Evaluation Criteria for ADSL AFE1302

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ABSTRACT

This paper describes several important asymmetrical digital subscriber line (ADSL) AFE1302 evaluation criteria and design limitation factors, including the relationship between total signal-to-noise ratio (SNR) and transmission data speed; loop attenuation variation with discrete multi-tone (DMT) signal frequency and its influence on the reach; the echo return loss of the hybrid circuit; and the impact of Multi-Tone Power Ratio (MTPR).

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1.1 Introduction

The AFE1302 chip and AFE (Analog Front End) reference design printed circuit board (PCB) are used for the ADSL CPE (customer-provided equipment) modem and CPE peripheral component interconnect (PCI) card design. The AFE1302 CPE modem is one practical ADSL AFE design and evaluation example. The key performance of the CPE modem is the maximum reach 18,000-foot loop with a downstream net bit rate of 928 Kbps and an upstream rate of 416Kbps.

The International Telecommunications Union (ITU) ADSL standard G.992 defines the maximum transmitted power spectral density (PSD) mask requirements. The crosstalk that comes from co-existing ADSL and integrated services digital network (ISDN) lines can be minimized by limiting the maximum strength of the transmitted ADSL signal power over the twisted−pair long wires. In addition, due to Electromagnetic Compatibility (EMC) society legislation, the ADSL transmission system is required to not interfere with AM/FM radio reception. These two specifications place a PSD limit on the strength of the transmitted ADSL signal power.

This paper will discuss some evaluation and design considerations that address transmitted data speed, telephone twisted-pair loop attenuation, the hybrid circuit, and MTPR.

1.2 Transmitted Data Speed and Total SNR

Transmitted data speed is the first consideration for ADSL CPE modem design and evaluation. The transmitted data speed is a function of total signal-to-noise ratio (SNR). The total SNR is the telephone loop SNR plus the modem receive path SNR.

The discrete multi-tone (DMT) modulation was standardized for the ADSL system by the telecommunication standardization sector of the ITU.

For DMT-based ADSL, each subcarrier or tone is spaced at 4.312KHz frequency intervals. The subcarrier assignment is defined by ITU standard G.992. For example, the subcarrier assignment in G.992.1 annex A can be used for a frequency division multiplexing (FDM) to separate upstream and downstream signals. Subcarriers 31−255 (ITU G.992.1), or subcarriers 31−127 (ITU G.992.2), are reserved for downstream transmissions. Subcarrier 0−30, for example, with a maximum of 31 total subcarriers, may be assigned for upstream signals. The lowest frequency subcarriers may be set to zero to allow for voice on the same line, such as plain old telephone service (POTS).

The lowest frequency subcarrier used for upstream is determined by the POTS/ADSL splitting filter. The number of the upstream subcarriers and the number of the downstream subcarriers are determined by the receive and transmit filters. The actual number of subcarriers employed to modulate data may be less than the maximum allowed, and is determined during the initialization sequence. The transmitter designates a subset of the maximum available subcarriers for a connection during the channel analysis phase.

The process of ADSL DMT modulation actually modulates each subcarrier as $2^{b(i)}$ quadrature amplitude modulation (QAM). The b(i) is the number of bits in the *i th* subcarrier. Subcarriers with lower SNR are assigned fewer bits to create a small number of QAM constellations. Subcarriers with higher SNR are assigned more bits to create a large number of QAM constellations. For example, if the *i th* subcarrier is assigned 8 bits, then the size of the carrier QAM-constellation is 2^8 = 256 QAM.

The bits are determined by the SNR measured during the channel analysis initialization procedure. There are five steps to the CPE modem initialization process:

- Handshake procedures
- Channel discovery
- Transceiver training
- Channel analysis
- Exchange

During the exchange phase, each receiver communicates to its far-end transmitter about the number of bits and relative power levels that are used on each DMT tone or subcarrier, as well as the final data rate information. After the successful initialization sequence, the transceivers can begin communication with actual data.

The channel analysis phase is used to measure the channel characteristics for both directions of transmission. In other words, channel analysis measures the channel transfer function versus the frequency response characteristic. The downstream channel characteristics are measured at the CPE side and the upstream channel characteristics are measured at the CO side.

During the channel analysis phase, the receiver estimates the transmitted channel gain of each subcarrier in preparation for computing the total SNR for each subcarrier. Then each subcarrier is assigned the number of bits it will carry. The sum of all the bits assigned to all of the subcarriers within the transmitting period (per DMT symbol) determines the transmitted data speed.

