USB 2.0 Power Budgeting

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Computing power use on the USB bus

This white paper describes the power considerations related to powering devices on the USB 2.0 bus, looking at power supplies, power draws, and cable losses. The USB 2.0 bus was chosen as it is the bus applicable to the LAVA SimulCharge USB line of tablet host mode adapter products, but the general principles of this white paper apply to USB 3.0 as well, making allowance for its higher power output.

Figure 1: LAVA SimulCharge USB TL-002

As USB-powered devices become more common, the demands on the USB bus to supply power increase. In many cases, USB peripherals are powered on USB ports supplying limited power, and users are disappointed with the results. Understanding the technical characteristics of powering electrical devices, and the specific characteristics and constraints of USB power, makes powering devices on USB more predictable and satisfying.

Theoretical underpinnings

Electrical power—wherever it occurs—conforms to a couple of basic formulas. The first of these, Ohm's Law, describes the relationship between voltage (V), current (I), and resistance (R).

Equation 1: Ohm's Law

$$V = I \times R$$

This is essentially a "flow" equation, and can be compared to the equation representing a flow of water, where electrical voltage is equivalent to water pressure; electrical amperage is equivalent to the rate of water flow; and electrical resistance is equivalent to the effect of flow restrictors in a pipe. The analogous formula in hydraulics would therefore be:

Equation 2: Hydraulic flow equation

$$Pressure = Flowrate \times Flowrestriction$$

In addition to Ohm's Law, a second equation defines the concept of "power" (P) as a function of voltage and current as follows:

Equation 3: Power equation (version 1)

$$P = V \times I$$

Power, in the electrical sense, is the amount of energy available to do something. Power, measured in Watts, is therefore voltage multiplied by amperage. USB power is defined as a nominal 5 volts. In that context, if a device consumes 300 milliamps (mA), we are saying that it consumes 300 mA at a nominal 5 volts. Placing these values into "Power equation (version 1)" above, we get a power value of 1.5 Watts. Similarly, if the voltage was 4 volts instead of 5 volts, then the current needed for 1.5 Watts would be approximately 400 mA (that is, 1.5/4).

It is also possible to combine Ohm's Law and the Power equation version 1 (Equations 1 and 3 above) to restate power as:

Equation 4: Power equation (version 2)

$$P = I^2 \times R$$

These electrical variables—voltage, resistance, amperage, and power—are the relevant characteristics of electrical devices and power supplies, and are used to determine the power budget in a USB setup where multiple devices share a power source (as well as in other shared electrical setups).

A Sample USB setup

The power supply

For this example, we will use the standard power supply that comes with Samsung tablets (model EP-TA10JWE). This power supply is typical of power supplies shipped with tablets and phones, and in this case the power supply is labelled with the following characteristics:

- Input: 100-240 V ~ 50-60 Hz 0.35A
- Output: 5.3V at 2.0A

Figure 2: Samsung EP-EP-TA10JWE

For the purposes of power budgeting, the input values are not particularly important as differences in input voltages are compensated for by the power supply. However, the output values are critical.

In keeping with the power specification for USB 2.0, USB power is a nominal 5 volts. But what does that mean?

It means that in a no-load situation the USB bus should be supplying between 4.75 and 5.25 volts to downstream ports while supplying from 0 A to 500 mA per port. (That is, when all USB ports are fully loaded (at 500 mA per port) and also when all USB ports are not loaded (quiescent).

In actuality, these Samsung power supplies test at between 5.08 and 5.32 volts. So the question arises: why the discrepancy between the USB specification and the power supply's actual output? The answer to this question is best approached with a background established in understanding the USB power budget. In other words, we'll answer it later.

The power budget is really about the *combination* of voltage and current: that is, Watts. At the same time, for a design and its components to comply to the USB specification, all three parameters must fall within specified bounds.

Additionally, the USB specification says that USB devices are allowed to consume, at most, 2.5 Watts. At the USB-specified 5 volts, 2.5 Watts has an amperage of 0.5 A.

