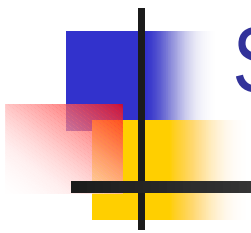
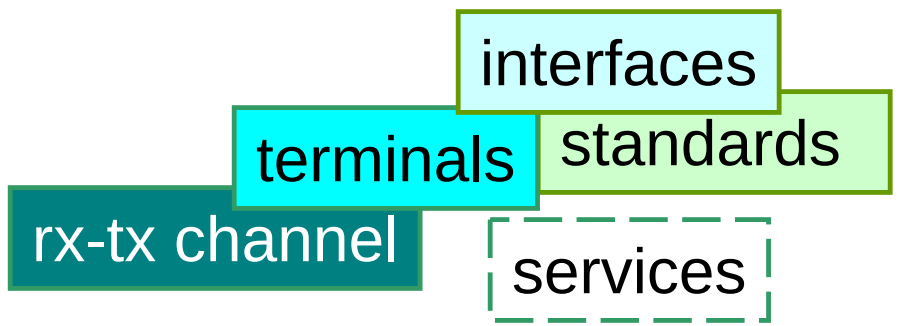
Asymmetrical Digital Subscriber Line (ADSL)



Asymmetrical Digital Subscriber Line

- Background
  - historical review
  - motivation for developing ADSL
- DSL end-to-end environment and reference model
- Line environment - characteristics of local loop (LL)
- Why conventional modems don't work *so* well in LL?
- Modem technology in ADSL
- DSL flavors: ISDN (!), HDSL, ADSL, VDSL ...
- Standards

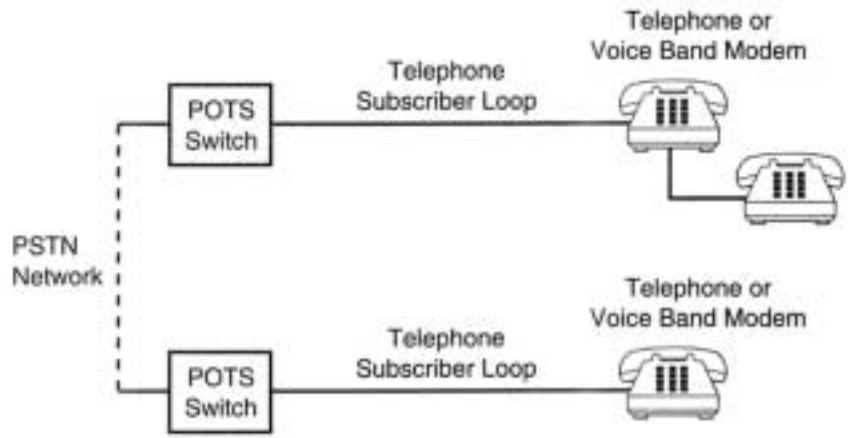


Short history of ADSL

1985 --	Bell Labs discovers a new way to make traditional copper wires to support new digital services - especially video-on-demand (VOD)
1990 --	Phone companies start deploying High-Speed DSL (HDSL) to offer T1 service on copper lines without the expense of installing repeaters - first between small exchanges
	Phone companies begin to promote HDSL for smaller and smaller companies and ADSL for home internet access
	1993 evaluation of three major technologies for ADSL: QAM, DMT and CAP
1995 --	Innovative companies begin to see ADSL as a way to meet the need for faster Internet access
1998 --	DMT was adopted by almost all vendors following ANSI T1.413 - issue 2 (in contrast to CAP)
1999 --	ITU-T produced UADSL G.992.2 (G.lite) and G.922.1 (G.full)

