SMBus and I^{2}C Bus Design

Rev. 1.0

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Introduction

The purpose of this document is to aid in the design of an SMBus or I^{2}C bus using SMBus and/or I^{2}C agents. This document covers design considerations of the SMBus and I^{2}C bus and also highlights the protocol, electrical, and timing differences between the SMBus and I^{2}C bus. Calculation of proper bus signal pullup resistor values is also covered. It is assumed that the reader is familiar with the concepts of both the SMBus and I^{2}C bus.

Protocol

This section shows the protocol differences between the SMBus and the I^{2}C bus. One should consider the protocol and specific addresses supported by all agents on the bus to ensure proper bus operation.

For a complete list and explanation of protocols supported by each type of bus, refer to the I^{2}C bus and SMBus specifications. The I^{2}C Bus specification is available from Philips Semiconductors. The SMBus Specification Revision 1.0 is available from the Reference Material section of this Web site.

SMBus and I^{2}C Bus Protocol Differences

The following protocol differences exist between the SMBus and the I^{2}C bus:

- The SMBus specifies device time-outs which can be used to signal a device error condition or that a device is not ready. Device time-out is accomplished by holding either SMBCLK or SMBDATA low for longer than TTIMEOUT.
- The SMBus allows a slave device to stretch the cumulative clock low time, in a single message, up to TLOW:SEXT.
- The SMBus allows a master device to stretch the commutative clock low time, in any single byte, up to TLOW:MEXT.
- The SMBus can specify the protocol an SMBus agent is allowed to use when acting as a slave when communicating with an SMBus host.
- The I^{2}C bus protocol doesn’t include the Quick Command, but it is valid and will not cause an error from I^{2}C devices. The Quick Command will look to I^{2}C devices as a command abort by the bus master.
- I^{2}C does not support a specific host address as does the SMBus.
- The SMBus reserves the same bus protocol addresses as the I2Cbus, as well as a second set of SMBus specific reserved protocol addresses.

The SMBus exclusive reserved protocol addresses are listed in Table 1.

Table 1. SMBus Reserved Addresses

Address	SMBus Function	I^{2}C Bus Function
0001 000	SMBus Host	Possible I^{2}C device address
0001 100	SMBus Alert Response	TDA 8045 QAM-64 demodulator
1010 001	SMBus Device Default	PLF8593 low power clock/calendar or any EEPROM device
0101 000	Reserved for ACCESS.BUS	Undefined
0110 111	Reserved for ACCESS.BUS default	Undefined
1001 0xx	Unrestricted Address	I^{2}C Group 9 video devices

Besides the addresses listed as reserved by the SMBus in Table 1, there is a list of command addresses reserved for protocol use by both the SMBus and the I^{2}C bus (Table 2). There is also a list of addresses used by current OPSD motherboards (Table 3).

Table 2. SMBus and I^{2}C Bus Reserved Protocal Addresses

Slave Address	Read/Write # Bit	SMBus and I2C Bus Function
0000 000	0	General call address
0000 000	1	START byte
0000 001	X	CBUS address
0000 010	X	Address reserved for different bus format
0000 011	X	Reserved
0000 1XX	X	Reserved
1111 1XX	X	Reserved
1111 0XX	X	10-bit slave addressing

Table 3. Currently Used Motherboard Addresses

Slave Address	Read/Write # Bit	SMBus and I2C Bus Function
1010 0XX	X	DIMM module serial EEPROM address
1001 110	X	I^{2}C Mux address
1101 001	X	Clock generator address
0101 101	X	Heceta ASIC address

IMPORTANT

Check your bus device addresses carefully. All SMBus addresses (other than those listed in Table 1 and Table 2) are reserved for assignment by the SMBus address coordination committee. Philips (the I^2C address assignment agency) has also reserved many addresses other than the common SMBus and I^2C protocol addresses for use by specific bus devices.

