Broadband Communications IC’s: Enabling the Connected World of the 21st Century

Henry Samueli, Ph.D.
Co-Chairman and Chief Technical Officer
Broadcom Corporation

Keynote Address
Hot Chips Conference, Stanford University
August 1999
The consumer communications industry will see revolutionary changes over the next decade
- Bandwidth to the home will increase over a thousand-fold from tens of kbits/sec to tens of Mbits/sec

Universal broadband connectivity will dramatically change our lives
- Interactive television for sporting events, movies, video games, video telephony and shopping will revolutionize entertainment and E-commerce
- Virtual LAN extensions to the home will finally make telecommuting a viable and productive way to work
Future Vision of the Connected Home

- Satellite and Wireless Service
- Cable Service Provider
- Local Telephone Provider
- Terrestrial Digital Broadcast

Broadband anytime, anywhere connects every type of device

- Kid’s Bedroom
  - Web Browser
  - Broadband Access

- Master Bedroom
  - IP Telephone
  - IP Video Phone
  - IP MPEG Video

- Study
  - Web Browser
  - Broadband Access

- Living Room
  - Digital Set-top Box
  - Integrated Web Browser
  - IP Video Phone

- Kitchen
  - IP Telephone
  - IP Video Phone

- Garbage
  - Standard Telephone

Broadband Gateway
Future Interactive TV
The Last-Mile Challenge

- The so-called “last-mile” connection to the home was never intended for broadband transmission
  - Telephone lines were designed for 3 kHz narrowband analog voice
    - Broadband signals are subjected to severe amplitude and phase distortion, crosstalk and ingress
  - Cable lines were originally designed for one-way broadcast analog video
    - Older cable systems need to be upgraded to handle two-way traffic

- Over 50% of cable plant is now two-way capable. Over 90% will be two-way capable by 2001
Advanced modulation and coding incorporating sophisticated adaptive signal processing techniques are required to combat the last-mile transmission challenges.

- Deep submicron CMOS has enabled multi-million transistor chips with multi-million operation per second DSP capability to be realized on a single device.

- Integration of the high-speed, high-precision analog front-ends on the same digital CMOS substrate has resulted in very cost effective complete “system on a chip” solutions.
Applications for Broadband Communications IC’s

- Direct Broadcast Satellite
- Digital Subscriber Lines (xDSL)
- Digital Cable-TV/Cable Modems
- Home Networking
- High-Speed LAN’s
Applications for Broadband Communications IC’s

- Direct Broadcast Satellite
- Digital Subscriber Lines (xDSL)
- Digital Cable-TV/Cable Modems
- Home Networking
- High-Speed LAN’s
QPSK Satellite Receiver IC

- DSS/DVB/Primestar compatible
- 2-90 Mb/s variable-rate QPSK receiver
- 512-MHz PLL and mixer
- Dual 8-bit 128-MHz ADC’s
- All-digital clock and carrier recovery loops
- 64-state Viterbi decoder
- T=8 Reed-Solomon decoder
- 1.2 M transistors, 22 mm²
- 0.35um 3.3V single-poly quad-metal CMOS

Ref: A. Kwentus, et. al., ISSCC’99, Paper 19.1
Applications for Broadband Communications IC’s

- Direct Broadcast Satellite
- Digital Subscriber Lines (xDSL)
- Digital Cable-TV/Cable Modems
- Home Networking
- High-Speed LAN’s
Twisted pairs have poor frequency response and are highly susceptible to crosstalk from other pairs in the same bundle.

