Analog Circuit Design

(X)DSL and other Communication Systems; RF MOST Models; Integrated Filters and Oscillators

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and Rudy van de Plassche
(editors)

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ANALOG CIRCUIT DESIGN

Preface

This new book on Analog Circuit Design contains the revised contributions of all the tutorial speakers of the eight workshop AACD (Advances in Analog Circuit Design), which was held at Nice, France on March 23-25, 1999. The workshop was organized by Yves Leduc of TI Nice, France. The program committee consisted of Willy Sansen, K.U.Leuven, Belgium, Han Huijsing, T.U.Delft, The Netherlands and Rudy van de Plassche, T.U.Eindhoven, The Netherlands.

The aim of these AACD workshops is to bring together a restricted group of about 100 people who are personally advancing the frontiers of analog circuit design to brainstorm on new possibilities and future developments in a restricted number of fields. They are concentrated around three topics. In each topic six speakers give a tutorial presentation. Eighteen papers are thus included in this book.

The topics of 1999 are:

(X)DSL and other communication systems
RF MOST models
Integrated filters and oscillators

The other topics, which have been coverd before, are:

1992	Operational amplifiers
	A-D Converters
	Analog CAD
1993	Mixed-mode A+D design
	Sensor interfaces
	Communication circuits
1994	Low-power low-voltage design
	Integrated filters
	Smart power
1995	Low-noise low-power low-voltge design
	Mixed-mode design with CAD tools
	Voltage, current and time references

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1996	RF CMOS circuit design
	Bandpass sigma-delta and other data converters
	Translinear circuits
1997	RF A-D Converters
	Sensor and actuator interfaces
	Low-noise oscillators, PLL's and synthesizers
1998	1-Volt electronics
	Design and implementation of mixed-mode systems
	Low-noise amplifiers and RF power amplifiers for telecommunications

I sincerely hope that this book may make an invaluable contribution to the understanding of the art and science of analog design.

Willy M.C. Sansen

Table of Contents

(X)DSL and other communication systems

Introduction

Modeling MOST transistors has once more gained importance because of the i(X)DSL and Other Communication Systems

Since its origin the telephone network consisted of a twisted pair of copper wires. The transmission speed over this pair has been limited to voice band. Over the years the needs for higher transmission speeds became evident. Different solutions exist eg. ISDN. Recently improved modem techniques resulted in much higher transmission speeds over the local network. Examples of these modem techniques and components for the implementation of different standards will be presented in this part of the book.

The first paper by Cornil et al gives an introduction to the different standards used and the modulation techniques that can be incorporated in these modem chips. A maximum transmission speed over 52 Mbit/s over a short distance is possible.
The second paper by Hester describes the architectures and the filter implementation problems involved in the design of an ADSL modem. An intelligent choice between a digital implementation and an analog implementation of the required filtering functions is described. The third paper by Geerts et al shows the implementaion and design criteria for high resolution, high speed Delta-Sigma Analog-to-digital converters required for ADSL modem applications. A MASH architecture is used for the A/D converter and the desing space is analyzed to obtain 15 bit resolution with a 1.1 MHz analog bandwidth using a 0.5 micron CMOS technology. The fourth paper describes clipping techniques to be implemented in receiver and transmitter chains for ADSL modems. Clever clipping in the receiver and transmitter chains relax the requirements for the analog circuitry in such systems. Finally Dru Cabler gives a survey of the different techniques used in analog circuit design for ADSL modems. Attentions is paid to the A/D and D/A converters and the requirements needed for modem implementation.

Rudy van de Plassche

"Building an ADSL Modem, the Basics"

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Abstract

Asymmetric Digital Subscriber Line (ADSL) is a new broadband communication technology that allows telephone companies to deliver multi-megabit data rate on their existing twisted pairs while simultaneously maintaining a traditional voice service. This new capabilities will boost multimedia internet applications by reducing the download time to a fraction of what it take today using classical voice-band modem.