Pay close attention to the specific addresses of the bus agents to avoid address conflicts. This especially applies when mixing SMBus devices and I^2C bus devices on the same physical bus.

Architectural Differences

The architectural differences between the SMBus and the I^2C bus are:

- The SMBus may have an optional SMBUS# signal used in power-down mode. This signal is an output from the system management device and is used to signal the state of system suspend mode.

- The SMBus may have an optional SMBALERT# signal used for a slave-only device to signal the bus master that it wishes to communicate. Response to the SMBALERT# signal generates a 7 or 10-bit alert response using the defined alert response address.

Electrical and Timing

This section describes the SMBus and I^2C electrical and timing differences. Since both the SMBus and I^2C bus are open-collector technologies, calculating the proper signal pullup resistor values will also be covered.

SMBus and I^2C Bus Electrical Differences

The main difference between the SMBus and I^2C Bus electrical characteristics is that the SMBus uses fixed levels and the I^2C bus uses levels relative to the Vcc of the bus device. Table 4 shows the electrical differences between the SMBus and the I^2C bus.

Table 4. Electrical Differences (SMBus and I^2C Bus)

Parameter	SMBus	I^2C Bus

	Min.	Max.	Min.	Max.
V_{il}	-0.5V	0.6V	-0.5V	0.3*V_{cc}
V_{ih}	1.4V	5.5V	0.7*V_{cc}	
V_{ol}		0.4V @I_{pullup} Min.	0	0.4V @ 3.0mA (0.6V @ 6.0mA fast)
I_{il}		+/- 10µA		+/- 10µA
I_{pullup}	100µA*	350µA*		3.0mA (6.0mA fast)
Note: * The value includes both the current through the pullup resistor and current from all bus agents. In this context the parameter Ipullup is equivalent to Iol.				

The value for I_{pullup} listed in the SMBus specification has been shown to be difficult to meet when larger numbers of agents are connected to the bus. For this reason, some SMBus devices may differ from the I_{pullup} parameter listed in Table 4. One example of this is the PIIX4. The PIIX4 SMBus lists a I_{pullup} of 3.0mA Max. It will guarantee a Vol of 0.4V @ I_{pullup} of 3.0mA. This allows a larger number of devices to be connected to the bus without violating the operating levels.

Bus and Agent Vcc Voltage Levels

The I^{2}C bus specifies that device input levels are in most cases dependent on Vcc. Note the voltage to which Vcc of each I^{2}C bus agent is connected and to what voltage the bus signal pullup resistors are connected. Mixing these voltages in the wrong way could cause improper input high levels.

In some cases, bus agents may only have 3.3V tolerant input levels and therefore the bus signals must only be pulled up to a V_{cc} of 3.3V. Any other bus agents will have to be connected to the proper voltage levels so that their input levels are compliant with that of the bus.

An example of this is the PIIX4 SMBus host. The input buffers of the SMBus in the PIIX4 are only 3.3V tolerant. Thus the bus must be pulled up to 3.3V to meet the PIIX4 requirements. All other bus agents, whether I^{2}C or SMBus, must connect to voltage levels that will allow their input levels to be compliant with that of the bus and the PIIX4 host.

SMBus and I^{2}C Timing Differences

The SMBus and I^{2}C Bus timing differences are mostly concerned with time-out and clock stretching protocols supported by the SMBus. These timing differences are listed in Table 5.

Table 5. Timing Differences (SMBus and I^{2}C Bus)

Parameter	SMBus	I^{2}C Bus

	Min.	**Max.**	**Min.**	**Max.**
Bus Frequency	10 KHz	100KHz	0	100KHz (400KHz Fast)
Time-out	25mS	35mS	N/A	N/A
Clock Low Extend (Slave)		25mS	N/A	N/A
Clock Low Extend (Master)		10mS	N/A	N/A

Bus Pullup Resistor Calculations

Due to the architecture of both the SMBus and the I^{2}C Bus, all agents on the bus must have open collector (drain) outputs. Because of the nature of these outputs, both the bus clock and data lines must be pulled up to some V_{cc} value. Both the SMBus and the I^{2}C bus specifications require only one pullup resistor per bus signal. As discussed in Section 020, the voltage used for the pullup resistors on the bus signals depends on the nature of all of the bus agents.