The number of bits assigned per subcarrier can be calculated as:

$$b(i) = \log_2 (1 + snr(i) \times g/\gamma \times m) \quad (1)$$

Further:

$$2^{b(i)} - 1 = snr(i \times g/\gamma \times m$$

$$10\log_{10}[2^{b(i)}-1] = 10\log_{10}[snr(i)] + 10\log_{10}(g) - 10\log_{10}(\gamma) - 10\log_{10}(m)$$

Only if $2^{b(i)} >> 1$, then

$$10\log_{10}(2^{b(i)}) = SNR(dB) + G(dB) - \Gamma(dB) - M(dB)$$

Therefore:

$$b(i) = [SNR(dB) + G(dB) - \Gamma(dB) - M(dB)]/3dB \text{ (bit)} \quad (2)$$

Where:

- b(i) is the number of bits in the *i th* subcarrier.
- i is the subcarrier index from 0 to N−1, N is the total useable subcarrier number, and the maximum N=256.
- snr(i) is the signal to noise ratio per subcarrier; it is a real value which shall represent the ratio between the received signal power and the received noise power for that subcarrier.

  $SNR(dB) = 10\log_{10}[snr(i)]$
- γ or Γ is a constant determined by the required bit error rate (BER).

For example:

$\gamma = 9.55$, $\Gamma = 10\log_{10}(\gamma) = 9.8$ (dB) for BER< = 10^{-7}.

- g or G = $10\log_{10}(g)$ (dB) is a gain provided by Reed-Solomon error correction coding to make the system robust against impulsive noise bursts.
- m or M = $10\log_{10}(m)$ (dB) is the margin to represent the amount of increased noise relative to the noise power that the system is designed to tolerate and still meet the target BER of 10 e−7, accounting for all coding (trellis coding and RS FEC) gains included in the design.

  This margin can prevent too many bits swapping if the SNR changes. Normally, M=6dB is used to prevent on-line swapping.

The G(dB), Γ(dB) and M(dB) are constants. One bit is added to the assigned b(i) if the SNR(dB) is increased 3dB in the subcarrier channel (known as the *one bit every 3dB* rule of thumb)

Assuming that G(dB) = 2dB, Γ(dB) = 9.8dB and M(dB) = 6dB, a typical b(i) and SNR(dB) vs. the tone number is shown in Figure 1.

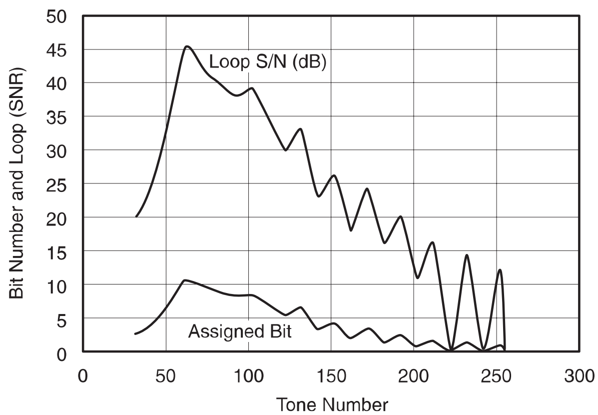

Figure 1. Bits Assignment and Loop SNR Relation

The transmitted data speed can be calculated by:

$$C=[\sum b(i)] / T \quad \text{for } i = 0 \text{ to } N-1 \qquad (3)$$

Example 1:

If the gain of trellis and Reed-Solomon coding is not included, the attainable net rate or the maximum data rate is:

$$C = \{\Sigma[SNR(dB) - \Gamma\ (dB) - M\ (dB)]/3dB\}/T\ (bit/s); \quad \text{for } i = 0 \text{ to } NSC-1$$

Example 2:

Additionally, if M = 6dB and G=6dB, the attainable net rate can be simplified as follows:

$$C = \{\Sigma[SNR(i) - \Gamma]/3dB\}/T\ (bit/s); \text{ for } i = 0 \text{ to } NSC-1$$

Where:

- C is the transmitted data speed.
- T is the transmission period.

For the duration of a DMT symbol, it is 250 µs. The data symbol rate is the net average rate at which symbols carrying data frames are transmitted (= 4000 data symbols/second). But in order to insert the synchronization symbol, the symbol rate is defined as the rate at which all symbols (including the synchronization symbol) are transmitted. This rate is $(69/68) \times 4000 = 4058.8$ symbols per second.