Slide 2 - Outline

The presentation starts by a few words on the evolution of the local loop, modem technology and network architecture able to provide broadband communication channels to telephone subscribers, and to satisfy future requirements of their multimedia applications.

The next section will describe main twisted pair characteristics and impairments encountered in ADSL systems. It will be followed by a description of the Discrete Multi Tone (DMT) modulation features and will show how DMT combats very efficiently channel non-idealities.

Once these concepts are defined, a step-by-step presentation of all key functions needed to build an ADSL modem will be performed, starting from the digital interface to the copper line.

The conclusion will outline some actual trends concerning ADSL evolution, capacity and deployment.

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Introduction

Slide 3 - Local Loop evolution

Twenty years ago, it was believed that fiber optic would replace copper lines for broadband access within a few years. However, the cost associated with the 'last mile' infrastructure has delayed the arrival of the fiber to every home (FFTH) for many years. Another, more economical technology was needed to bridge the gap between growing data rates, pulled now by the Internet, and current modem capabilities.

ADSL (Asymmetric Digital Subscriber Line) provides an answer to that demand. Downstream bitrates of up to 8 Mbits/s and upstream rates of a couple of hundreds kbits/s are feasible. Distances up to a few kilometers can be covered. In this way, ADSL transforms the twisted pair from one limited to voice and low-rate data to a powerful bit pipe. Meanwhile, ADSL leaves the existing (analog) telephone service intact and undisturbed but adds the ability to access a multitude of new multimedia services.

xDSL provides also the interim technology needed to bridge the gap before the advent of FFTH (as commented by Bell Atlantic's CEO , "ADSL is an interim technology for the next 40 years..."). This gives also POTS operators the opportunity to turn their buried lines pairs (almost 1 billion installed lines!) into a new copper mine, with a strategy supporting a more economically viable and progressive introduction of the fiber from the core network to customer premises (ADSL->VDSL->FFTC->FFTH).

Slide 4 - Modem evolution

Since the early 1960's, voice band modems have been developed to transport digital data over the telephone network. These modems modulated the data at the transmitter, then were transported (over one or two pairs) transparently through the telephone network, and finally demodulated at the receiver. Different modulation techniques have been used, starting with FSK (Frequency Shift Keying) in the ITU-T standard V.21, over DPSK (Differential Phase Shift Keying) in V.26, V.27 and V.29 ([1]), to QAM (Quadrature Amplitude Modulation) in V.22bis, V.33 and V.34 ([2]). Also different duplexing techniques have been applied: full duplex transmission

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1 V.29 makes use of a variant of DPSK: ADPSK (Amplitude Differential Phase Shift Keying).

2 V.33 and V.34 also make use of Trellis coding: 128-QAM with Trellis coding in V.33 and 4-dimensional Trellis coded QAM in V.34.

over a single pair with separated (FDM, Frequency Division Multiplexing) or overlapping (EC, Echo Canceling) frequency bands for both directions of transmission, dual simplex transmission over two pairs and half-duplex transmission over one pair. The bitrates range from 300 bit/s in V.21 to a remarkable 33.6 kbit/s (near the theoretical capacity limit of 10b/Hz/s for voice-band channel) in V.34. Very recently (1997) bitrates of 56 kbit/s have been achieved (V.90). However, these very high rates are only possible in particular configurations where e.g. an Internet service provider has a *digital* connection (= without quantization noise) to the central office, and only in the downstream direction, i.e. towards the customer.

Providing access to the 'information superhighway' for residential customers requires new technologies capable of improving the performance and capacity of these copper lines above the 64kb/s limit. A first step in that direction was the introduction in the 1980s of ISDN-BRA (Integrated Services Digital Network, Basic Rate Access) offering a bi-directional 144 kbit/s, but still based on the PSTN switching.

During the past several years, evolution in Digital Signal Processing techniques coupled with high speed packet switching capabilities enabled the design of several new modem technologies, such as ADSL and very recently VDSL, both able to break the symbolic Mb/s barrier on classical phone lines.