General Bus Pullup Resistor Calculations

There are three cases that must be considered when calculating the pullup resistor values for either an SMBus or I^{2}C Bus:

- V_{ih} level at rated current.
- V_{il} level at rated current.
- Rise and fall time conditions.

Use the above three cases when calculating the bus pullup values. The DC values of V_{ih} and V_{il} will be used to define a solution space and the rise and fall time requirements will select a specific value in that solution space. We recommend this approach to provide a direct method of resistor value calculation that will satisfy all applicable conditions.

The steps to calculate the solution space are listed in the “Determine Maximum Pullup Resistor Value” and “Determine Minimum Pullup Resistor Value” procedures in the following sections.

Procedure 1. Determine Maximum Pullup Resistor Value

To find the maximum pullup resistor value to use on clock and data lines, follow these steps:

1. Identify the minimum value of the V_{cc} rail (V_{ccmin}) where the bus signal pullup resistors will be connected.
2. Identify the minimum V_{ih} value for each bus agent when powered by the minimum V_{cc} value found in step 1. Use the highest of these V_{ih} values (V_{ihmm}) for the calculations. Choosing the highest minimum V_{ih} value will guarantee all other V_{ih} conditions are met.
3. Choose a desired noise margin (NM_{min}) for the logic high condition on the bus. This value is typically 0.1V - 0.2V above the maximum value chosen for V_{ih}. It

is recommended that the first choice for the noise margin be 0.2V. This will be the minimum noise margin for the system when V_{cc} is at a minimum value. As the system V_{cc} increases to typical and maximum value, the noise margin will also increase.

4. Find the total maximum current (I_{ihmax}) sunk by all agents for the input high condition.
5. Calculate the maximum value (Rp_{max}) for the bus pullup resistor from the following equation:

$$Rp_{max} = (V_{ccmin} - (V_{ihmm} + NM_{min}))/ I_{ihmax} \qquad \text{Equation 1}$$

This result is the upper limit (maximum value) of the pullup resistor solution space. An example of how to use this equation appears in Section 05.

Procedure 2. Determine Minimum Pullup Resistor Value

To find the minimum pullup resistor value to use on clock and data lines, follow these steps:

1. Identify the maximum value of the V_{cc} rail (V_{ccmax}) where the bus pullup resistors will be connected.
2. Identify the lowest V_{ol} value (V_{olmin}) for a particular bus master.
3. Identify the maximum current sunk (I_{olmax}) by this bus master at the V_{olmax} value.
4. Calculate the minimum value (Rp_{min}) for the bus pullup resistor from the following equation:

$$Rp_{min} = (V_{ccmax} - V_{olmin}) / I_{olmax} \qquad \text{Equation 2}$$

This result is the lower limit (minimum value) of the pullup resistor solution space. An example of how to use this equation appears in Section 05.

Now we have a minimum and maximum resistance value that our pullup resistor can be while satisfying the DC specifications of our bus. This is our solution space for choosing a resistor value that will satisfy our rise and fall times.

Procedure 3. Perform Bus Signal Rise and Fall Time Calculations

The value found from the rise and fall time calculations, together with the solution space defined from the bus DC bus values, will determine the proper value for the bus pullup resistors. The solution from the rise and fall time calculations should fall within the DC solution space to satisfy all bus requirements.

If a value of pullup resistor is found that satisfies our rise and fall time requirements but is not in our DC solution space, parameters in the calculations or the bus design itself may need to be modified.

A good rule of thumb for the pullup value is $Rp < T_{rise} / 2 * C_{bus}$. Where T_{rise} is the maximum allowable rise time minus some margin and C_{bus} is the total capacitance on the bus.

