Optimizing the switching frequency of ADSL power supplies

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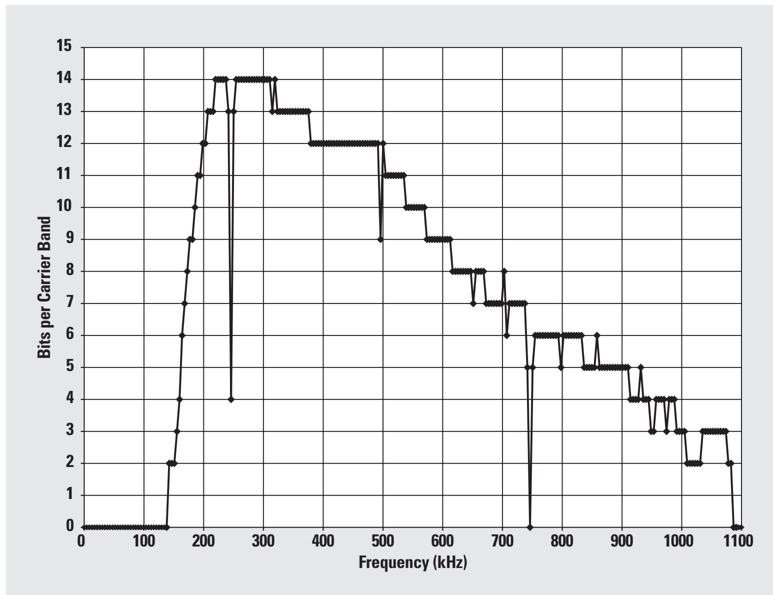
Introduction

DSL modems send their signals through a twisted-pair telephone line. As the length of this copper line increases, the high-frequency signal becomes attenuated. The modem bit rate starts decreasing after just a few thousand feet. It continues to decrease with loop length, out to a maximum loop length of about 3 miles, where the connection becomes marginal. Data rates as high as 8 Mb/s are achievable with short loops but drop off to around 100 kb/s with the longest loops. As the line length exceeds 3 miles, the bandwidth decreases and data throughput drops off quickly. Transmission signal attenuation of 80 to 90 dB is possible at these line lengths, forcing the modem to implement noise reduction techniques that produce high signal-to-noise ratios (SNRs), minimize crosstalk and interference, and have large dynamic signal ranges. The SNR measurement of the modem has a trough at the power supply's switching frequency. This trough negatively affects the modem's performance by reducing the number of data bits transmitted, thereby reducing the modem's overall data transfer rate. If attention is not given to the power-supply noise, modem performance suffers and customers are forced to accept a lower data transmission rate.

Figure 1. 250-kHz power-supply frequency and its harmonics reduce bit rate throughput



An ADSL modem uses a 25-kHz to 1.1-MHz frequency spectrum for data transmission. The downstream direction (server to client) uses the 138-kHz to 1.1-MHz band. The upstream direction (client to server) uses the 25-kHz to 138-kHz band. The modem divides this spectrum into 256 equally spaced carrier bands, or "bins," each having a 4.3125-kHz bandwidth. The carrier bands are allocated to voice transmission, upstream and downstream data, and buffer zones. The number of bits assigned to each carrier band depends on the level of noise and interference present. Figure 1 shows how the switching noise from a power supply affects the number of data bits per carrier band on an ADSL client modem. An 80-mV$_{pp}$, 250-kHz square wave imposed on the 3.3-Vdc voltage significantly reduces the available bits at the 250-kHz carrier band, its 750-kHz harmonic, and to a lesser extent the 500-kHz harmonic (due to distortion present on the square wave signal). The harmonics of a square wave follow a sin(x)/x function, which has peaks at multiples of the odd harmonics. The data in Figure 1 represents 11,000 ft of transmission line length.