But what if we are right at the bottom of the USB voltage allowance (4.75 volts)? To supply the maximum 2.5 Watts, a higher amperage than 0.5 A is now needed: approximately 0.52 A.

Complications arise as more devices are added. As that happens, the summed demands of the devices can exceed the total USB power budget for a power supply or port.

To begin with, a fully discharged tablet needs more than 0.5 A to charge, and USB can be asked at the same time to supply hosted devices also. To look at specifics, a Samsung Galaxy Tab 4 10.1" will draw up to 1.5 A (typically in the range of 1.25 A to 1.3 A). A Samsung Galaxy Tab S 10.5" or Galaxy Tab PRO 12" will draw 1.5 A but at that point will not be charging, or charging ineffectually.

Imagine a full picture: a tablet and a couple of hosted USB peripherals on a hub. Specifically, a fully discharged tablet that will draw up to 1.5A at 5V: that's 7.5 Watts; plus two fully demanding USB devices at 2.5W total, gives a total demand of 10 Watts.

Therefore, a discharged tablet and a couple of fully consuming USB devices is taking the power supply's full supply: and that's IF those two USB devices are at a distance of zero from the voltage regulator in the power supply, and that's IF the hub itself uses no power.

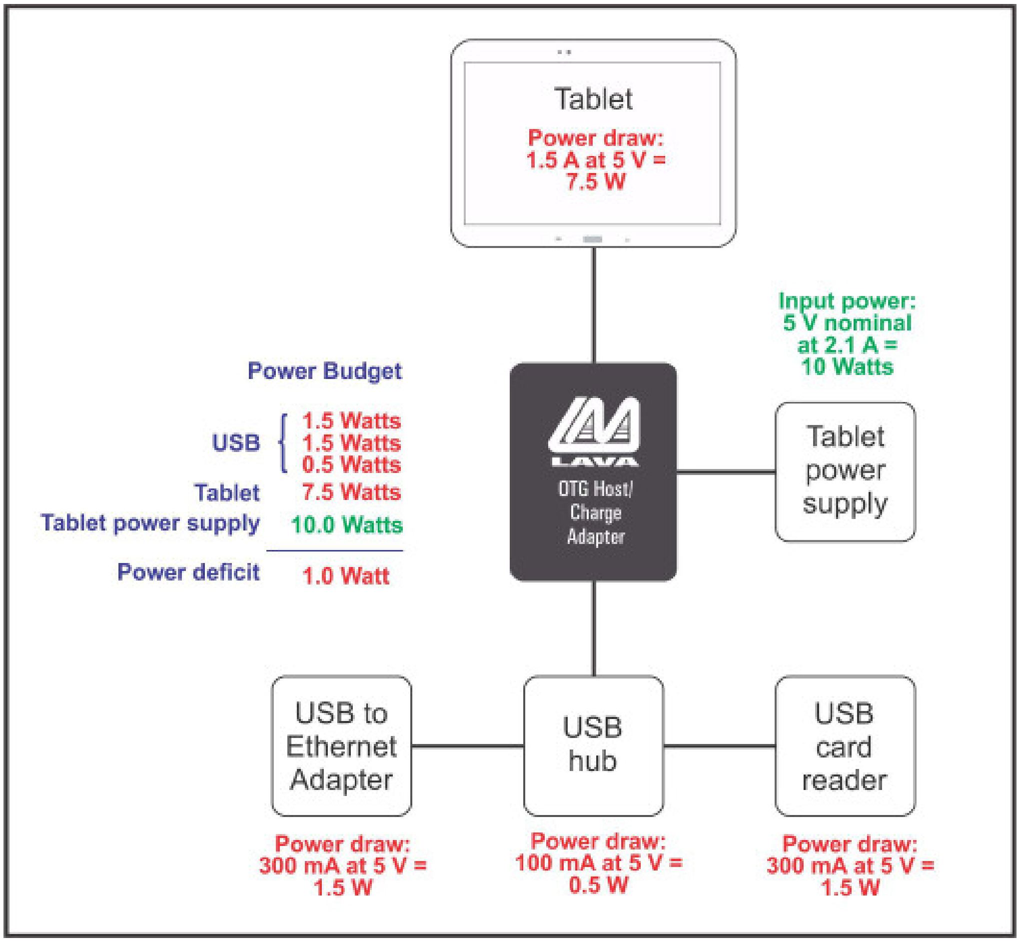
The "zero distance" qualifier is another way of saying that the cables involved are "lossless"; that is, there is no voltage drop over the length of the cable. For our first look at power budgeting, we will make that a working assumption. However, we will look later at the real-world impact of cabling on USB power budgeting.