In this document, a more precise calculation will be used to calculate the pullup resistor values. This calculation will also help verify the rule of thumb calculation. The equation that will be used to calculate signal rise time is one for charging capacitors. The general form of this equation is:

$$V_c = V_{cc} + [V_o - V_{cc}]\, e^{-t/RC} \qquad \text{Equation 3}$$

where R is pullup Rp, C is the total bus capacitance, t is the rise time, V_o is the initial voltage on the bus capacitance, and V_c is the voltage across the bus capacitance at any given time (in this case V_{il} and V_{ih} values).

Solving Equation 3 for the rise time t yields:

$$t = -RC\ln[(V_c - V_{cc})/(V_o - V_{cc})] \qquad \text{Equation 4}$$

Procedure 3 (continued): Rise Time Calculation

Use the following steps to calculate the bus rise time:

1. The maximum rise time for both the SMBus and the I^2C Bus is defined to be 1.0µs.
2. Choose a rise time margin such that the desired rise time is less than the maximum allowed rise time of 1.0µs. Usually this is around 50 - 100nS.
3. Calculate the total capacitance of the bus. This includes the capacitance of the bus and of all bus agents.
4. For a rising edge, 0 to 1 transition, assume an initial starting voltage (V_o) for the logic 0 state. Assuming the bus has settled out to a ground state, this value would be approximately 0V. For worst case bus calculations, assume an initial voltage of approximately 0V.
5. Determine the minimum value of V_{cc} (V_{ccmin}) in the system where the pullup resistor will be connected.
6. Determine the maximum value for V_{ih} (V_{ihmm}) for the minimum value of V_{cc} found in step 5.
7. Solve Equation 5 for the pullup resistor R and substitute the known values for the bus parameters. This will yield an equation for the value of the pullup resistor needed.

$$Rp = -t / (C * \ln [(V_{ihmm} - V_{ccmin})/ (V_o - V_{ccmin})]) \qquad \text{Equation 5}$$

An example of how to use this equation appears in Section 05.

If the value obtained from Equation 5 is not in the solution space found in the “General Bus Pullup Resistor Calculations” Section 1.4.1 for the DC levels, one of two steps must be taken.

If the value from the above rise time equation is greater than the maximum limit of the DC solution space found in Equation 4, the resistor value may be reduced to a value within the solution space. Lowering the resistor value will satisfy the DC solution space and will not violate the rise time specification. A lower resistance value than the one found in Equation 5 will not violate the maximum rise time parameter but will in fact make the rise time less. This can be seen from Equation 4. Assuming no parameters change except for the resistance R, a lower resistance value will yield a lower rise time t.

If the result of Equation 5 is lower than the minimum value for the DC solution space found in Equation 2, either the factors influencing the minimum value for the DC solution space must be changed or the factors influencing the value from the rise time calculation must be changed.

In the case of the minimum value in the DC solution space, this value must be lowered. From Equation 2 we see that the resistance value may be lowered if the product of V_{ccmax} - V_{olmin} is decreased and/or I_{olmax} is increased. Since I_{olmax} and V_{olmin} are a function of the bus agent in question, the only solution without changing the driving bus agent is to select a lower V_{ccmax} of the system.

In the case of the value for maximum rise time, this value must be raised. From Equation 5 we can see that in order to make the value for Rp greater we must increase the desired maximum rise time, decrease the bus capacitance, decrease the $V_{ihmax} – V_{ccmin}$ product, and/or increase the $V_o – V_{ccmin}$ product.

Generally, the bus capacitance is a function of the bus agents and cannot be changed unless the number of bus agents is changed or the characteristics of the bus agents are changed. The products of $V_{ihmax} – V_{ccmin}$ and $V_o – V_{ccmin}$ can be changed appropriately by decreasing the value of V_o. The fact that V_{ihmax} is a function of V_{ccmin} means changing one will change the other so that no net change will occur when the division of the numerator and denominator is performed. The most easily changed parameter is the desired rise time. If some margin has been added to the rise time, the amount of margin can be decreased so that the desired maximum rise time will increase.