Broadband transmission is VERY challenging.
• Reduced twisted-pair loop lengths enable broadband digital transmission capable of delivering voice, video, and data
• 0-52 Mb/s variable-rate transmitter and receiver
• Supports 4,16,32,64,128, 256-QAM modulation
• 10-bit, 60 MHz A/D and D/A converters
• 96-tap decision-feedback equalizer
• All-digital clock and carrier recovery loops
• T=8 Reed-Solomon FEC
• 1.0 M transistors, 33 mm$^2$
• 0.35um 3.3V single-poly quad-metal CMOS

Ref: R. Joshi, et. al., ISSCC’99, Paper 14.7
Broadband DSL Challenges

• Loop plant noise and loop length uncertainty makes universal DSL coverage difficult
  – FTTN helps solve this problem with fiber backbones and shorter twisted-pair loops to the home

• Uncontrolled in-house wiring and noise makes distribution of broadband data difficult
  – Poor quality cabling and random “rat’s nest” wiring topology create huge variations in loop frequency response
  – Significant noise sources: light dimmers, refrigerator motors, fans, microwave ovens, etc.
Applications for Broadband Communications IC’s

• Direct Broadcast Satellite
• Digital Subscriber Lines (xDSL)

• Digital Cable-TV
• Home Networking
• High-Speed LAN’s
Hybrid Fiber Coax (HFC) Technologies

• Over 65% of the 100 million U.S. television households currently subscribe to cable-TV
  – Modern cable plants consist of fiber-based backbones combined with coax-based connections to the home
  – Nearly 1 GHz of bandwidth is available on these networks

• Many new services will be deployed over modern HFC networks:
  – Digital interactive TV
  – Cable modem Internet access
  – Voice and video telephony services
Hybrid Fiber Coax Network Architecture Overview

- **Master Headend**
  - Fiber Ring
  - ~100,000 Homes/Hub

- **HUB**
  - ~20,000 Homes/Hub
  - ~500 Homes/Node

- **AMP**
  - Coax
  - Fiber

- **Frequency Plan (MHz)**
  - Downstream Video Carriers
    - Older All-Coax Plants: 5, 54
    - Newer HFC Plants: 350, 550/750
    - Digital Video/Data: 860

- **Upstream**
  - Cable Modems & Telephony: 42

- **Video Servers**
  - Satellite Receivers
  - Video Modulators
  - Telephone Switches
  - Internet Routers

- **Video Servers**
  - Upstream Video Servers
  - Satellite Receivers
  - Video Modulators
  - Telephone Switches
  - Internet Routers
The Conversion from Analog to Digital Cable-TV

- Analog cable-TV systems typically allocate the 54-550 MHz band for 6-MHz NTSC channels
  - Can support approximately 80 analog channels

- 64-QAM modulation can support a payload of 27 Mb/s in a 6 MHz channel (256-QAM can support 38 Mb/s)
  - Using MPEG-2 compression, high quality video can be achieved with a payload of 3-4 Mb/s

- The conversion to digital will expand the channel capacity by an order of magnitude to many hundreds of channels
Digital Cable Set-Top Box Block Diagram

- Coax Cable
- 5-42 MHz
  - Amp
  - Diplex Filter
  - 70-130 MHz RF Tuner
  - 54-860 MHz RF Tuner
- QPSK/16-QAM Upstream Transmitter
- QPSK Control Channel Receiver
- 64/256-QAM Downstream Receiver
- Single-Chip Xcvr
- Conditional Access Module
- MPEG Video/Audio Decoders and DAC's
- Graphics Engine/NTSC Encoder
- Microprocessor
- User Interfaces
  - USB
  - 1394
  - Video
  - Audio
  - Remote Control
- DRAM ROM Flash Memory
- QPSK
- Control
- Channel Receiver
- 54-860 MHz
- RF Tuner
- 70-130 MHz
- RF Tuner
- 5-42 MHz
- 64/256-QAM
- Downstream Receiver
- 54-860 MHz
- RF Tuner
- 70-130 MHz
- RF Tuner
- QPSK/16-QAM
- Upstream Transmitter
- Coax Cable
QAM Cable Receiver Block Diagram

A/D

Variable Rate Demod

Nyquist

FFE and Phase Rotation

Nyquist

DFE

Forward Error Correction (FEC)

De-Interleaver RAM

MPEG Transport Output

PLL Clock Generation

AGC Loop

Carrier Recovery Loop

Timing Recovery Loop

DDFS

I

Q

10

Amp

44 MHz IF Input

IF

44 MHz IF Input

10
Current Set-Top Box Transceiver

- 43 Mb/s 64/256-QAM video channel receiver
  - 30 MS/s 10-bit ADC
- 2 Mb/s QPSK control channel receiver
  - 20 MS/s 6-bit ADC
  - 100-200 MHz PLL with 10 kHz tuning steps
- 20 Mb/s QPSK/16-QAM upstream transmitter
  - 200 MHz 10-bit DAC
- 2.3 M transistors, 64 mm$^2$
- 0.35um 3.3V single-poly quad-metal CMOS

