Carefully Evaluate Your ADSL Line-Driver Efficiency

By Scott Wurcer

A symmetric digital subscriber line (ADSL) has become one of the major delivery systems of broadband to the home, providing up to 10 Mbits/second over the already installed base of twisted-pair phone lines. Each customer has a dedicated “port” in the central office, which consists of a data pump, an analog front end and a line driver. Though the digital data pump has scaled readily with ever-decreasing CMOS feature sizes, the power requirements and voltage levels for the line driver, on the other hand, make a CMOS solution difficult to deploy. By default, this use of nonstandard processes means the line driver continues to require high-speed bipolar processes. As a result, the driving function has eaten up an increasingly large share of the overall power budget.

As system designers attempt to increase board density and reduce system complexity, it’s critical to minimize the driver amplifier’s power consumption. Fortunately, designers have addressed the line-driver efficiency problem with improvements like synthesized output impedance and new classes of amplifier architectures. This article outlines some simple rules that enable one to quickly assess the relative power efficiency of different line-driver architectures.

To state the problem, the line driver must place a 20.4-dBm (110-milliwatt) signal on an ordinary 100-Ω twisted pair. Through sound analysis, the line-driver power bottleneck can be overcome on the road to full central-office line-card integration.

The ADSL signal consists of 256 discrete tones at a power density of –40 dBm/Hz. The resulting signal has noiselike characteristics with a root mean square (rms) level of 3.31 volts. To maintain a low bit-error rate, the peak signal must not exceed the amplifier’s output range, or clipping will result. The present specifications require that signals of 5.3 times the rms level (17.54 V peak) be passed undistorted. The power supplies for the amplifier must therefore be large enough to accommodate this high peak-to-average ratio, which forms the crux of the efficiency problem.

A Class AB amplifier driving a resistive load is shown (Fig. 1). If it is ideal, the power delivered to the load is \( V_{\text{rms}}^2 / R_L \), while the power supplied to the system is proportional to the product of the time-average current drawn by the supplies \( V_{\text{mos}} / R_L \) and the supply voltage \( V_c \). The efficiency is simply the ratio of those two quantities. The quantity \( V_{\text{rms}} / V_{\text{rms}} \) is easily computed for many waveforms: square wave, 1; sine wave, \( 2\sqrt{2}/\pi \); Gaussian noise, \( \sqrt{2/\pi} \). For an ideal amplifier \( V_c \) is simply equal to the peak output.

Figure 1: For an ideal Class AB amplifier driving a resistive load, the characteristics of the output signal (i.e., the rms, average and peak value) are all that are needed to compute the efficiency.

Figure 2: In a first-generation Class AB differential ADSL driver, the amplifier must deliver 23.4 dBm to the load—half of which is lost in the termination resistors. That must be taken into account when computing the net power consumption (\( P_o = 220\,\text{mW} \)).
The efficiency in this case reduces to \( \frac{V_{p}^{2}}{V_{p}V_{0\text{ave}}} \). In other words, the characteristics of the output signal, that is, the rms, average and peak value, are all that are needed to compute the efficiency, which for an ideal Class AB amplifier in the case of an ADSL (Gaussian) signal is 0.24 (\( V_{c} = 17.54 \) V, \( V_{0\text{rms}} = 3.32 \) V, and the quiescent power \( P_{q} = 0 \) (in Equation 2)). For more on efficiency calculations go to www.comms-design.com/story/OEG20030109S0014.

### Real-world issues

Two real-world issues complicate matters, however. First, there will always be some quiescent power \( P_{q} \) used for bias or reference circuitry that is not delivered to the load. The second is that \( V_{s} \) for a real amplifier will always be higher than \( V_{p} \) to allow for unavoidable voltage drops in transistors and other devices. The peak current on the line for an ADSL signal is approximately 175 mA. At this level a good line driver can be expected to require 1 to 2 V of headroom. This high crest factor—that is, the ratio of peak to rms voltage—of the ADSL waveform remains the real problem. The supply voltage required to provide headroom for the rarely occurring peaks is obviously much greater than that needed to support the average output, and therefore increases both the quiescent and average power.

It is important to note that some of the bias current in the amplifier’s output stage is actually delivered to the load. This means that the \( P_{q} \) term will in most cases be less than the number quoted on the data sheet and will be different for each amplifier architecture. By substituting the actual supply voltage, \( V_{s} \) for \( V_{p} \) and adding a quiescent power term, \( P_{q} \), the efficiency equation can be rewritten as shown in Equation 1, where \( P_{o} \) is the total power delivered to the load at the output of the amplifier and \( P_{o}/E \) is the total power consumed by the system. For the ADSL signal, this becomes Equation 2.

