REQUIREMENTS FOR EMBEDDED DATA CONVERTERS IN AN ADSL COMMUNICATION SYSTEM

H.J. Casier

Alcatel Microelectronics

ABSTRACT: The requirements for the analogue front-end for an ADSL modem are discussed, based upon the modem performance and the signal, noise and distortion-signal flows in the system. The relation between the various blocks and the asymmetric nature of the transmission are highlighted and their impact on the different blocks of the analog front end is indicated. The SNR specification of the A/D converter is calculated and other important limitations are discussed.

1. INTRODUCTION

In a first paragraph, the transmission system of the ADSL modem is described. This transmission system allows the implementation of ADSL alongside the voice band or ISDN band on the same twisted pair. The Frequency Division Multiplexing or Echo Cancelling operation modes are also described. In a second paragraph, the major challenge for the ADSL Analog Front End is described in detail. A block diagram of the Analog Front End is shown and the signal, noise and distortion-signals are each discussed in detail. Finally, the link between the transformer ratio and the driver supply voltage is calculated. Based on the detailed description above, the SNR specification and other important design considerations of the ADC converter are defined in the third paragraph.

2. THE ADSL MODEM

2.1 DMT transmission

Asymmetric Digital Subscriber Line (ADSL) is an established broadband communication technology, that allows multi-megabit transmission over a single twisted pair copper telephone line. In the downstream direction from the Central Office (CO) to the Customer Premises Equipment (CPE), a high data rate up to 8 Mbit/sec can be achieved. In the other direction (upstream), a lower data rate up to 1 Mbit/sec can be reached. This high data rate is achieved by sending and receiving signals on the twisted pair cable over a broad frequency spectrum up to 1.104 MHz. In order to approach the highest possible data rate, as predicted by the Shannon-Hartley relation

$$Capacity(bps) = \int_{f_{\min}}^{f_{\max}} \log_2 (1 + SNR(f) \cdot df$$

a DMT (Discrete Multi-Tone) transmission schema is used. The frequency band is divided in 255 subcarriers with a frequency spacing of 4.3125 kHz. Each of these subcarriers is individually QAM modulated with a variable number of data bits (2…15 bits) dependent on the Signal-to-Noise-Ratio (SNR) of the channel.

2.2 ADSL over POTS and ISDN

According to the ADSL specifications [1] [2], all 255 subcarriers can be used: subcarriers 1…31 for the upstream data and subcarriers 1…255 for the downstream data. In most ADSL implementations, the lowest subcarriers, which overlap or interfere with the 4 kHz voice band are not used. This allows the simultaneous transmission of the voice band services (POTS and data services up to 56 kbit/sec) and the high speed data transmission (ADSL) over the same twisted pair. In the same manner an ADSL implementation, which does not overlap the ISDN band has been defined [2].

2.3 FDM or Echo Cancelling

Since the tone allocation is not defined in the ADSL spec, the overlap of the upstream and the downstream bands is not mandatory and two operating modes have been defined. In Category I, the upstream and downstream bands are non-overlapping (Frequency Division Multiplexing - FDM). In Category II, the tones up to tone 31 overlap and Echo Cancelling (EC) is required. Figure 1 shows the Power spectrum of a category I ADSL system with POTS. The tones are QAM modulated and individually optimised as a function of the channel quality. Some tones are not used when the channel quality is too low.

The FDM system splits the Transmit and the Receive frequency bands. It offers better upstream

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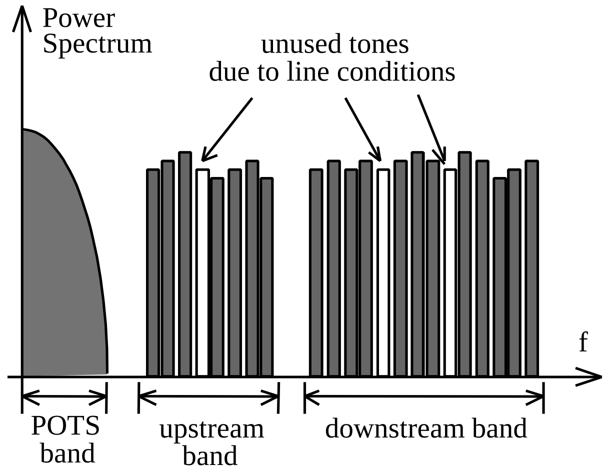

