Improve power management in USB wireless modems

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A USB wireless modem, USB dongle, or USB data card can be used along with notebook and tablet PCs to access the Internet as needed. Recently, LTE (Long Term Evolution) supportive modems have been introduced to make a step towards the 4G generation of mobile telephony.

This article focuses on power management solutions for GSM/GPRS mobile systems. It has been a challenging task for designers to cope with 2A peak current pulsed load during data transmission mode, which enables the output power to easily exceed the USB power specification of 5V/500mA. The design study in this article is classified into two different topologies depending on the place of a current limit switch and a step-down converter. The article also determines which topology is better in diversified demand. The FAN5353, a 3A rated monolithic synchronous buck converter operating at 3MHz frequency and FPF2165R, an integrated load switch, limit the USB input current and are applied for the design consideration of both topologies.

![Figure 1. System Block Diagram of Multi-band Network USB Wireless Modem](image)

**Design Challenges**

As the most popular interface among electronic devices, the USB port has become almost ubiquitous. The USB 2.0 specification indicates that one USB port supplies 2.5W, 5V and 500mA power to downstream functions as a host, but in practice most USB power designs are
considered with some margin to give more current than 500mA. This depends on electronic device manufacturers and sometimes goes up to 1.5A a port.

Figure 1 shows a general system block diagram of a multi-band network USB wireless modem. The front end power block includes a current limit switch, a step down converter, and a couple of mF range reservoir capacitors. Its output voltage is 3.6~3.8V which depends on design criteria.

In the case of the GSM/GPRS modem, extra caution needs to be taken because a 2A peak current is required for one or a couple of slots out of 8 time slots in a GSM/GPRS frame during transmission. The 2A peak current has a 577us pulse width and 4.615ms period (217Hz) as shown in Figure 2. Power design supporting class 8 (1 uplink + 4 downlink) and class 10 (2 uplink + 4 downlink) is discussed.

From a system power standpoint, the design challenge is that $V_{BUS}$ should be maintained more than 4.4V to meet the USB 2.0 specification and the minimum input voltage of the GSM/GPRS PA needs usually 2.9~3.0V for safe operation.

Figure 3 shows a typical waveform at the GSM/GPRS class 8 condition. The brown line indicates the buck converter’s output voltage set to 3.8V or input voltage for the RF PA, which is dropped down to 3.3V during 2A peak load in green. The $V_{BUS}$ in blue, however, is stable thanks to limiting input current from the USB host while a reservoir capacitor is supporting transient peak power beyond the input USB power.
Two Topologies

There are two different approaches to the front end power block by the configuration of a current limit switch: a DC/DC converter and a large tantalum reservoir capacitor as shown in Figure 4. The topology A is in order of USB - OCP (Over Current Protection) - DC/DC and the topology B is in order of USB - DC/DC - OCP.

In Topology A, the current limit switch prevents the USB input current from going over a preset current level and the buck converter provides powers to downstream blocks while the topology B gives a dedicated current limiting function to the GSM/GPRS PA before the reservoir capacitor. It is beneficial for designers to understand advantages and disadvantages of each topology in satisfying different design requirements.
**Topology A**

From Figure 4 (a), topology A allows designers to simply limit the input current from the USB host since the current limit switch is placed on the front end and can be programmed to a needed current level, resulting in short circuit protection to the total system. The input current can’t flow through the switch over the preset current level at a reasonable limit tolerance, which is normally ±25%, but a tighter tolerance such as 10% is preferred. In addition, a relatively smaller reservoir capacitor can also be utilized due to a more allowable voltage drop at the reservoir capacitor, resulting in reduced BOM cost and solution size.

![Diagram of Topology A](image)

(a) Topology A: USB – OCP – DC/DC

On the other hand, topology A has disadvantages in implementing a USB modem design. First, a more than 2A rated buck converter is required to provide powers downstream such as GSM/GPRS PA which needs 2A pulsed current, baseband and PMIC. An over 2A output current rated converter can be a reasonable choice with some margin. Second, regarding the reservoir capacitor, it needs a relatively higher breakdown voltage, 6.3V at least because of $5V_{BUS}$ and it could affect solution costs. Lastly, the output voltage of the buck converter can fluctuate.

![Diagram of Topology B](image)

(b) Topology B: USB – DC/DC – OCP

**Figure 4. Power Implementations by Configuration**
depending on reservoir capacitance and maximum allowable input current from the USB host. Figure 5 shows an example of capacitance values.

