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

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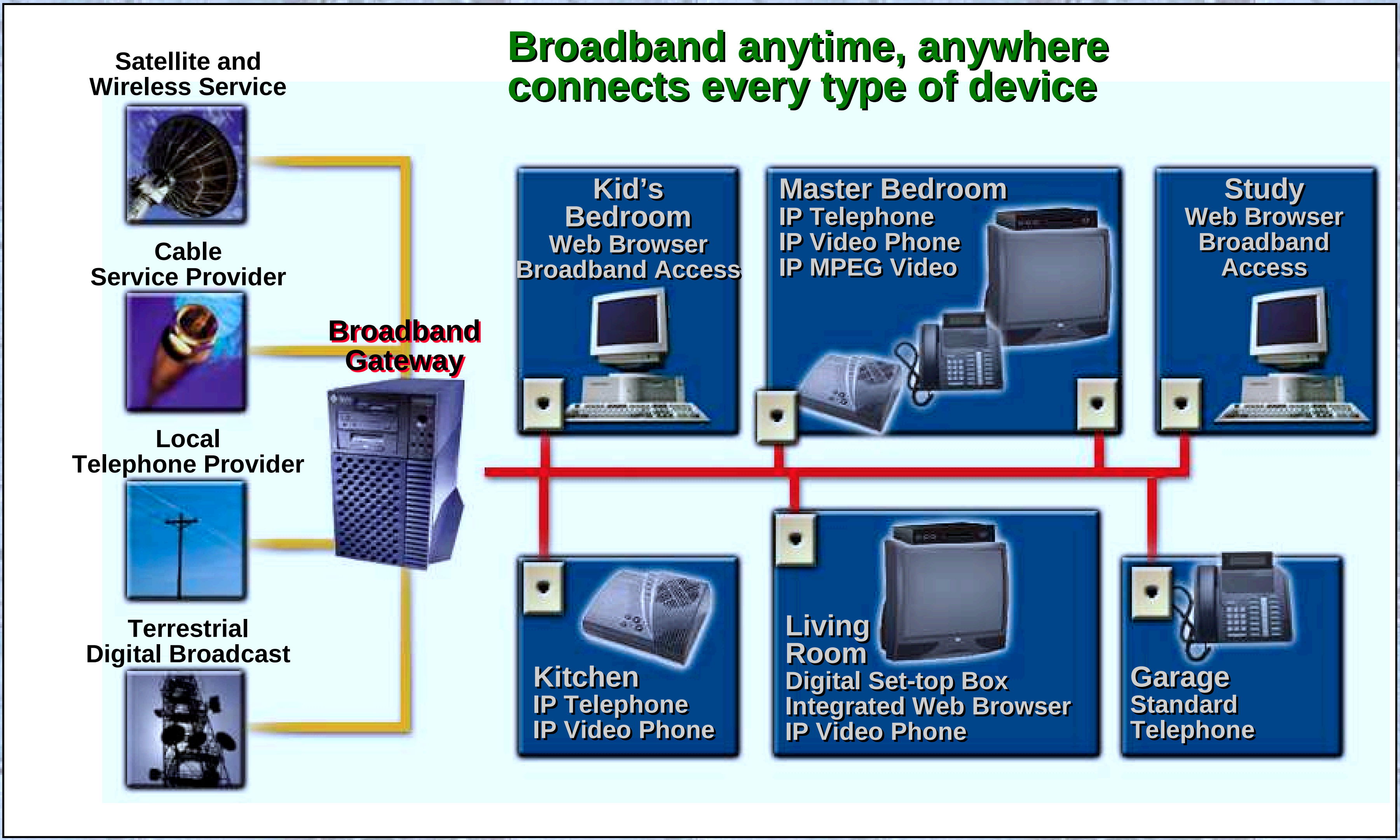
The Broadband Revolution

- **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



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**

The Last-Mile Solution

- **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

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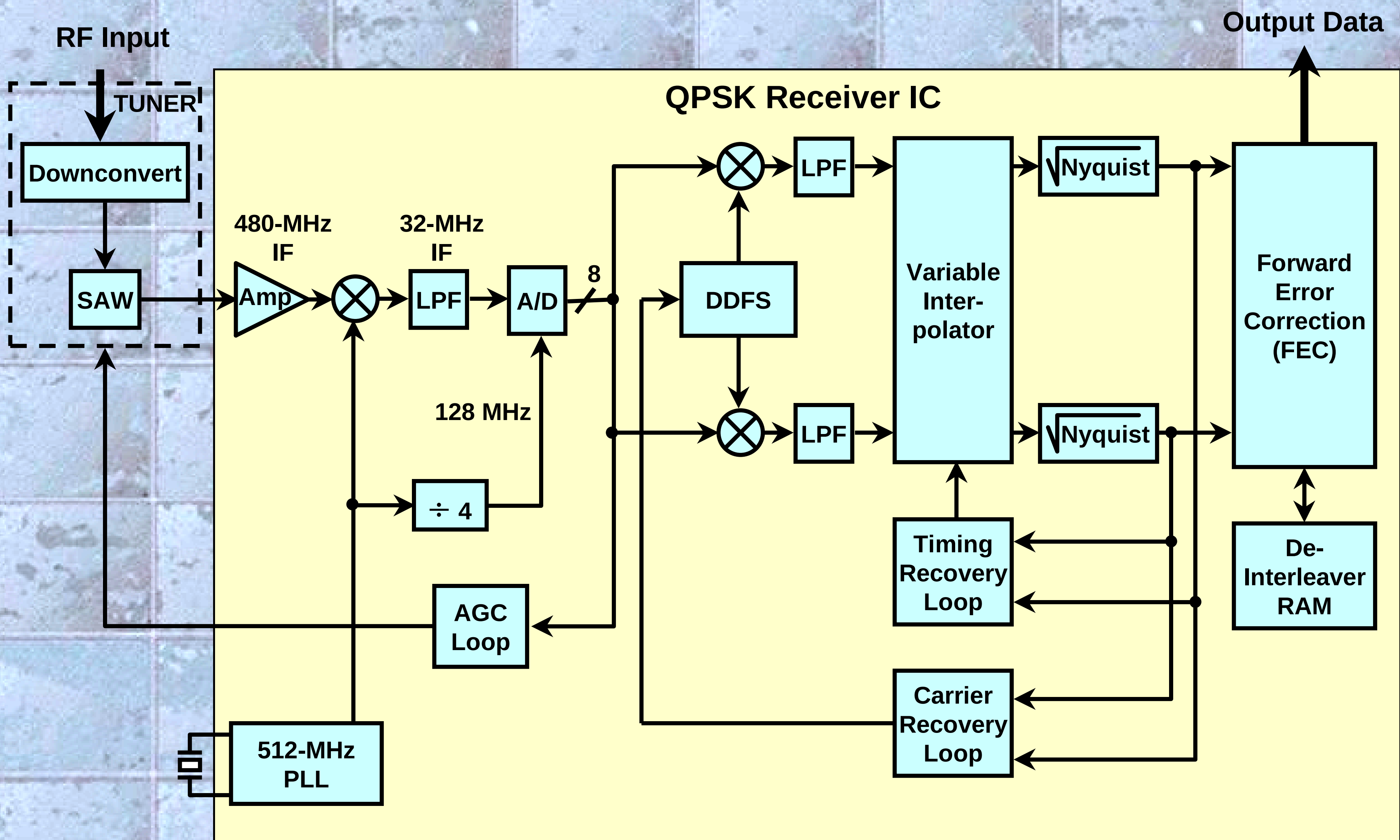
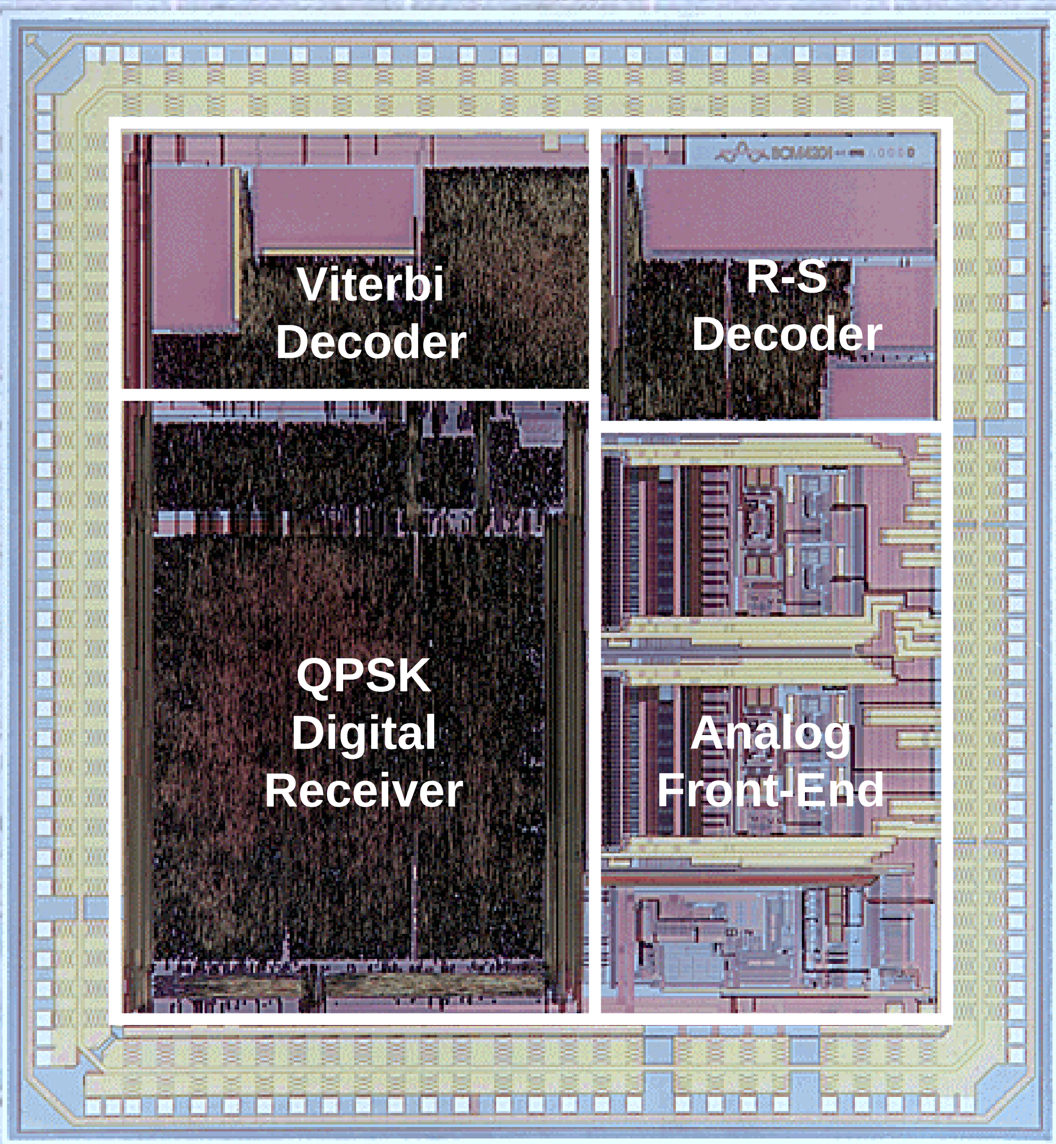
QPSK Receiver Architecture