Now, let’s apply those results to a first-generation Class AB ADSL driver (see Fig. 2). The termination of the return signal is provided passively with resistors, each equal to one-half of the desired impedance. This means that the amplifier must deliver 23.4 dBm to the load and half of the output power is lost in those resistors. Consequently, we must take that
into account when computing the net power consumption ($P_o = 220 \text{ mW}$). Also, since this is a fully differential circuit, we must be careful to use half of the differential $V_{\text{rms}}$ in the efficiency equation.

The transformer provides isolation as well as impedance transformation. Its turns ratio can match drive requirements to supply voltage. In fact it is important to note that for an ideal amplifier, that is, one with no headroom requirement and no quiescent current, each value of turns ratio ($N$) will have a corresponding value for $V_s$ that gives the same maximum efficiency. On the other hand, high turns ratios give very low drive impedance, high peak-current requirements and higher passive losses so they are generally avoided. Since $P_i$ will increase with $V_s$ and headroom requirements (as a percentage of total supply) decrease with $V_s$, a real amplifier will have a peak efficiency at one given turns ratio. If the value of $V_s$ and peak output current implied at that turns ratio are compatible with the system requirements, it becomes a good choice. Typical values for first-generation amplifiers were ±15-V supplies and 15-mA quiescent currents with a turns ratio of 2:1, thereby giving a total power consumption of 2.4 W. Considering that the rest of the per-port power has been reduced to less than 400 mW, this is no longer acceptable.

The current generation of ADSL systems almost universally uses synthesized output impedance to reduce the transmit power lost in the reverse-termination resistors (see Fig. 3). It is possible to compute the resistor values to give proper termination and forward gain. The main penalty of that technique is attenuation of the return signal. Fortunately, the noise performance of the receive amplifiers has improved enough to reduce the size of the line-terminating resistors by as much as a factor of 10, and therefore the amplifier only needs to provide 121 mW at its output for 110 mW on the line. Class AB drivers have also improved and now use currents as low as 4 mA on ±12-V supplies, yielding a total power consumption of the vicinity of 750 mW.

### Two-supply designs

With a second set of supplies, designers have tried to get the best of both worlds. A lower set of supplies absorbs most of the quiescent current and output drive, and a higher set of supplies exists for just the signal peaks. Amplifiers of that type come in at least two varieties. One is referred to as Class G, where there are multiple sets of external supplies and the other is Class H, where charge pump circuits boost the lower supply voltages on demand. Class H operation has the advantage of not needing the extra set of external high-voltage supplies. An ADSL drivers have a BSEE from MIT.

It is evident that the efficiency in the Class G case has a peak value when $V_{T1}/V_{\text{rms}}$ approximates 2, which implies a switching point of approximately 3.3 V. A perfect Class G amplifier would have $V_{s1}$ be 3.3 V and $V_{s2}$ again just equal to the peak signal, 8.77 V. The efficiency in this case is 0.51.

In a dual-supply system the charge pumps can increase $\pm V_s$ by a factor of 3, so a perfect Class H amplifier would have a $V_s$ of 2.92 V (8.77 V/3) and an efficiency of 0.58. Headroom and allowance for a diode drop to isolate the two supplies implies more-realistic primary supplies of around ±5 V. With 5-V rails and 10 mA of quiescent current, a Class H amplifier would achieve a total power consumption of 450 mW, a considerable improvement.

The results for various classes of amplifiers are summarized (see Fig. 4). In all cases, the circuit of Fig. 5 is used. The first step is to compute $P_o$ and $V_{\text{rms}}$. $P_o$ is the total output on the line (110 mW) plus any losses. Here, only the power lost in the back-termination resistors is considered for a total of 121 mW. Vo is the voltage on the line transformed by N and divided by k. N and k were chosen to give a net factor of 1 for a $V_{\text{rms}}$ of 1.66 V.

For more on ADSL design, see “Study of the Impact of PPTC Devices on ADSL Equipment”; [www.commsdesign.com/story/OEG20021206S0003](http://www.commsdesign.com/story/OEG20021206S0003)

Scott Wurcer (scott.wurcer@analog.com) is an ADI Fellow working in the Advanced Linear Products group at Analog Devices Inc., where he architected the AD8393 Class H ADSL line drivers. He has a BSEE from MIT.