

# Careful power-distribution design ensures standard-compliant USB operation

LARRY MAZER AND KEVIN LYNN, MICREL SEMICONDUCTOR

The USB standard is designed to deliver plug-and-play capability, along with enhanced multimedia performance and computer-telephony integration, to the PC. In addition, the USB distributes operating power to peripherals, eliminating the need for external power supplies in low-power peripherals. These attributes make the USB a compelling technology but also place stringent qualifications on power distribution. Thus, the standard defines the electrical requirements and depicts how power should be distributed among, and to, peripherals within the USB network topology. Designers therefore need to use proper methods for USB peripheral power distribution, which is crucial to ensuring full compliance with the USB specification, particularly with EMI and voltage and transient regulation.

## Architectural differences

To understand the issues involved in USB power distribution, it's important to grasp how the USB specification defines the types of devices used in USB-compliant systems. The specification defines self- and bus-powered classes of devices differentiated by varying power requirements.

Self-powered devices include hubs and functions. Such

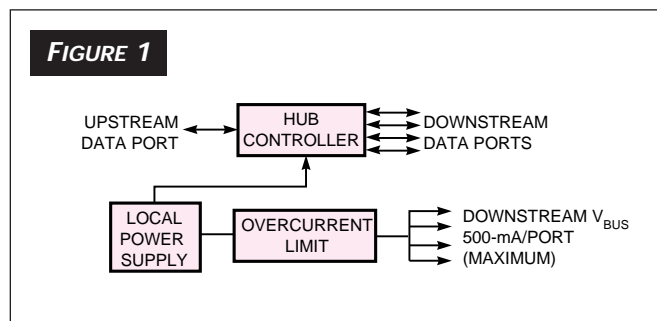
Proper component selection and design make your USB system operate properly and adhere to the USB specification.

devices obtain their operating power from a source other than the bus, because their power requirements exceed that of the bus. Examples of self-powered devices are PCs, monitors, printers, and scanners.

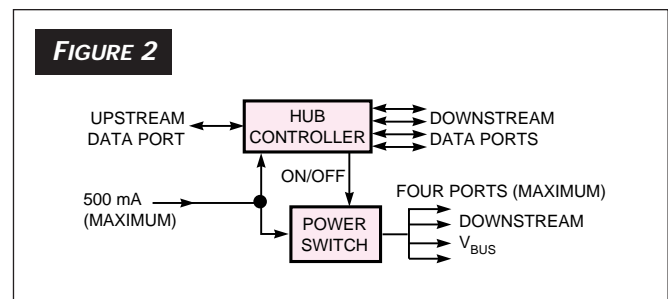
Self-powered hubs distribute data and power to other functions (Figure 1) and have the following requirements under the USB specification:

- 500-mA minimum current capacity per port,
- 5A per port current limit,
- Ganged (group of ports) or individual (per port) current limiting,
- Overcurrent-limit report to host.

Even though self-powered hubs cannot consume operating power from the bus, they may draw as much as 100 mA from an upstream (toward the host) cable to power the local USB controller only. This move allows for the hub to report status (often called "enumeration" within the USB specification) to the host, even though the hub's internal function may be powered off. For example, a monitor with an integrated hub may actually be turned off, but the host can still obtain its operating status, provided the local USB controller is still powered from the cable.



Self-powered USB hubs distribute data and power to other USB functions.



Bus-powered hubs also distribute data and power but have limited sourcing capacity because they draw power from the bus.

## POWER DISTRIBUTION FOR USB DESIGN

The 5A current limit is designed to meet the UL regulatory limit of 25 VA, which protects against fire hazards resulting from fault conditions. On detecting this limit, the local controller must report this condition to the host via a hub status register. Currently, there is no standard method for the host to handle an overcurrent condition. As such, on detecting an overcurrent condition, the host removes power from the offending port. Thus, to bring the system back to an operational state, the user must intervene and replace the faulty device.