Fig.1. ADSL Category I (FDM) spectrum

performance than the EC system because the reflected Transmit signal (Echo) and the crosstalk from other ADSL Transmitters in the same cable bundle (Near End ADSL Crosstalk – self-NEXT) can be filtered before the Receive input. This improves the SNR of the used tones and limits the required dynamic range of the Low Noise Amplifier (LNA) and the A/D converter at the Receive input. The EC system on the other hand, reaches higher downstream performances on short loops due to its wider frequency bandwidth. Note that Far End Crosstalk (FEXT) from other ADSL Transmitters and NEXT of other transmission types e.g. ISDN, HDSL, T1 … generate in-band noise.

3. ANALOG FRONT END CHALLENGE

3.1 AFE Block Diagram

A Block diagram for the Analog Front End (AFE) is shown in Figure 2. It shows the DAC and ADC interfaces to the digital signal processing circuits.

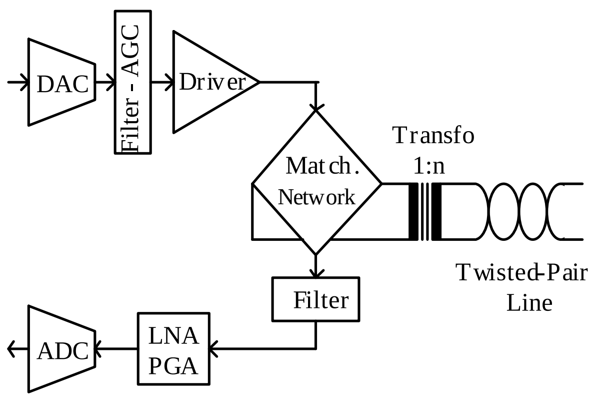

Fig.2. Analog Front End Reference Model

The DAC is followed by a smoothing filter-AGC and the power driver. The ADC is preceeded by the LNA/PGA. The matching network performs the two-wire to four-wire conversion and provides impedance matching to the transformed Line Impedance. The filter selects the upstream or downstream band in the FDM system. The transformer isolates the modem from the line and transforms the impedance and signal voltages between the 100 Ω twisted pair and the modem. The same block diagram is valid for the CPE and CO sides of the modem but the specifications of each block are different. e.g. the CPE – DAC, Filter and Driver generate the upstream band signals and the Filter, LNA and ADC work in the downstream band. The matching network and transformer encompass the complete ADSL band.

3.2 AFE performance challenge: SNR

The major challenge for ADSL is to maximise the transmission data rate for various twisted pair lines. According to the Shannon-Hartley relation, this is equivalent to maximising the transmission SNR. The largest SNR is obtained for the highest signal power, the lowest noise power and the lowest distortion power at the input of the digital circuits. In Figure 3, a schematic overview is given for the signals [S_{xx}], the noise signals [N_{xx}] and the distortion signals [D_{xx}], which define the SNR at the CPE side of the ADSL modem. Also shown are the various losses in the matching network [MN], in the filter [F] and in the twisted-pair line [Line]. The transformer turn ratios are 1:n for the CPE side and 1:m for the CO side [3].

3.3 High Signal Power

The highest signal power on the Line is fixed by the standard [1] [2], e.g. -40dBm/Hz for CO. As the signal travels through the twisted pair, it is attenuated as a function of the line length, the signal frequency and several loop impairments (bridged taps, gauge transitions …). The received signal power is not changed in the CPE transformer but the signal voltage is divided by the transformer ratio n. This is important since the signal power is mostly dissipated in the matching network and only the transformed signal voltage is sent to the $CPE_{Rx-input}$. The relation between the transformer ratio and the driver supply voltage is described in a next paragraph. After the transformer, the signal is further attenuated by the matching network loss and the filter loss. The matching network loss is a function of the matching network and of the level of impedance synthesis.

