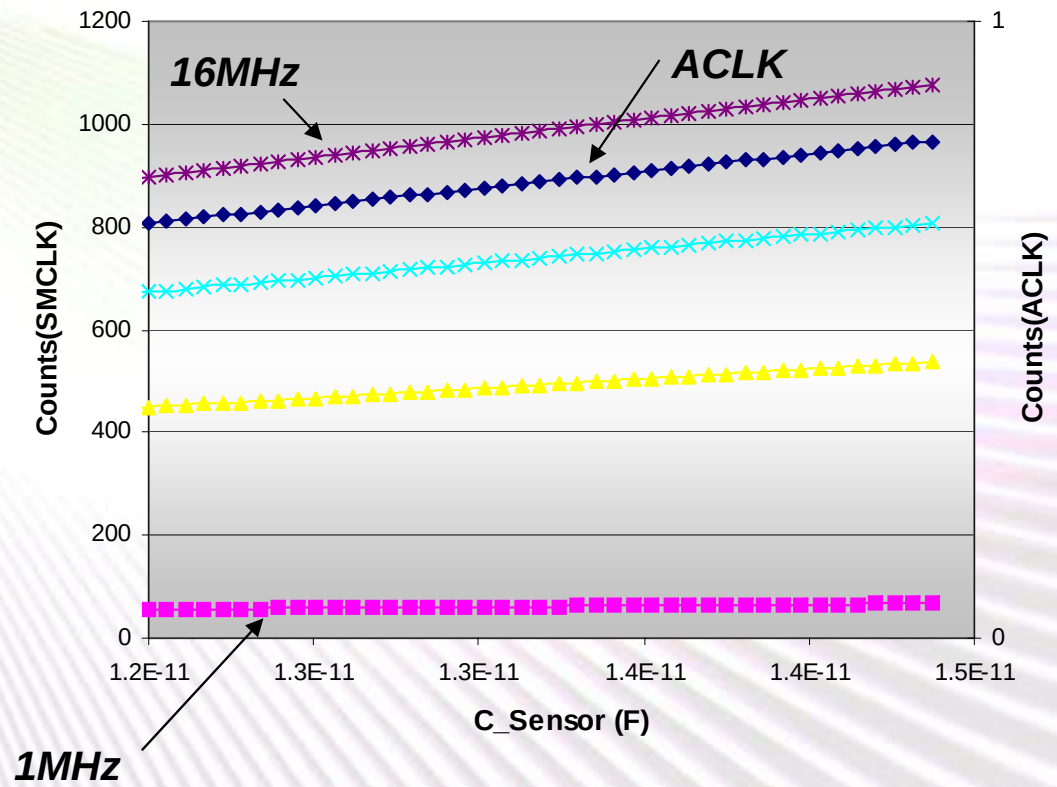
$$t_{\text{discharge}} = -RC \times \ln(0.4), t_{\text{charge}} = -RC \times \ln(1 - 0.6)$$

$$t_{CLK} = \frac{1}{f_{DCO} / DIV_{SMCLK}}$$

$$counts_{\text{discharge}} = \frac{t_{\text{discharge}}}{t_{CLK}}, counts_{\text{charge}} = \frac{t_{\text{charge}}}{t_{CLK}}$$

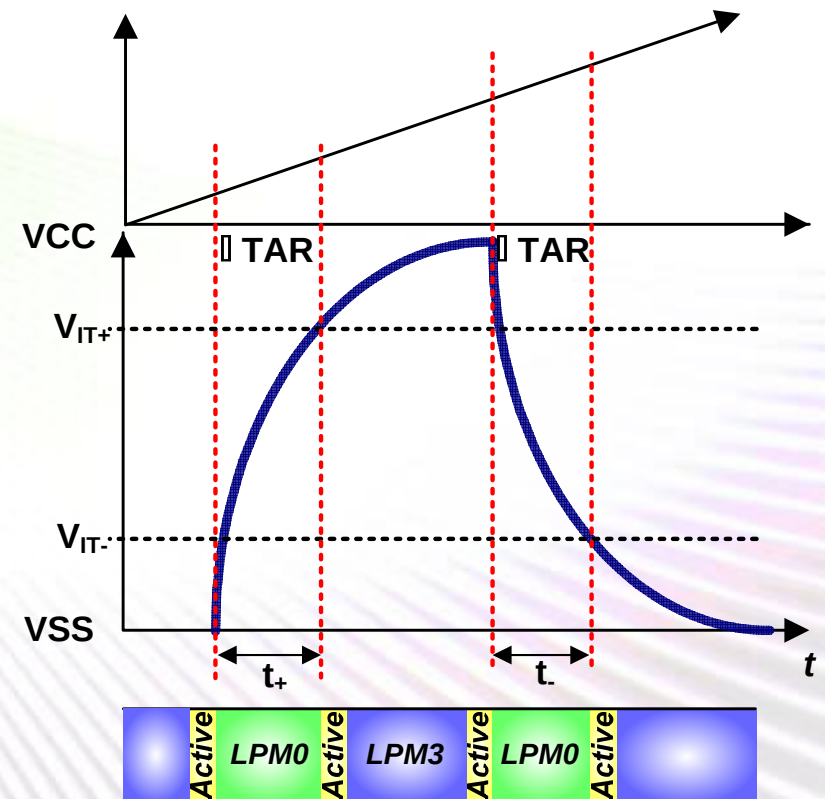
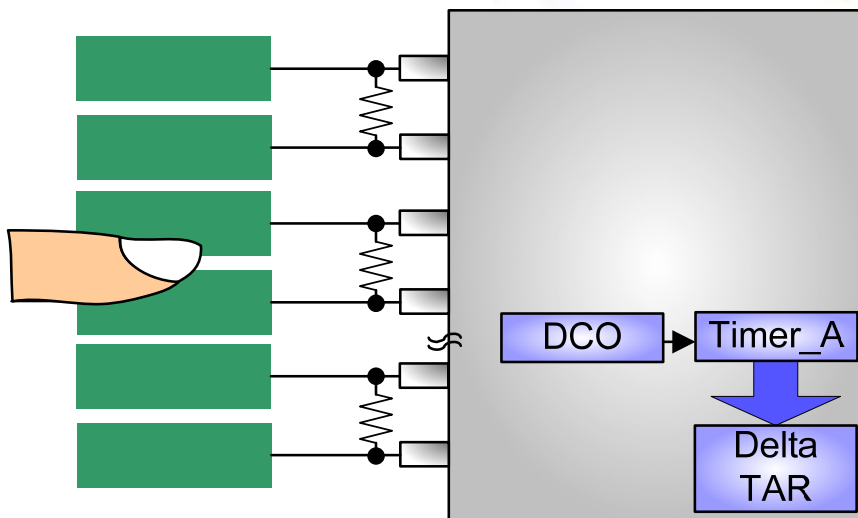
$$counts_{\text{avg}} = \frac{counts_{\text{discharge}} + counts_{\text{charge}}}{2}$$