The FAN5353, a 3A rated monolithic synchronous buck converter, and FPF2165R, an adjustable current limit switch with 10% tolerance, are used in this article. A 600mA current limit and 3.7Vout are set respectively. Figure 5-(a) shows Vout being regulated at 3.7V without a remarkable drop during the 2A pulsed load period since a large reservoir capacitance of 3mF is applied. From Figure 5-(b) there is a 400mV drop on the input line of the GSM/GPRS PA as the 1.5mF reservoir capacitor is discharged like the waveform in blue.

**Topology B**

Topology B as shown in Figure 6 makes a constant output voltage for the baseband and PMIC except for the GSM/GPRS PA. It provides an advantage because it does not have to worry about voltage fluctuation or drop from the main communication chipset.

![Figure 5. Key Waveforms with Topology A under GSM/GPRS Class 10](image-url)
Secondly, a relatively low breakdown voltage rated tantalum reservoir capacitor before the GSM/GPRS PA can be used because the Vout of the buck converter is typically regulated to be between 3.6 and 3.8V so a 4V rated bulk capacitor is enough to save BOM costs.

Lastly, a relatively lower current rated buck converter can be applied as long as it provides the current of the preset current limit level in front of the PA and a max load current of other power blocks. A 1A rated buck converter normally works, which is a big advantage compared to topology A in saving BOM costs.

However, disadvantages can be as follows. First, it is comparatively difficult to design in regulating the USB input current to meet the USB specification. As shown in Figure 4 (b), the current limit is dedicated to the GSM/GPRS PA and designers should take PA load conditions, other power blocks, and the USB input current into consideration.

Figure 6. Key Waveforms with Topology B under GSM/GPRS Class 10
Second, some larger reservoir capacitance is essential depending on the allowable voltage drop for the GSM/GPRS PA input and current limit threshold, which results in increasing BOM costs and form factor as well.

From Figure 6, the Vout for the GSM/GPRS PA drops down to 3.1V with 3mF capacitance at the 600mA current limit condition. If less drop voltage of the PA input is needed, bigger capacitance is required.

In a nutshell, Table 1 summarizes the comparison between topology A and B. Designers need to make a proper choice considering the trade-offs.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| A        | 1. Keep USB current fixed  
        | 2. Smaller reservoir capacitance  
        | 3. Direct over current protection | 1. More than 2A rated buck converter  
        | 2. Higher breakdown voltage rated tantalum capacitors  
        | 3. Fluctuating input for comm. chipset during GSM/GPRS transmission |
| B        | 1. Constant voltage for comm. chipset  
        | 2. Lower breakdown voltage rated tantalum capacitors  
        | 3. 1A rated buck converter | 1. No direct way to keep USB power fixed  
        | 2. Larger reservoir capacitance |

Table 1. Advantages and Disadvantages by Topology

Design Example
Appropriate USB Power
In most of the system power designs, one of the basic items is to check if an input power source is enough to supply output power demand sufficiently and efficiently. USB wireless modems are not an exception.

Some designers are sometimes confused with this point since they expect that large tantalum reservoir capacitors can support the rest of the power continuously without exceeding USB power. But the main reason for the reservoir capacitors is to support only transient peak power during GSM/GPRS transmission.

The calculated average current, 499mA from GSM/GPRS Class 10 in Figure 2 is required during transmission.

\[
I_{avg} = \frac{1.15 \text{ms} \times 2A}{4.615 \text{ms}} = 499mA
\]
If an additional 300mA is needed for the communication chipset, 799mA in total is in demand from the 3.7Vout of the buck converter and it translates into 2.96W.

Assuming 90% system efficiency is expected depending on the on-resistance of the current limit switch, the buck converter’s efficiency, and the PCB trace, the input power should be at least 3.29W. In this case, it is impossible to implement the design under a 2.5W USB power source. Figure 7 shows failed modem operation with limited 500mA USB current. The way to solve this malfunction is to increase the USB current limit value.

Figure 7. Failed Waveform under GSM/GPRS Class 10 plus additional 300mA Load Current

Design Specification

Designers need to know the criteria such as allowable maximum USB power, allowable minimum input voltage for GSM/GPRS PA, GSM/GPRS class and maximum communication chipset load during transmission at worst case. BOM cost should be a big challenge as well.

Design criteria of a USB wireless modem based on GSM/GPRS are given in the following example.

- Allowable USB power : \( V_{BUS} = 5V / \text{max 700mA} \)
- Output voltage of buck converter : 3.7V
Selecting Buck Converter and Current Limit Switch

Choosing an appropriate buck converter and current limit switch are required to optimize the power solution. In this design, FAN5353 and FPF2165R are chosen. The FAN5353 is a 3A rated monolithic synchronous buck converter in a 3x3.5mm MLP package. It’s operating switching frequency is 3MHz, allowing a smaller output filter such as inductance and capacitance. An internal compensation feature makes the design simple as well. The high efficiency over all load
conditions in Figure 8 (a) and the input over voltage protection at 6.2Vin shown in Figure 8 (b) lead to a reliable design.