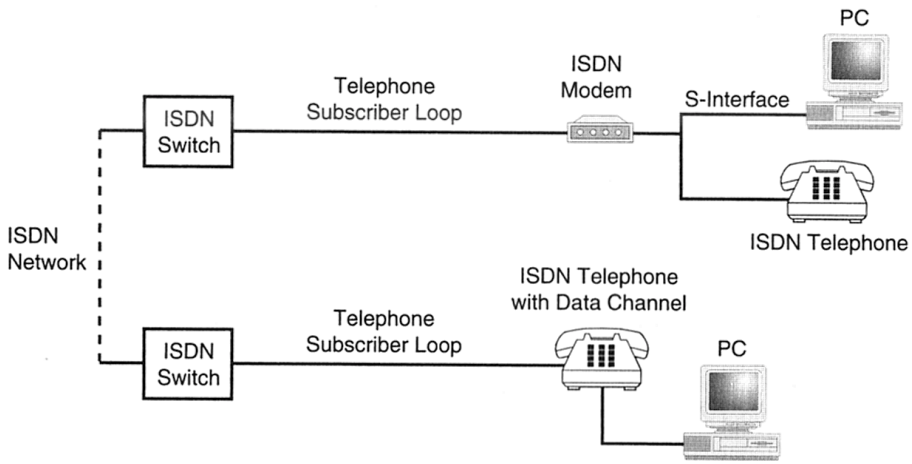
History of digital access in PSTN

The first DSL technique



Through analog voice:

- Connecting a voice-band modem (as V.90)
- No switch or network infra changes



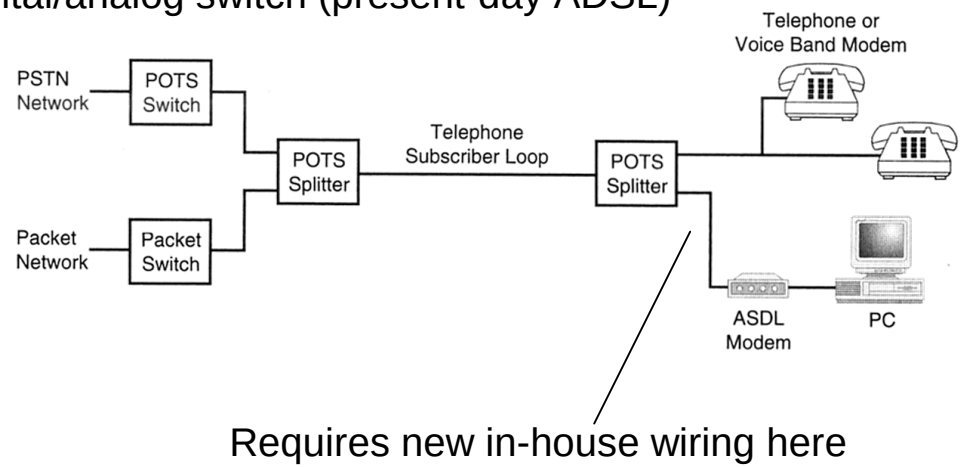
Through ISDN switch:

- Yields basic rate interface (BRI)
- Fixed throughput 2B+D

Digital access in PSTN (cont.)

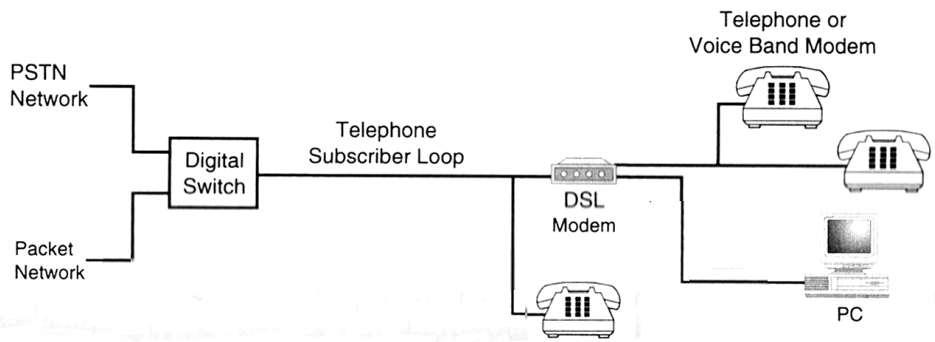
Digital/analog switch (present-day ADSL)

