I^2C Pull-Up Resistor Values for RICH Hardware Interlocks

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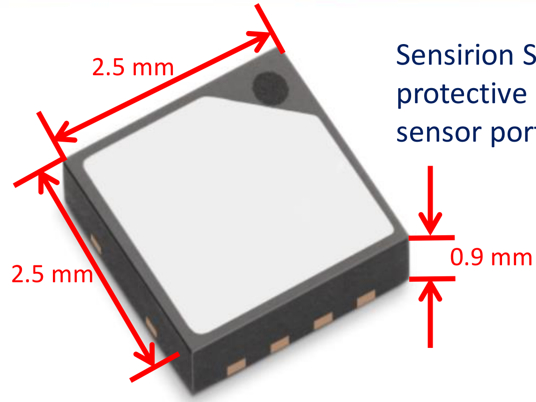
Contents

RICH-II Hardware Interlock System

- Hardware interlock system for RICH-II will use Sensirion SHT35 sensors to monitor environment
  - Better accuracy than previous sensors
  - Allow monitoring of more locations since not limited by number of cRIO modules
    - 24 locations vs. 16 locations
  - Cost less per location than previous version
    - $50 vs. $140
- SHT35 sensors are read using I^2C communication



Sensirion SHT35 with protective membrane over sensor port

	Parameter	Specification
Humidity	Accuracy	±1.5% RH
	Long-term drift	<0.25% RH/year
	Operating range	0–100% RH
	Resolution	0.01% RH
	Repeatability	0.08% RH
Temperature	Accuracy	±0.1°C
	Long-term drift	< 0.03 °C/year
	Operating range	–40 to 125 °C[1]
	Resolution	0.01°C
	Repeatability	0.04 °C
Communication interface		I^2C

Honeywell humidity sensors have ±3.5% RH accuracy

Omega RTDs have ±0.15° C accuracy

SHT35 specifications
DSG Note 2020-28 by Peter Bonneau

I^2C Communication

- I^2C communication allows a controller to send commands to and read from a peripheral device using serial communication
- I^2C has different modes allowing maximum data transfer speed capability
  - Standard mode will be used for RICH-II interlocks
    - For SHT35 sensors, ~100 bits of data are transmitted/received for every temperature and humidity measurement
      - Using full 100 kbit/s speed would be ~1000 times faster than slow controls systems need to read

Mode	Data Transfer Speed
Standard-mode	100 kbit/s
Fast-mode	400 kbit/s
Fast-mode plus	1 Mbit/s
High speed	3.4 Mbit/s

Pull-up Resistors

- I^2C devices are open-drain—a device can only pull a signal line to the low level
- To get signal to return to high level, line is connected to the I^2C bus voltage through a "pull-up" resistor
  - Resistor limits current on the line while it is pulled high
- Minimum pull-up resistor value is determined by the output specifications of the device
- Maximum pull-up resistor value is determined by I^2C bus capacitance and maximum allowable rise time t_r of I^2C signal
  - t_r = 1 µs (10^{-6} s) for standard mode

Minimum Pull-Up Resistor Value

- Minimum pull-up resistor value determined by specifications of device to prevent over-current conditions on signal line
  - Device for RICH interlocks is the PCA9600 buffer driver

$$R_{min}[\Omega] = \frac{V_{CC} - V_{OL}}{I_{OL}}$$

$V_{CC} = \text{I}^2\text{C bus voltage} = 3.3\ V$

$V_{OL} = \text{Buffer driver's output low voltage level} = 1.0\ V$

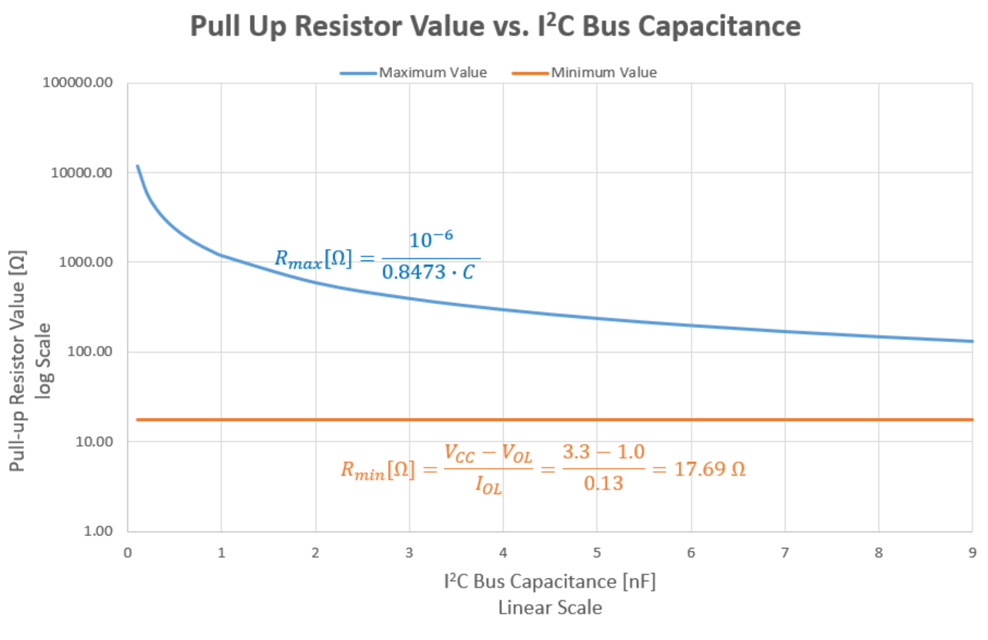
$I_{OL} = \text{Current that buffer driver sinks at } V_{OL} = 0.13\ A$