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 mm^2
- 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
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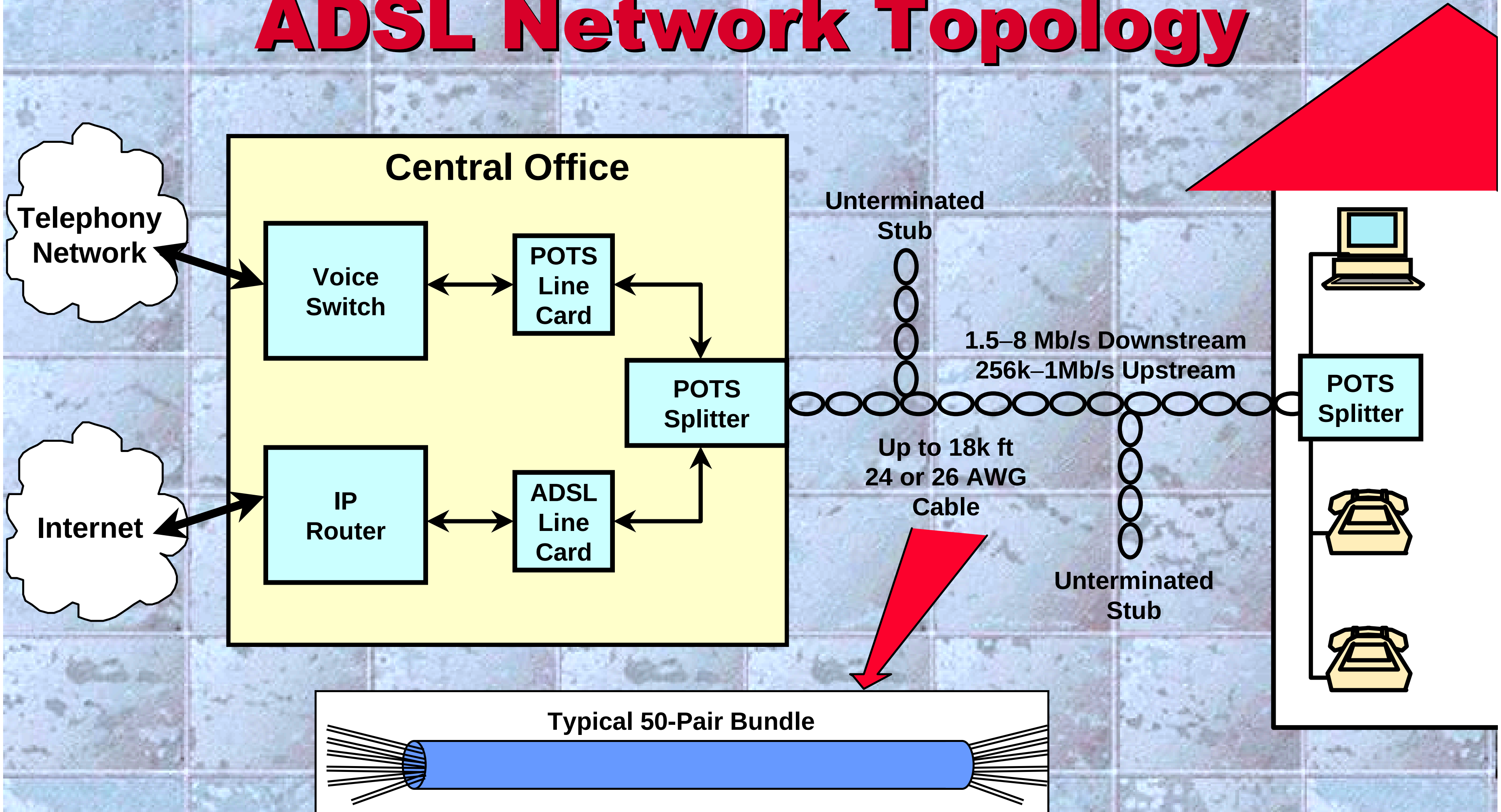
ADSL Network Topology

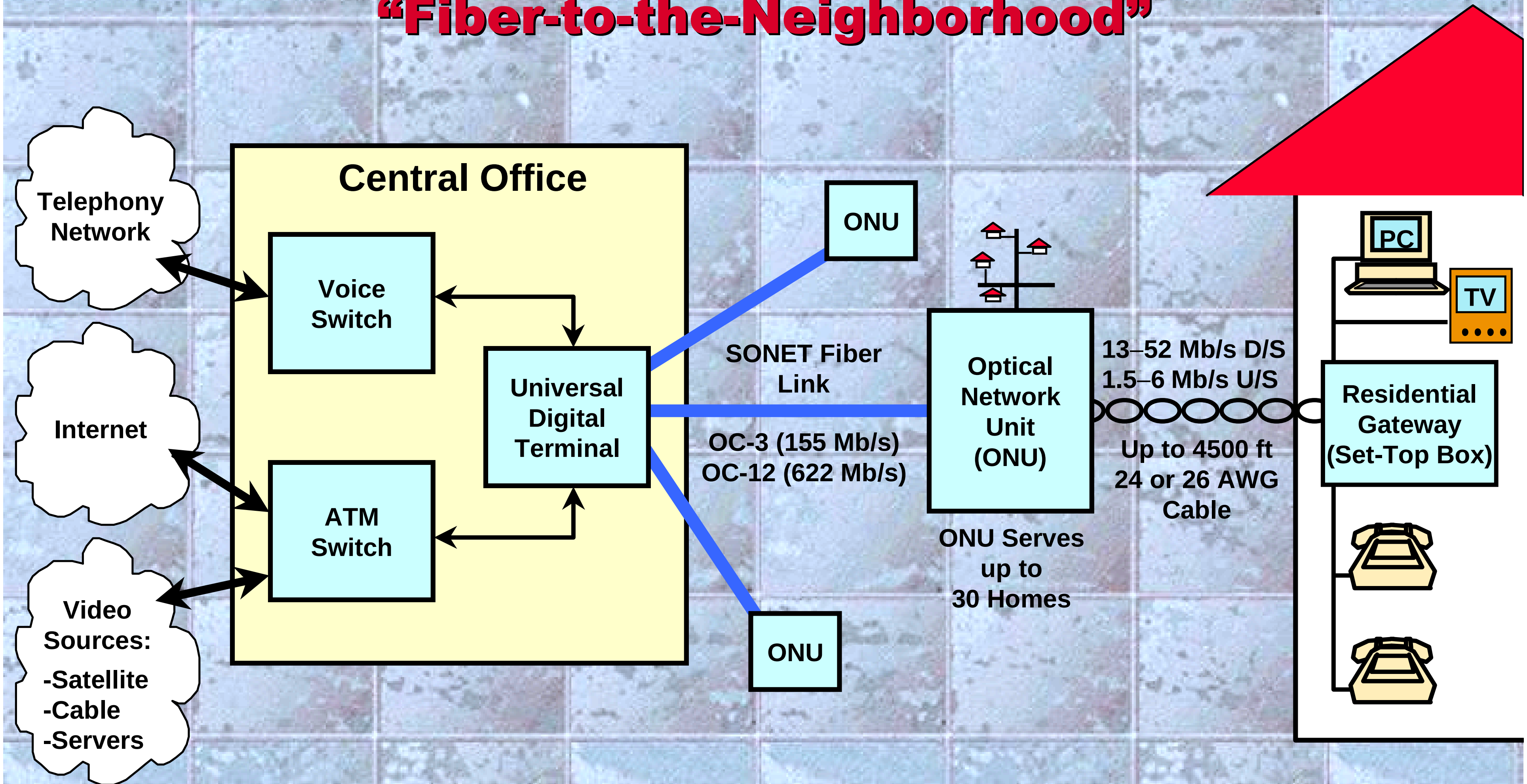


- Twisted pairs have poor frequency response and are highly susceptible to crosstalk from other pairs in the same bundle

➔ **Broadband transmission is VERY challenging**

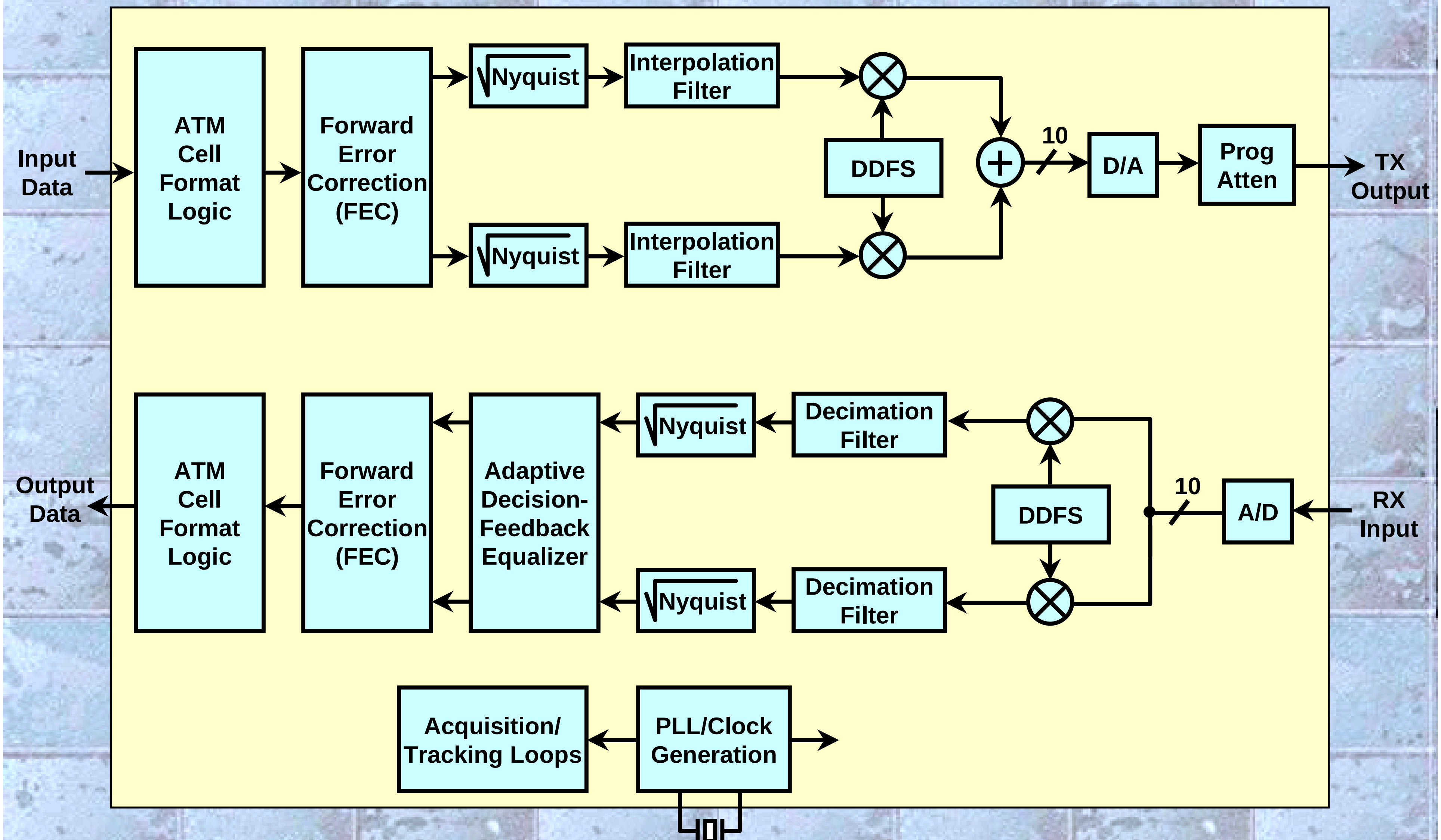
VDSL Network Topology

"Fiber-to-the-Neighborhood"