Table 1 shows the reduction in the overall modem bit rate versus power-supply switching frequency and ripple amplitudes. The data shows that both the amplitude and the frequency of the ripple affect the overall modem data rate. Increasing the ripple voltage amplitude reduces the overall modem data rate. The increase in ripple reduces the SNR in the carrier bands corresponding to the ripple frequency and its harmonics, which lowers transmission rate in the affected bands. Higher power-supply switching frequencies have less effect on the overall modem

Table 1. Power-supply ripple voltage reduces ADSL modem data rate

INJECTED SQUARE WAVE AMPLITUDE (mV$_{pp}$)	DATA TRANSFER RATE			
	100-kHz POWER-SUPPLY SWITCHING (Mb/s)	250-kHz POWER-SUPPLY SWITCHING (Mb/s)	500-kHz POWER-SUPPLY SWITCHING (Mb/s)	1-MHz POWER-SUPPLY SWITCHING (Mb/s)
2	6.8	6.8	6.8	6.8
10	6.7	6.7	6.7	6.7
20	6.5	6.6	6.7	6.7
60	6.4	6.5	6.6	6.6
80	6.2	6.3	6.5	6.6

data rate for two reasons. First, higher switching frequencies affect higher-frequency “bins,” which already have lower bit rates. Second, the harmonics are spaced farther apart so that fewer “bins” are affected. Power-supply switching frequencies greater than 1.1 MHz typically have minimal or no impact on the modem data rate because the fundamental of the switching frequency is above the frequencies used to transmit data. Reducing the switching frequency below 100 kHz will move the fundamental below the first downstream modem carrier band; however, the harmonics will affect many carrier bands up to 1.1 MHz.

The effects of switching frequency

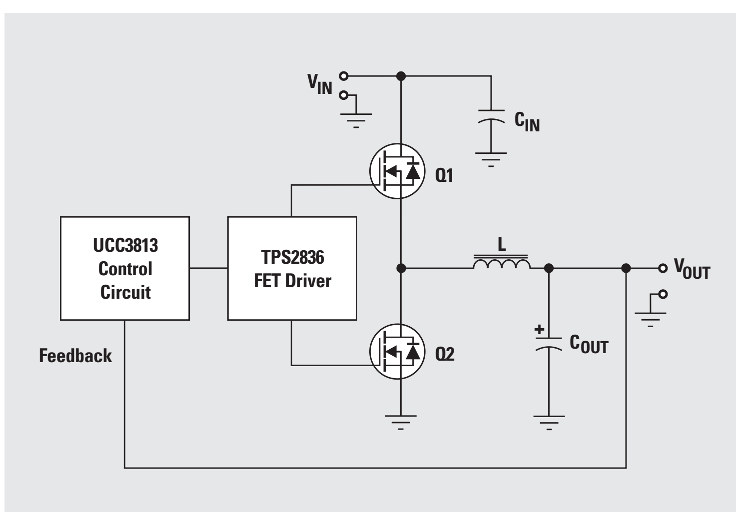
Based on throughput only, a power-supply switching frequency greater than 1 MHz is desirable. However, there are other power-supply factors that are affected by the switching frequency. Some of these factors include overall supply cost, size, efficiency, and reliability. None of these factors can be optimized independently of the others; and, in many cases, optimizing only one supply parameter leads to a less than optimal overall solution.

A typical power-supply requirement for the client modem core consists of a 3.3-V at 3.6-A output that is generated from an input voltage ranging from 10 to 14 V. Figure 2 shows a simple block diagram for a synchronous buck topology that is easily implemented using a Texas Instruments UCC3813 controller with a TPS2836 synchronous buck MOSFET driver. The supply was operated at 100 kHz, 250 kHz, 500 kHz, and 1 MHz. The output ripple of the supply was adjusted at each switching frequency to keep a constant data transfer rate of 6.7 Mb/s, per Table 1.

Increasing the switching frequency of an ADSL power supply reduces the overall volume for two reasons: smaller passives and higher allowable ripple. Table 1 shows that lower switching frequencies require a lower output ripple to maintain a data rate of 6.7 Mb/s. For example, at 100 kHz, the allowable ripple for 6.7 Mb/s is 10 mV_{pp}; while at 1 MHz, the allowable ripple is 80 mV_{pp}. Power-supply filter components are inversely proportional to switching frequency. Not only is more filtering needed at lower frequencies, but filtering a lower-frequency signal requires larger components. The 100-kHz circuit requires a 22-µH inductor, while the 1-MHz circuit requires only a 2.2-µH inductor. Inductor volume is proportional to inductor value; therefore, the 100-kHz inductor is significantly larger than the 1-MHz inductor. The decrease of inductor volume with size is not linear. At some point, an additional increase in switching frequency does not significantly decrease the inductor volume. As the inductor becomes smaller, the packaging and solder pads take up an increasing percentage of overall volume, thereby diminishing the reduction in inductor volume with increasing frequency. Shielded inductors with closed flux paths are preferred to “open” bobbin-type cores. These closed-core structures contain or hold most of the flux lines within the magnetic material, which prevents it from coupling into nearby components and etch. The flux field is highest near the gap of the inductor, so care must be taken during layout to keep sensitive and high-impedance circuits away from it. Shielded inductors have current ratings that are approximately 25% less than the non-shielded variety, due to the additional core volume and the smaller-gauge wire that must be used.