$$R_{min}[\Omega] = \frac{3.3\ V - 1.0\ V}{0.13\ A} = 17.69\ \Omega$$

Maximum Pull-Up Resistor Value

- Maximum pull-up resistor value is determined by I^2C bus capacitance and I^2C standard mode's 1-µs maximum rise time t_r

$$R_{max}[\Omega] = \frac{t_r}{0.8473 \cdot C} = \frac{10^{-6}}{0.8473 \cdot C}$$



V_{CC} = Pull-up voltage level
V_{OL} = Specified low-level output voltage of buffer driver
I_{OL} = Specified low-level current sink at V_{OL} of buffer driver

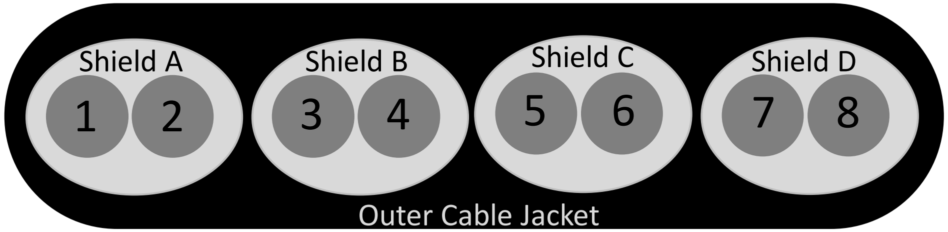
Plot of pull-up resistor values vs. I^2C bus capacitance. Equations for both maximum (blue) and minimum (orange) resistor values are shown in plot.

Measuring Cable Capacitance

- Capacitance of cable depends on specifications:
  - Cable length (*L*)
  - Radius of individual conductor in cable (*r*)
  - Distance between conductors in cable (*d*)
- For the simplest case (two parallel wires):

$$C = \frac{\pi \epsilon L}{\operatorname{arcosh}\left(\frac{d}{2r}\right)} \quad \epsilon = constant;\ permitivity\ of\ material\ between\ conductors$$

- Since RICH-II cable will be CAT7 (four individually-shielded, twisted pairs), measuring capacitance is easier than calculating it