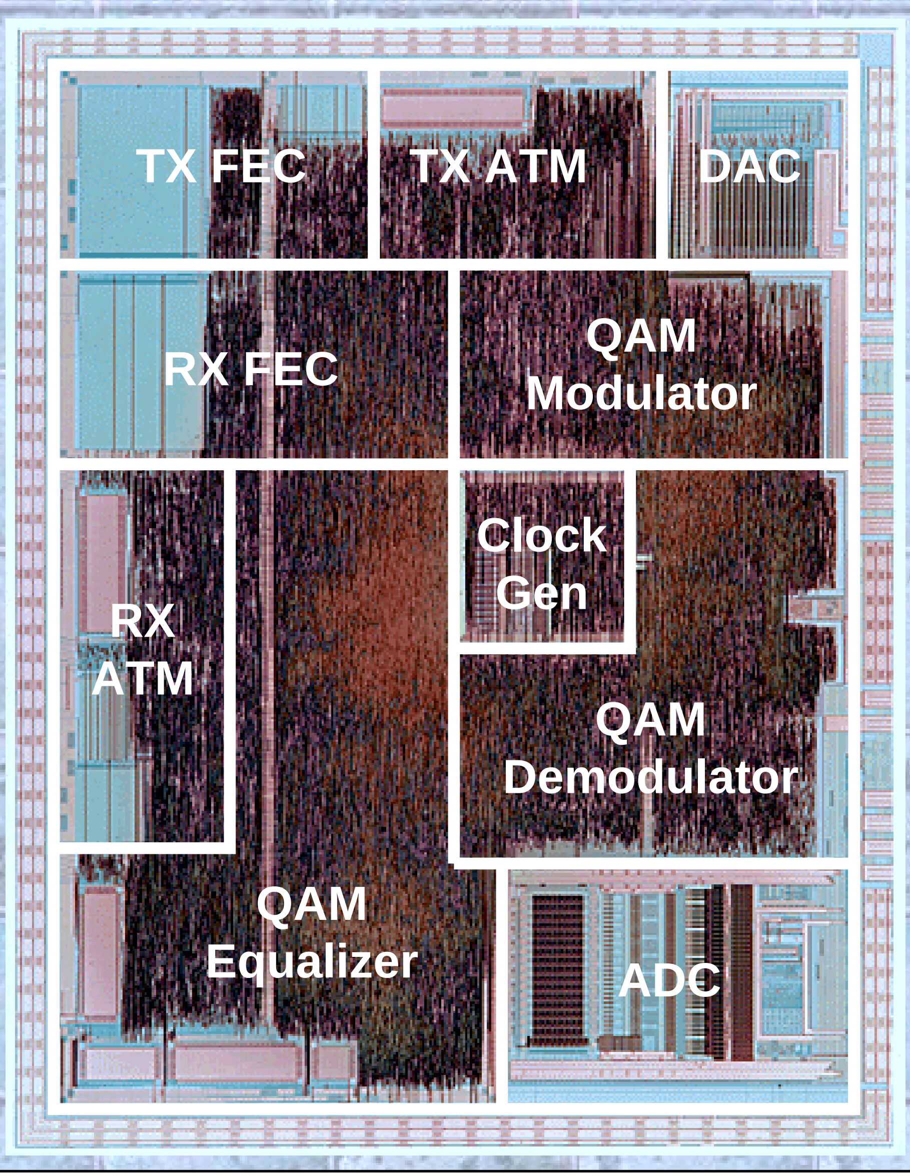


- Reduced twisted-pair loop lengths enable broadband digital transmission capable of delivering voice, video, and data

QAM DSL Transceiver Block Diagram



QAM DSL Transceiver IC



- 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.

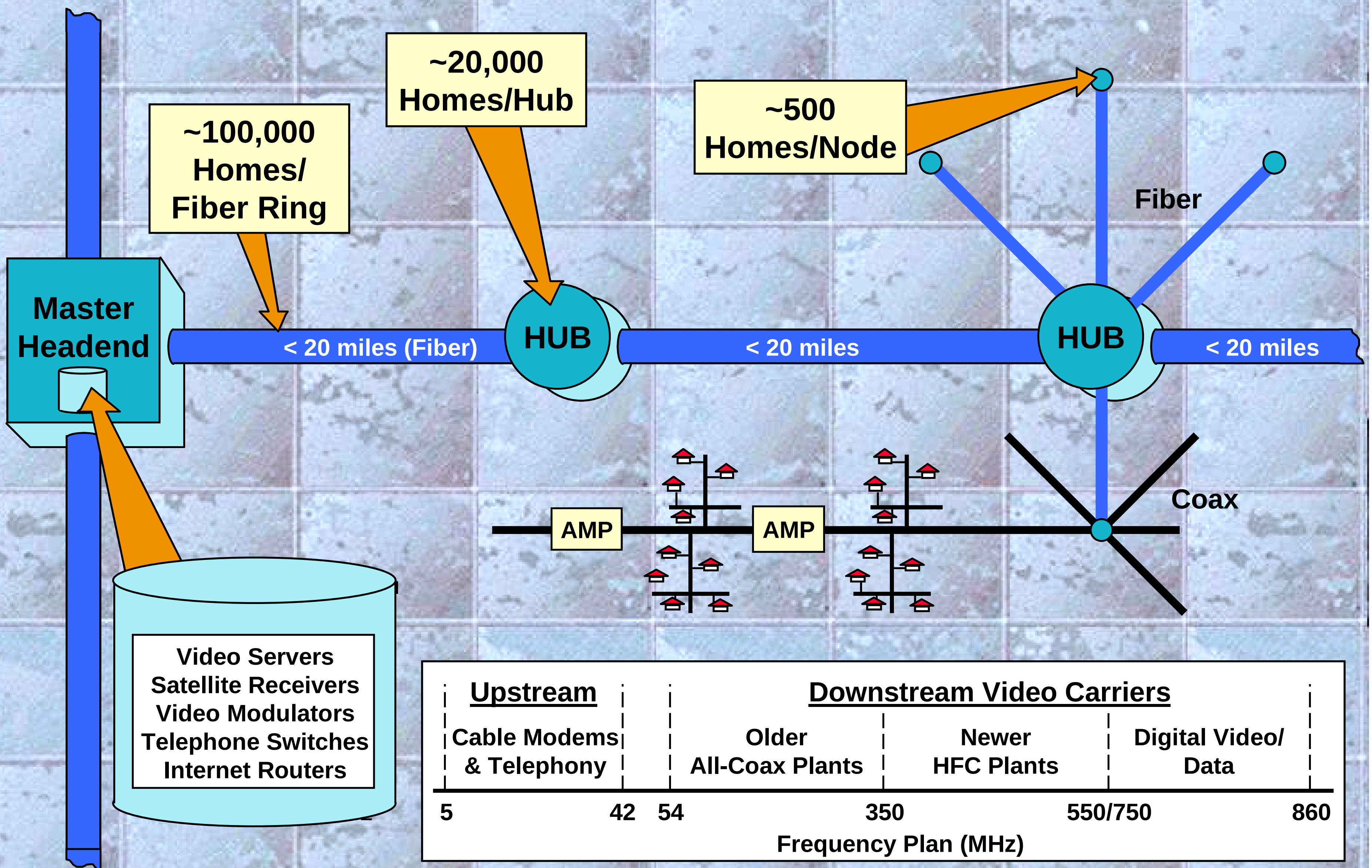
Applications for Broadband Communications IC's

- 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

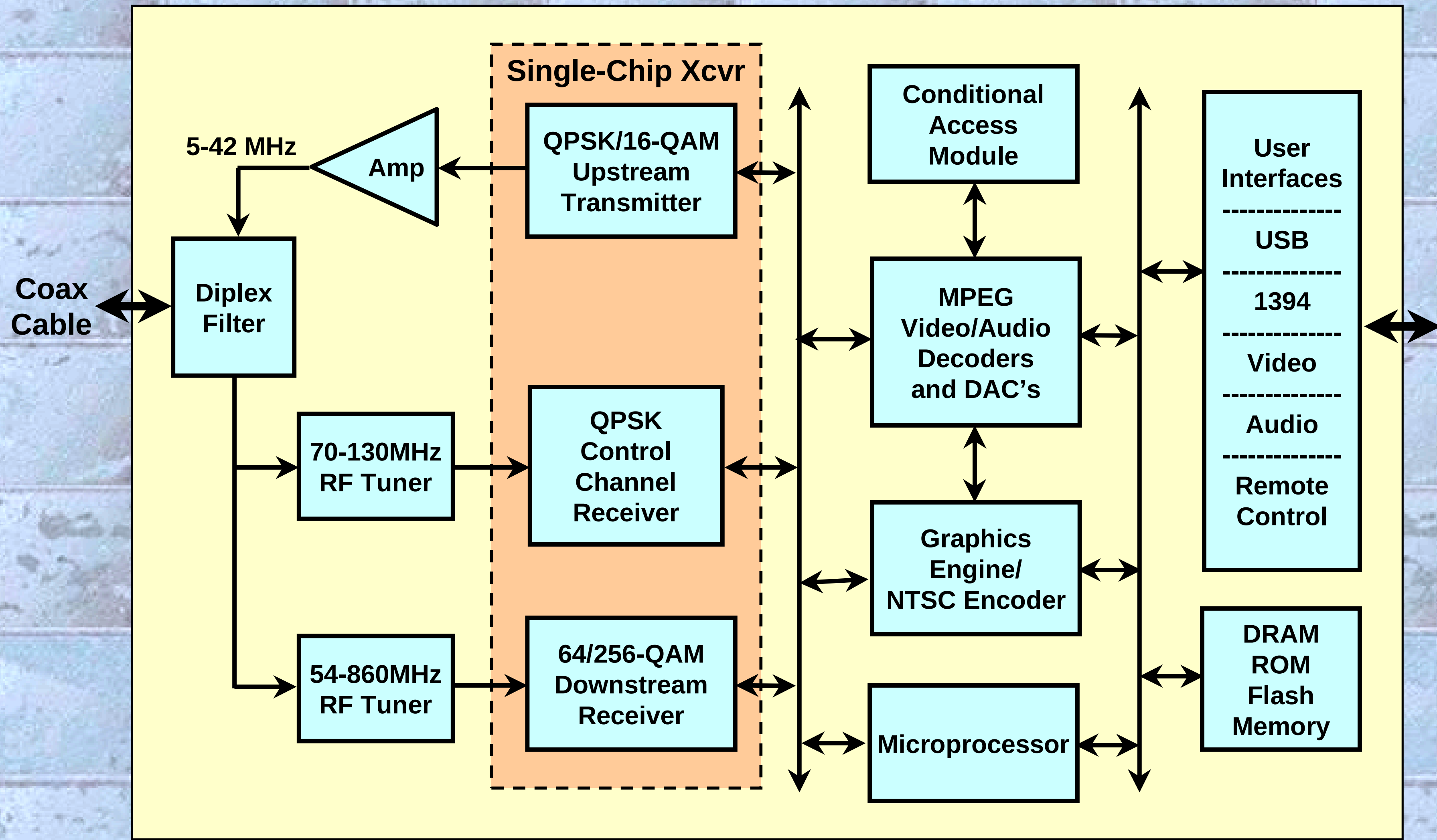
Hybrid Fiber Coax Network Architecture Overview