RC Counts vs. C_Sensor



RC Optimizations

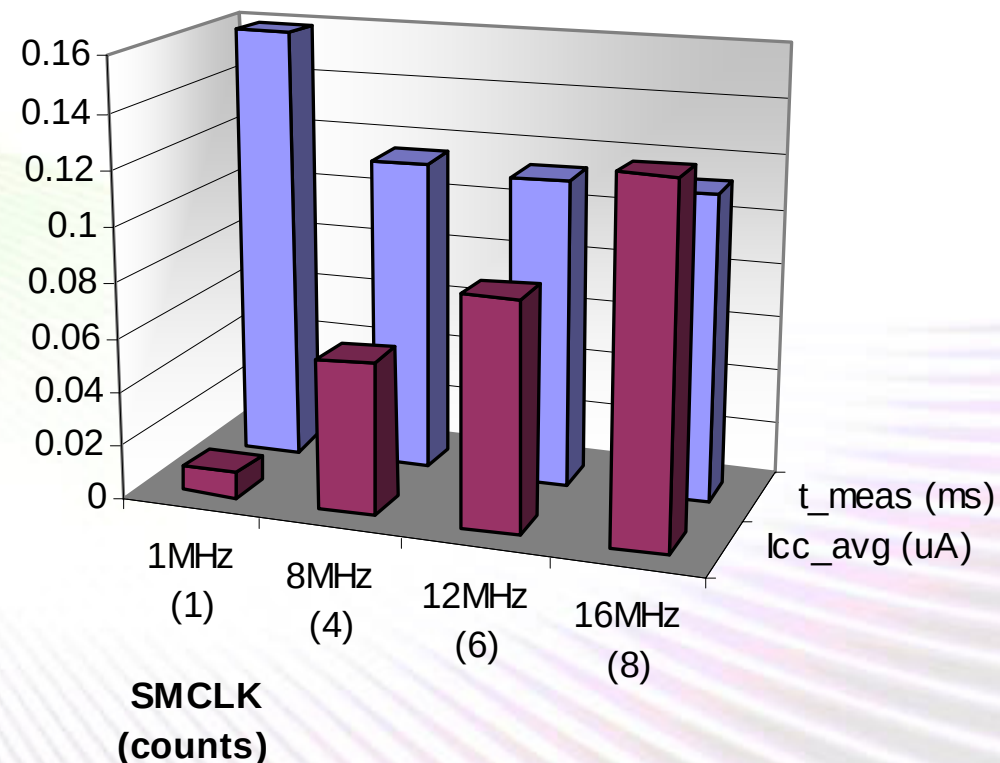
- Two sensor elements can share a single R
- Each sensor can be charged, then discharged for an average result: better noise rejection



RC Current Consumption

- **t_measure is constant:**
~2*t_RC_charge
 - R = 5.1Mohm
 - Counts TACLK
- **Average Icc depends on**
 - Tau = RC
 - DCO current consumption
- **Set TACLK for adequate counts for application**
 - Bigger delta C, lower f_DCO can be used
 - Design to fewest counts needed for lowest current

Current & Measurement Time vs.
Measurement Window (1% C_delta)



RC System Careabouts

- **Requires interrupt enabled GPIO for measurement**
- **One pin per sensor, shared resistor per two sensors**
- **R is Mohm's (5.1M)**
 - With pF C, large R required for a measurable charge/discharge time
- **Low pin leakage of MSP430 ideal for the methodology**
- **Noise rejection aided by charge/discharge average**
- **Measurement window is fixed by RC charge/discharge time: high freq reference clock needed to "count"**
- **Measurement counts dependent on Vcc & Temp (DCO)**