Using POTS splitters



- POTS FDM splitters separate voice and DSL channels

Using digital switch



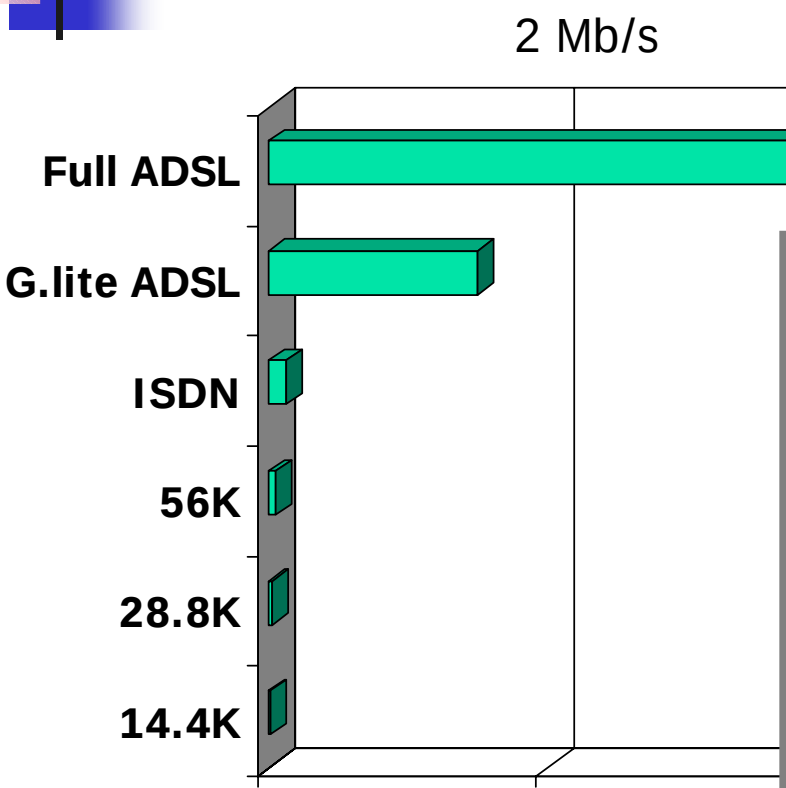
- Next generation intelligent switch recognizes subscriber devices and adjusts its HW parameters (PSTN telephone, voice-band modem, DSL modem)

Motivation for adaptation of ADSL

- Need for high-speed Internet access - also telephone modem speeds have peaked and cable modems have turned out to lack speed *with many users*
- DSL means methods to transmit high speed data to local loop by using unshielded 2-wire twisted pairs
- DSL allows rates varying from 160 kb/s up 50 Mb/s on down link (DL) depending on technology used!
- In the most popular commercial ADSL maximum rate 640 kbit/s upstream and 8 Mb/s downstream
- Different operation modes developed to serve symmetric and asymmetric traffic requirements and different rates (STM and ATM supported by ADSL)

STM-n: Synchronous Transfer Module (of SDH): DS-1,2: 1.544 Mb/s, 6.312 Mb/s
ATM: Asynchronous Transfer Mode
DL: Down Link - Down stream

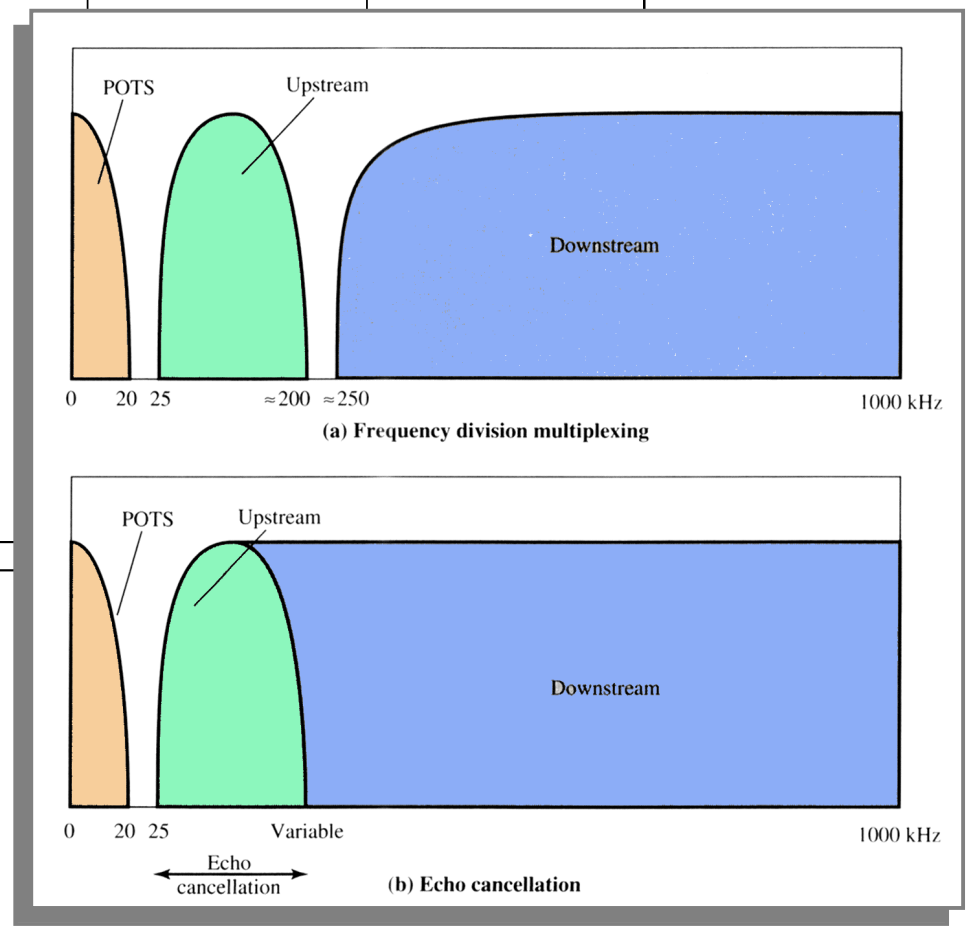
ADSL rates (DL) and channel frequency band allocation in local loop