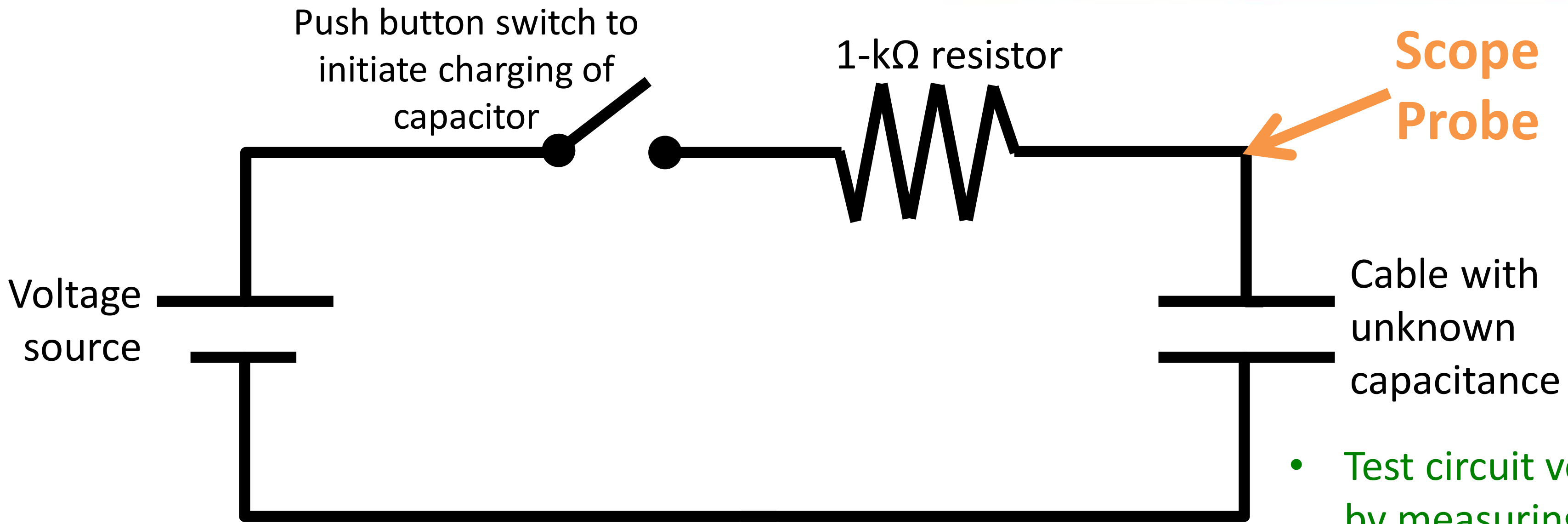
Simplified cross-section of flat, CAT7 cable. For conductor #1, 11 other components (seven other conductors, four twisted pair shields) must be considered for the cable's capacitance.

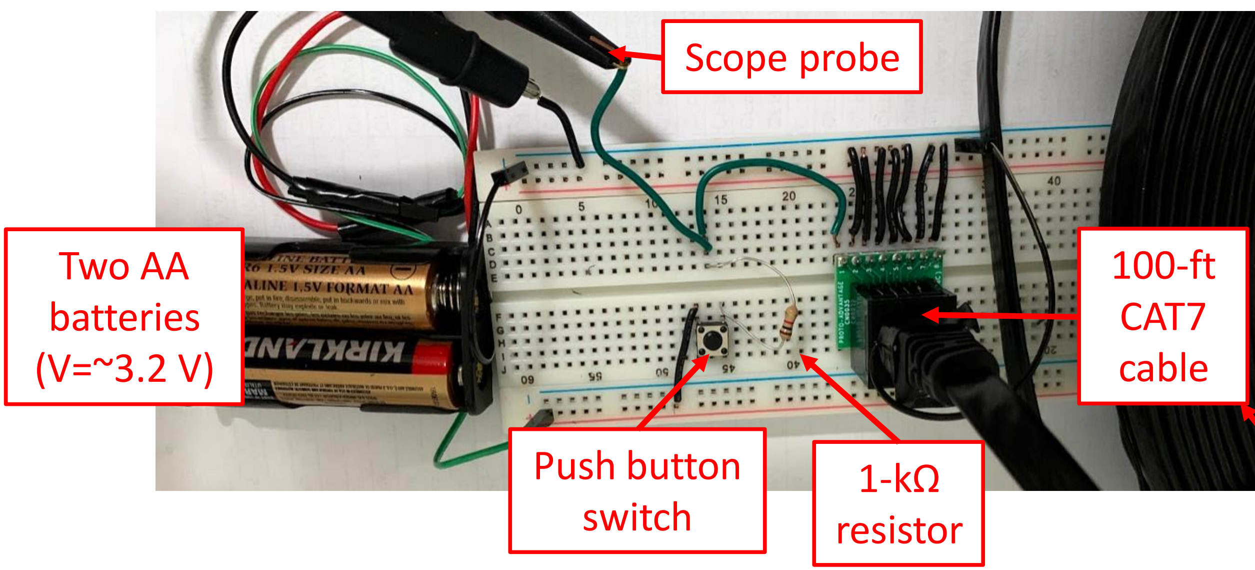
Measuring Cable Capacitance

- Resolution of Fluke 87V multimeter is too low to accurately measure capacitance of cable
  - Total capacitance of cable is low enough to be in the noise of the multimeter's measurement
- Cable capacitance can be determined using an oscilloscope to measure the *RC* time constant (τ) of a circuit with the cable in series with a known resistance
  - τ is time taken for the capacitor in the circuit to charge to 63.2% of its final voltage level or discharge to 36.8% of its initial voltage level