The FPF2165R is a 0.15A~1.5A adjustable current limit switch in a 2x2mm MLP package. It keeps 5VBUS stable from the 2A pulse load of the PA. The FPF2165R also features 10% current limit accuracy with a 1% external resistor which reduces design error compared to the conventional 20~25%. While disabled, the reverse current blocking function is also fit for USB applications from a USB 2.0 specification. The FPF2165R’s low on-resistance of typical 95mΩ at 5V can reduce voltage drop and increase system efficiency as shown in Figure 9.

![Figure 9. FPF2165R RON vs VIN](image)

**Reservoir Capacitance Calculation**

Regarding the reservoir capacitance, both discharging and recharging periods during GSM signal transmission should be taken into consideration. A larger capacitance without a recharging period will result in the system failing since it discharges and eventually drops down to below UVLO at the operating area at the DC/DC converter.

Eq.1 and Eq.2 are given for capacitance calculation with topology A and B respectively.
Where,

**I\_\text{lim}**: current limit threshold of FPF2165R and it is equal to the max allowable USB current = 700mA.

**V\_\text{out}**: output voltage set of FAN5353 = 3.7V

**I\_\text{load}**: max load current of communication chipset during GSM/GPRS transmission = 300mA

**η**: efficiency of FAN5353 = 90%

**Ron**: max On-resistance at 5V = 130mΩ

**D\_\text{max}**: max duty cycle of FAN5353 = 90%

\[
C_{in\_\text{min}} = \frac{\left(\frac{V_{out} \times (2A + I\_\text{load})}{\eta \times 5V} - I\_\text{lim}\right) \times 1.15ms}{5V - \left(\frac{Ron \times I\_\text{lim} + \frac{V_{out}}{D\_\text{max}}}{D\_\text{max}}\right)}
\]

(b) **Recharging Period**

\[
C_{in\_\text{max}} = \frac{\left(\frac{I\_\text{lim} - \frac{V_{out} \times I\_\text{load}}{\eta \times 5V}\right) \times 3.465ms}{5V - \left(\frac{Ron \times I\_\text{lim} + \frac{V_{out}}{D\_\text{max}}}{D\_\text{max}}\right)}
\]

**Cap\_\text{min}**

\[
Cap\_\text{min} = \frac{(2A - I\_\text{lim}) \times 1.15ms}{V_{out} - (Ron \times I\_\text{lim} + Vin\_PA\_\text{min})}
\]

**Cap\_\text{max}**

\[
Cap\_\text{max} = \frac{I\_\text{lim} \times 3.465ms}{V_{out} - (Ron \times I\_\text{lim} + Vin\_PA\_\text{min})}
\]

Where,

**I\_\text{lim}**: current limit threshold of FPF2165R to keep USB input current not to exceed allowed current of 700mA, which is equal to Pin* η / Vout-I\_\text{load} = 550mA

**Vout**: output voltage set of FAN5353 = 3.7V

**I\_\text{load}**: max load current of communication chipset during transmission = 300mA
η: efficiency of FAN5353 = 90%
Ron: on-resistance at Vout, 3.7V = 160mΩ
Vin_PA_min: min Vin for GSM / GPRS PA allowed = 3.2V

Basically all equations come from the following relationship.

\[ C = \frac{I \times \Delta T}{\Delta V} \]

They key concept in topology A is to keep the input voltage above 4.1Vin to maintain 3.7Vout, while considering a max duty cycle of 90% under a limited current of 700mA by placing the reservoir capacitor in front of the FAN5353 during transmission.

Topology B has a somewhat different approach compared to topology A. The reservoir capacitor is dedicated to the GSM/GPRS PA and the capacitance is needed to maintain 0.5V voltage drop from 3.7Vout to 3.2Vin_PA_min during transmission under limited current. In this case, the current limit value should be \( \text{Pin} \times \eta / \text{Vout} – I_{\text{load}} = 550\text{mA} \) to keep the USB current less than 700mA.

Reservoir capacitance should be chosen between Cap_min and Cap_max in order to work properly. (See Table 2)

<table>
<thead>
<tr>
<th>Allowable Max USB Current (mA)</th>
<th>Capacitance with Topology A</th>
<th>Capacitance with Topology B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>500</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>600</td>
<td>NG</td>
<td>NG</td>
</tr>
<tr>
<td>700</td>
<td>1.71mF</td>
<td>1.96mF</td>
</tr>
<tr>
<td>800</td>
<td>1.6mF</td>
<td>2.43mF</td>
</tr>
</tbody>
</table>

Table 2. Calculated Capacitance and Test Result under GSM/GPRS Class 10 plus 300mA Load Condition

Design Verification

Table 2 shows the result of the comparison by topology under GSM/GPRS Class 10 and additional 300mA load condition by allowable USB current. NG means it can’t operate due to lack of input power. A minimum of 700mA is needed to meet the design criteria.
Design evaluation is conducted based on the 700mA USB current condition at which 1.72mF out of 1.71~1.96mF and 4.5mF out of 4.05~4.63mF are chosen for topology A and B respectively. Each result waveform is shown in Figure 10.