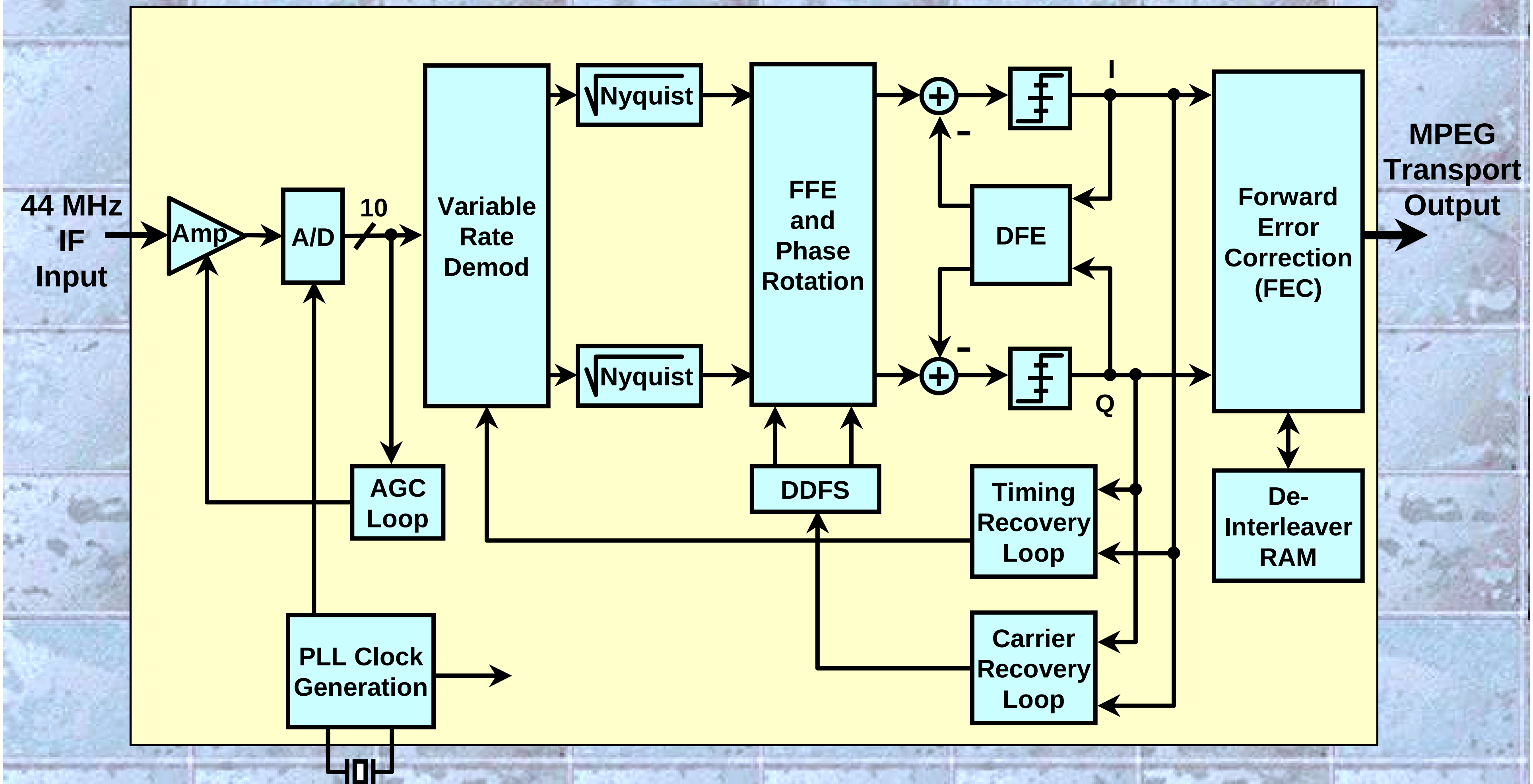
The Conversion from Analog to Digital Cable-TV

- **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**

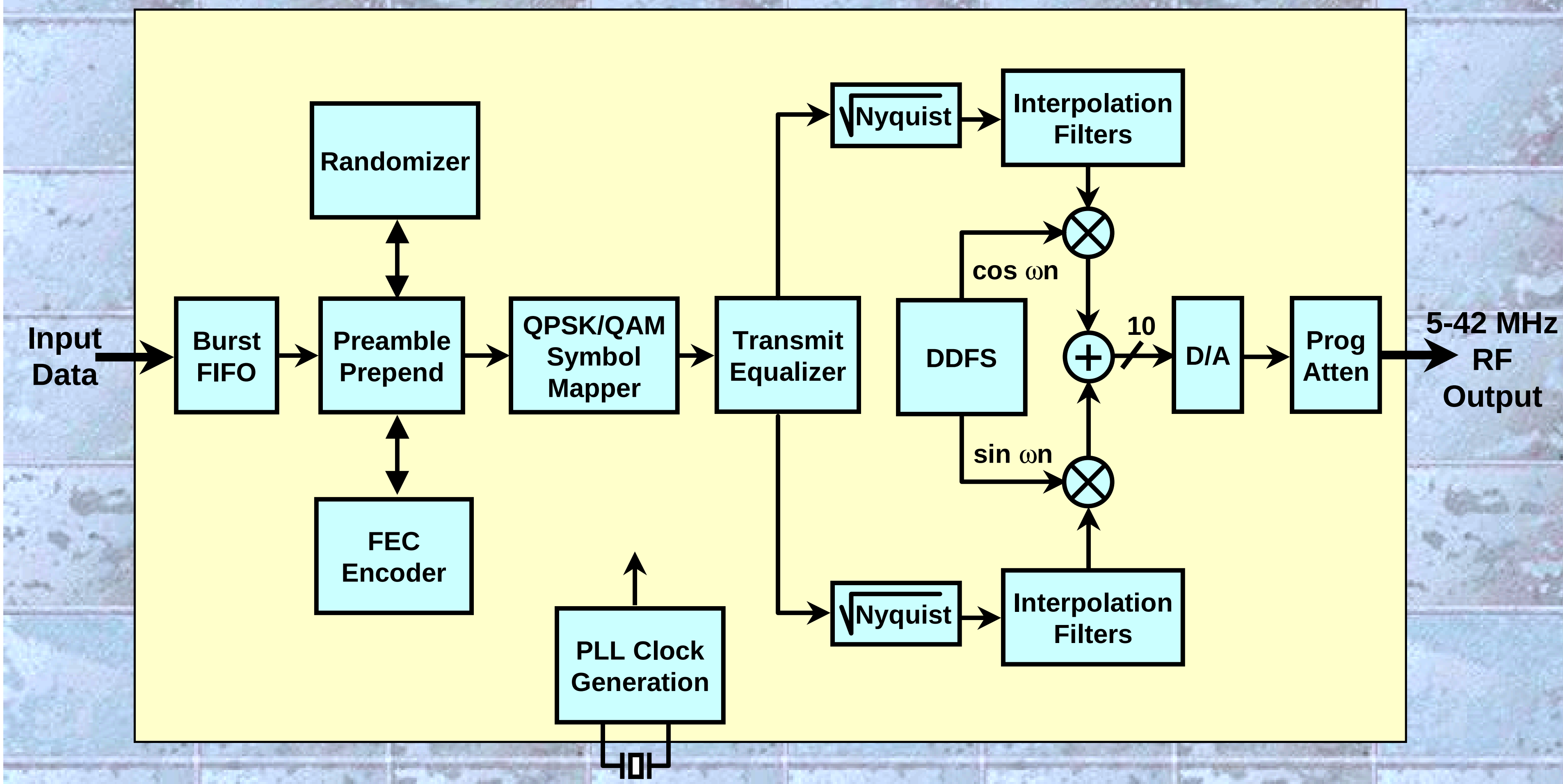
Digital Cable Set-Top Box Block Diagram



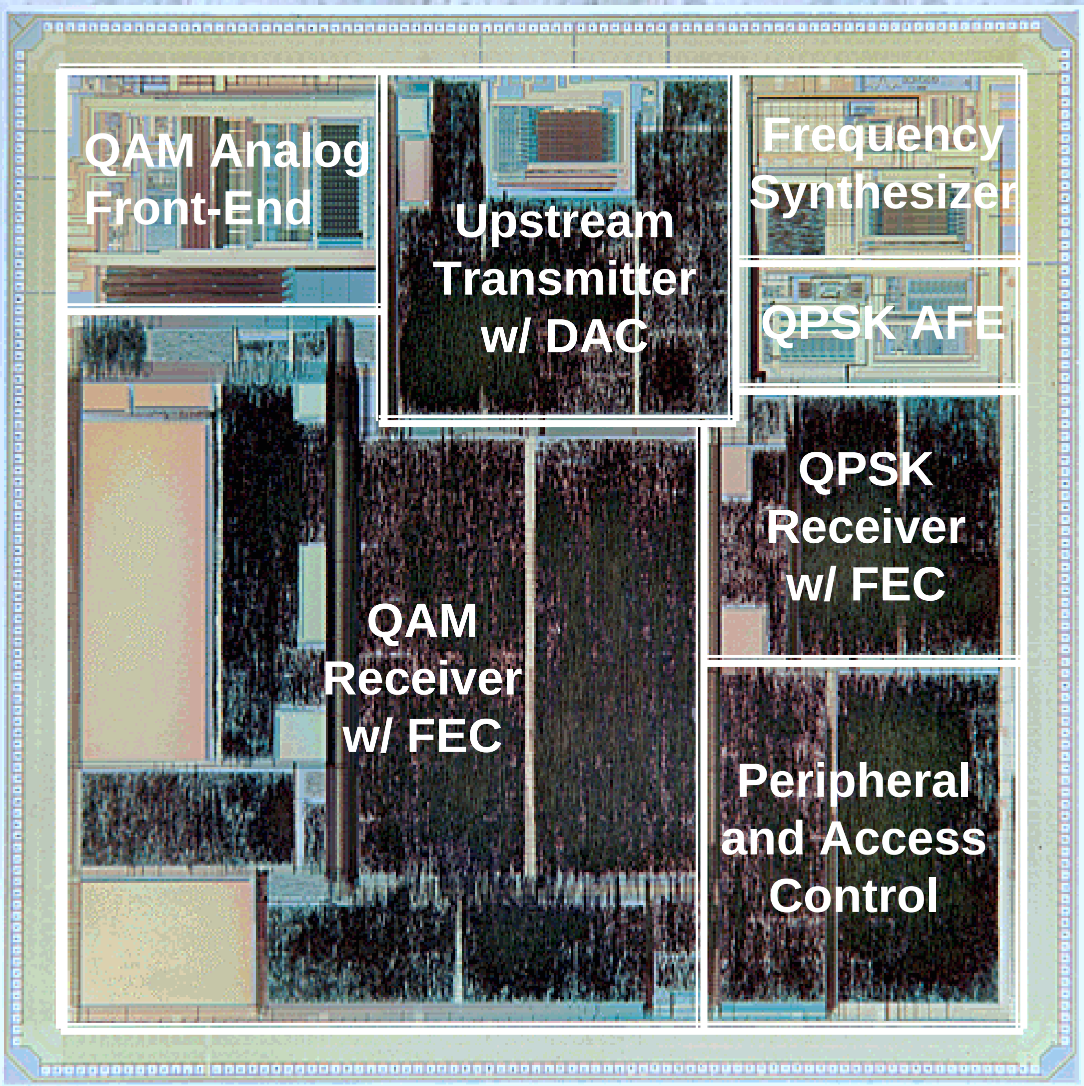
QAM Cable Receiver Block Diagram



QAM Cable Transmitter Block Diagram



Current Set-Top Box Transceiver



Ref: L. D'Luna, et. al., ISSCC'99, Paper 19.2

- 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

Applications for Broadband Communications IC's

- Direct Broadcast Satellite
- Digital Subscriber Lines (xDSL)
- **Cable Modems**
- Home Networking
- High-Speed LAN's