Ref: L. D’Luna, et. al., ISSCC’99, Paper 19.2
Applications for Broadband Communications IC’s

- Direct Broadcast Satellite
- Digital Subscriber Lines (xDSL)
  - **Cable Modems**
- Home Networking
- High-Speed LAN’s
Telco modems use a point-to-point network architecture

- There is a dedicated link between each subscriber modem and a modem port in the central office
  - A modem port remains tied up even if no data is being sent

Cable modems use a point-to-multipoint shared network architecture

- The downstream channel is shared using time division multiplexing (TDM)
- The upstream channel is shared using burst-mode frequency/time division multiple access (FDMA/TDMA)
FDMA/TDMA Protocol

• FDMA/TDMA protocol is very efficient for accommodating many users with highly varying bandwidth demands
  – Users send upstream data in bursts as needed
  – Even though a subscriber is active, network resources are not being used unless data is being transmitted
  – Instant Internet connectivity is achieved. Users can leave their cable modems logged on indefinitely
  – Graceful bandwidth degradation occurs as the load is increased, and additional RF carriers can be provisioned to optimally regulate the load
Single-Chip Cable Modem IC

- 43 Mb/s 64/256-QAM video channel receiver
  - 30 MS/s 10-bit ADC
- 20 Mb/s QPSK/16-QAM upstream transmitter
  - 200 MHz 10-bit DAC
- 5-65 MHz direct RF output
- MCNS/DOCSIS Compliant Media Access Control
  - Supports Voice over IP
- 3.5 M transistors, 67 mm²
- 0.35um 3.3V single-poly quad-metal CMOS
Next Generation Web-Enabled Cable Set-Top Box Integration
Future Convergence of Data, Video, and Voice Over Cable

- Local / Long Distance Voice Telephony
- Video Telephony
- High Speed Internet Access
- Web Enhanced Interactive TV
- Interactive Gaming
- Advanced 2D/3D Graphics
- High Definition TV
- 5.1 Channel Digital Audio
## Applications for Broadband Communications IC’s

- Direct Broadcast Satellite
- Digital Subscriber Lines (xDSL)
- Digital Cable-TV/Cable Modems
- **Home Networking**
- High-Speed LAN’s
Home Networking Market Opportunity

RJ-45

2 million miles installed today
100 million connected PCs

RJ-11

20 million miles existing today
50 million unconnected PCs

Source: IDC, Jupiter Comm. And Partner Estimates

Millions of Miles
10 Mbps Home Networking System Architecture

Existing premises POTS

InsideLine™

MAC

Ethernet CSMA/CD with QoS

PHY

QAM modulation

POTS xDSL iLine10 HPNA 1.0

Upstream Downstream 4MHz 10MHz
Applications for Broadband Communications IC’s

• Direct Broadcast Satellite
• Digital Subscriber Lines (xDSL)
• Digital Cable-TV/Cable Modems
• Home Networking

• High-Speed LAN’s
• Ethernet is the predominant LAN technology in use today
  – Over 85% of all networks are Ethernet. Current worldwide installed base is approximately 200 million nodes
  – First generation 10Base-T (10 Mb/s) networks do not provide sufficient bandwidth to handle broadband multimedia traffic

• 100Base-T (100 Mb/s) is rapidly replacing 10Base-T as the mainstream LAN transmission technology
Typical Ethernet LAN Configuration
100Base-TX Fast Ethernet Transceiver Block Diagram

100Base-TX Transceiver IC

- TX DAC
- Scrambler
- 4B5B Encoder
- Baseline Wander Correction
- ADC
- Adaptive Equalizer
- Descrambler/4B5B Decoder
- Clock Recovery & Clock Generator
- Bias Generator
- MII Registers
- MII Management Control

Media Access Control (MAC)