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Touch Sensor Careabouts

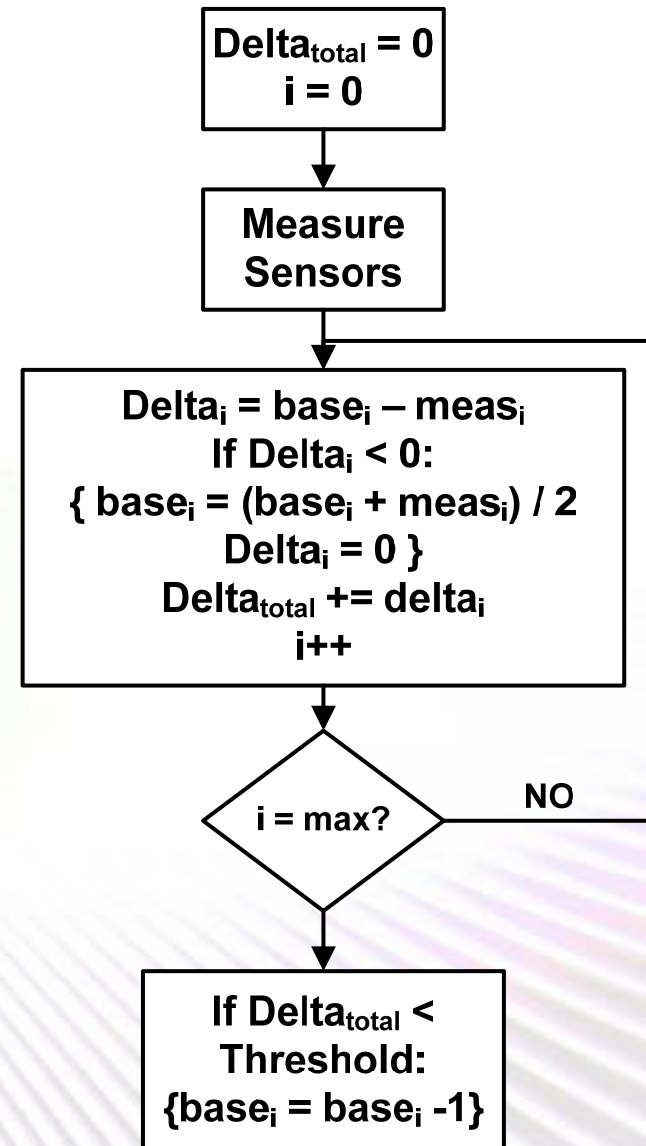
- **What is the application:**
 - A switch replacement?
 - Position detection? (e.g. slider)
- **Threshold: Establish a “usable” limit**
 - Can it be reached?
 - Enough noise margin?
 - Tolerant to manufacturing changes?
- **Filtering: Noise coupling**
 - Given large R in RC method, noise can easily couple in
 - Multi-result averaging: RC charge/discharge method
 - RO method inherently immune due to multiple cycles per measurement
- **Tracking: Baseline capacitance can shift**
 - Periodically adjust base capacitance count set-point
 - Take care to exclude a “touched” sensor result from any tracking algorithm

Tracking C_base

- **C_base measurement result can change over time**
 - Humidity effects
 - Temperature
 - Component tolerances
 - Voltage drift
- **Failure to track this change adequately can result in false key events or inability to detect events**
- **Algorithm basics:**
 - Adjust for a decreasing C rapidly, e.g. on each measurement, since this is not a function of sensor excitation
 - Adjust for increasing C very slowly as this may be due to a finger hovering over a key, not just C_base drift
 - Exclude an increasing C adjustment when any keys are pressed as it may be caused by the user, not C_base drift

Example: C base Tracking

- **Adjust base result quickly when cap decreases**
 - Ex: re-average with current result
- **Adjust base result slowly when cap increases**
 - Ex: adjust by 1 with each measurement
 - Only adjust if no keys are pressed
- **Set “Threshold” level low enough that the sum of all key deltas will be greater if any key is press**
 - Alternatively, can adjust on per key basis
- **Note: sign of delta calc changes for the two methods**
 - RO: counts decrease when key excited
 - RC: counts increase when key excited



Data Filtering

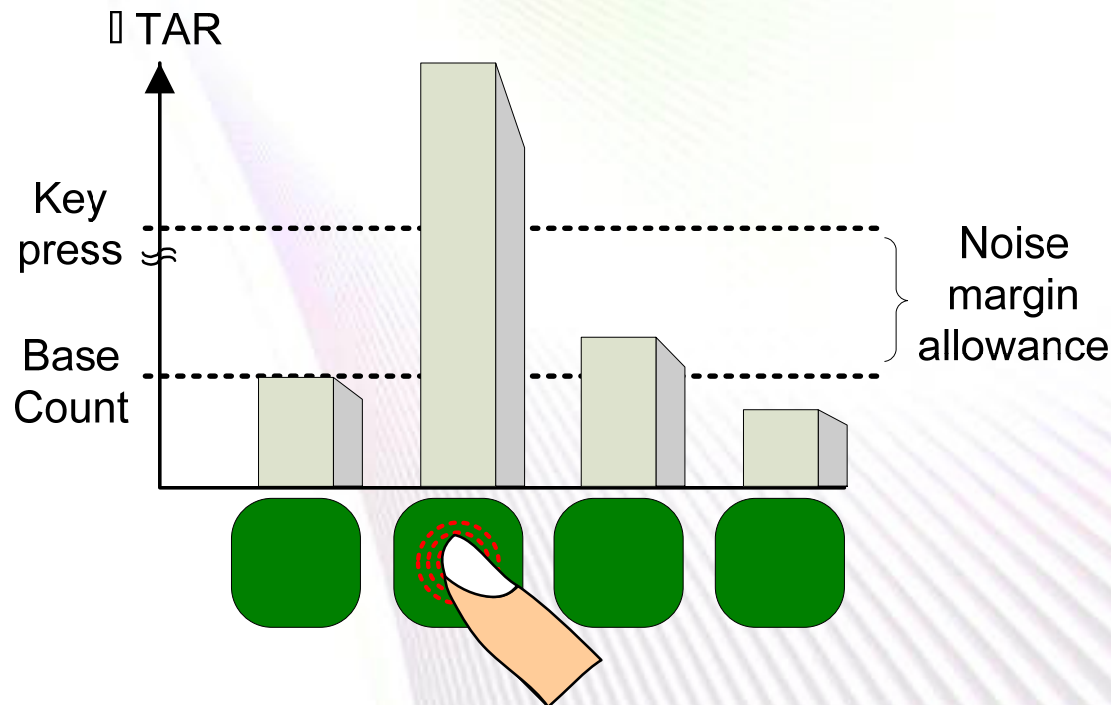
- **Measurement results often noisy due to a number of factors including voltage supply**
- **When enough counts can be measured, simply throwing away the LSBs may be good enough**
 - Works ok for simple key press detection
- **A low pass filter of each key result will more adequately remove any unwanted noise and help stabilize the results, especially when measuring position on a slider**
- **Critical when counts are at a premium in the system due to constraints such as the PCB, insulator and power budget**

Key Press Detection

- **Measurement Flow**

- Step 1: Establish a base count measurement
- Step 2: Set a key press count threshold
- Step 3: Scan keys

- **Set detection threshold ~50% of maximum count delta expected from the given implementation**