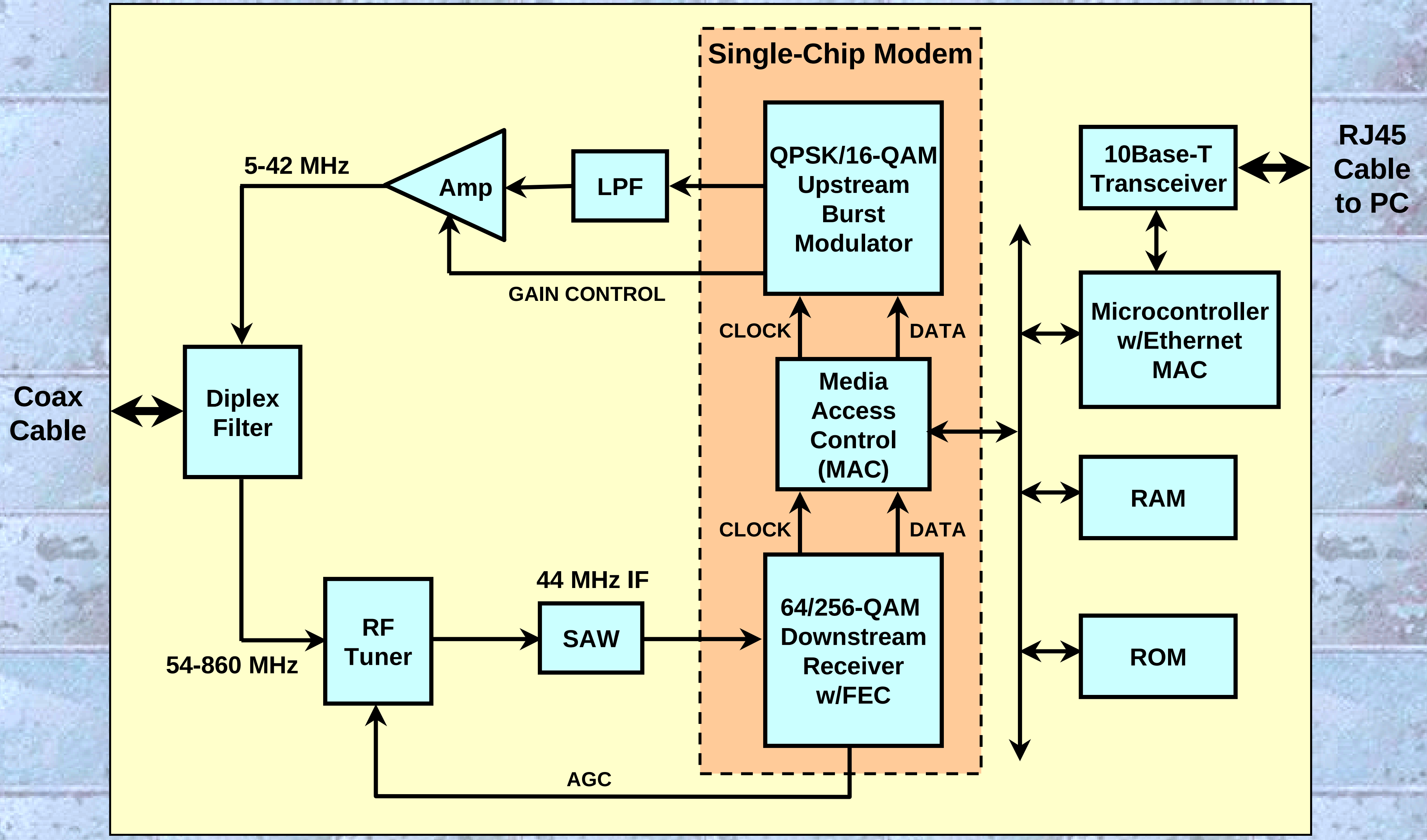
Point-to-Point vs. Point-to-Multipoint Architecture

- **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)