The above cases are listed for completeness. In general, the resistor from the rise time calculation will either be in the DC solution space or will be greater than the DC solution space. In these cases little or no work will be needed to adjust for a resistor value that is acceptable for proper bus operation.

Procedure 3 (continued): Fall Time Calculations

The calculations for fall time involve equations that require knowledge of the output driver, as well as several integrations over the active regions of the output driver. These calculations are beyond the scope of this document and need not be used here.

Instead, we can use the fact that the SMBus and I^2C Bus specifications require a maximum fall time of 300ns. We can also use the fact that these same specifications require that the output driver of a compliant bus master must guarantee a maximum fall time of 250ns over a bus capacitance of 10 - 400pF with up to 3.0mA (6.0mA in the fast I^2C case) of sink current.

NOTE

Although the SMBus specifies a maximum fall time of 300ns, it makes no specification of the output driver guaranteed fall time. Only the I^2C bus specifies the 250ns guaranteed driver fall time, as mentioned above.

From the previous paragraph we can assume our bus fall times to be within the 300ns specification if three criteria are matched:

- All agents that are capable of driving the bus are I^2C compliant to guarantee fall times of 250ns maximum.
- Our bus has a total capacitance of between 10 and 400pF.
- The total current that has to be sunk by any output driver in the low state is 3.0mA or less (6.0ma or less in the fast I^2C case).

For the total bus current that has to be sunk by any driver in the low state, you can use this equation:

$$I\ total = ((V_{cc}-V_{olmin})/Rp) + \sum I_{il}\ from\ all\ bus\ agents$$

Note that the maximum pullup resistor current occurs at V_{olmax} and V_{ccmax}.

Pullup Resistor Calculation Example

The following is an example of a pullup resistor calculation for an SMBus using I^2C slave agents and a SMBus host.

Assume a SMBus design with seven I^2C compliant agents. The bus master is a PIIX4 SMBus controller.

PIIX4 SMBus specs:

- V_{ih} = 0.6V max.
- V_{il} = 1.4V min.
- I_{il}, I_{ih} = +/- 10µA
- V_{ol} = 0.4V max. @ rated I_{ol}
- I_{ol} = 3.0mA max.
- $C_{i/o}$ = 12pF max.

NOTE

The PIIX4 SMBus inputs are only 3.3V tolerant so they bus up to a 3.3V supply. In this case Vcc3 is specified at 3.3V +/- 5%.

At the time this document was written, the PIIX4 SMBus driver rise and fall times were not specified. In this example, standard SMBus rise and fall times are assumed for the PIIX4.

I^{2}C compliant bus agents specs.

- $V_{ih} = 0.7*Vcc$ with $V_{cc} = 3.0 - 3.6V$: V_{ih} = 2.1V min., 2.52V max.
- $V_{il} = 0.3*Vcc$ with $V_{cc} = 3.0 - 3.6V$: V_{il} = 0.9V min., 1.08V max.
- I_{il}, I_{ih} = +/- 10µA
- V_{ol} = 0.4V max. @ rated I_{ol}
- I_{ol} = 3.0mA max.
- $C_{i/o}$ = 10pF max.

NOTE

All of the bus agents have the same specs when they are driving the bus low. This greatly simplifies our calculations since we only need to perform one set of calculations for these common output characteristics.

First we will calculate the pullup resistor solution space from the specified DC parameters for the various agents. In this example we will select a minimum noise margin (NM_{min}) of 0.2V. We see the largest minimum value for V_{ih} on any bus agent is 2.1V at minimum V_{cc}. We also note that I_{ihmax} for the seven agents receiving is 7*10µA .