Two ways to allocate transmission band in PSTN local loop cables

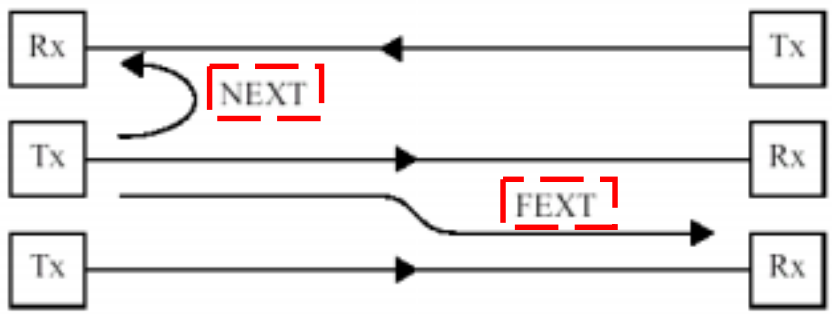
a) **FDM**

b) Echo cancellation enables adaptivity between UL and DL bands



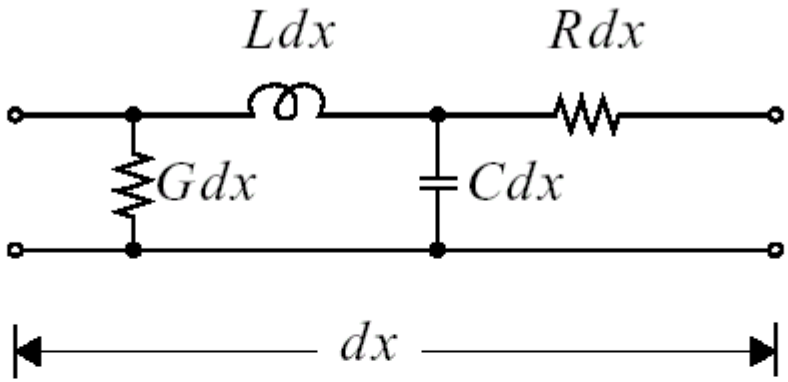
ADSL challenge: bad quality local loop cables

- **Attenuation:** Frequency dependent (next slides)
- **Crosstalk:**
  - Near-end crosstalk (NEXT) appears between TX and RX of the near-end
  - Far-end crosstalk (FEXT) appears between TX and RX of the far-end
- **Interference**: other lines, overlapping RF-spectra
- **Bridged taps, loading coils**
- **Weather-conditions** (moisture, temperature) affect crosstalk and line impedance



Modeling the loop cable

- Modeled as a transmission line.