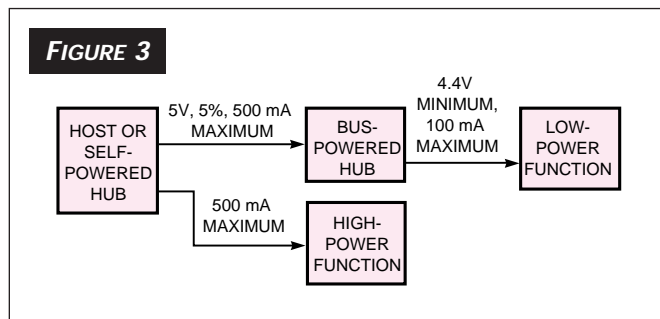
In contrast to self-powered devices, bus-powered devices include hubs and high- and low-power functions. High-power functions require operating current greater than 100 mA but less than 500 mA. However, they can draw only 100 mA maximum on power up. After enumeration, the functions may request as much as 500-mA additional current from the host.

Low-power functions require less than 100 mA of operating current. Bus-powered hubs draw all of their power from the upstream cable. Like high-power functions, bus-powered hubs may draw as much as 100 mA on power up and draw as much as 500 mA total after enumeration. Note that this 500 mA is split between embedded functions and external ports. If more power is required, then the hub must be self-powered.

Bus-powered hubs, like their self-powered-hub counterparts, also distribute data and power to USB functions but have limited power capacity because they draw power from the bus (Figure 2). Bus-powered hubs require the following:

- Power to downstream ports must be switched under control of the local USB controller. Each port may be individually switched, or all ports may be gang-switched. Hubs can accommodate a maximum of four downstream ports.
- As much as 400 mA may be distributed among downstream ports (100 mA must be allocated to the internal function, such as the USB controller). Each downstream port must provide a minimum of 100 mA.
- Switching must employ a controlled turn-on (soft-start) characteristic to minimize voltage transients on the upstream bus voltage.

To ensure that your design complies with USB specifications, it's important to understand the various design methodologies and trade-offs involved in power distribution.



Various USB-device classes have defined voltage and current constraints.

The main issues involve the USB specification's voltage-regulation requirements, which ensure that peripherals have the necessary supply voltage to operate under all conditions, and transient regulation, which addresses bus-voltage parameters during hot-plug events. Figure 3 depicts the USB requirements among various device classes. Note that you must consider voltage-regulation requirements for both self- and bus-powered hubs. Self-powered hubs and hosts provide a bus voltage of  $5V \pm 5\%$  with a current to 500 mA at each downstream port. To supply this voltage, self-powered hubs employ an internal power source.

Figure 4 depicts the components within a self-powered hub or host that you must take into account for proper design. Critical design components include the resistances of the pc-board traces and connectors, the current-limit device, and the ferrite beads. The power source should have a 3% or better tolerance, which is not difficult or expensive given the technology available today. This requirement allows for 2% of the power-supply tolerance to be distributed among system components.

The power-supply tolerance limits the allowable voltage drop for the system. For the model in Figure 4,

$$V_{\text{BUS(REG)}} \geq V_{\text{PS(REG)}} - V_{\text{PCB}} - V_{\text{OC}} - V_{\text{BEAD}}$$

where  $V_{\text{BUS(REG)}}$  and  $V_{\text{PS(REG)}}$  are the 5 and 3% tolerances of the bus voltage and internal power supply, respectively, and  $V_{\text{PCB}}$ ,  $V_{\text{OC}}$ , and  $V_{\text{BEAD}}$  are the voltage drops across the pc-board traces, overcurrent-limiting device, and ferrite beads, respectively. Continuing the analysis,

$$V_{\text{BUS(REG)}} \geq V_{\text{PS(REG)}} - I_{\text{MAX}}(R_{\text{PCB}} + R_{\text{OC}} + R_{\text{BEAD}})$$