$$\tau = RC \rightarrow C = \frac{\tau}{R}$$

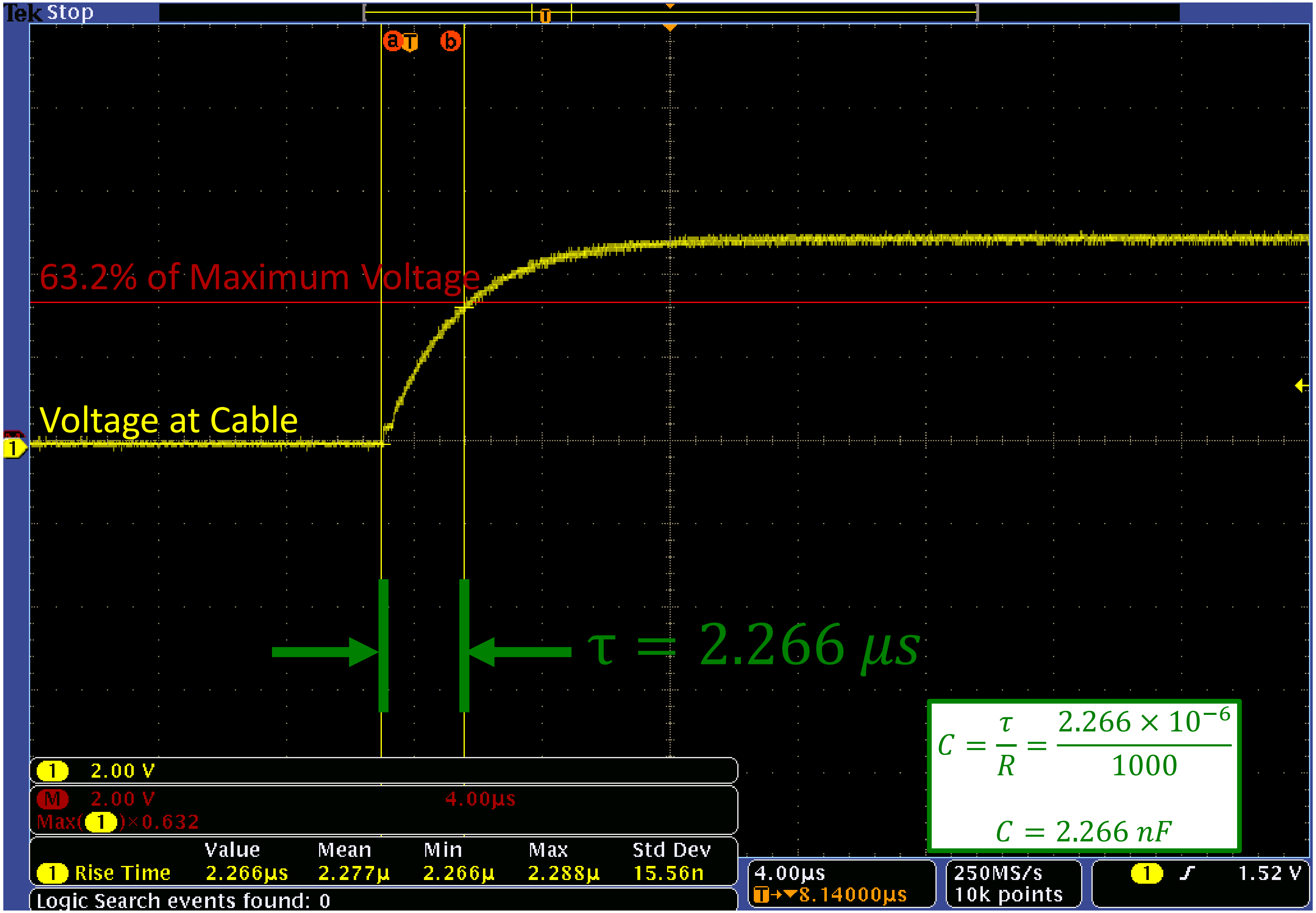
Measuring Cable Capacitance – Test Circuit