Twisted-Pair Typical Parameters:

- $R(f) = (1+j)\sqrt{f/4}\ \Omega/\text{km}$ due to the skin effect
- $L = 0.6\ \text{mH/km}$ (relatively constant above 100kHz)
- $C = 0.05\ \mu\text{F/km}$ (relatively constant above 100kHz)
- $G = 0$

Cable attenuation

- Cable gain in dB is

$$H_{dB}(d, \omega) \approx -k_R \times d \times \sqrt{\omega}$$

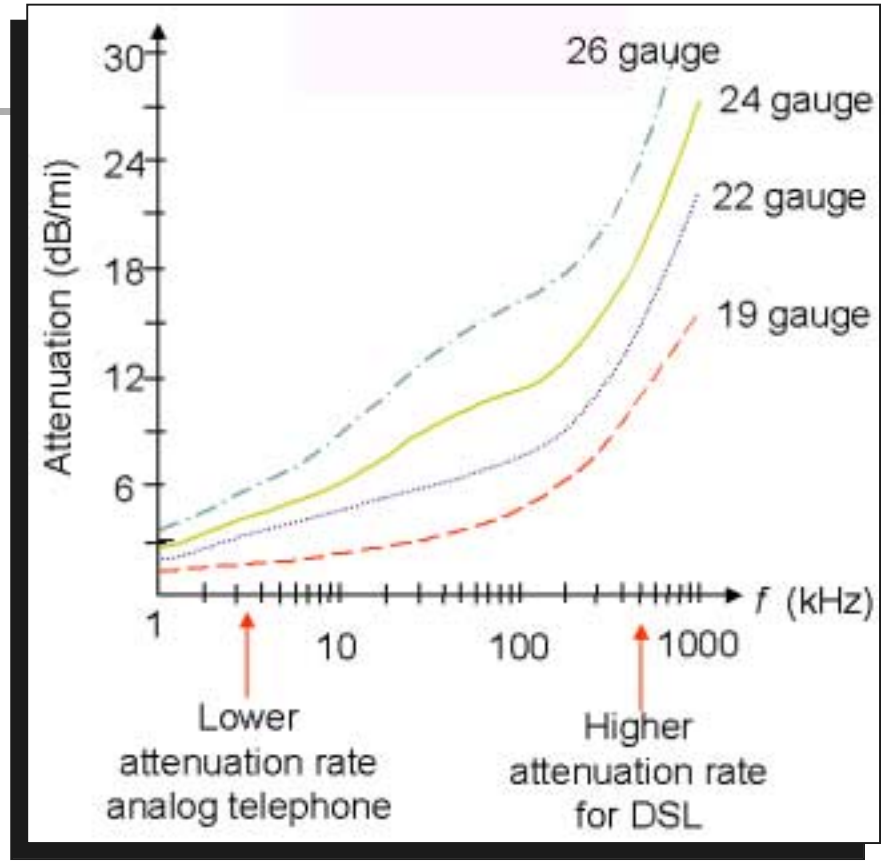
- k_R — cable constant (typically 0.008)
  d — cable distance in km
  ω — frequency in rad/s
- Attenuation in dB is proportional to cable length
  — 2x distance doubles attenuation in dB
  — reduce atten by using larger diameter cable
- Attenuation also proportional to root-frequency
  — 4x frequency doubles attenuation in dB
  — fast rolloff once attenuation reaches 20dB

Twisted cables

- Comes in different wire thickness,
  e.g. 0.016 inch (24 gauge)
- The longer the cable, the smaller the bandwidth

Standard	Data Rate	Distance
DS-1	1.544 Mbps	18,000 feet, 5.5 km
DS-2	6.312 Mbps	12,000 feet, 3.7 km
1/4 STS-1	12.960 Mbps	4500 feet, 1.4 km
1/2 STS-1	25.920 Mbps	3000 feet, 0.9 km
STS-1	51.840 Mbps	1000 feet, 300 m