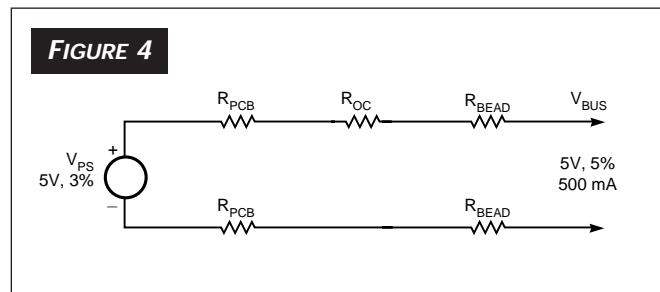
Solving for the limits on the maximum allowable resistance for the current-limit device yields

$$R \leq \frac{V_{\text{BUS(REG)}} - V_{\text{PS(REG)}}}{I_{\text{MAX}}}$$

where R represents the sum of pc-board-trace, connectors, and current-limit-device resistances. Using the specified values yields

$$R \leq \frac{(0.05 \cdot 5) - (0.03 \cdot 5)}{0.5} = 200 \text{ m}\Omega$$

This value guarantees that the design meets the USB voltage-regulation specification of 5V, 5% under full- and no-load



Analysis of the self-powered-hub voltage drops shows partitioning of allowable resistances.

## POWER DISTRIBUTION FOR USB DESIGN

conditions. When you consider the summed resistances of pc-board trace, connectors, and ferrite beads, your remaining budget for the current-limit device equals 150 mΩ.

This calculation is for a single port. For ganged ports, you must lower the current-limit-device resistance by factor N, where N represents the number of ports. For example, the resistance of a single current-limit device protecting four ports must be less than 200 mΩ/N, or 50 mΩ, without considering pc-board-trace and other resistances.

Note that this analysis is based on assuming pc-board-trace and ferrite-bead resistances, which are system-dependent parameters. However, it clearly demonstrates that you must take care in your pc-board layout and in the selection of components, such as ferrite beads and, more important, current-limit devices.

Bus-powered hubs can draw a total of 500 mA from the bus. This current supply is split between internal functions and downstream ports. A bus-powered hub can supply an aggregate of as much as 400 mA among its downstream ports. However, each port must supply a minimum of 100 mA.

Each port must also be switched under host control. The minimum voltage at each port equals 4.4V, which provides enough margin for bus-powered functions to operate correctly. A 350-mV maximum drop is allowed from the upstream cable connector to the bus-powered-hub downstream connector. This drop includes the resistance of the cable, connectors, switch, and pc-board traces and components.

Figure 5 and the USB specification show the following limits and the equation representing bus-powered-hub voltage drops. Solving for  $R_{\text{SWITCH}}$

$$V_{\text{OUT}}(\text{MIN})=4.40\text{V} \geq V_{\text{IN}}(\text{MIN})-V_{\text{CABLE}}-V_{\text{CON}}-V_{\text{SWITCH}}-V_{\text{PCB}} \\ =4.75\text{V}-I_{\text{MAX}}(4R_{\text{CON}}+2R_{\text{CABLE}})-(0.1\text{A}\cdot N)R_{\text{SWITCH}}-10\text{mV},$$

where  $V_{\text{BUS}}=V_{\text{IN}}(\text{MIN})=4.75\text{V}$ .

From Section 6-4 of USB Specification 1.0,  $R_{\text{CONNECTOR}}=30\text{m}\Omega$  max, and  $R_{\text{CABLE}}=190\text{m}\Omega$  max (5m cable).

Allowing for 100 mV across the FET switch and pc board leaves 250 mV for cable and connector drops. The equation then reduces to  $R_{\text{SWITCH}} \leq 90\text{mV}/(0.1\text{A}\cdot N)=900\text{m}\Omega$  per port. For ganged switching with N ports,  $R_{\text{SWITCH}}$  equals 900, 450, 300, and 225 mΩ for N of 1, 2, 3, and 4, respectively.