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Key Pad Current Consumption

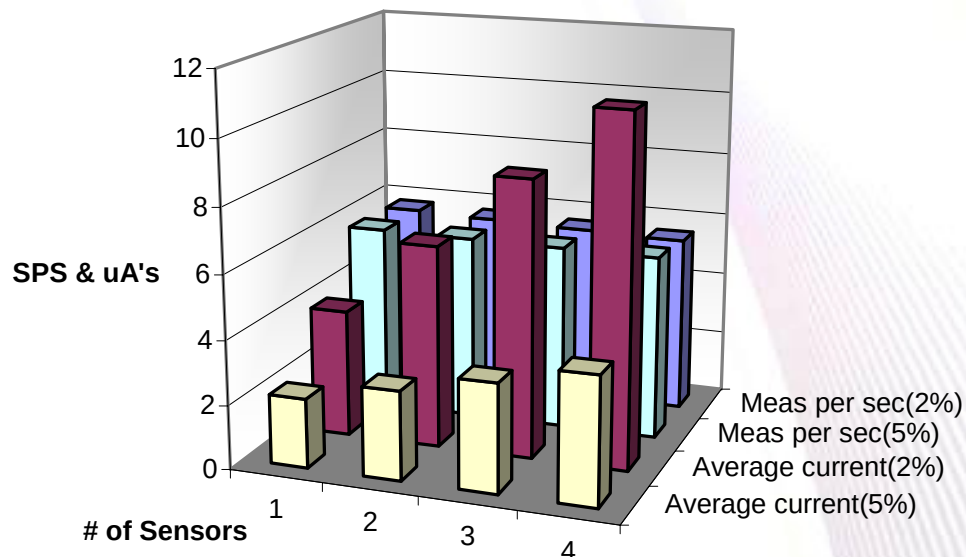
RO Method

- Use smallest t_{meas} (lowest SMCLK) for needed counts
 - ΔC 5% 1MHz, WDT= SMCLK/1/512
 - ΔC 2% 1MHz, WDT= SMCLK/4/512

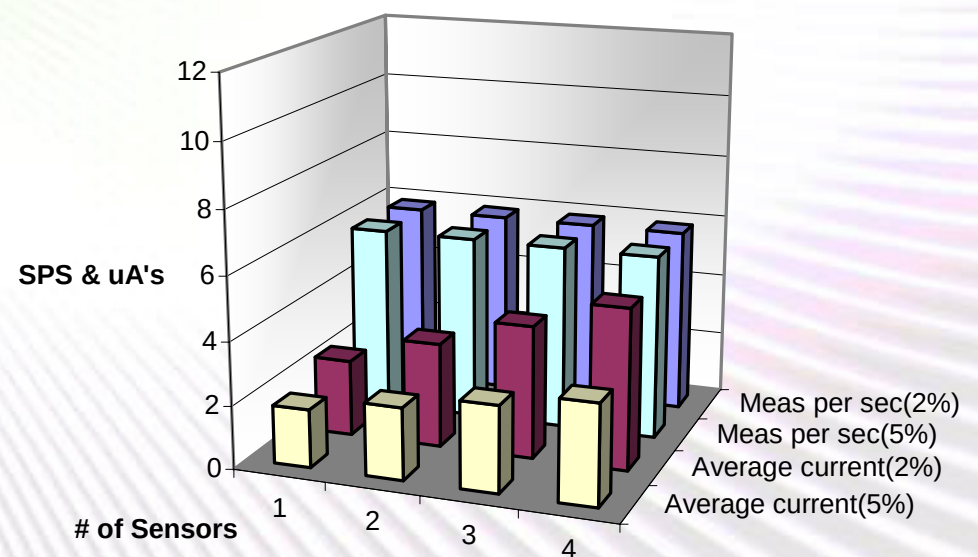
RC Method

- Use lowest TACLK for needed counts
 - ΔC 5% 8MHz TACLK
 - ΔC 2% 16MHz TACLK

Sensor Switch Application- RO
Current & SPS vs. Sensor Count (~20 counts)



Sensor Switch Application- RC
Current & SPS vs. Sensor Count (~20 counts)



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Demo: ULP Key Detection

- RC measurement flow

```
// RC Method: Measurement Excerpt  
...  
P1OUT &=~(BIT0+BIT1+BIT2+BIT3); // everything is low  
P1OUT |= active_key; // Charge the sensor  
_NOP();_NOP();_NOP(); // short time for hard pull high  
P1IES |= active_key; //-ve edge trigger  
P1IE |= active_key;  
P1DIR &= ~active_key; // set the active key to input  
timer_count = TAR; // Take a snapshot of the timer  
LPM0;  
meas_cnt[i]= timer_count;  
... // Now repeat with charging cycle and average results
```

```
// Port ISR  
...  
timer_count=TAR-timer_count; // Get charge/discharge time  
...
```

Demo: ULP Key Detection

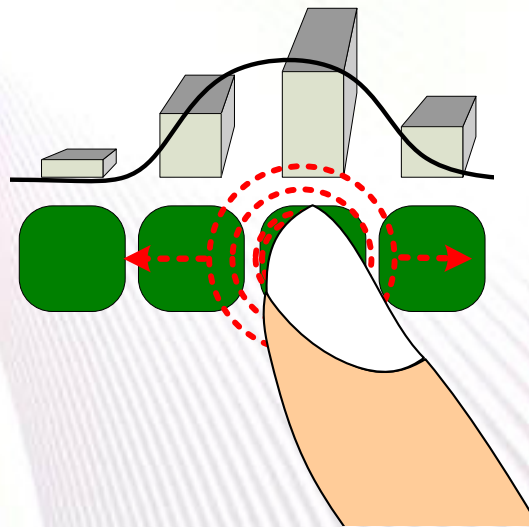
- RO measurement flow

```
// RO Method: Measurement Excerpt
TACTL = TASSEL_0+MC_2;           // TACLK, cont mode
TACCTL1 = CM_3+CCIS_2+CAP;       // Pos&Neg Capture
CACTL1 |= CAON;                  // Turn on comparator
for (i = 0; i<Num_Sen; i++)
{switch (i)
  {case 0: // Sensor 1
    CAPD = CA_Ref+S_1; // Disable I/O:CA1 ref, 1st sensor
    CACTL2 = CA_1+CA_2; // CA1 ref, CAx sensor
    break;
    ...}}
WDTCTL = WDT_meas_setting; // Set duration of sensor measurement
TACTL |= TACLR;             // Clear Timer_A TAR
LPM0;                       // Wait for WDT interrupt
meas_cnt[i] = TACCR1;        // Save result
```

```
// WDT ISR
...
TACCTL1 ^= CCIS0;           // Create SW capture of CCR1
...
```