3.4 Low Noise Power

The various noise inputs to the $CPE_{Rx-input}$ are shown in Figure 3. The first noise source is the input referred noise of the LNA/PGA and the ADC. A part of the out-of-band noise of the CPE Driver (DAC+Filter+Driver) is in-band noise for the CPE input. This noise is attenuated (echo cancelled) by the matching network (12…20dB)., The noises of the filter and the matching network are negligible for a proper design. The thermal noise of the twisted pair: Additive White Gaussian Noise (AWGN) is the lowest noise limit for ADSL: $N_{AWGN} = -140 dBm/Hz$ (Bellcore). Finally, the in-band noise of the CO-Driver is attenuated together with the CO-signal and is negligible.

3.5 Low Distortion Power

The various distortion inputs to the $CPE_{Rx-input}$ are also shown in Figure 3. The first distortion source is the intrinsic non-linearity of the LNA/PGA and the ADC. A part of the out-of-band harmonic and intermodulation distortion of the CPE Driver (DAC+Filter+Driver) is in-band distortion for the CPE input. This distortion is also attenuated (echo cancelled) by the matching network (12…20dB). The distortion of the filter is normally negligible. Not shown on Figure 3 is the transformer distortion. For a properly designed transformer, this distortion remains below –80dB except for the highest crest factors and lowest frequencies. Many distortions are generated in te twisted pair line. Linear distortions in the transmission line, bridged taps and gauge transitions distort the transmitted signal and can be compensated in the digital circuit. Uncorrelated signal crosstalk: NEXT, FEXT, POTS and various interferences: Impulse noise, Ingress, Radio Frequencies (RFI) can not be compensated and constitute a situation dependent limitation for the ADSL system performance. Finally, the in-band distortion of the CO-Driver is attenuated together with the CO-signal and is negligible.

3.6 Driver Power and Transformer Ratio

The transformer ratio is calculated in three steps. First the CO driver rms-power ($P_{Driver-rms}$) is backwards calculated from the standardised signal rms-power on the twisted-pair line (-40 dBm/Hz downstream or $P_{Line-rms} = 20.4dBm \approx 110mW$ over the downstream signal band), the loss in the matching network ($MN_{loss} \approx 2$ if no impedance synthesis is used) and the small transformer power loss ($Tr_{loss} \approx 1$).