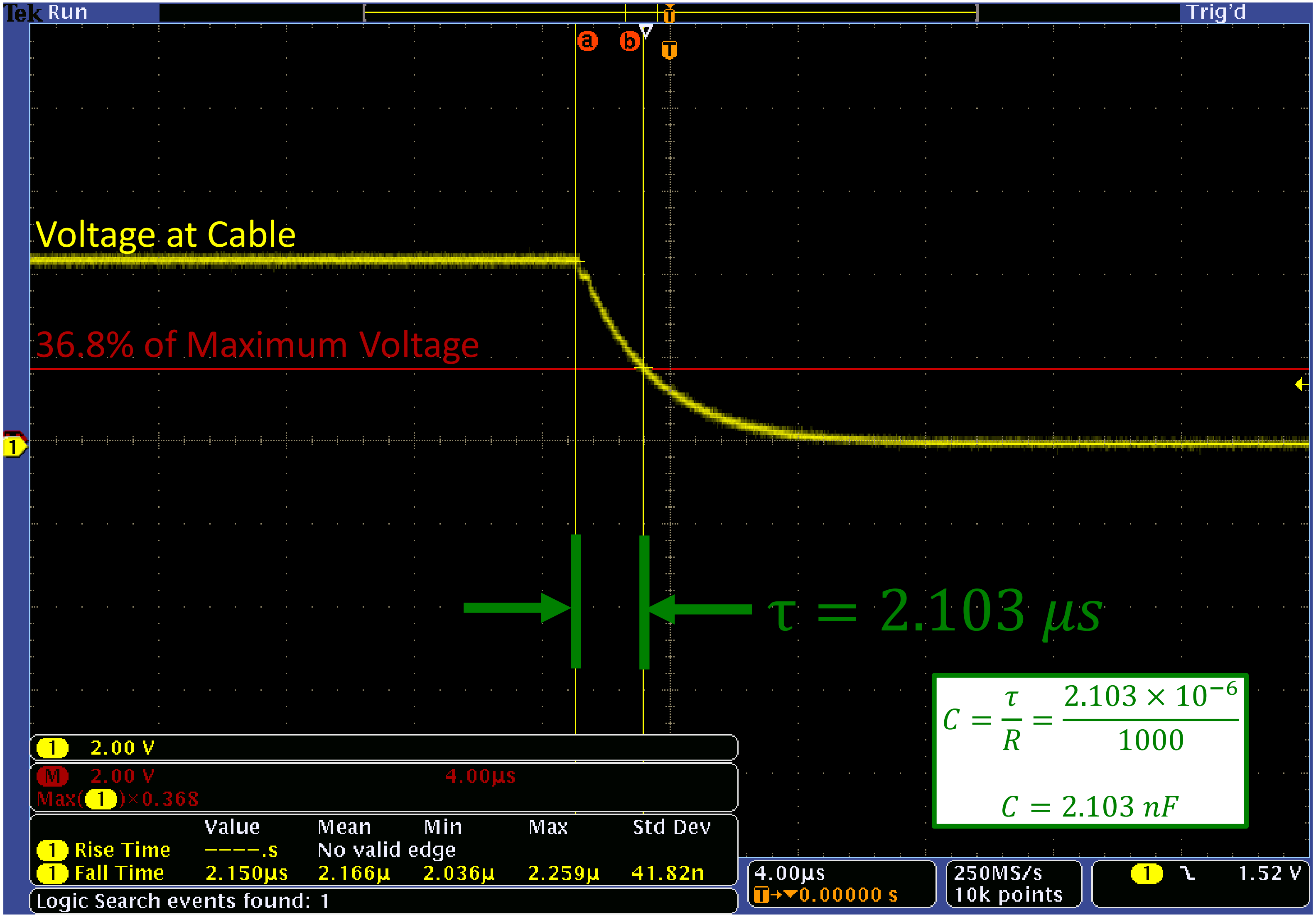
- Test circuit verified by measuring τ to determine capacitance of known 10 nF and 100 nF capacitors
- Three cable lengths measured: ~1 ft, ~50 ft, 100 ft

Measuring Cable Capacitance – 100-ft Cable Oscilloscope Results



Oscilloscope screen shot from test of 100-ft cable when capacitor is charging.

Measuring Cable Capacitance – 100-ft Cable Oscilloscope Results



Oscilloscope screen shot from test of 100-ft cable when capacitor is discharging.

Measuring Cable Capacitance – Results & Pull-Up Resistor Values

Cable Length [ft]	Capacitance [nF]	Max Pull-Up Resistor [Ω]
1	0.0286	41,266
50	1.26	936
100	2.18	541

Capacitance noted is average of capacitance found during charging and discharging.

- As expected, capacitance seen is proportional to cable length
- Maximum pull-up resistor value determined by equation $R_{max}[\Omega] = \frac{10^{-6}}{0.8473 \cdot C}$

Conclusion

- For RICH-II hardware interlock's I^2C communication to SHT35 sensors
  - Minimum pull-up resistor value will be 18 Ω
  - Maximum pull-up resistor depends on length of cables used
    - Cable length affects cable's capacitance
    - Capacitance of flat, CAT7 cable to be used found to be ~28 pF/ft
      - Capacitance found using cable as the capacitor in a simple RC circuit
- For SHT35 sensor readout, ~300-Ω pull-up resistor selected
  - Well above minimum value
  - Allows for length variations up to ~140 ft
  - Verified to work in SHT35 prototyping set up