The switch resistance can be much higher for a bus-powered hub due to the lower current requirements. You must pay special attention to the pc-board layout and component selection so that the IR drop constraints are satisfied. Note that the calculations above assumed only 10-mV drop through pc-board-trace and ferrite-bead resistance. Table 1 shows representative pc-board-trace resistances. You must choose an FET switch with lower on-resistance if these com-

## DEAL WITH GANGED SITUATIONS

The USB specification allows for downstream ports to be protected or switched either on a ganged basis or individually. The method you use is specified in the hub descriptor register, as described in the USB specification. Ganged protection provides the most economical solution, but it requires you to use a much lower resistance overcurrent-protection device to satisfy USB voltage-regulation requirements at these higher currents. (Note that each port requires a multiple of 500 mA.) From a practical standpoint, each ganged current-limit device should not control more than seven ports to stay within the 5A UL requirement.

In addition, it's not possible for the system to detect which port is the offending one. Therefore, the host must shut down all ports until the fault is removed, which can cause undesirable system issues. For instance, a user would not like the modem to be disabled just because the keyboard or mouse malfunctions and causes the fault. Ganging ports also makes control of transients during hot-plug events more difficult, because the ports have little isolation between them compared with individual port switching or protection.

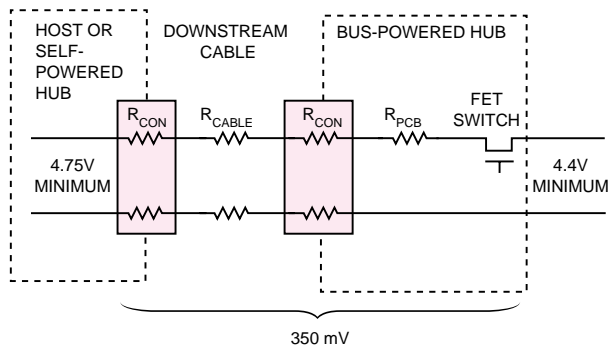
Individually protected ports overcome these issues, because each port can provide overcurrent status indicating the faulty port. In addition, each device has less stringent resistance requirements; and, in general, the ports offer a more reliable and robust method of protection, because each port is isolated from the others.

ponent resistances are higher. To minimize EMI radiation and to reduce ac impedance during hot-plug events, all components must reside as near to the I/O connector as possible.

The USB specification allows downstream ports to be protected or switched on a ganged or individual basis (see sidebar "Deal with ganged situations"). It also lets users attach devices to a USB hub or host at any time. This provision places strict requirements on how the circuitry must manage the transients caused by such an event. Whenever a USB device connects to a powered hub or host port, the device load causes a voltage transient due to the relatively high inrush currents that occur in charging the load capacitance.

To minimize the problem, the specification requires that you use a minimum bulk capacitance of 120 μF at the output

FIGURE 5



Analysis for the bus-powered hub, similar to that for the self-powered hub, shows additional sources of voltage drop.

## POWER DISTRIBUTION FOR USB DESIGN

of each downstream-port voltage bus. This value provides the transient current required to charge the device's input capacitance, thereby minimizing the associated bus voltage droop (330 mV maximum). Additionally, the USB specification also limits the maximum input capacitance a device can have to 10  $\mu\text{F}$ , which also helps to control voltage transients. By specifying a maximum input capacitance, the USB specification bounds the magnitude of the voltage droop.

It's also important to consider that individually protected or switched ports have superior transient regulation due to the impedance of the inline switch, because the switch resistance reduces the transient currents. However, with ganged ports there is no resistance isolating one port from another. Therefore, a hot-plug event on one port has a greater effect on adjacent ports and may exceed the 330-mV voltage-droop specification.

Thus, it is a good idea to use ferrite beads at each port to yield better isolation. Tests show that these beads help the system meet USB transient-regulation specifications. Note that the currents associated with hot-plug events can be greater than 2A—with a duration of approximately 30  $\mu\text{sec}$ . Even electrolytic capacitors as small as 100  $\mu\text{F}$  at the downstream port cause a much larger voltage droop because of their higher ESR.