Slider Scanning

- **Measurement Flow**
 - Step 1: Establish a base count measurement
 - Step 2: Set a key press count threshold
 - Step 3: Scan keys
 - Step 4: Calculate position based on counts for each key
- **Apply linear weighting algorithm**
- **Filter noise counts for jitter-free operation**



Position

- Establish design to steps/sensor required
 - Sensor size
 - Insulator thickness
- Smoothly linearize steps across the slider

Set max delta expected

Set steps per key ($\text{steps}_{\text{KEY}}$)
Step size = $\text{max delta} / \text{steps}_{\text{KEY}}$
(slider steps = $\text{steps}_{\text{KEY}} * \#\text{keys}$)

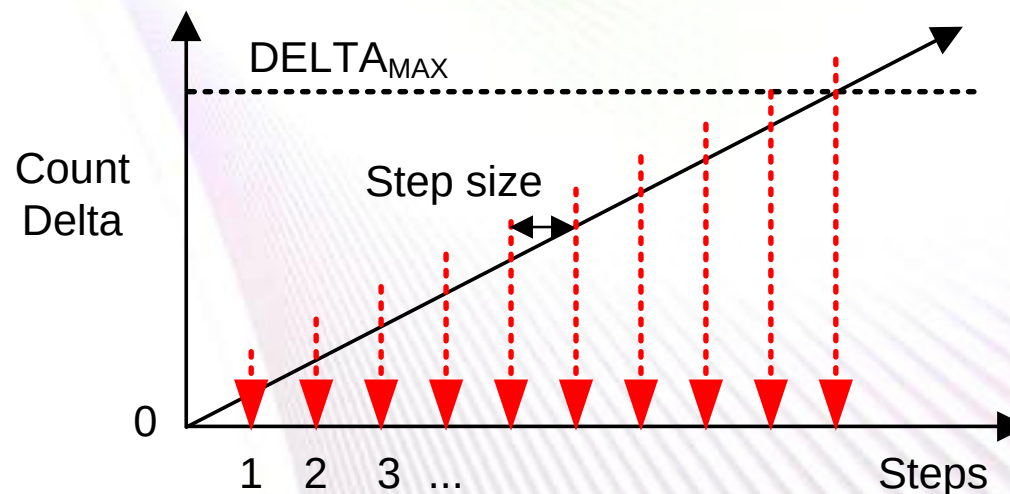


Get key delta & limit to max value

$\text{position}_{\text{KEY}} = \text{delta} / \text{step size}$



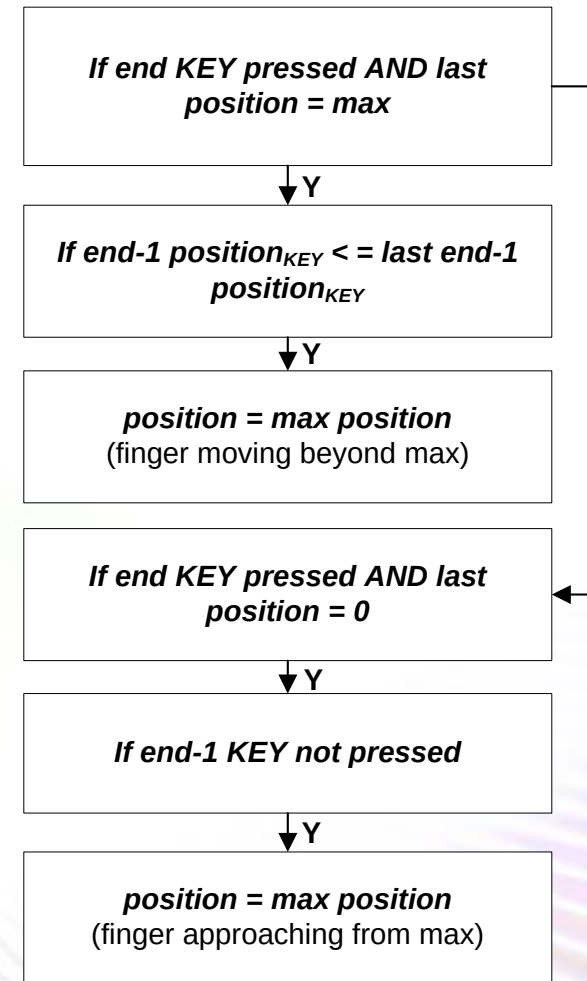
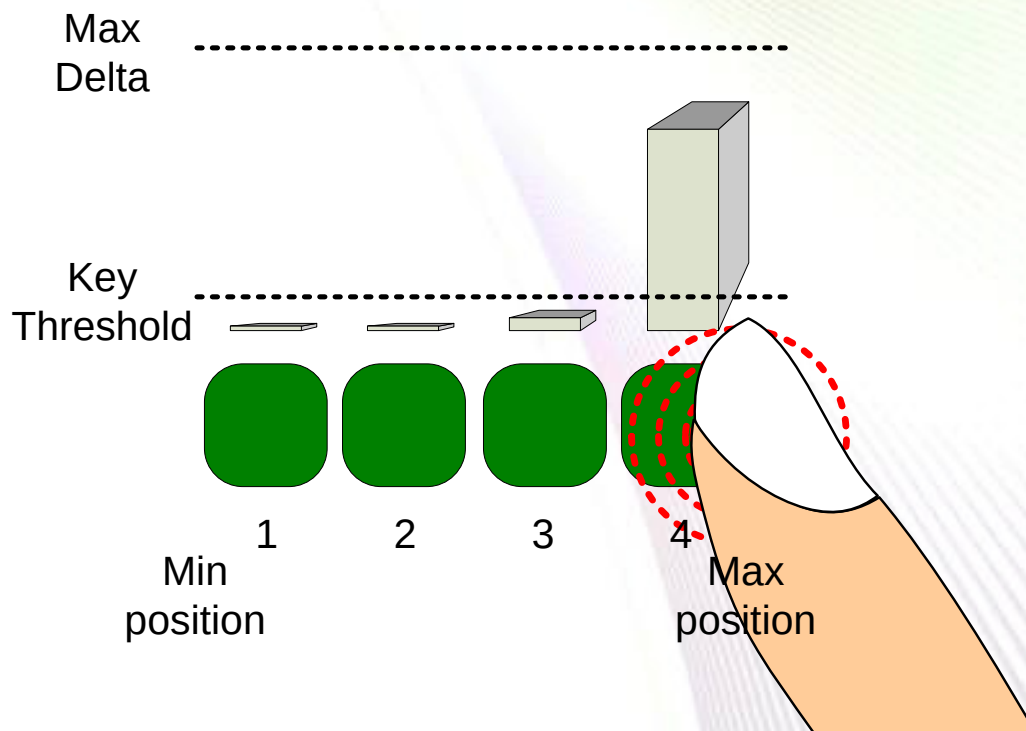
If KEY pressed: Slider position =
 $\text{position}_{\text{KEY}} + \text{steps} * \text{weight}_{\text{KEY}}$
(0, 1, 2, 3...)