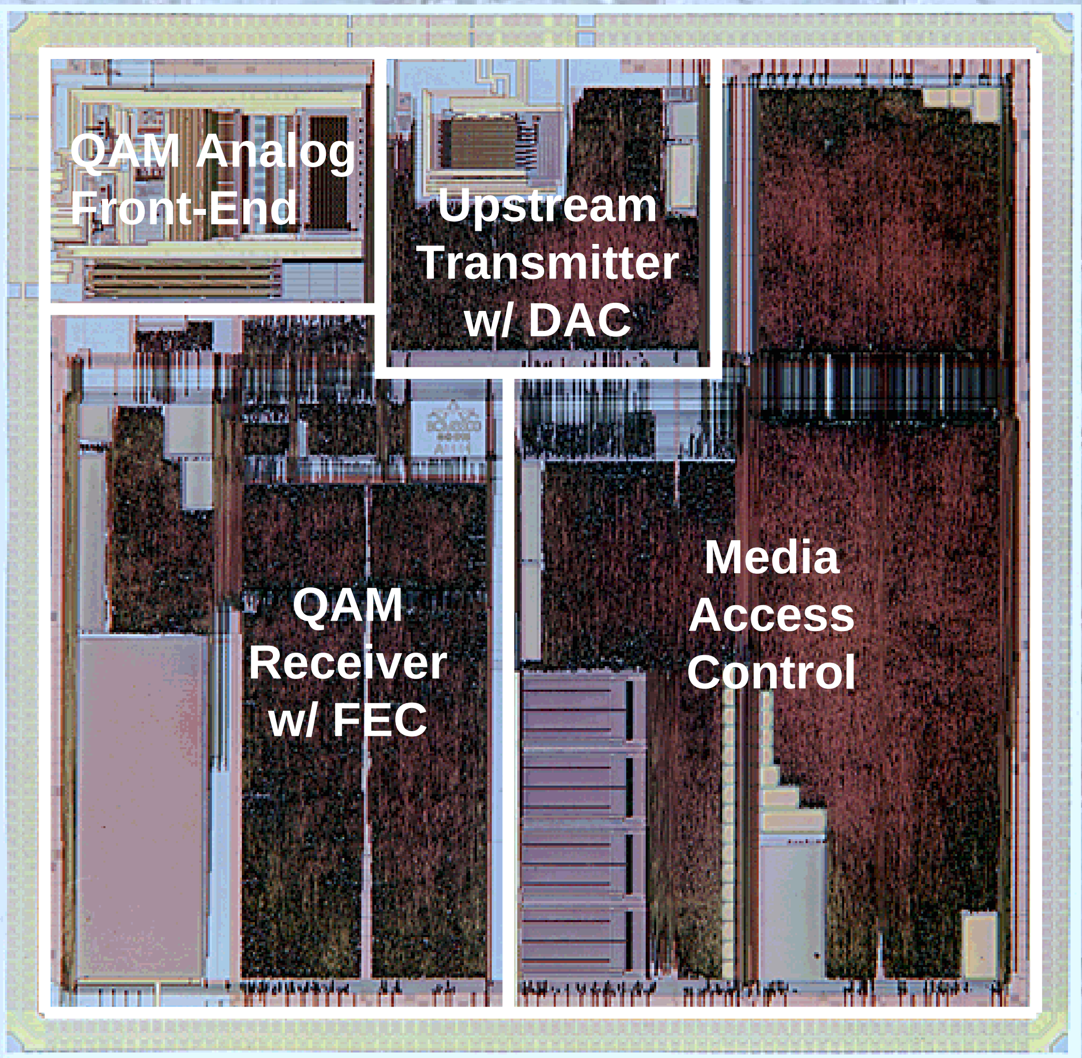
FDMA/TDMA Protocol

- **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

Cable Modem Block Diagram

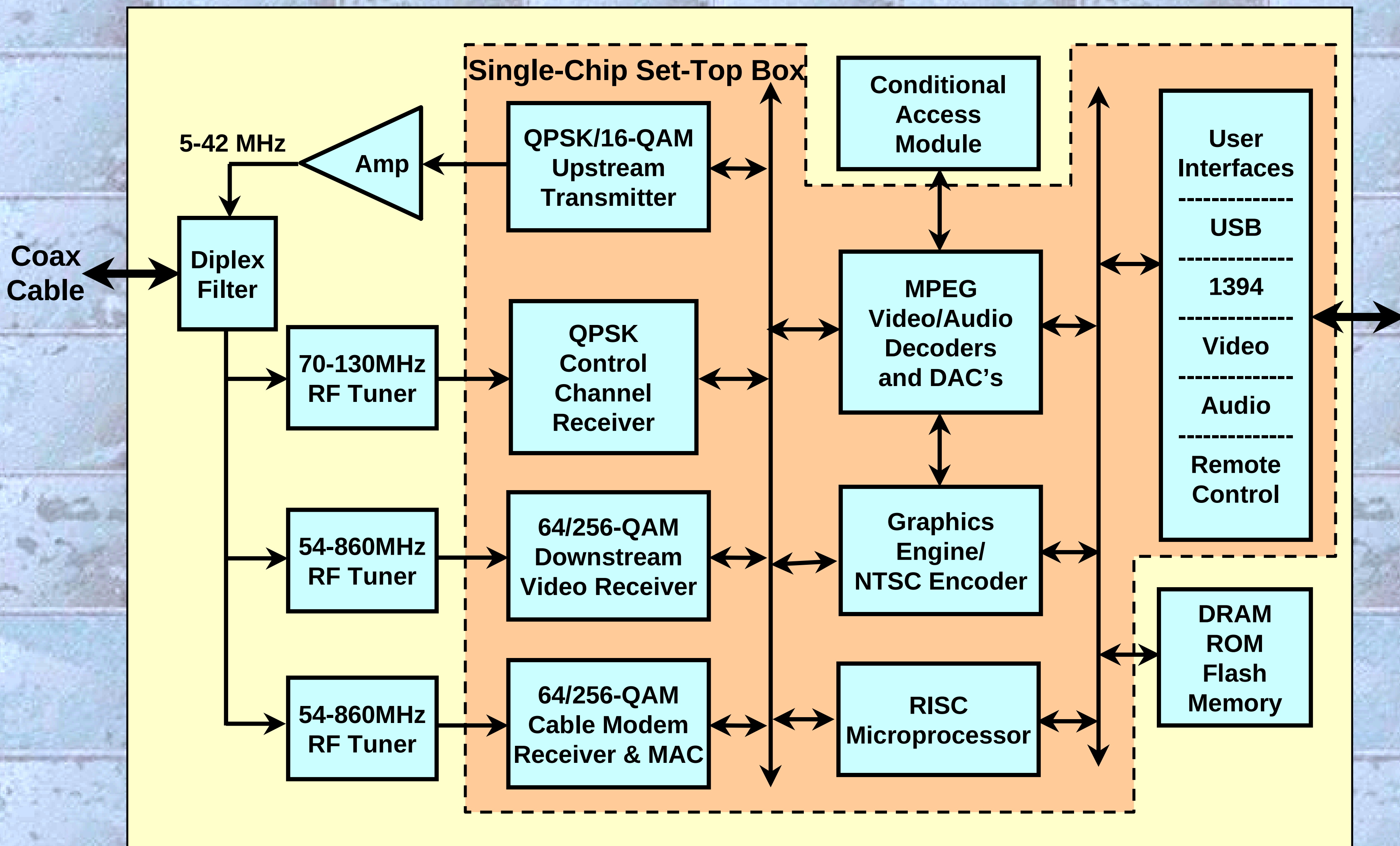


Single-Chip Cable Modem IC

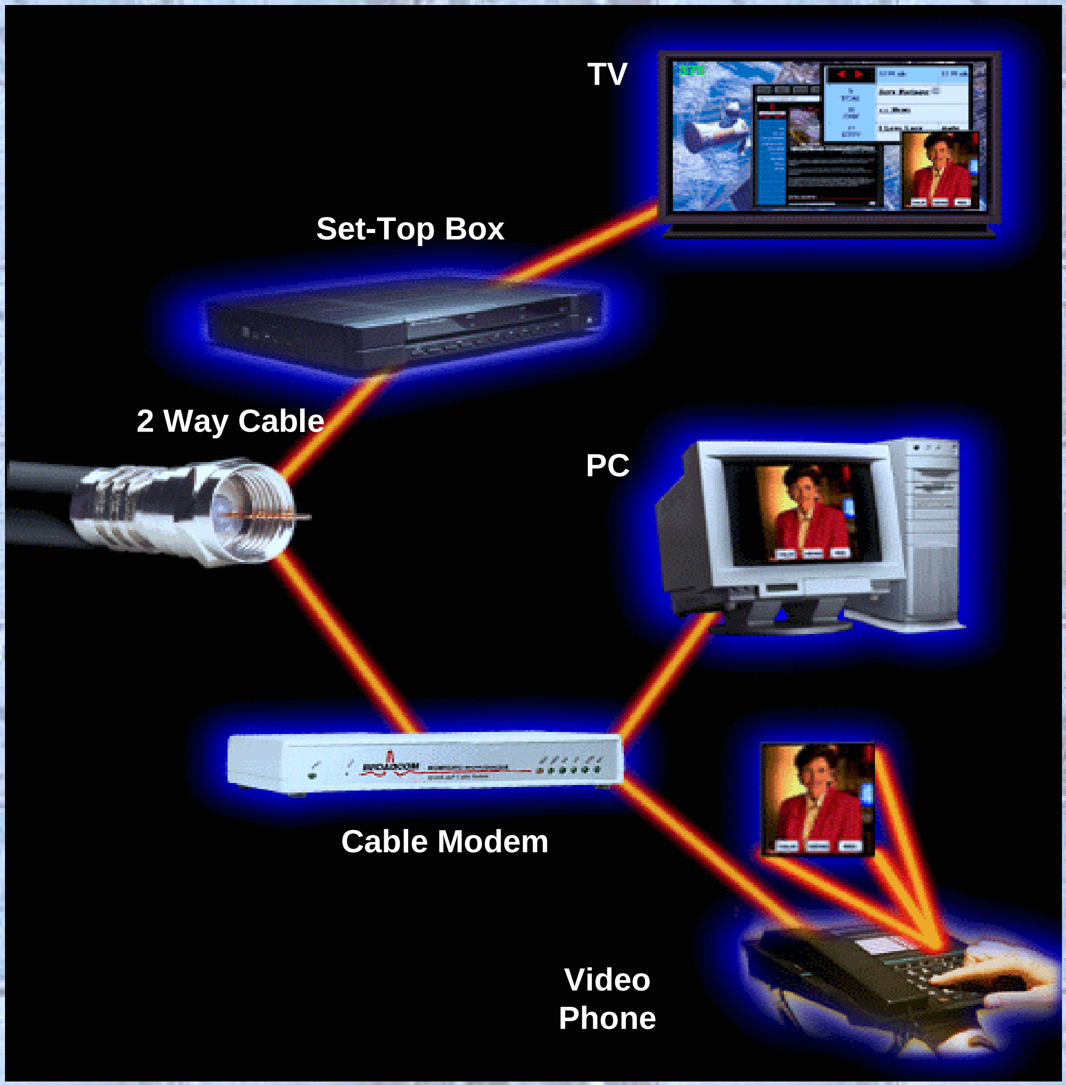


- 43 Mb/s 64/256-QAM video channel receiver
  - 30 MS/s 10-bit ADC
- 20 Mb/s QPSK/16-QAM upstream transmitter
  - 200 MHz 10-bit DAC
- 5-65 MHz direct RF output
- MCNS/DOCSIS Compliant Media Access Control
  - Supports Voice over IP
- 3.5 M transistors, 67 mm^2
- 0.35um 3.3V single-poly quad-metal CMOS

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

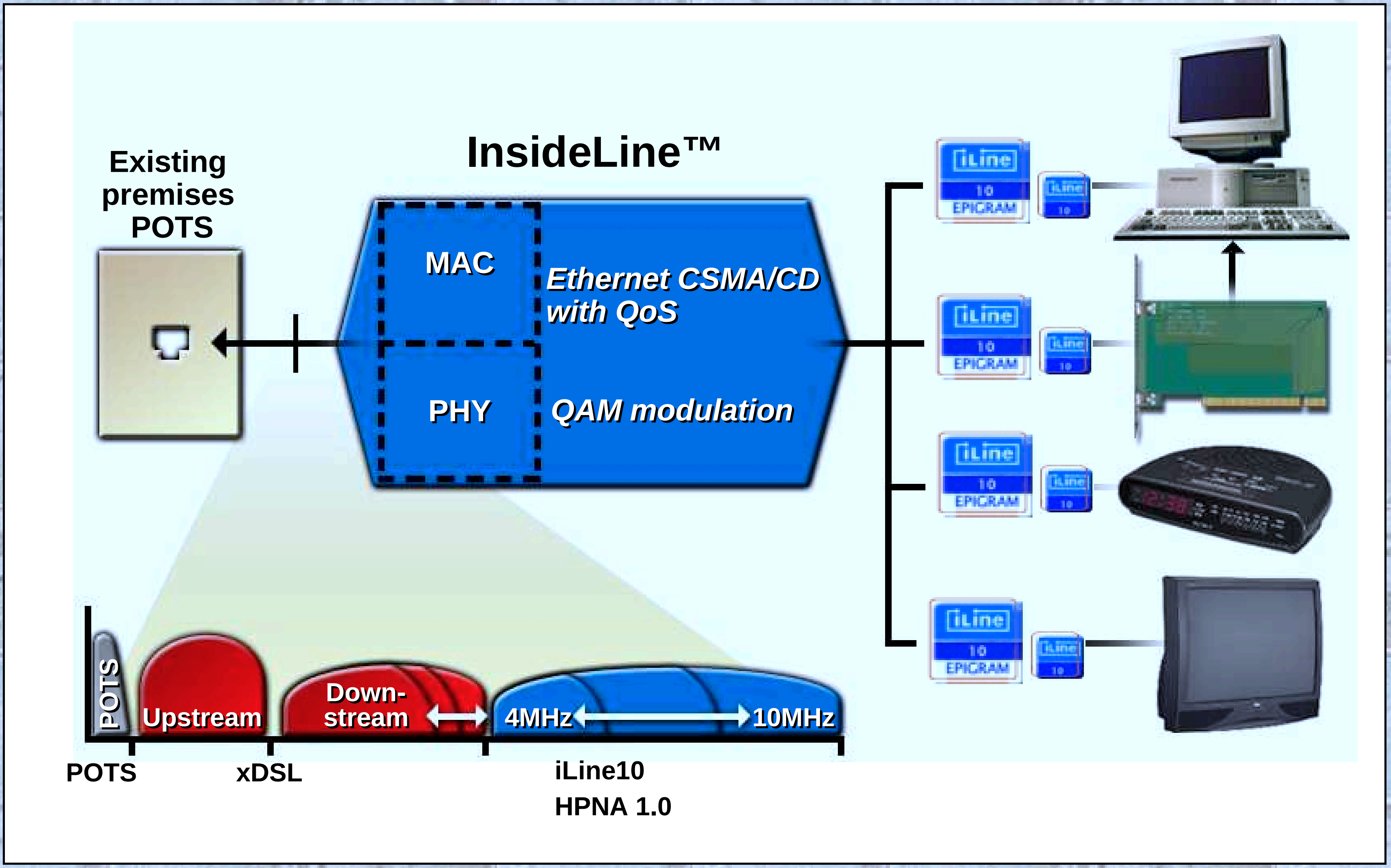
20 million miles existing today
50 million unconnected PCs

5M	10M	15M	20M

Source: IDC, Jupiter Comm. And Partner Estimates

Millions of Miles

10 Mbps Home Networking System Architecture



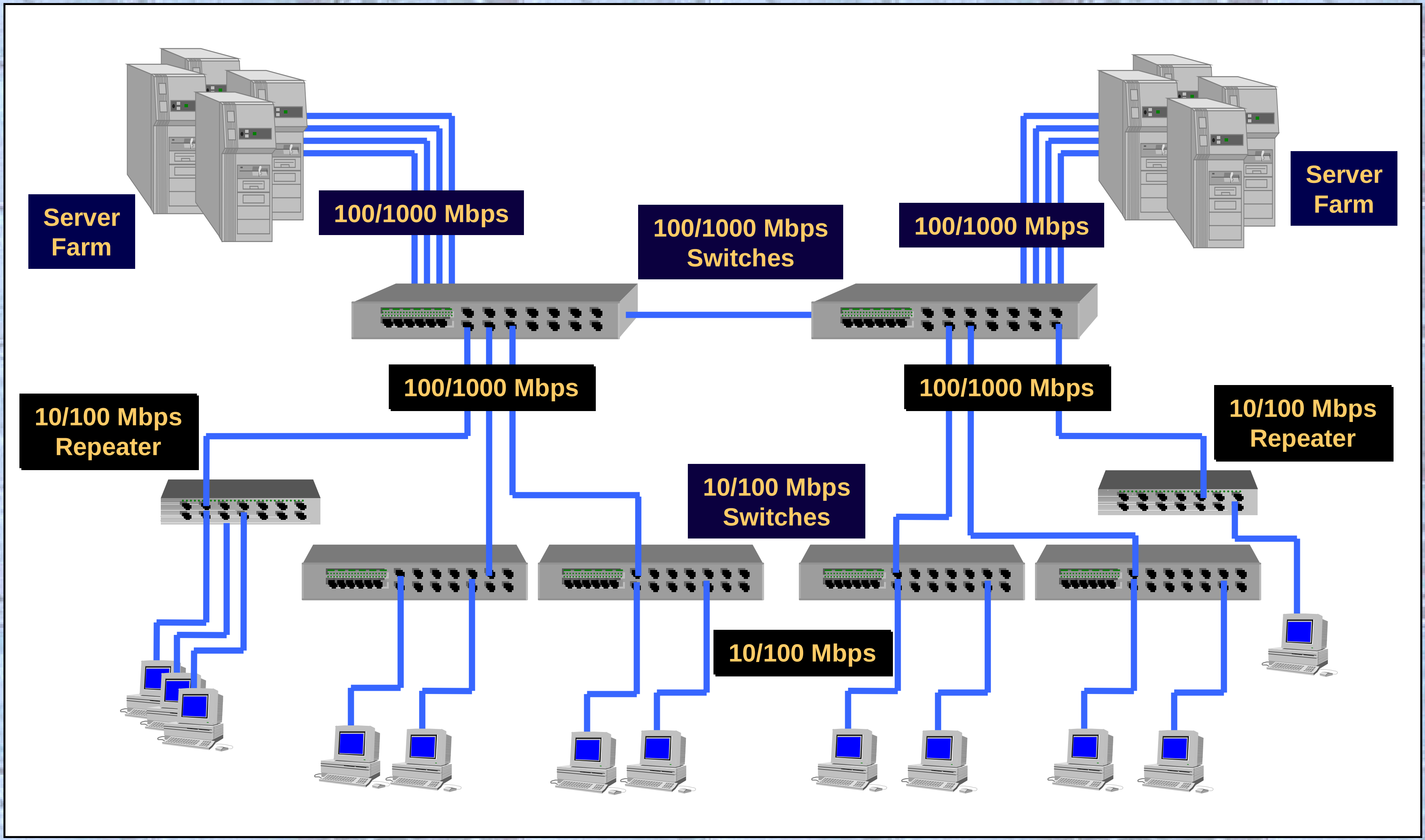
Applications for Broadband Communications IC's