From equation (3), the transmitted data speed is determined by the total SNR. The modem RX path noise is not discussed in this report. The transmitted DMT signal power and loop noise are specified in the recommended ITU G.992 as follows:

1. For G.992.1, the downstream PSD is –40dBm/Hz from 25.875 to 1104KHz for a total transmission power not greater than 20.4 dBm if all subcarriers are used.
2. For G.992.2, the downstream PSD is –40dBm/Hz from 25.875 to 552KHz for a total transmission power not greater than 16.2 dBm if all subcarriers are used.
3. The upstream normal transmit PSD, for the channel analysis signal (R−REVERB1) and all subsequent upstream signals, is –38dBm/Hz. This rate is equivalent to –1.65dBm total transmit power in any 4.3125KHz subcarrier. The maximum transmit PSD shall be no higher than –37dBM/Hz, for an aggregate transmit power not greater than 12.5dBm if all subcarriers are used.
4. The telephone loop noise is assumed to be 31.62nv/rt−Hz or –140dBm/Hz.
5. It is specified as the quiet line noise PSD N(f) for a particular subcarrier in G.992.3−ADSL2, and it is the rms level of the noise present on the telephone line, when no ADSL signals are present on the line.

A practical evaluation result of the transmission channel capacity is the net data speed for the AFE1302 CPE modem. The evaluation is based on using the subcarriers 36 to 127 for downstream with a total transmission power of less than 15.99dBm during the training phase and 6.06dBm during the SHOWTIME state. The SHOWTIME state is the normal operation state and after all initialization and training are completed. Taking into account all noise contributions, the loop noise test results referred to the telephone line are less than −148dBm/Hz over receiver bandwidth for the AFE1302 CPE modem. The tested downstream net bit rate can reach 928 kbit/s with a 18,000 ft loop. The test environment parameters are:

- Loop simulator NSA400 is set as a 26AWG twisted-pair telephone wire without a bridged tap
- Noise margin is 6 dB
- Interleave depth is 16 with no trellis coding

1.3 Twisted-Pair Telephone Loop Attenuation

A reach distance is directly affected by twisted-pair telephone loop attenuation. The reach of an ADSL system is the distance over telephone lines that it can transmit and receive information. Reach is the key performance parameter for ADSL.

Telephone loop attenuation is defined as the difference between the total maximum transmitted power at one end of the telephone line and the total received power at the other end of the line. ADSL reach is limited by telephone loop attenuation.

Loop attenuation is mainly determined by wire diameters, loop length and the transmitted signal frequency. The most frequently used telephone twisted wire diameters are 0.4mm for 26 AWG wire and 0.5 mm for 24 AWG wire. The typical loop length varies from 6000 to 18,000 feet in North America, European and Asia. ADSL signals cover the bandwidth of 25.875KHz to 1104KHz as specified in ITU G.992.

According to POTS application statistics, the typical voice signal loss through a telephone loop is 3 to 6 dB per mile within the voice bandwidth of 300Hz to 4KHz. Because ADSL signal frequency is much higher than the POTS signal, the loop attenuation is greater within the ADSL signal bandwidth because line attenuation increases as signal frequency increases.

The transfer function of a telephone twisted pair is dominated by the skin effect. The skin effect means that high frequency currents tend to flow only in the outer portion on the skin of the conductor. The skin effect results in an increase of the attenuation at higher frequencies. In the case of a twisted-pair, the attenuation is a function approximately proportional to $f^{1/4}$ for frequencies below 350KHz, but it is a function approximately proportional to $f^{1/2}$ for frequencies above 350KHz.

From the experimental data shown in Figure 2, the loop attenuation increases from approximately 5dB per km at 10KHz to over 15dB per km at 1MHz. This means that a 13.12Kft (for example, 4km) 24 AWG twisted-pair telephone loop has an attenuation of more than 20dB at 100KHz, and more than 70dB at 1MHz. The twisted-pair loop attenuation varies by more than 50 dB across the ADSL signal bandwidth.

During channel analysis, the CO side receiver calculates the average loop attenuation.

Based on the channel analysis signal (R−REVERB1) using subcarriers 7 through 18, the average upstream loop attenuation is calculated as the difference between the total transmitted power at the CPE side and the total received power measured at the CO side.