Endpoint

- **Handle end-point touch**

- Press beyond max
- Movement beyond max
- Movement from max



4-key Slider Current Consumption

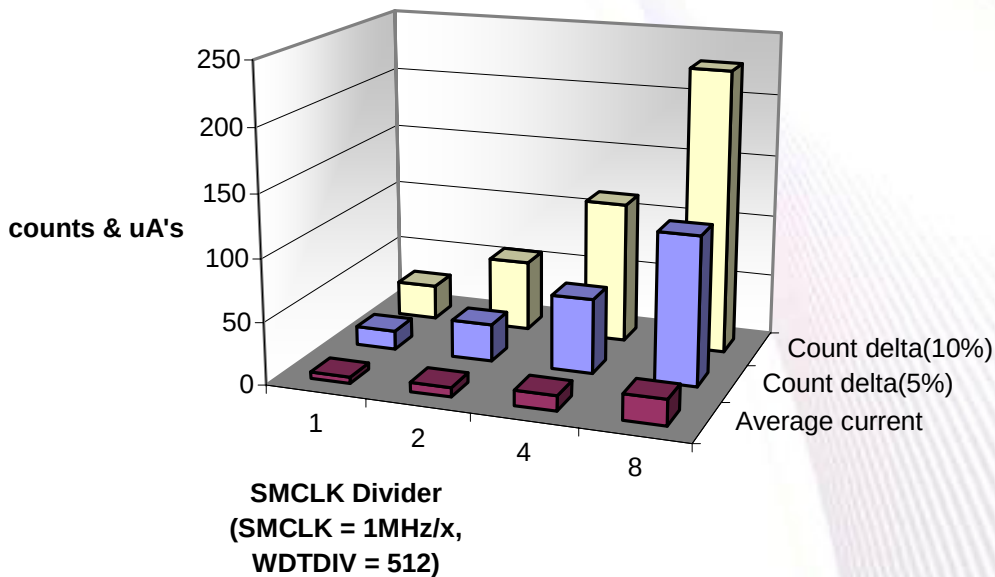
RO Method

- **t_meas user programmable**
 - Larger window = more counts
 - Define smallest window for needed counts, use lowest DCO for window

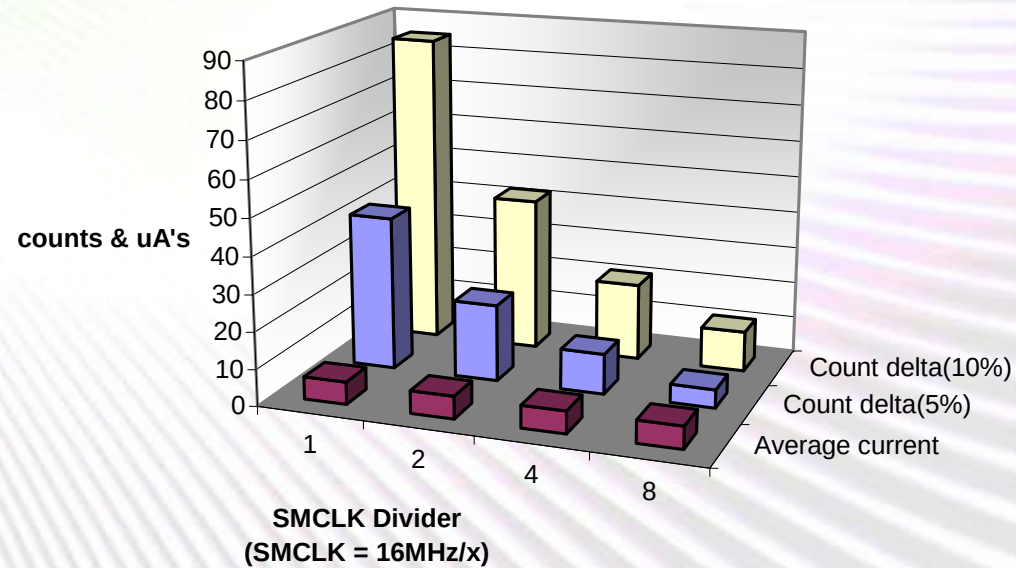
RC Method

- **t_meas is fixed by RC**
 - Faster TACLK = more counts
 - Don't divide TACLK, set = to fastest DCO required for needed counts

Sensor Slider Application- RO
Count Delta & Current Consumption vs. SMCLK (~5SPS)



Sensor Slider Application- RC
Count Delta & Current Consumption vs. SMCLK (~5SPS)