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

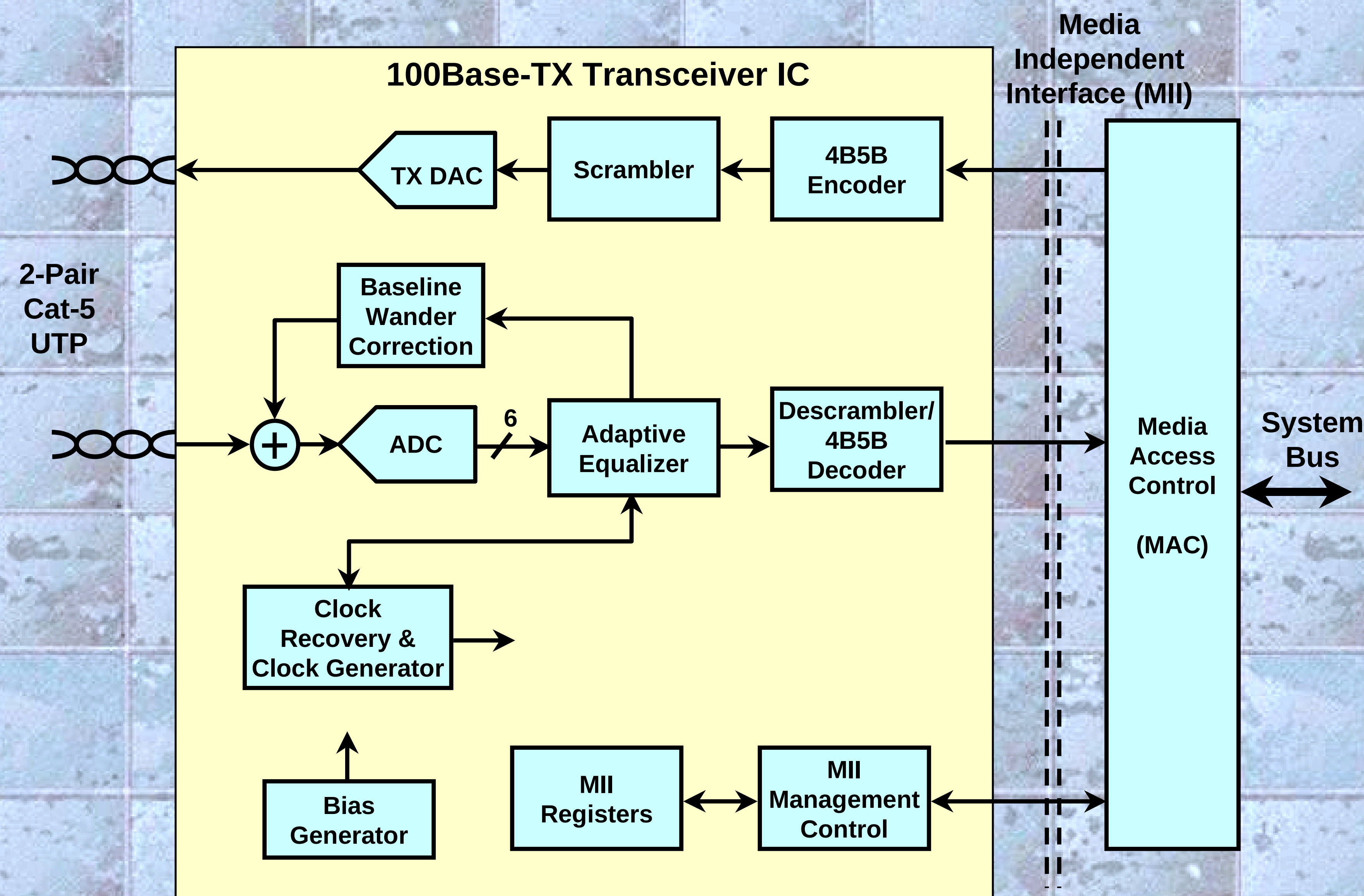
High-Speed Local Area Networking Technologies

- **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**

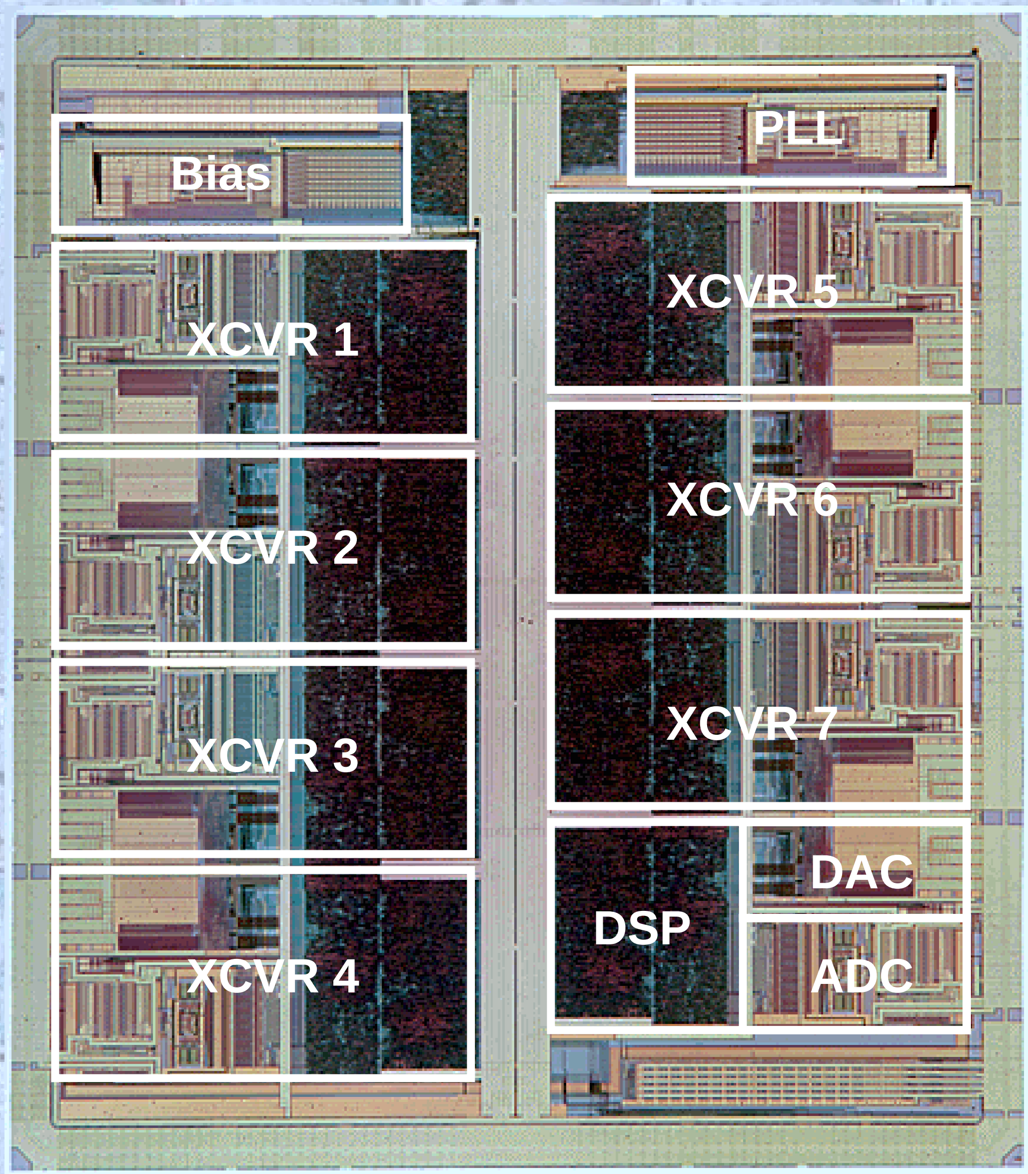
Typical Ethernet LAN Configuration



100Base-TX Fast Ethernet Transceiver Block Diagram



Octal 10/100Base-T Transceiver

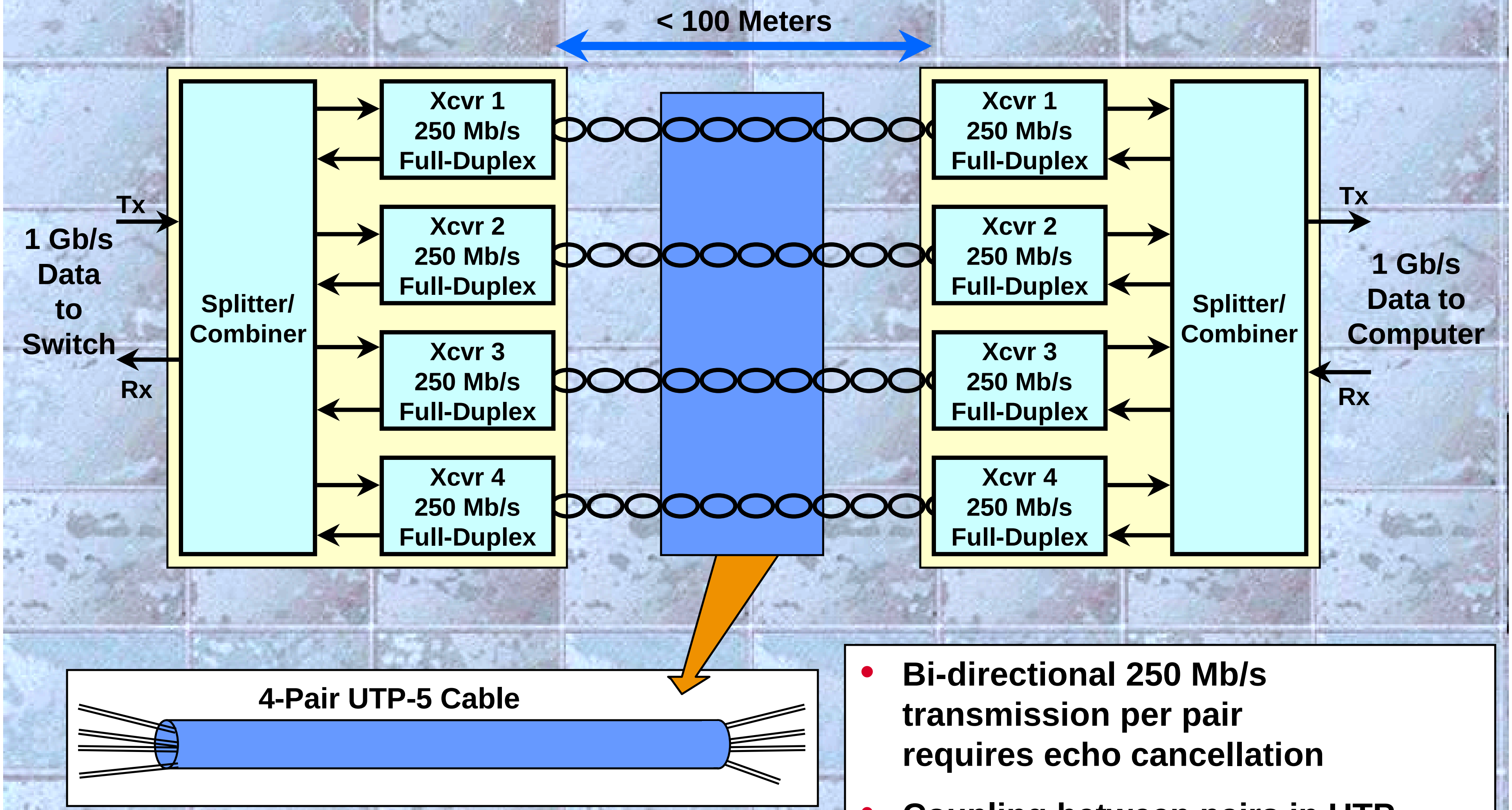


- Eight 10Base-T/100Base-T Ethernet transceivers
- All-digital DSP-based architecture
  - Adaptive decision-feedback equalization
- Eight 125-MHz 6-bit ADCs
- Eight 125-MHz DACs and line drivers
- $<10^{-12}$ BER over 160 meters Cat-5 UTP cable
- $<4\ mm^2$ per transceiver slice
- 0.35um 3.3V single-poly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