Remember that a given power supply is rated for three parameters, *none of which can be exceeded*:

- a certain current
- a certain voltage
- a certain power output.

Figure 1 below shows a slightly different setup, in which the USB 2.0 power budget is exceeded.

Figure 3: USB bus powered setup: power budget exceeded



Cable loss

Cable loss is a frequently disregarded aspect of power budgeting in USB—we could almost call it the "elephant in the room". For USB layouts that are operating near their limits, cable losses (and the associated implications for voltage and amperage values) can become critical.

Cable loss in a wire is a function of cable diameter, cable length, cable material, temperature, and the number of strands in the wire, among other things. In total they are the cable's "resistivity".

The cable running from the power supply to the central distribution point (the SimulCharge USB in the diagram) is the focus of our analysis of cable loss as a factor in the USB power budget. The Samsung power supply involved has a 1 meter long, 24 gauge cable.

Figure 4: USB Power supply cable

The published resistivity for 24 gauge wire is 0.084 Ohms per metre. Because ground and power wires are both involved the functional distance is 1 meter multiplied by 2.

So for example, what is the voltage drop on a 1 meter long 24 gauge cable, with a current of 1.9 A?

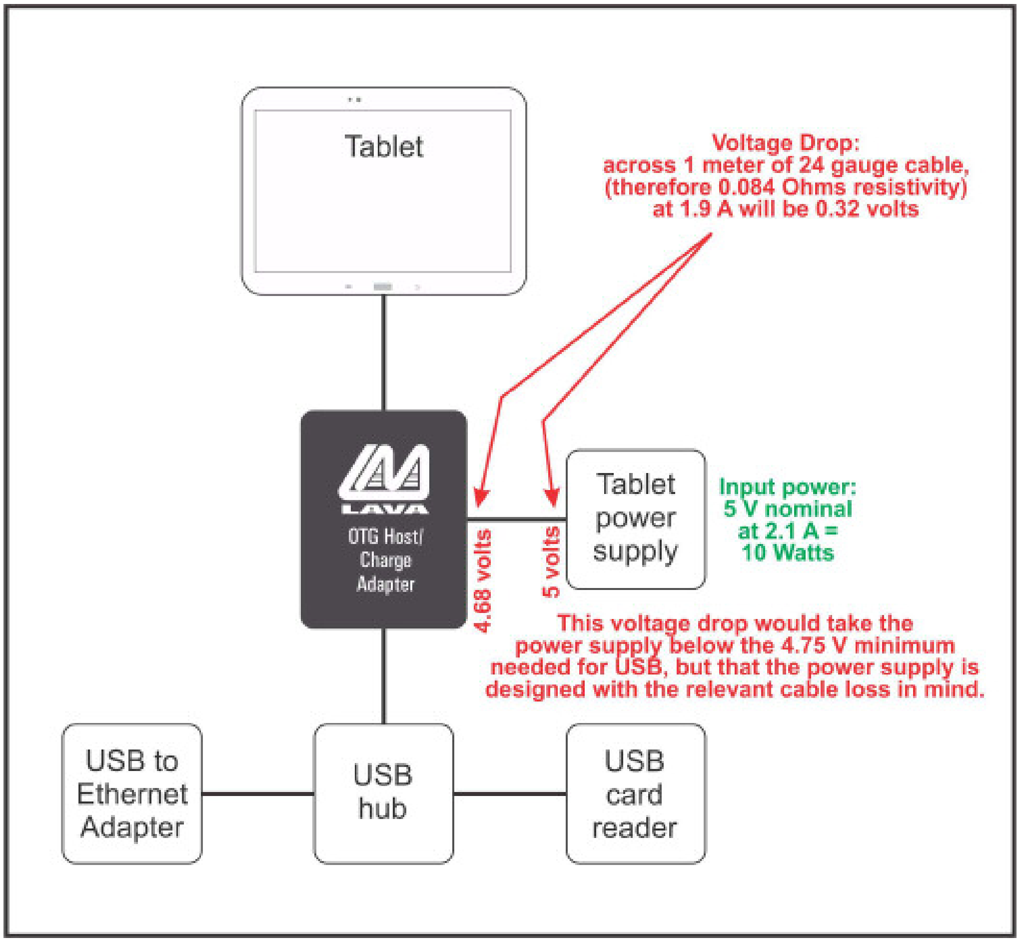
Given:

R = 0.084 x 2
Current = 1.9 A
Voltage drop = 0.319 Volts (say 0.32 Volts)

Consequently, the voltage at the SimulCharge USB is 5.0-0.32 volts: is this now below spec?

Well, recall that earlier we said: "In actuality, these power supplies test at between 5.08 and 5.32 volts." and asked: "WHY THE DISCREPANCY?": now we are seeing why. The fact is that if we take the low end of a *nominal* 5 V, that is , 4.75 V, and add the voltage drop across the supplied cable, we get 4.75 + 0.32 = 5.07 volts, say 5.08 volts. We can see that the power supply manufacturers have in fact designed their power supplies with allowance for cable loss over the cables typical in the application: 24 gauge and 1 meter.

Figure 5: Voltage drop



For the connection to be within specifications with a voltage of 4.75 V (allowing for a voltage drop of 0.32 V), the amperage will be correspondingly higher. How much higher precisely is the result of an iterative calculation that feeds the first changed amperage value back into the system and recomputes the system's values repeatedly. This process converges to an overall set of system values. (For the mathematically curious, this is a "Runge-Kutta" calculation).

Remembering that none of voltage, amperage, or power output can go outside specifications, the implication of cable loss is that there is little room to move a system that is outside of specifications back into conformity without changes to cables, either through heavier cables, shorter cables, or a combination of both these changes.

Powered Hubs

The Samsung tablet's power supply has a small surplus of power that can be used to drive USB peripherals. However, in fully loaded situations with demanding peripherals, or with tablets with depleted batteries, or with tablets operating with bright screens and active radios, and so forth, the power budget for the tablet's power supply alone is soon exceeded.

When the available power will be insufficient to power the complete setup through the single power source of the tablet's power supply, consider adding a separately powered USB hub to power the USB peripherals, leaving the task of powering the tablet purely to the tablet's power adapter.