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Demo: ULP Slider Detection

```
// Sensor slider definitions
#define Num_Sen      4      // # of sensors
#define KEY_lvl      5      // min count for a "key press"
                          // Must be less than step_size

#define max_cnt      100    // Set below actual max delta expected
#define num_steps    16     // How many steps per key?
#define step_size    (max_cnt/num_steps) // Step size for position

if (delta_cnt[i] > max_cnt) // count exceeds preset upper delta
    delta_cnt[i] = max_cnt; // limit to set point

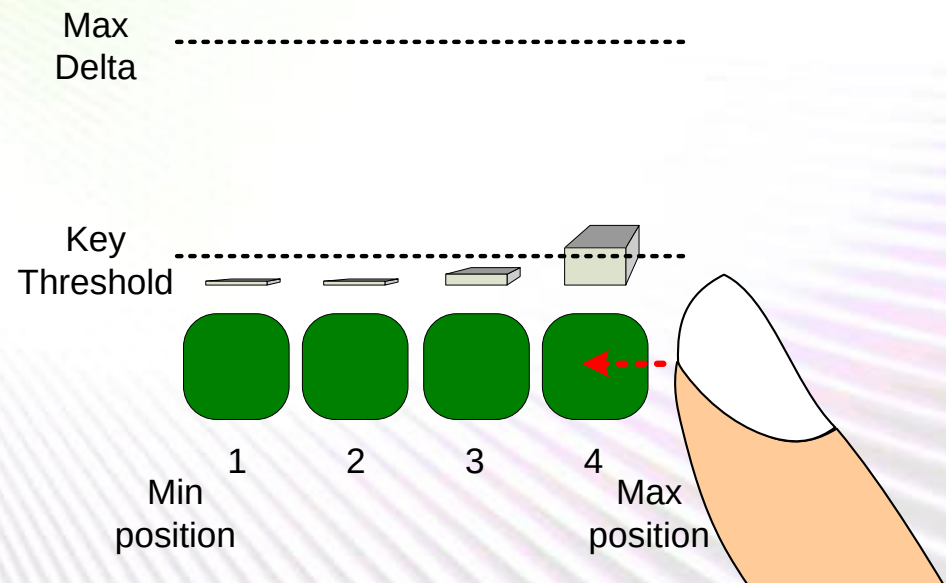
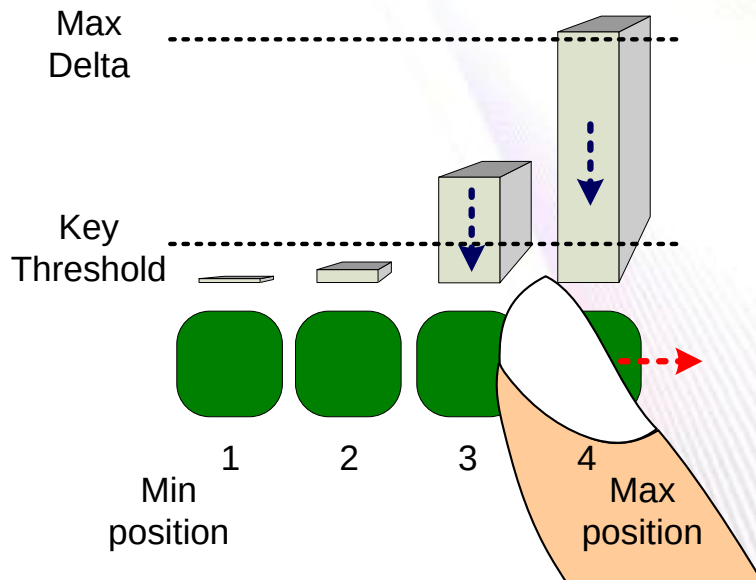
key_pos[i] = delta_cnt[i]/step_size; // individual "position"

if (key_pos[i] > 0)         // If the key is "pressed",
    position = key_pos[i] + num_steps*(i); // Pos=0-16, key weight
```

- Determine legitimate number of steps for a given application
- Linearize across all sensors for entire slider span

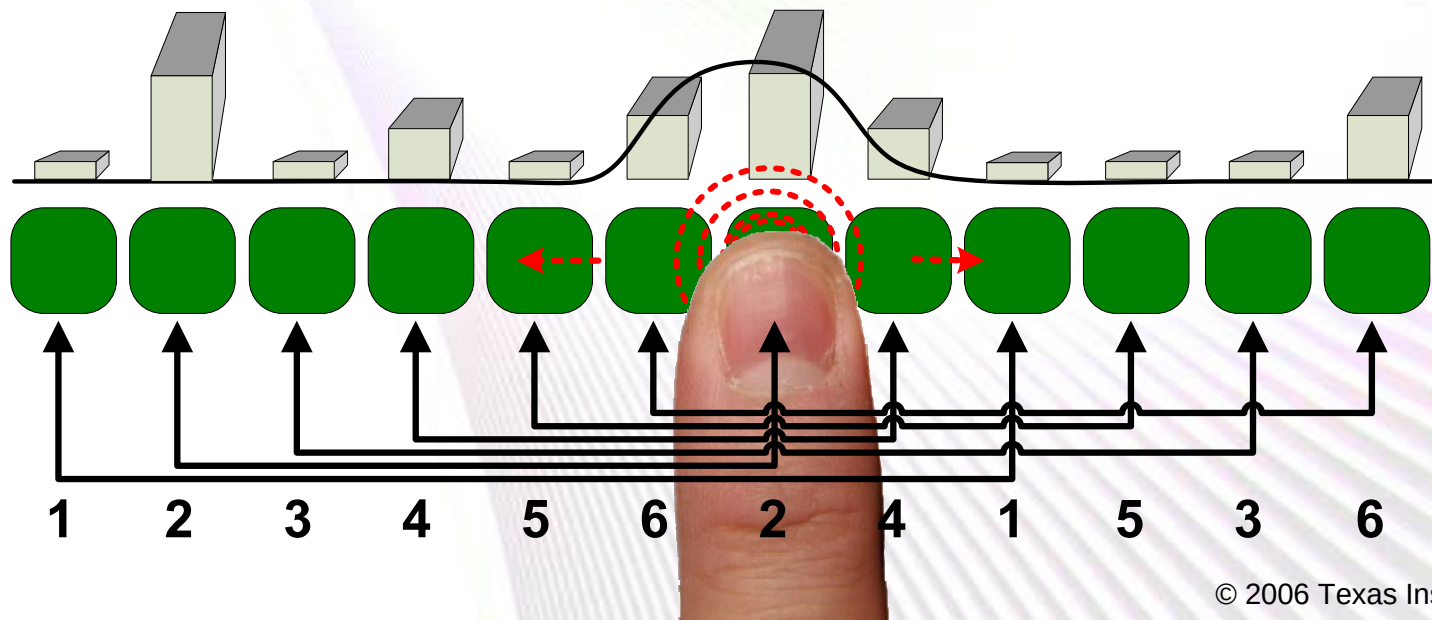
Demo: ULP Slider Endpoint

```
// Handle max end of slider
if (key_press[3] && position_old == Num_Sen*num_steps)
{if (key_pos[2]<key_pos_old[2] || key_pos[2]==key_pos_old[2])
    position = Num_Sen*num_steps; // moving beyond the max
}
else if (key_press[3] && position_old == 0 && !key_press[2])
    position = Num_Sen*num_steps; // approaching from max
```