Bus-powered hubs have the same transient-regulation issues as self-powered hubs. Therefore, they also require 120- $\mu\text{F}$  bulk capacitance. In addition, bus-powered hubs require a soft-start circuit to minimize the voltage droop caused by the switches turning on into such a high capacitance load. Without a slow and controlled turn-on, the resulting high inrush currents cause the upstream bus voltage to droop below the minimum voltage required for downstream peripherals to operate correctly.

## USB hub reference designs

You can provide the overcurrent-protection device required in a host or self-powered hub in several ways. Overcurrent-protection devices include poly-

**TABLE 1—PC-BOARD-TRACE RESISTANCE**

Conductor thickness (oz/ft <sup>2</sup> )	Conductor width (in.)	Resistance (m $\Omega$ /in.)
0.5	0.025	39.3
	0.050	19.7
	0.100	9.8
	0.200	4.9
1.0	0.025	19.7
	0.050	9.8
	0.100	4.9
	0.200	2.5
2.0	0.025	9.8
	0.050	4.9
	0.100	2.5
	0.200	1.2
3.0	0.025	6.5
	0.050	3.2
	0.100	1.6

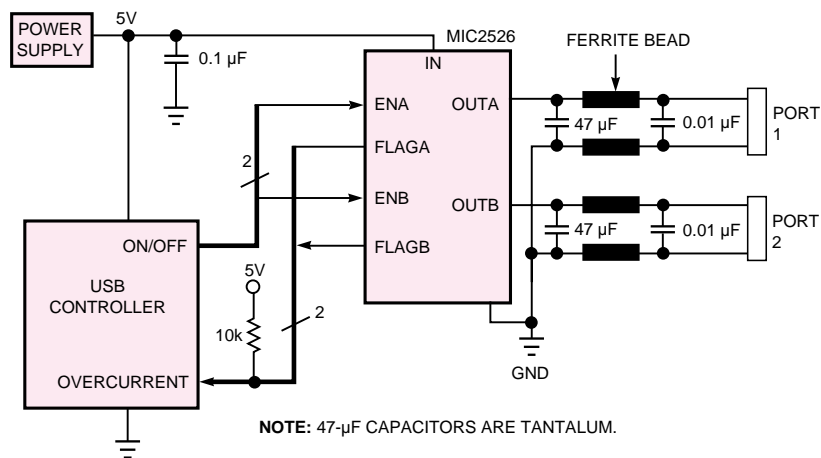
fuses, standard fuses, and solid-state or MOSFET switches. The objective of these overcurrent-protection circuits is to prevent catastrophic device failures resulting from problems such as short-circuited connectors.

Resettable polymer positive-temperature-coefficient fuses (also known as "PPTC" or "polyfuse" fuses) are self-resetting fuses that, in response to high currents, enter a high-impedance state until the fault is removed. Once tripped, however, their on-resistance increases, so you must ensure that the post-tripped resistance meets design parameters. Polyfuses can satisfy USB specifications and provide adequate, cost-effective protection, but you face a trade-off between their trip time and on-resistance. Devices with lower on-resistance have longer trip times,

and vice versa. In addition, designers, especially of mobile products, must be aware that even in fault conditions, polyfuses have relatively high leakage currents.

The familiar one-time fuse has a similar cold on-resistance value to that of a polyfuse, with faster time to trip, but one-time fuses require operator intervention and replacement once they trip. Few designs currently use such fuses.

**FIGURE 6**



A two-port USB host design minimizes effects of one port on the other's operation.