In G.992.3−ADSL2 for a given length loop, the loop attenuation is defined as:

$$\text{LATN(dB)} = 10 \times \log\left[\Sigma|H(f)|^2/\text{NSC}\right] \text{ for } i = 0 \text{ to NSC}-1 \quad (4)$$

Where:

- NSC is the number of subcarriers.
- H(f) is the channel characteristic function per subcarrier.

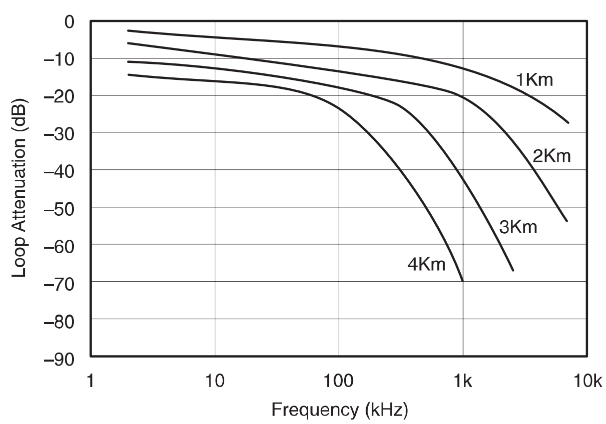

Figure 2. 24 AWG Twisted-Pair Telephone Loop Attenuation versus Frequency

LATN is the difference in dB between the power received at the near end and the power transmitted from the far end over all subcarriers; its dynamic range is from 0dB to 102.2dB.

For example, assume that LATN = 58.2dB, N = −140dBm/Hz, G = M = 6dB, the transmitted signal power is –30dBm/Hz, and the received signal power is S = −88.2dBm/Hz for a particular subcarrier.

By using equation (2), b(i) is calculated as 14 bits, which means that 14 bits of data are assigned on that subcarrier. However, if LATN increases to 88.2 dB for a longer loop, b(i) is only 4 bits (as a result of the one-bit-per-3dB rule).

Longer reach loop and higher subcarrier frequency result in greater loop attenuation, which means that fewer data bits can be assigned to subcarriers, and lower data speeds can be achieved.

1.4 Hybrid Circuit

An ADSL hybrid circuit is a three-port network used to:

- Pass the transmit signal from the AFE transmission port to the telephone loop port
- Pass the receive signal from telephone loop port to the AFE receive port
- Eliminate the transmit signal from the receive signal in the receive path

The ADSL hybrid circuit allows full-duplex transceiver operation in a telephone twisted-pair connection. The ADSL hybrid echo return loss is the amount of attenuation between the transmitted signal power and the reflected echo power in the receive path, normally expressed in dB. It is a key target of evaluation and design for an ADSL AFE. The higher the echo return loss, the less transmitted signal power enters the receive path.

$$H_{echo} = 10 \times |\log(P_{echo}/P_{tx})|$$

Where:

- H_{echo} is the hybrid echo return loss.
- P_{tx} is the transmitted signal power.
- P_{echo} is the portion of transmitted power that enters the receive channel. P_{echo} is also called the reflected echo power in the receive path.

The actual twisted-pair loop impedance Z(f) is the frequency function of the telephone line. The magnitude of the twisted-pair impedance is approximately 600Ω for POTS bandwidth. For the ADSL signal bandwidth, the magnitude is approximately 100Ω without bridged taps, and varies from 60Ω to 100Ω with bridged taps.

The hybrid circuit used in the AFE1302 CPE modem is purely resistive and essentially an electrical bridge circuit. When the differential drive resistive network becomes balanced, the amount of hybrid echo is minimized.

In DMT-based ADSL systems, the ADSL hybrid circuit and the receive path filter are the critical factors for receiver performance. The transmit path signal and noise power must be sharply attenuated by the hybrid echo path and receive filter to ensure significant improvement of CPE modem reach and downstream data speed, as shown in Figure 3.

For the typical value of 100Ω equivalent twisted-pair loop impedance, the minimum evaluation and design requirement is a total 40dB attenuation of a hybrid circuit and receive high pass filter. A 20dB return loss can be easily achieved through the hybrid circuit. The hybrid plus the 3rd order LC RX filter on board can provide a total of more than 40dB echo loss. That is, it can attenuate the transmitted power and noise by 40dB.

1.5 The Multi-Tone Power Ratio

Multi-Tone Power Ratio (MTPR) is an important feature in the evaluation and design of DMT-based ADSL systems. Better MTPR performance in both the transmission and receive paths results in higher data rates throughout the ADSL system.