$$P_{Driver-rms} = P_{Line-rms} \cdot MN_{loss} \cdot Tr_{loss}$$

The peak power, which must be handled by the

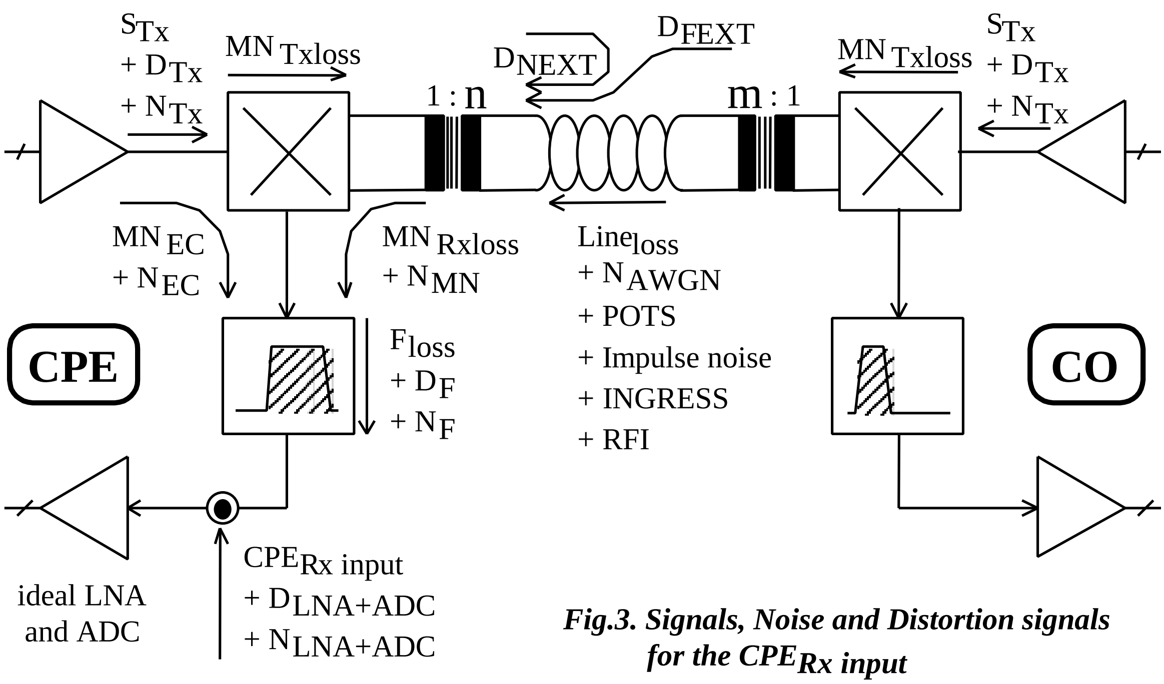

Fig.3. Signals, Noise and Distortion signals for the CPE$_{Rx}$ input

CO driver is much higher than the rms value. In the DMT signal, more than 200 uncorrelated tones are added together, which results in a theoretical voltage crest factor $CF > 200$. With a large number of carriers, the amplitude of the DMT signal approaches a Gaussian distribution and the probability of a large crest factor decreases rapidly. For a crest factor of 5.6, the probability becomes less than 10^{-8}. Clipping the signal above this level introduces a low enough disturbance to meet the bit error rate (BER) of 10^{-7}. From the CO driver rms-power, the voltage crest factor (CF) and the maximum voltage swing amplitude of the driver ($V_{max-ampl}$) the load impedance of the driver is calculated.

$$Z_{L-Driver} = V^2_{\max-ampl} \Big/ CF^2 \cdot P_{Driver-rms}$$

Note that for a differential push-pull driver, the maximum voltage swing amplitude equals the minimum supply voltage minus the margin over the driver transistors.

The transformer ratio (m:1) is finally calculated from the load impedance of the driver, the loss in the matching network and the 100 Ω characteristic line impedance for ADSL.

$$m = \sqrt{\frac{100\Omega}{Z_{L-Driver}} \cdot MN_{loss}}$$

From these formula also the minimum supply voltage can be calculated as function of the transformer ratio.

4. CONVERTER SPECIFICATIONS

4.1 The SNR Specification

The SNR of the ADC is derived as follows. [4]

First, for each bit in the QAM code, a 3 dB SNR is required and on top a 3 dB margin is added:

→ 48 dB SNR @ 15 bit QAM + 3 dB margin

The crest factor is the second major factor. The minimum crest factor is 5.6 or 15 dB.

→ 17 dB SNR @ crest factor + margin

The signal attenuation can be very low for short lines and more than 60 dB for high frequencies on long lines. The signal attenuation is compensated in the LNA/PGA amplifier, which precedes the ADC. It does not result in an increase of the SNR.

→ 0 dB SNR @ line attenuation.

Due to the limited selectivity of the filters in the Category I system and the absence of filters in Category II, the out-of-band Driver signal is not completely attenuated. This signal increases the received signal and sets an upper limit to the LNA/PGA amplifier gain.

→ 10…20 dB SNR @ incomplete analog EC

The ADC is not the only contributor to the system SNR. The LNA/PGA and the bandpass filters before the ADC also contribute.

→ 10 dB SNR @ cascade of receiver blocks.

The sum of all these SNR gives

→ 85…95 dB SNR Total or 14…16 bit ADC.

4.2 Other Specifications

Due to DMT coding, the ADC resolution has to be maintained over the full signal bandwidth, up to 1.104 MHz..

The input referred noise of the ADC +LNA/PGA must be lower than the transformed and attenuated $N_{AWGN} \approx 31nV/\sqrt{Hz}$. This noise limitation becomes dominant for low supply voltages and high impedance synthesis ratios.

Uncorrelated signal crosstalk (NEXT, FEXT, POTS …) limits the performance of the ADSL system by lowering the SNR of the received signal. Since this crosstalk is situation dependent, this feature can not be used to relax the spec.

5. CONCLUSION

The ADSL modem requires a high resolution converter and many other high performance analog circuits in order to fullfill its complete performance. The interdependency of the specifications of these different analog circuits is quite high and a good distribution of the specifications between the different analog blocks and between the analog and digital circuits is very important for the overall system performance.

6. REFERENCES

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