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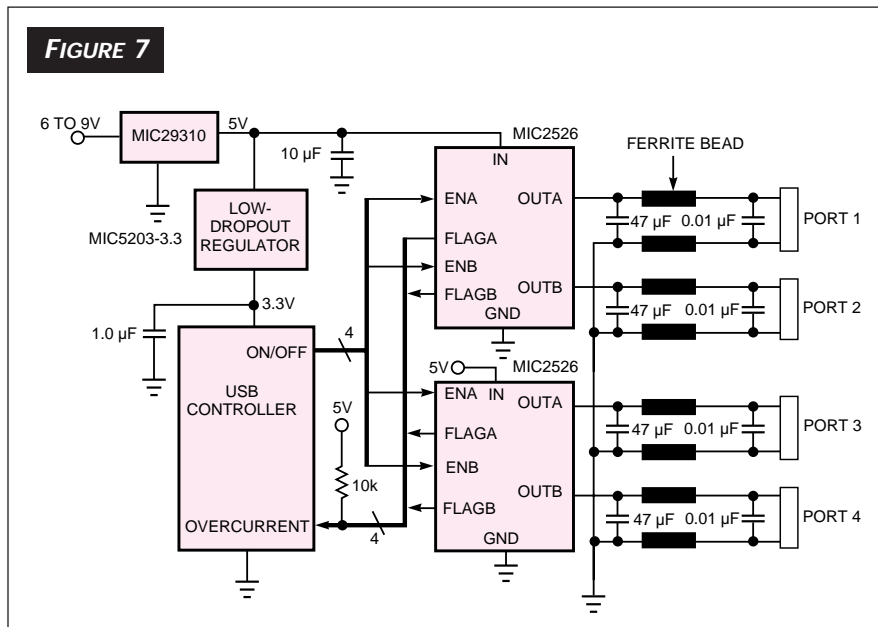
Integrated MOSFET switches provide the best opportunity to satisfy USB requirements for both self- and bus-powered hubs and hosts. Integrated MOSFETs offer very low (and predictable) on-resistance and can be controlled with logic-compatible signals. Some switches, such as Micrel's ([www.micrel.com](http://www.micrel.com)) MIC25xx series, Texas Instruments' ([www.ti.com](http://www.ti.com)) TPS20xx devices, or Maxim's ([www.maximic.com](http://www.maximic.com)) MAX890 series, also offer current limiting, thermal protection, and current-limit flag outputs. Some of these devices also provide a soft-start circuit, which bus-powered hubs require to eliminate transient issues during turn-on.

**Figure 6** shows a two-port design, typical of today's PCs that offer one or two USB ports. The USB controller is usually integrated within the PC chip set. The MIC2526 is a two-port integrated high-side MOSFET switch providing overcurrent protection via its current-limiting feature. When an overcurrent fault occurs, the flag output activates and indicates to the host that a fault condition exists. The host can then disable the offending port, and the other port remains unaffected.

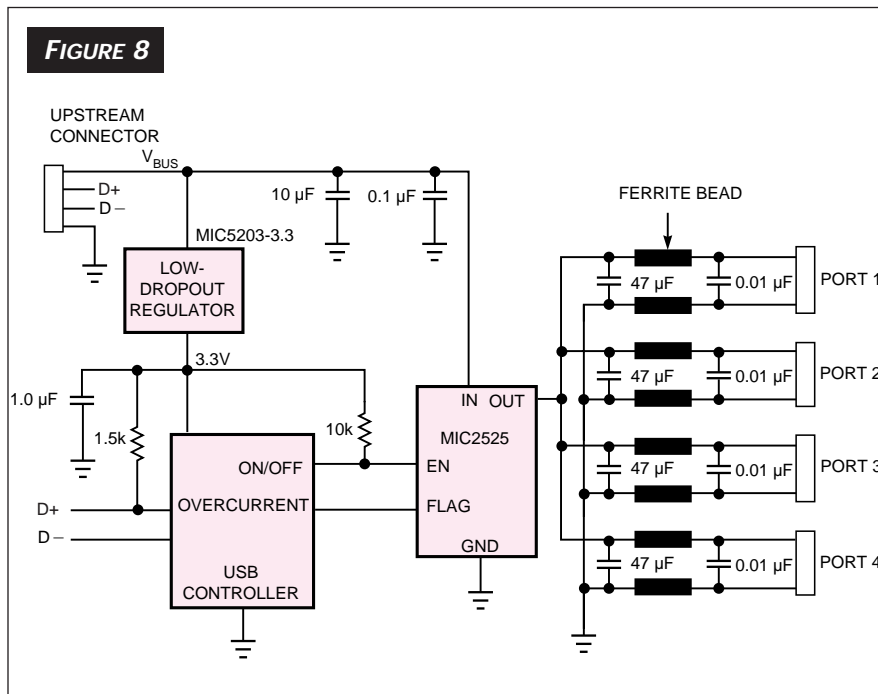
In addition to appropriate circuit topology, be sure to place all circuitry as close to the connector as possible to minimize trace impedance during hot-plug events and also to reduce EMI. The 0.01- $\mu\text{F}$  capacitor at the connector not only helps to reduce EMI but also ensures compliance to IEC 1000-4-2 (ESD immunity). Note that the 47- $\mu\text{F}$  bulk capacitors should be low-ESR units, such as tantalum. If you use electrolytic capacitors, you need to increase their values to 100  $\mu\text{F}$  because of their higher ESR.