The minimum input and output capacitance requirements are also inversely proportional to frequency. As the frequency increases, the required filtering is reduced; so smaller capacitance values are required. At lower frequencies, ceramic capacitors do not have the bulk capacitance necessary for the required filtering; therefore, aluminum electrolytic, organic electrolytic, or specialty polymer capacitors are used. Because these capacitors are ESR and ripple current limited, their volume varies little with switching frequency. Around 500 kHz and above, ceramic capacitors become a viable option. Ceramic capacitors have very low ESR; therefore, they are capacitance limited. As the switching frequency increases, the amount of charge per cycle delivered by the capacitors is reduced. The capacitance values are determined by the charge requirements; therefore, the capacitance requirements decrease

Figure 2. Simplified synchronous buck block diagram



as frequency increases. As with inductors, the packaging issues diminish the reduction in capacitor volume as switching frequency is increased. While power-supply filter component areas are reduced with increasing frequency, the control circuitry area stays constant. Figure 3 shows the overall power-supply area as well as the breakdown of area between the control circuit and the filter. Note that the total area is reduced by about 23% when going from 100 kHz to 250 kHz but is reduced by only 13% when going from 250 kHz to 500 kHz.

Switching frequency has a direct impact on power-supply efficiency. The main power-loss component in a power supply is typically in the power FETs. Power FET losses are comprised of several different terms, some being frequency-dependent and some not. Conduction losses in the FET are independent of frequency. This loss term is a function of power-supply current and FET resistance. FET losses that are directly proportional to frequency include gate drive, Coss, reverse recovery, body diode conduction, and switching losses. Each of these terms dissipates a fixed amount of energy each time the power supply completes a switching cycle. The more times per second the power supply switches, the more power is dissipated by these frequency-dependent loss components. At lower frequencies, FET conduction losses dominate. At higher frequencies, the conduction losses remain constant; while the frequency-dependent losses increase. At maximum output power, the fixed losses in the power supply are 892 mW at both 100 kHz and 1 MHz. The frequency-dependent losses are 165 mW at 100 kHz but increase to 1650 mW at 1 MHz. Figure 4 shows a graph of efficiency versus load and switching frequency.

Figure 3. Power-supply area vs. switching frequency

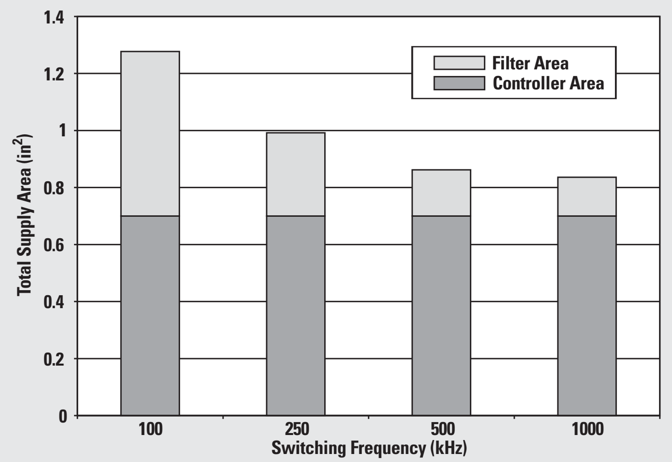
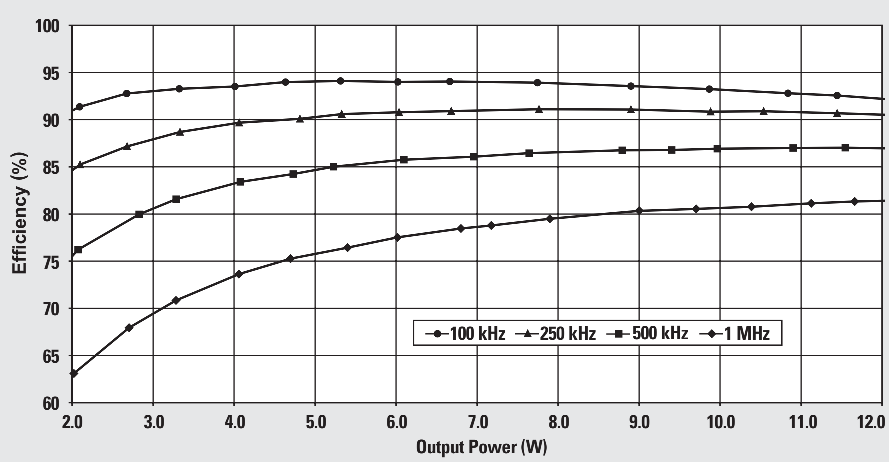