Multiplexed Sliders

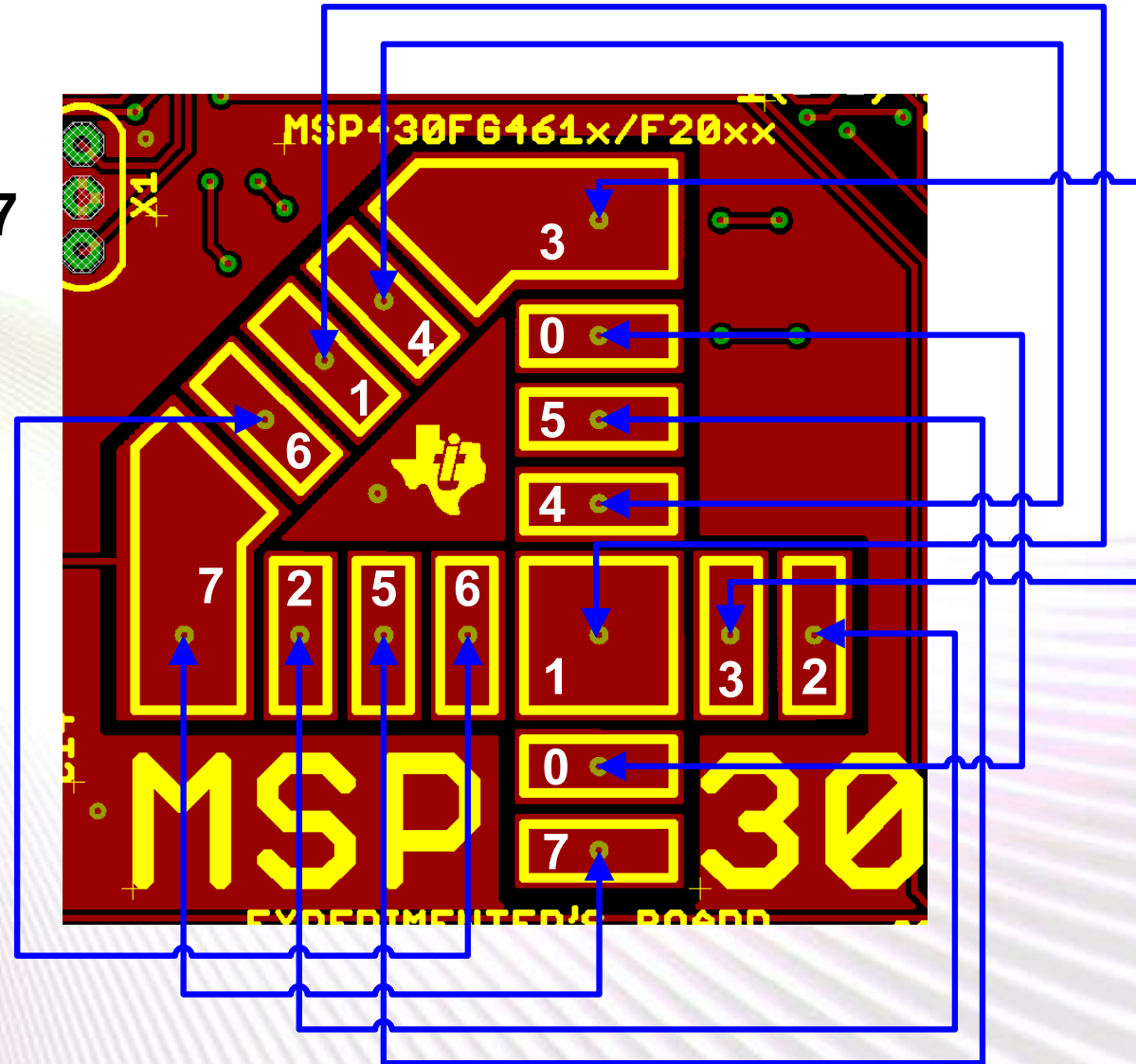
- **Multiplex sensors for better pin:sensor ratio**
 - Increases base capacitance
 - Measured delta C will be lower
- **Mux for unique pattern for each position**
- **Multiple sensors should be excited for proper location & direction detection**



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ATC2006 Touchpad Interface

- 8 port pins used
- $2 \times 8 = 16$ sensors
- 0-7: P1.0-P1.5, P2.6, P2.7



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Summary

- **Capacitive touch sensing can be an attractive option**
 - ...for existing switch replacement
 - .. and more: potentiometer replacement, multi-position switches
- **MSP430 RO Method**
 - Works in Comp_A+ devices
 - Number of independent sensors limited by CA+ mux
 - Needs 1 external R per sensor + reference ladder
 - Sensitivity limited by current consumption, flexible measurement time
- **MSP430 RC Method**
 - Can be implemented on any MSP430
 - Up to 16 independent sensors (16 interruptible GPIOs)
 - Single external R per two sensors
 - Sensitivity limited by on-chip max clock frequency, fixed measurement time
 - Lowest power implementation

IMPORTANT NOTICE

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