**Figure 7** shows a four-port self-powered-hub reference design, which can be a hub integrated within a USB monitor, for example. To minimize costs, the monitor usually has a supply voltage generated from a filament winding. The MIC29310 acts as a preregulator, providing a regulated 5V source for the downstream ports routed through an MIC2526 high-side dual MOSFET switch. Because many USB controllers require a 3.3V supply, a low-dropout regulator powers the USB  $\mu\text{C}$ .

For example, for a four-port bus-powered-hub reference



For a four-port, self-powered-hub design, each port has a high-side MOSFET switch for isolation.



You can minimize costs in a four-port, bus-powered-hub design by using a single switch to control all ports.

design—a USB keyboard with an integrated hub—you could use ganged switching to minimize costs (**Figure 8**). A single switch, such as an MIC2525, controls all four ports. You must use a low-dropout regulator to provide power to a 3.3V USB

## POWER DISTRIBUTION FOR USB DESIGN

controller and to provide the termination voltage for the speed-sense resistor that must be connected to either the D+ or D- lines to set high- or low-speed operation, respectively. Low dropout is required because the 330-mV voltage droop and cable drops can cause  $V_{BUS}$  to go as low as 4.1V at the hub, leaving only 0.8V across the voltage regulator, which must be able to function at this voltage. To support individual port switching, use MIC2526 switches similar to the way they were used in the self-powered-hub design.

The USB specification states that a peripheral in suspend mode cannot consume more than 500  $\mu\text{A}$  on average. This challenge is particularly difficult given that the speed-sense pullup resistor in **Figure 8** can consume approximately 220  $\mu\text{A}$  itself, leaving only 280  $\mu\text{A}$  for the USB controller and other circuitry. Therefore, use low-leakage capacitors in bus-powered peripherals.

You can't ignore ESD, either. As process technology continues to approach finer line geometries—0.5  $\mu\text{m}$  and below—devices are more susceptible to ESD damage. In addition, many OEMs face stricter compliance to regulatory standards, such as IEC 1000-4-2. To meet this standard, you can include external ESD protection via transient-protection devices, such as those from Bussman-Coopers' ([www.busscc.com](http://www.busscc.com)) SurgeX series. Such devices protect the USB-controller data lines from damage and let you develop a robust design.

### Authors' biographies



*Larry Mazer is a product-marketing manager at Micrel Semiconductor ([www.micrel.com](http://www.micrel.com)). He has worked on USB, PCMCIA, and other PC-systems-interface and power-management products. Mazer holds an MSEE degree from California State University—Northridge.*



*Kevin Lynn, PE, is a senior applications engineer at Micrel Semiconductor, where he focuses on analog and power-IC layout, interface, and selection of USB power switches. He earned an MS degree from the University of Southern California (Los Angeles).*

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