Figure 4. Higher switching frequencies result in lower efficiency



Power-supply reliability and cost are indirectly related to switching frequency. Reduced efficiency at higher switching frequencies translates into higher operating temperatures. Failure rate for semiconductors doubles for every 10°C rise in temperature. An estimate of temperature rise above ambient is shown in Figure 5. The data in Figure 5 assumes natural convection cooling with the board area shown in Figure 3. The designer has a few options to maintain a reasonable temperature rise for the higher switching frequencies. One is to increase the available area for cooling. This may include using either larger or multiple components in parallel in conjunction with a larger PWB to help spread the heat. For example, replacing one SO-8 package with two SO-8s or a D-Pak can significantly reduce junction temperatures. Another option is to provide additional cooling in the form of fans, heat sinks, or both. Both options increase the overall cost and size of the supply. The power supply shown in Figures 6 and 7 has over 2.5 in^2 of surface area; therefore, it runs with a temperature rise of only 45°C at 1 MHz and maximum load.

Figure 5. Power-supply temperature increases rapidly with frequency

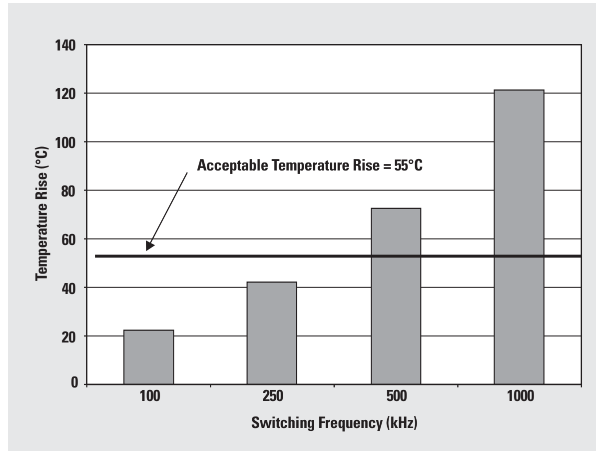
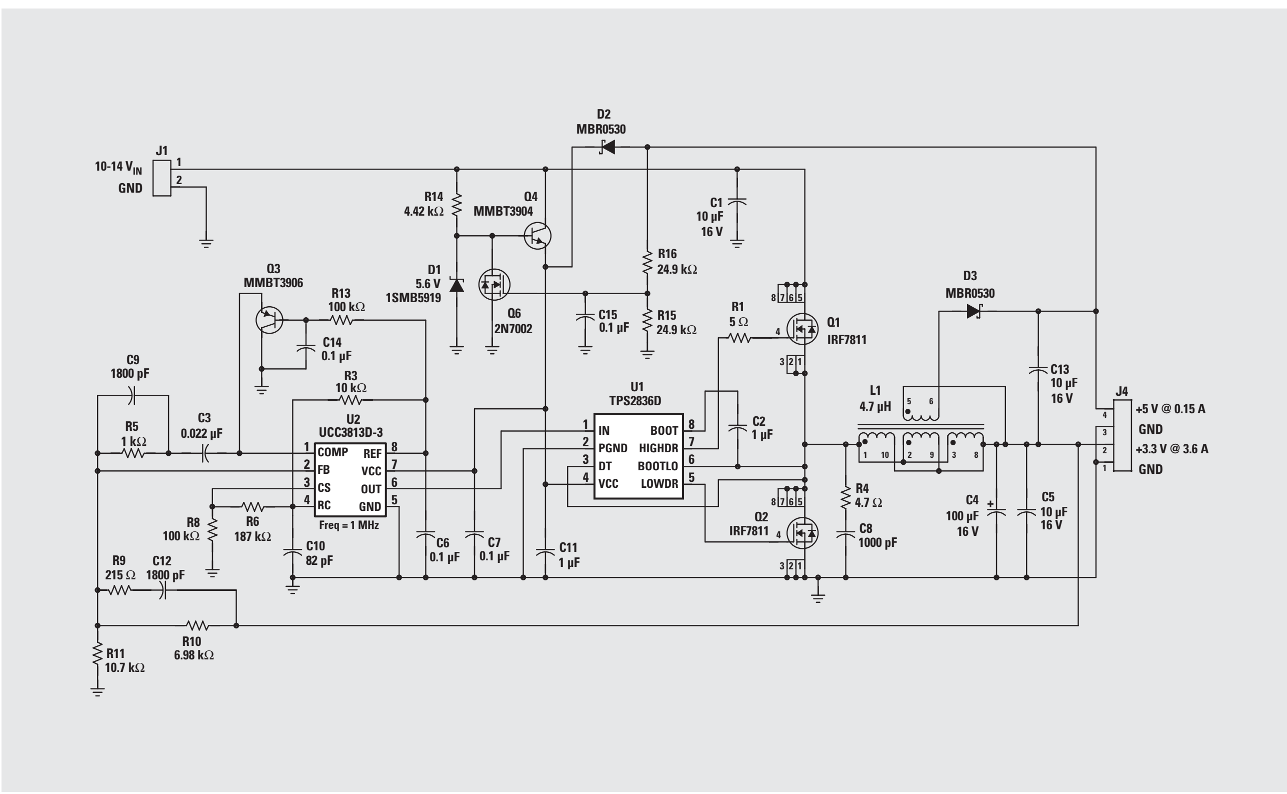