Figure 10. Result Waveform by Topology
From the results, even though both topologies meet the design criteria, designers need to consider the tradeoffs between the two topologies in order to select the right design.

In summary, Table 3 shows design factors and calculated capacitance by topology.

<table>
<thead>
<tr>
<th>Block</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>USB</td>
<td>1. Min $V_{IN}$</td>
<td>5.00</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>2. Max allowable current</td>
<td>0.70</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>3. $V_{OUT}$</td>
<td>3.70</td>
<td>V</td>
</tr>
<tr>
<td>DC/DC Converter</td>
<td>4. Efficiency at $5V_{IN}$ and $V_{OUT}$</td>
<td>90.00</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>5. Max duty</td>
<td>90.00</td>
<td>%</td>
</tr>
<tr>
<td>Current Limit S/W</td>
<td>6. Max $R_{on}$ at Min $V_{IN}$ for Topology A only</td>
<td>0.13</td>
<td>Ω</td>
</tr>
<tr>
<td></td>
<td>7. Max $R_{on}$ at $V_{OUT}$ for Topology B only</td>
<td>0.16</td>
<td>Ω</td>
</tr>
<tr>
<td>System</td>
<td>8. Peak current at GSM PA during Tx</td>
<td>2.00</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Average current at GSM PA for Class 8</td>
<td>0.25</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Average current at GSM PA for Class 10</td>
<td>0.50</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>9. Min allowable $V_{IN}$ for GSM PA</td>
<td>3.20</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>10. Additional load current for BB, PNC and ETC</td>
<td>0.30</td>
<td>A</td>
</tr>
</tbody>
</table>

**Topo A**

| DC/DC Converter     | Total $P_{OUT}$ Class 10                         | 2.95  | W    |
|                     | USB current drawn at Class 10                    | 0.66  | A    |
|                     | Total $P_{OUT}$ Class 8                          | 2.04  | W    |
|                     | USB current drawn at Class 8                     | 0.45  | A    |
|                     | Min output current rating                        | 2.30  | A    |
| Current Limit S/W   | Min I LIM                                        | 0.70  | A    |
| Reservoir Cap       | $C_{in}$ for Class 10                            | 1711  | μF   |
|                     | $C_{in}$ for Class 10                            | 1962  | μF   |
|                     | $C_{in}$ for Class 8                             | 858   | μF   |
|                     | Max $C_{in}$ for Class 8                         | 2286  | μF   |

**Topo B**

| DC/DC Converter     | Total $P_{OUT}$ Class 10                         | 2.93  | W    |
|                     | USB current drawn at Class 10                    | 0.65  | A    |
|                     | Total $P_{OUT}$ Class 8                          | 2.05  | W    |
|                     | USB current drawn at Class 8                     | 0.46  | A    |
|                     | Min output current rating                        | 0.85  | A    |
| Current Limit S/W   | Max I LIM to meet USB power                      | 0.55  | A    |
|                     | Min I LIM selected                               | 0.55  | A    |
| GSM PA              | $V_{IN}$ for GSM PA for Class 10                 | 3.95  | V    |
|                     | $V_{IN}$ for GSM PA for Class 8                  | 3.49  | V    |
| Reservoir Cap       | $C_{in}$ for Class 10                            | 4047  | μF   |
|                     | $C_{in}$ for Class 10                            | 4626  | μF   |
|                     | $C_{in}$ for Class 8                             | 2031  | μF   |
|                     | Max $C_{in}$ for Class 8                         | 5391  | μF   |
|                     | Cap selected                                     | 4050  | μF   |

Table 3. Design Table by Topology
Figure 11 shows the evaluation schematics and actual board picture.

Figure 11. Evaluation Board with FAN5353 and FPF2165R
It is a challenge for designers to optimize power solutions for USB wireless modems in terms of performance and BOM cost. Two design approaches - topology A and B - are discussed, in addition to trade-offs, considerations, design procedures and an actual verification using the FAN5353 and FPF2165R.

As a result, topology A is an effective solution with respect to reservoir capacitance, solution size and BOM cost reduction. FAN5353 and FPF2165R offer reliable solutions to design a GSM/GPRS RF based USB wireless modem.

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