xDSL data rates for 24-gauge twisted pair



Twisted cable attenuations

DS-1,DS-2: Digital Signal 1,2
Synchronous Digital Hierarchy (SDH) levels

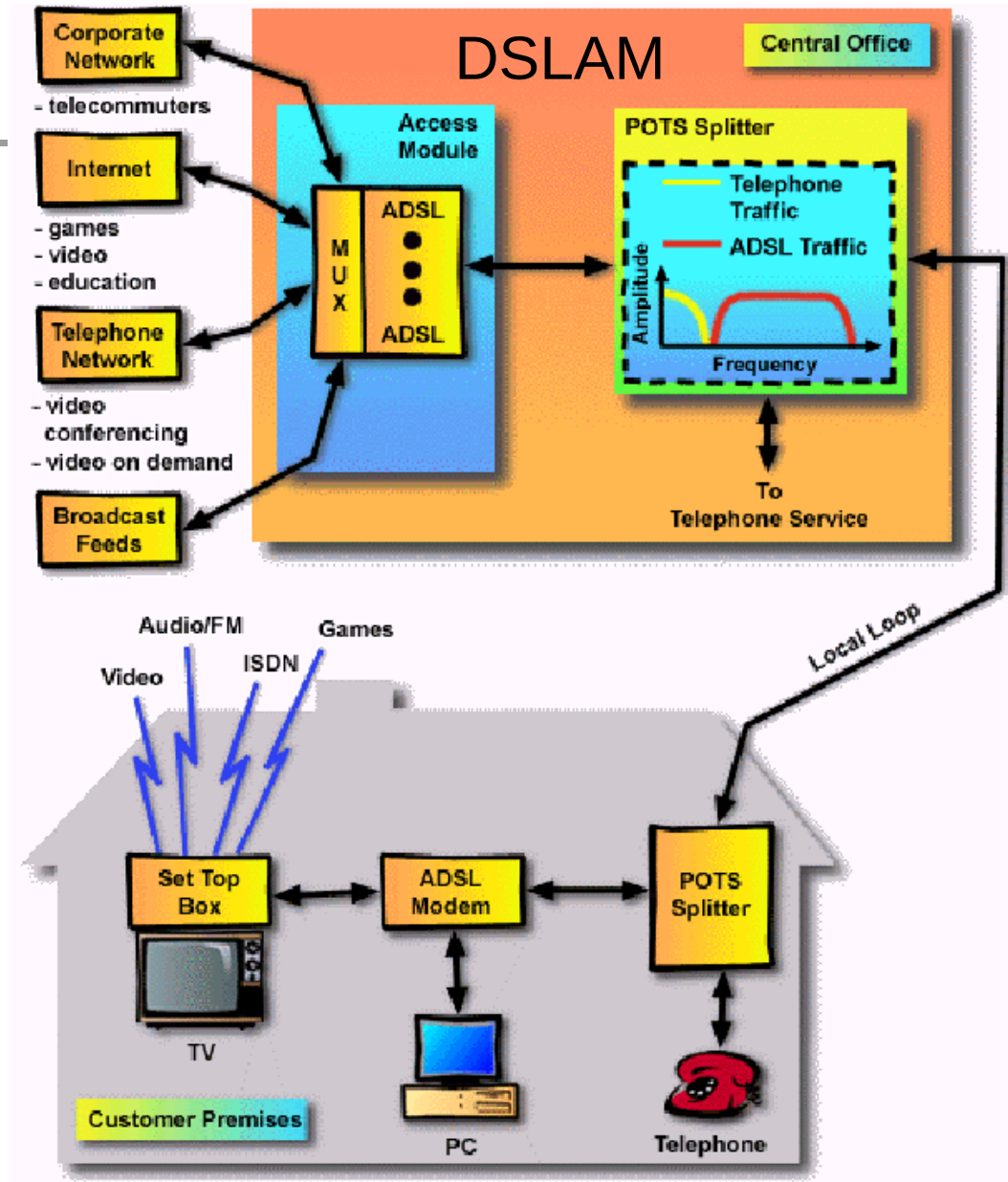
STS-1: Synchronous Transport Signal level-1, Synchronous Optical Network's (SONET) physical level signal

ADSL meets local loop challenges

- Restricted bandwidth
  - careful allocation of bits for each sub-carrier
- Changing circumstances (whether, bridged taps)
  - Adaptive setup phase
- High attenuation
  - Usage of relatively high bandwidth for transmission
- Compatibility to old POTS
  - Own band for POTS by FDM (splitters)
- Interference and cross-talk
  - Coding
  - Interleaving
  - Modulation (OFDM/DMT)
  - Echo cancellation