Figure 6. Complete ADSL power-supply schematic (with aux output)



Conclusion

Figure 8 summarizes the trade-offs between switching frequency versus ripple, size, and efficiency while maintaining a constant modem throughput. It may be tempting to try to optimize a particular power-supply parameter, but Figure 8 shows that changing one parameter may negatively impact the other parameters. The power-supply designer must act as a system engineer at the power-supply level, taking into account all design parameters to produce the optimal solution. If minimum area is a concern, the designer may choose a switching frequency around 500 kHz. At 500 kHz, the power-supply area is minimal due to the decreased sensitivity of the modem to switching noise; and the efficiency is still at an acceptable level. If minimum losses are the driving factor due to limited cooling or input-power constraints, the supply should be run somewhere between 200 kHz and 300 kHz. Within that range, frequency-dependent losses are minimized and the power-supply efficiency is near its maximum level; however, the volume is increased due to the additional filtering required to maintain an acceptable modem throughput.

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Figure 7. Dual-output (3.3-V/5-V) circuit operates at 1 MHz

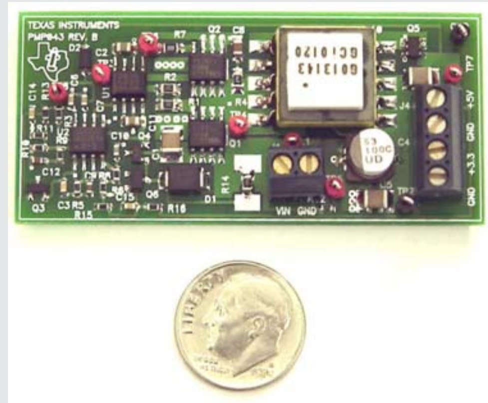
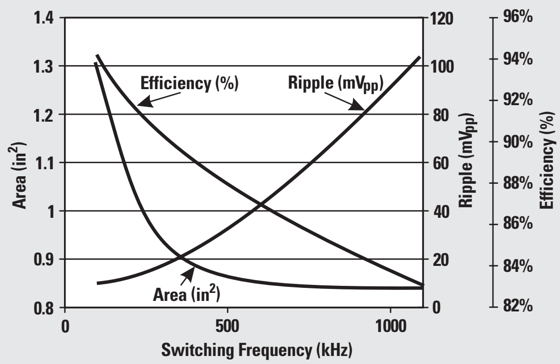


Figure 8. Trade-offs for a constant modem throughput



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