I2C Bus Pullup Resistor Calculation

Rajan Arora

ABSTRACT
Pullup resistor calculation for I2C interface is a commonly asked question. In this application note we show how to use simple equations for this calculation.

Contents
1 Introduction ................................................................................................................... 1
2 Pullup Resistor Calculation .......................................................................................... 2
3 Speed Versus Power Trade-off .................................................................................... 4
4 Example ........................................................................................................................ 4

List of Figures
1 Application Example Showing I2C Communication Between the Different IC’s on a System and With Pullup Resistors on I2C Bus ............................................................................................ 2
2 Minimum Pullup Resistance \[R_p (\text{min})\] vs Pullup Reference Voltage \(V_{cc}\) ........................................ 3
3 Maximum Pullup Resistance \[R_p (\text{max})\] vs Bus Capacitance \(C_b\) .................................................... 3

List of Tables
1 Parametrics from I2C specifications................................................................................... 3

1 Introduction
I2C communication standard is the mostly widely used inter-chip communication standard in today's electronic systems. It is an open-drain/open-collector communication standard which implies integrated circuits (IC's) with different voltage supply rails can be connected for communication. Pullup resistors need to be connected from the I2C lines to the supply to enable communication as shown in Figure 1. The pullup resistors pull the line high when it is not driven low by the open-drain interface. The value of the pullup resistor is an important design consideration for I2C systems as an incorrect value can lead to signal loss. In this article we show the simple equations for the pullup resistor calculation which the system designer can use to do quick calculations for their design.
2 Pullup Resistor Calculation

A strong pullup (small resistor) prevents the I2C pin on an IC from being able to drive low. The $V_{OL}$ level that can be read as a valid logical low by the input buffers of an IC determines the minimum pullup resistance $R_p(\text{min})$. $R_p(\text{min})$ is a function of $V_{CC}$, $V_{OL}(\text{max})$, and $I_{OL}$:

$$R_p(\text{min}) = \frac{(V_{CC} - V_{OL}(\text{max}))}{I_{OL}}$$  \hspace{1cm} (1)

The maximum pullup resistance is limited by the bus capacitance ($C_b$) due to I2C standard rise time specifications. If the pullup resistor value is too high, the I2C line may not rise to a logical high before it is pulled low. The response of an RC circuit to a voltage step of amplitude $V_{CC}$, starting at time $t = 0$ is characterized by time constant $RC$. The voltage waveform can be written as:

$$V(t) = V_{CC} \times \left(1 - e^{-\frac{t}{RC}}\right)$$  \hspace{1cm} (2)

For $V_{IH} = 0.7 \times V_{CC}$:

$$V_{IH} = 0.7 \times V_{CC} = V_{CC} \times \left(1 - e^{-\frac{t_{IH}}{RC}}\right)$$  \hspace{1cm} (3)

For $V_{IL} = 0.3 \times V_{CC}$:

$$V_{IL} = 0.3 \times V_{CC} = V_{CC} \times \left(1 - e^{-\frac{t_{IL}}{RC}}\right)$$  \hspace{1cm} (4)

The rise time for the I2C bus can be written as:

$$t_r = t_2 - t_1 = 0.8473 \times R_p \times C_b$$  \hspace{1cm} (5)

The maximum pullup resistance is a function of the maximum rise time ($t_r$):

$$R_p(\text{max}) = \frac{t_r}{(0.8473 \times C_b)}$$  \hspace{1cm} (6)

where parametrics from I2C specifications are listed in Table 1.
Table 1. Parametrics from I2C specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard Mode (Max)</th>
<th>Fast Mode (Max)</th>
<th>Fast Mode Plus (Max)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_r ) Rise time of both SDA and SCL signals</td>
<td>1000 ns</td>
<td>300 ns</td>
<td>120 ns</td>
<td>ns</td>
</tr>
<tr>
<td>( C_b ) Capacitive load for each bus line</td>
<td>400 pF</td>
<td>400 pF</td>
<td>550 pF</td>
<td>pF</td>
</tr>
<tr>
<td>( V_{OL} ) Low-level output voltage (at 3 mA current sink, ( V_{CC} &gt; 2 ) V)</td>
<td>0.4 V</td>
<td>0.4 V</td>
<td>0.4 V</td>
<td>V</td>
</tr>
<tr>
<td>( V_{OL} ) Low-level output voltage (at 2 mA current sink, ( V_{CC} \leq 2 ) V)</td>
<td>–</td>
<td>( 0.2 \times V_{CC} )</td>
<td>( 0.2 \times V_{CC} )</td>
<td>V</td>
</tr>
</tbody>
</table>

The \( R_P \) (min) is plotted as a function of \( V_{CC} \) in Figure 2. The \( R_P \) (max) is plotted as a function of \( C_b \) in Figure 3 for standard-mode and fast-mode I2C.