System Bus

2-Pair Cat-5 UTP

Media Independent Interface (MII)
Octal 10/100Base-T Transceiver

- Eight 10Base-T/100Base-T Ethernet transceivers
- All-digital DSP-based architecture
  - Adaptive decision-feedback equalization
- Eight 125-MHz 6-bit ADCs
- Eight 125-MHz DACs and line drivers
- <10^-12 BER over 160 metersCat-5 UTP cable
- <4 mm^2 per transceiver slice
- 0.35um 3.3V single-poly quad-metal CMOS
Gigabit Ethernet

• Gigabit Ethernet over fiber optic cables is currently being deployed in LAN backbones

• Gigabit Ethernet over 100 meters of Category-5 unshielded twisted-pair cable (1000Base-T) has been adopted as a new IEEE standard (802.3ab)
  – Over 80% of corporate networks are wired with Cat-5 cable
  – Initial applications for 1000Base-T are backbone switch and server connections
  – 1000Base-T will eventually migrate to the desktop as well as multimedia traffic becomes more pervasive
1000Base-T Gigabit Ethernet Overview

- Bi-directional 250 Mb/s transmission per pair requires echo cancellation
- Coupling between pairs in UTP cable requires crosstalk cancellers
Transceiver IC Design Challenges

• Mixed-Mode System Design: RF / IF / Baseband Analog / DSP / Random Logic / Memory
  – A few years ago such systems occupied multiple circuit boards and cost thousands of dollars -- now they consist of a few chips and cost tens of dollars!

• Design teams must be very tightly coupled and engineers need to be “vertically integrated”
  – Knowledge of systems, DSP, and IC design is required
  – Systems engineers/architects MUST understand IC design implications of their block diagrams
    » The analog/digital partitioning is critically important
Mixed-Mode CMOS Design Issues

• Mixed-mode transceivers are typically dominated by high-speed digital circuits
  – Analog circuits must tolerate large substrate noise

• For cost reasons, analog design in an all-digital CMOS process (single poly) is preferred
  – Robust analog circuits are required so that parametric yield loss of analog has minimal effect on overall chip yield

• Analog designers are heavily penalized in mixed-mode design
  – Digital designers are largely unaffected!
Mixed-Mode Technology Scaling Issues

• Arguments for scaling digital circuits are obvious and compelling
  – Density and power improve by approximately a factor-of-two in each new process generation (0.5um, 5V --> 0.35um, 3.3V --> 0.25um, 2.5V --> 0.18um, 1.8V, etc.)

• Unfortunately analog circuits don’t scale well because of reduced supply voltages
  – Ref: K. Bult, ISSCC’99, Paper 4.6

• For cost reasons mixed-mode chips generally stay one generation behind the latest process technology
### 10-Bit DAC Scaling Example

<table>
<thead>
<tr>
<th>Technology</th>
<th>Voltage</th>
<th>Normalized Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50µm, 5V</td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>0.35µm, 3.3V</td>
<td></td>
<td>0.63</td>
</tr>
<tr>
<td>0.25µm, 2.5V</td>
<td></td>
<td>0.44</td>
</tr>
</tbody>
</table>
10-Bit ADC Scaling Example

<table>
<thead>
<tr>
<th>Technology</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50µm, 5V</td>
<td>0.35µm, 3.3V</td>
</tr>
</tbody>
</table>

Normalized Areas

1.0 1.0 1.0
Design Complexity Issues

• IC process technology is improving faster than IC design technology
  – A 10M transistor ASIC is relatively easy to fabricate but is exceedingly difficult to design
  – We have reached the point where back-end physical design and verification takes far longer than front-end system, architecture, and logic design!

• In the next few years 100M transistor ASIC’s will be technically feasible to fabricate
  – However, fundamental advances in design methodology and CAD tools will be required to manage the overwhelming design and verification complexity
Conclusions

• The ubiquitous availability of broadband interactive services will revolutionize society

• The availability of low-cost highly-integrated broadband communications IC’s is the key enabler to the widespread deployment of these services

• The next decade will be very exciting and challenging for IC designers

• The opportunities for creativity are endless!