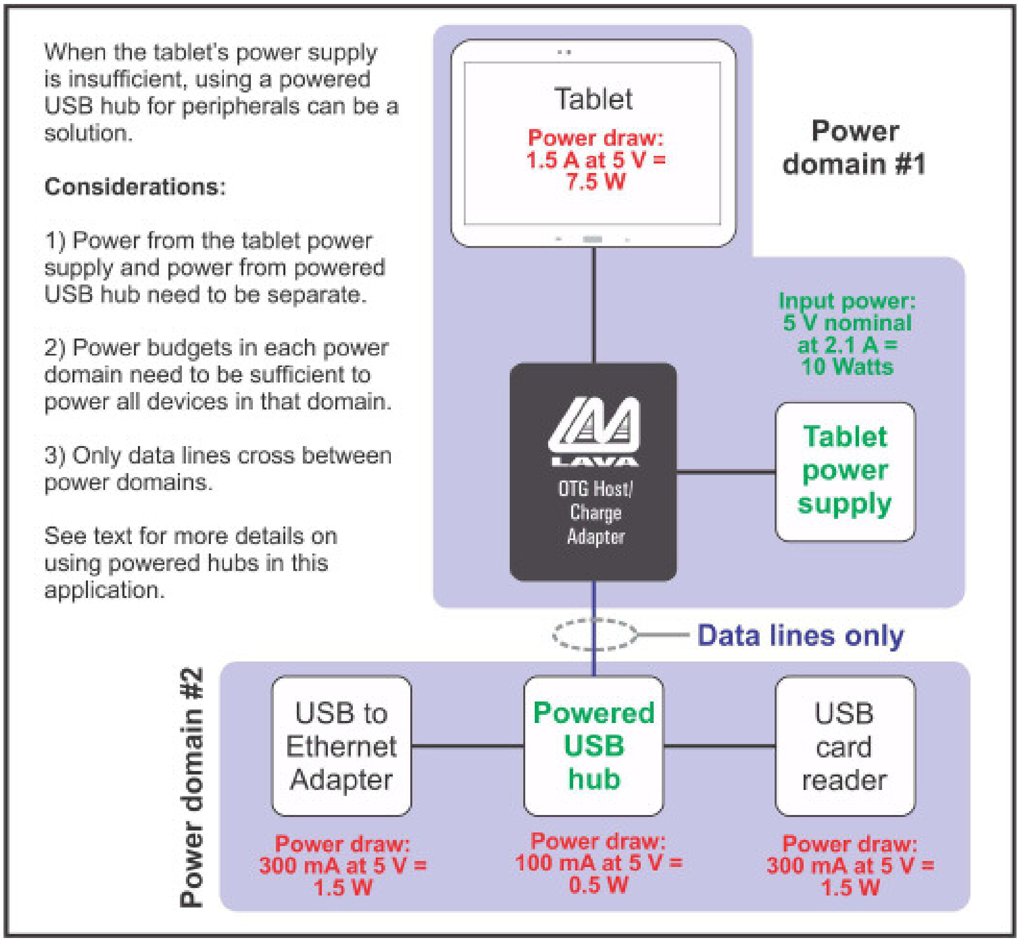
However, when implementing a second power source into the mix, additional considerations arise.

In particular, the power input from the tablet's power supply and the power input from the powered USB hub need to be kept in separate power domains.

This separation is not possible with many inexpensive powered USB hubs, which can lack an isolating diode needed to prevent power feeding through from the power domain of the powered USB hub to the power domain of the tablet's power supply.

This need for isolating power sources occurs in other contexts beyond that of the SimulCharge USB adapter. In the case of the Raspberry Pi—a single board computer powered using USB power—adding peripherals to a system that is often powered by a cell phone charger causes frequent problems. In response, those in the Raspberry Pi community have documented numerous powered hubs that meet the requirement to isolate their power from adjacent power domains. (See http://elinux.org/RPi_Powered_USB_Hubs).

Figure 6: Isolating USB power domains



Conclusion

In summary, USB-powered configuratons of peripherals and tablets (or other, similar USB-powered setups) require careful consideration of the power requirements they generate. Because USB power, especially USB 2.0 power, is closely constrained and not generous to begin with, it is not hard to exceed its power budget, leading to failures or unpredictable results.

Solutions include careful system design, ensuring that devices are operating efficiently. Such considerations might, in the case of a tablet, include selecting an undemanding screen brightness, or seeing that the tablet's radios (WiFi or Bluetooth) are only operating as needed.

When a system's power demands cannot be contained within the USB power budget, additional power, such as that from a properly integrated powered USB hub, can help. Also, carefully selecting cable for low resistivity gauges and lengths can often make the difference between success and failure when powering a system through USB.