Figure 2. Minimum Pullup Resistance \([R_P \text{ (min)}]\) vs Pullup Reference Voltage \((V_{CC})\)

Figure 3. Maximum Pullup Resistance \([R_P \text{ (max)}]\) vs Bus Capacitance \((C_b)\)
3 Speed Versus Power Trade-off

Once the minimum and maximum value of the pullup resistor has been selected, the decision for the value of resistor can be made based on trade-off between the speed and power budget. A smaller resistor will give a higher speed because of smaller RC delay, and a larger resistor will give lower power consumption.

4 Example

For Fast-mode I2C communication with the following parameters, calculate the pullup resistor value.

\( C_b = 200 \text{ pF}, V_{CC} = 3.3 \text{ V} \)

Solution:

Taking the values from Table 1:

\[
R_P(\text{max}) = \frac{t_r}{(0.8473 \times C_b)} = \frac{300 \times 10^{-9}}{(0.8473 \times 200 \times 10^{-12})} = 1.77 \text{ k}\Omega
\]

\[
R_P(\text{min}) = \frac{V_{CC} - V_{OL(\text{max})}}{I_{OL}} = \frac{(3.3 - 0.4)}{(3 \times 10^{-3})} = 966.667 \text{ } \Omega
\]

Therefore, we can select any available resistor value between 966.667 Ω and 1.77 kΩ. The value of the pullup resistor can be selected based on the trade-off for the power consumption and speed.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have not been so designated is solely at the Buyer’s risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

**Products**

- **Audio**: [www.ti.com/audio](http://www.ti.com/audio)
- **Amplifiers**: [amplifier.ti.com](http://amplifier.ti.com)
- **Data Converters**: [dataconverter.ti.com](http://dataconverter.ti.com)
- **DLP® Products**: [www.dlp.com](http://www.dlp.com)
- **DSP**: [dsp.ti.com](http://dsp.ti.com)
- **Clocks and Timers**: [www.ti.com/clocks](http://www.ti.com/clocks)
- **Interface**: [interface.ti.com](http://interface.ti.com)
- **Logic**: [logic.ti.com](http://logic.ti.com)
- **Power Mgmt**: [power.ti.com](http://power.ti.com)
- **Microcontrollers**: [microcontroller.ti.com](http://microcontroller.ti.com)
- **RFID**: [www.ti-rfid.com](http://www.ti-rfid.com)
- **OMAP Applications Processors**: [www.ti.com/omap](http://www.ti.com/omap)
- **Wireless Connectivity**: [www.ti.com/wirelessconnectivity](http://www.ti.com/wirelessconnectivity)

**Applications**

- **Automotive and Transportation**: [www.ti.com/automotive](http://www.ti.com/automotive)
- **Communications and Telecom**: [www.ti.com/communications](http://www.ti.com/communications)
- **Computers and Peripherals**: [www.ti.com/computers](http://www.ti.com/computers)
- **Consumer Electronics**: [www.ti.com/consumer-apps](http://www.ti.com/consumer-apps)
- **Energy and Lighting**: [www.ti.com/energy](http://www.ti.com/energy)
- **Industrial**: [www.ti.com/industrial](http://www.ti.com/industrial)
- **Medical**: [www.ti.com/medical](http://www.ti.com/medical)
- **Security**: [www.ti.com/security](http://www.ti.com/security)
- **Space, Avionics and Defense**: [www.ti.com/space-avionics-defense](http://www.ti.com/space-avionics-defense)
- **Video and Imaging**: [www.ti.com/video](http://www.ti.com/video)

**Mailing Address**: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

Copyright © 2015, Texas Instruments Incorporated