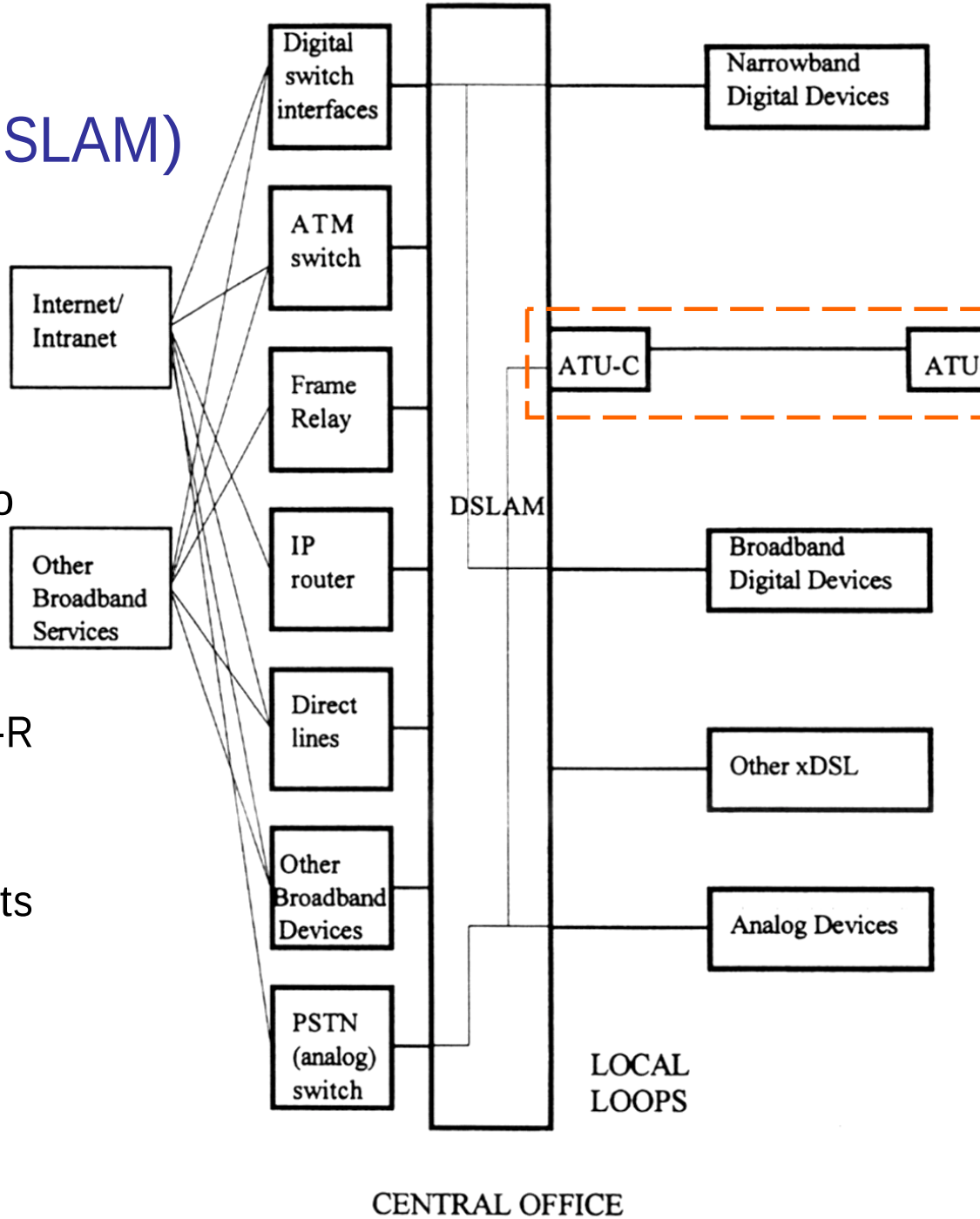
Note: loading coils must be removed from cables in order to ADSL to work