Slide 5 - Network evolution

Slide 5 depicts Internet access by means of a voice band modem (top) and an ADSL modem (bottom). The main difference is that voice-band operates over an end-to-end PSTN connection, whereas ADSL operations are limited to the local loop.

Key for voice band modems is, as the name implies, that the data is modulated in the voice band (from 300 to 3.4 kHz) and carried transparently over the network end-to-end. This requires also higher Quality Of Service (QOS) from the network in order to be able to maintain complex & efficient modulation schemes. However, classical PSTN switches were optimized using voice call duration as parameter for their design, and have 'some' difficulties to avoid blocked calls when faced with "always on" Internet connections. Another disadvantage of this end-to-end connection is that the bandwidth of the resulting communication is not only limited by local loop performances and/or modem type but also by parameters of the network and remote site capabilities.

In order to solve above issues, signals modulated by high speed and/or bursty data have to be limited to the local loop and terminated before entering the local telephone exchange.

This is the case with ADSL, where the transmission on the twisted pair is terminated in the Line Termination (LT) at the local exchange and the Network Termination (NT) at the subscriber side. The 'POTS-splitter' in the LT separates the analog telephone signal from the ADSL data signal. The first one is sent to the PSTN network, the second to the broadband network (e.g. ATM switch or router).

Slide 6 - ADSL Spectrum Allocation

The ADSL transmission system offers an asymmetric capacity to the residential subscriber. In the downstream direction (towards the subscriber), it provides a capacity up to 10 Mb/s (or even more), while in the upstream direction it can go up to 1 Mb/s.

ADSL DMT modulation uses 256 QAM modulated carriers occupying a bandwidth of 1.104MHz. For the separation of the up- and downstream transmissions, two bandwidth allocation schemes are possible. The first one uses overlapping spectra for up- and downstream transmission and applies echo canceling (EC). The second option uses frequency division multiplexing (FDM) in which case no tones are shared by the up- and downstream bands. The latter is illustrated on this slide. The upstream band ranges from about 25 kHz to 138 kHz (carriers 6 to 32) while the downstream band extends up to 1.104 MHz (carrier 256). The lowest carriers are not modulated to avoid interference with POTS.

DMT transmission for ADSL has been standardized in ANSI/T1E1.4 [1] and is supported by ETSI/TM6.

Twisted pair characteristics

In this section we will analyze the main parameters of twisted pair telephone loops. Accurate channel models will enable simulations to be performed in order to understand transmission performances under different system assumptions.

Slide 8 - Loop length distribution

This slide shows the distribution of loop lengths for some representative countries. It can be seen that, in order to reach almost all European, or more than 90% of US potential subscribers (US loop plant distribution tends to be longer than in other countries), ADSL should allow broadband communication within a reach of 6km (18kft). The trends goes also clearly towards a reduction of the average loop length due to increasing Digital Loop Carrier deployment (DLC using CSA rules, see below), mainly in new growth and business areas. Only 15% of telephone lines (loaded coils) in the world will require an upgrade to allow xDSL communication.

Slide 9 – ADSL test loops

Both ANSI and ETSI have specified a set of worst-case test loops (including their RLCG parameters) with their associated noise and crosstalk distributions for the qualification of ADSL modems. But most of modern loops show better characteristics and follow Carrier Serving Area (CSA) guidelines, which specify among others, a maximum distance of 9kft for 26AWG and 12kft for 24AWG.

Slide 10 - Distributed model

Twisted-pair phone lines may be accurately modeled for frequencies up to a few tenth of MHz using classical transmission line techniques. A infinitesimally small portion of the line is characterized, as illustrated on this slide, by 4 frequency dependent primary parameters: R(f), L(f), C(f), G(f) representing resistance, inductance, capacitance and conductance per unit length respectively. The transfer function of the line can then be obtained by cascading these small portions and solving the associated differential equations.