Gigabit Ethernet

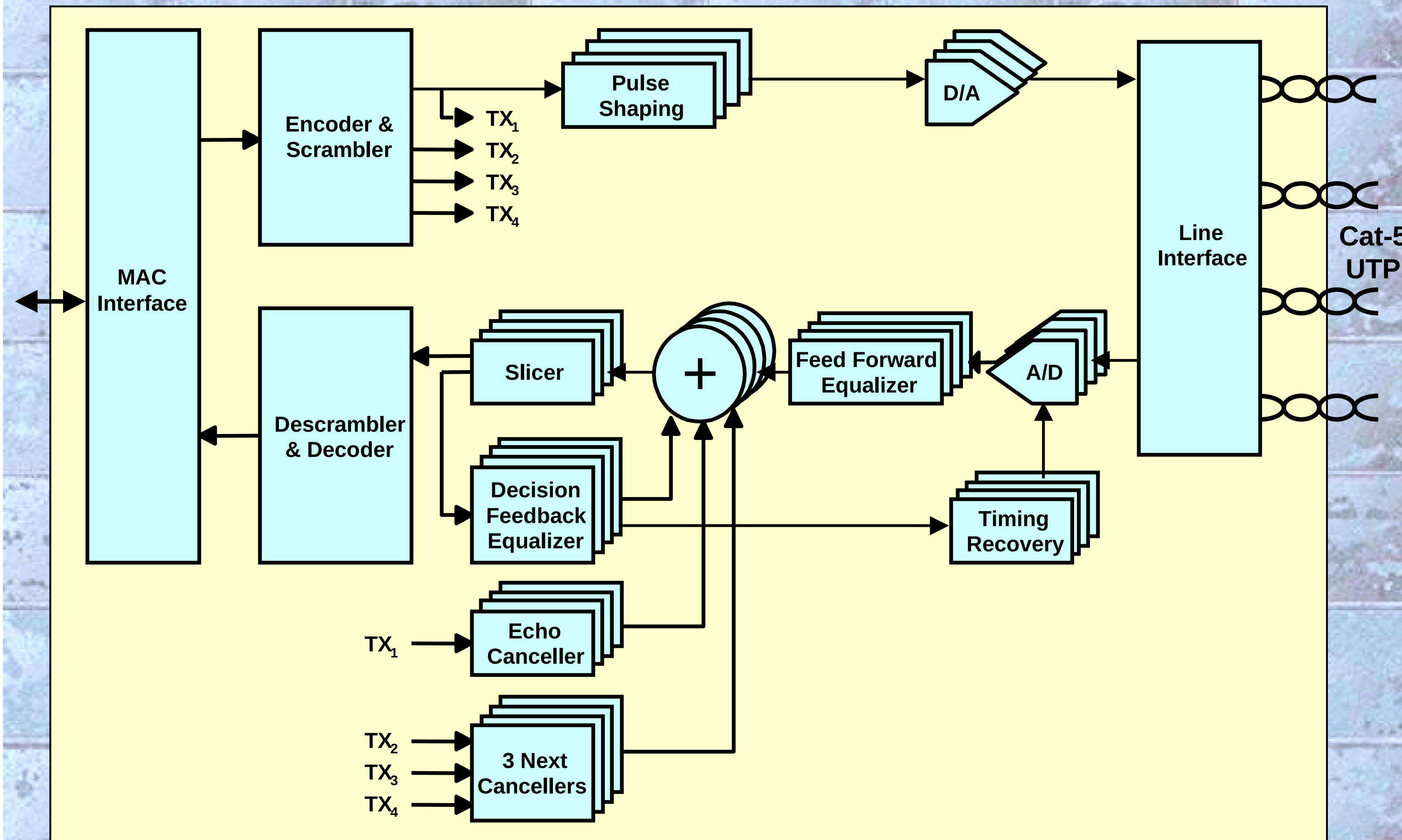
- **Gigabit Ethernet over fiber optic cables is currently being deployed in LAN backbones**
- **Gigabit Ethernet over 100 meters of Category-5 unshielded twisted-pair cable (1000Base-T) has been adopted as a new IEEE standard (802.3ab)**
  - Over 80% of corporate networks are wired with Cat-5 cable
  - 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**

1000Base-T Transceiver Block Diagram



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

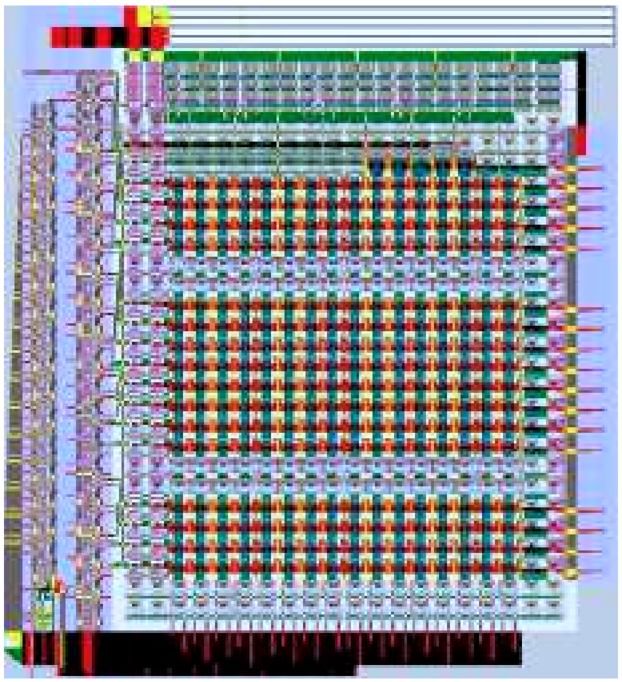
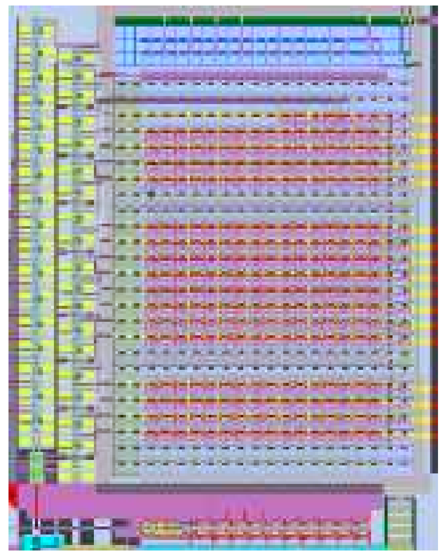
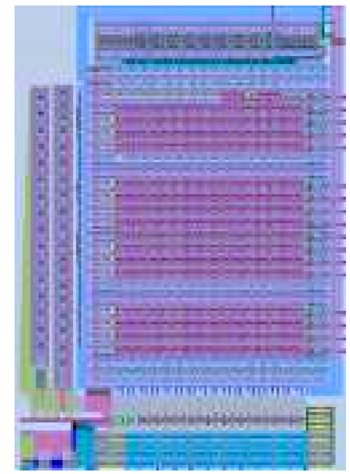
Mixed-Mode CMOS Design Issues

- **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

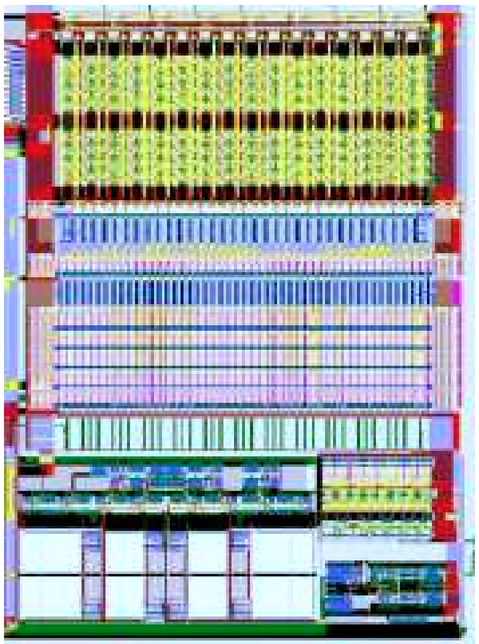
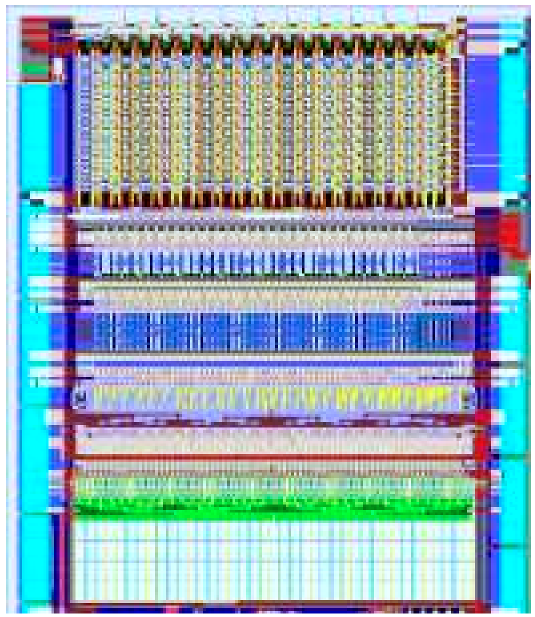
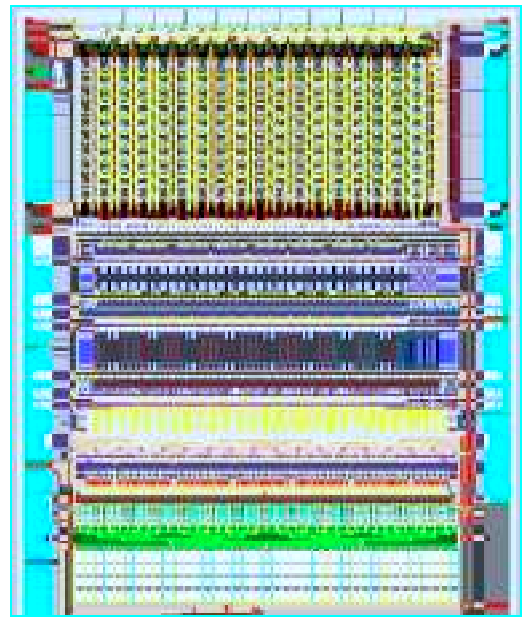
- **Arguments for scaling digital circuits are obvious and compelling**
  - Density and power improve by approximately a factor-of-two in each new process generation (0.5um, 5V --> 0.35um, 3.3V --> 0.25um, 2.5V --> 0.18um, 1.8V, etc.)
- **Unfortunately analog circuits don’t scale well because of reduced 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

0.50μm, 5V	0.35μm, 3.3V	0.25μm, 2.5V
		
1.0	0.63	0.44

Normalized Areas

10-Bit ADC Scaling Example

0.50µm, 5V	0.35µm, 3.3V	0.25µm, 2.5V
		
1.0	1.0	1.0

Normalized Areas

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!