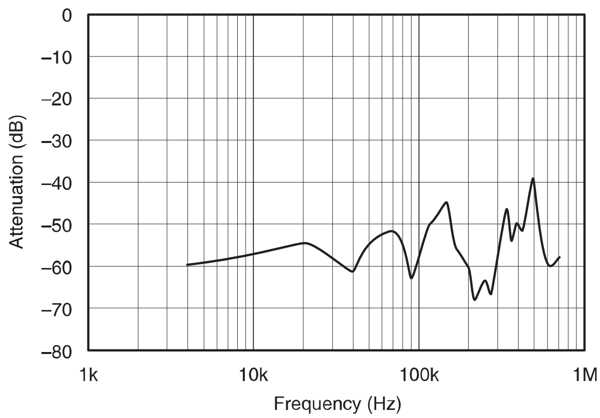

Figure 3. Hybrid Echo Return Loss and RX Path Filter Attenuation versus Frequency

MTPR is the ratio of the power in one subcarrier to the noise power in another selected empty subcarrier. There are no data bits assigned to the selected empty subcarrier in a DMT modulation. MTPR indicates the degree that a subcarrier QAM signal is corrupted by distortion from all other subcarrier QAM signals.

The measurement and evaluation for this kind of corruption are different from the traditional single tone distortion. Signal-to-noise + distortion (SINAD), spurious free dynamic range (SFDR), single-tone harmonic distortion, two-tone intermodulation distortion (IMD), 3rd order intercept (IP3) and total harmonic distortion (THD) are used only for expressing single tone or 2-tone signal integrity and spectral properties.

Multi-tone power ratio, on the other hand, indicates how the tested device, such as the line driver, receiver, line transformer, transmit (TX) filter, receive (RX) filter and digital-to-analog (DAC)/analog-to-digital (ADC), responds to the discrete multi-tone signal which is not one or two tones, but may be up to 255 tones or more.

One of the design tasks for the ADSL CPE modem is to maintain the fidelity of the discrete multi-tone signal. All the analog components used on the modem, such as the line transformer, common mode choke, hybrid circuit, transmit filter, receive filter, line driver and receiver must be designed so that they cause minimum corruption on the discrete multi-tone signal.

For any subcarrier, the minimum transmitter MTPR shall be at least 38dB, as specified in the ITU ADSL standard G.992. G.992.3 recommends a minimum MTPR of at least 44dB.

The MTPR of a tested device can be measured as the dynamic range from peak power in a subcarrier to the peak distortion in an empty tone. For example, a test result shows that a MTPR of 65.82dB can be achieved in the AFE1302 CPE modem transmission path. The test tool is National Instruments PXI−1002 Arbitrary waveform generator 5411.

As shown in Figure 4, the transmitter path is defined as the path from the DSP interface TX output to the twisted-pair telephone line interface with 100Ω impedance. The transmitted multi-tone is from tone 6 to 29 and with notch tone 16 and 17. The internal AFE1302 TX PGA Gain = 0dB, external TX line driver gain = 15dB. The tested result of MTPR is 65.82dB.

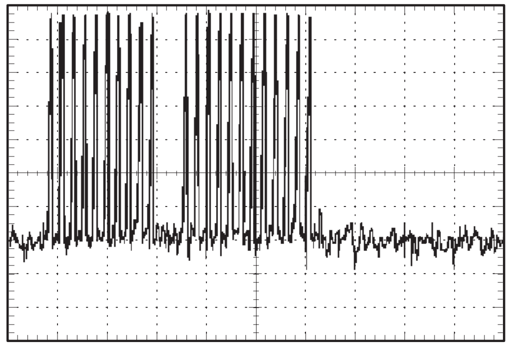

Figure 4. AFE1302 TX Path MTPR Performance

1.6 Summary

This report discussed evaluation and design considerations for an ADSL AFE.

The most critical evaluation criterion is ADSL transceiver data speed, which is limited by the total SNR. The second issue is variation of telephone loop attenuation with frequency and its impact on reach. This paper further points out that improvement on hybrid echo return loss increases the received data speed and the reach significantly. The MTPR, a type of corruption that differs from the traditional single-tone distortion, is another important criterion for design and evaluation an ADSL AFE.

References:

(1) ITU-T Draft Recommendation G.992.3−ADSL2. Geneva, 29 April—10 May, 2002.

(2) ADSL AFE1302 Data Sheet, literature number SBWS014, Texas Instruments, Dec. 2000.

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