This results in a frequency dependent propagation constant $\gamma(f,d)$ and characteristic impedance $Z_0(f)$. The real part of $\gamma(f,d)$ is very important for xDSL design and will determine the attenuation of the line (far from being lossless !). The frequency dependency of the imaginary part leads to dispersion of the signal energy in time and generates Inter Symbol Interference (ISI=overlap of successive symbols).

Slide 11 - Transfer function

The characteristic impedance $Z_0(f)$ is obtained by taking the ratio of the forward-going and backward-going waves (see figure on the right). This impedance has to be used to terminate the line in order to avoid reflection (echo) and to optimize energy transfer towards the receiver. Typical values for frequency higher than a few 100KHz (downstream band) are real and around 100 ohms (reference value used in ADSL), while for lower frequencies the line impedance increases and becomes complex.

The figure on the left illustrates the attenuation of the signal, as a function of frequency, after propagation over a 1 km, 26 AWG ([3]) twisted pair.

Slide 12 - Loop impairments (1/2)

The transmission channel capacity depends highly on the twisted pair characteristics and suffers from a number of impairments. This section enumerates the major loop impairments that an ADSL modem design has to taken into account. The way they are tackled will be the subject of the next section.

- ***Background noise:***
  The analysis of transmission performance over twisted-pair is based on the assumption that the background noise is gaussian. Analysis performed by Bellcore during the standardization process validated the above assumption and resulted in a worst case Aditive White Gaussian Noise (AWGN) level of –140dBm/Hz. This gives approximatively 30 nV/√Hz on a 100 ohms line.

- ***Crosstalk:***
  Between different wires in the same cable there exists capacitive and inductive coupling. The coupling increases, when the wires are closer to each other's. It causes unwanted crosstalk between the pairs. The crosstalk is typically worse between two pairs in the same binder than for

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[3] AWG: Average Wire Gauge. 24 AWG and 26 AWG are equivalent to 0.5 mm and 0.4mm cable respectively.

wires in adjacent binders ([4]). It can be reduced by the optimization of the twist of the individual pairs and by the topology of the cable.

Two types of crosstalk can be distinguished. Near-End crosstalk (NEXT) occurs at a receiver that is collocated with the disturbing source, while Far-End crosstalk (FEXT) occurs at a remote receiver. NEXT increases at a typical rate of 4.5 dB/octave ($f^{3/2}$) while FEXT increases by 6 dB/octave (f^2).

FEXT is attenuated by propagation through the loop while NEXT is not. Therefore, NEXT dominates FEXT by far for echo canceled systems. Using a different frequency band for upstream and downstream (FDM) reduces the (self-)NEXT impact.

Slide 13 - Loop impairments (2/2)

- ***Bridged Tap :***
  Some subscriber loops have open-circuited wire pairs tapped onto the main wire pair, called bridged taps. The existence of bridged taps in the loop plant differs from country to country and depends upon the cabling rules used in the past. Their presence causes reflections (echo) and affects the frequency response of the cable, leading to pulse distortion and inter-symbol interference combined with frequency dependent attenuation. A loop can also be built up of wires with different diameters (referred to as gauge transitions), leading to reflections and distortion as well.
- ***Impulsive Noise:***
  Copper transmission suffers from impulsive noise that is characterized by high amplitude bursts of noise, with duration of a few microseconds to hundreds of microseconds. It can be caused by a variety of sources such as central office switching transients, ringing, ring trip, dial pulses and lightning.
- ***RFI:***
  The telephone network consists of copper pairs that are usually twisted. The twist improves the egress and ingress properties of the wire: it reduces the electromagnetic radiation as well as the pick-up of unwanted signals if submerged in an electromagnetic field. As a result of the cable unbalance, RF (Radio Frequency) signals can be picked-up during propagation over the wire and interfere with the transmitted data at the

[4] A 10 dB crosstalk reduction is often assumed in capacity simulations to reflect the adjacent binder effect.

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