From our equation for maximum pullup resistance:

$$Rp_{max} = (V_{ccmin} - (V_{ihmax} + NM_{min})) / I_{ihmax}$$

$$Rp_{max} = (3.0 - (2.1 + 0.2)) / 70x10^{-6}$$

$$Rp_{max} = 10.0 \text{ K}$$

Next we need to calculate the pullup resistor minimum value. The minimum V_{ol} value for any agent driving the bus is 0V at an I_{ol} of 3.0mA Max. Max. V_{cc} has been determined to be 3.6V. From our equation for Rp_{min}:

$$Rp_{min} = (V_{ccmax} - V_{olmin}) / I_{olmax}$$

$$Rp_{min} = (3.6 - 0) / 3x10^{-3}$$

$$Rp_{min} = 1.2 \text{ K}$$

We now have our solution space and may calculate our specific pullup value based on desired rise and fall times.

We have a maximum rise time for both the SMBus and I^{2}C bus of 1.0µs. We now choose a margin for rise time, in this case 100nS. Thus our maximum rise time is 900nS.

Note that we now have eight input loads on the bus at any one time during a logic high condition. Seven of these loads are the same, 10pF, and the PIIX4 is 12pF. Thus, we have a total bus capacitance of 82pF.

Voltage conditions are V_{ccmax} = 3.6V, $V_{ihmax}+NM$ = 2.7V, and our assumed worst case V_{ol} is approximately 0V.

Substituting back into Equation 5 (our Rise Time Calculation), we may now calculate the pullup value based on the above conditions:

$$Rp = -t / (C * ln[(V_{ihmax}+NM - V_{ccmax}) / (V_o - V_{ccmax})])$$

$$Rp = -900x10^{-9} / (82x10^{-12} * \ln[(2.7 - 3.0) / (0 - 3.0)])$$

$$Rp = 4.77 \text{ K}$$

We see from our result that the resistor value falls in the pullup resistor solution space calculated from our DC parameters. We may choose this value or choose a different resistor value, as long as it is in the calculated solution space and is less than the value derived from the above rise-time calculation.

Our decision to choose a different resistor value than the one calculated may be the desire to use a more standard resistor value or the desire to use a value that is already used elsewhere in our design. This decision is left to the designer.

In this example, we will choose a more standard resistor value for our pullup. Let this resistor be 4.7K. As mentioned previously, we may adjust the pullup value to be less than the value derived from our rise-time calculation, without causing the bus to function improperly. We see from Equation 4 that if the resistance *Rp* is decreased, the rise time of the bus will decrease accordingly. This change will not violate the maximum rise time but will instead add more margin to our rise time.

We can verify this by calculating the rise time with our chosen value of pullup resistor from the equation:

$$t = -R * C * \ln[\,(V_{ohmax} - V_{ccmax}) / (V_{olmax} - V_{ccmax})\,]$$

$$t = -\,4.7 \times 10^{3} * 82 \times 10^{-12} * \ln[\,(2.7 - 3.0) / (0 - 3.0)\,]$$

$$t = 887 \text{ ns}$$

To verify that our choice does not violate the bus fall time we must check that we do not violate the specification for maximum current sunk by an output driver. We note that I_{total} delivered to the output driver is:

$$I_{total} = ((V_{ccmax} - V_{olmin}) / Rp) + \sum I_{il} \text{ from all bus agents}$$

$$I_{total} = ((3.6 - 0) / 4.7 \times 10^{3}) + 70 \times 10^{-6}$$

$$I_{total} = 836 \mu\text{A}$$

This is significantly less than the rated current of 3.0mA, so our value for *Rp* is satisfactory.

SMBus and I^2C Bus Design Checklist

Here is the Best Known Method (BKM) checklist for SMBus and I^2C Bus Design:

Table 6. SMBus and I^2C Bus Design Checklist

Function	Reference	Notes	Completed By	Date
☐ Procedure 1. Determine the maximum pullup resistor value				
☐ Procedure 2. Determine the minimum pullup resistor value				
☐ Procedure 3. Perform the bus signal rise and fall time calculations				
☐ All tests were completed and passed				
Notes/Comments:				