Using ADSL

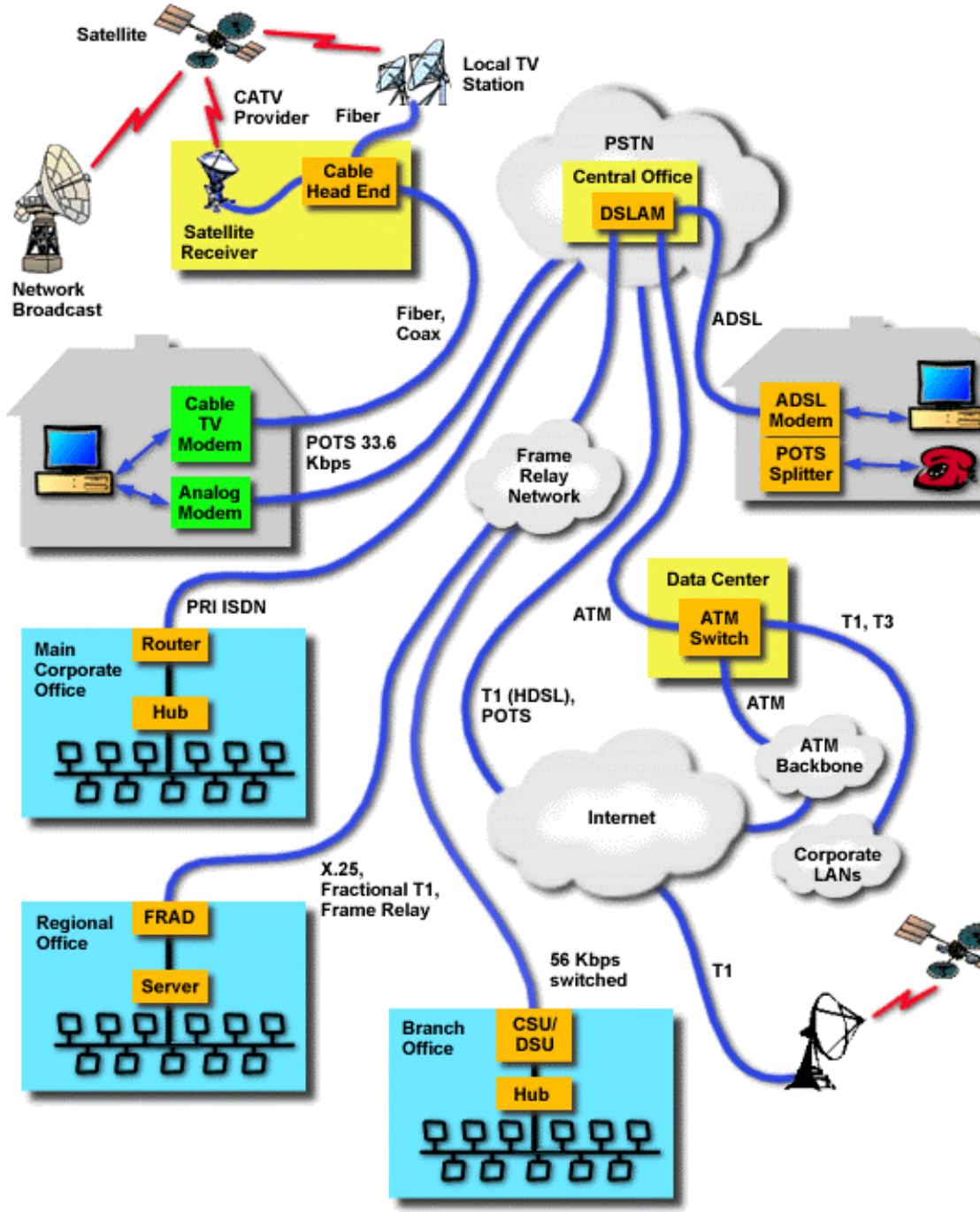

Corporate Network
- telecommuters
Internet
- games
- video
- education
Telephone Network
- video conferencing
- video on demand
Broadcast Feeds
DSLAM
Central Office
Access Module
M U X
ADSL
ADSL
POTS Splitter
Telephone Traffic
ADSL Traffic
Amplitude
Frequency
To Telephone Service
Audio/FM
Video
ISDN
Games
Local Loop
Set Top Box
TV
ADSL Modem
PC
POTS Splitter
Telephone
Customer Premises

DSL access multiplexer (DSLAM)

- DSLAM provides access to LANs, WANs and other services at CO
- DSLAM interfaces:
  - subscriber links (ATU-R to ATU-C)
  - connections to other DSL/broadband-circuits
  - Internet core
  - with ISDN exchange

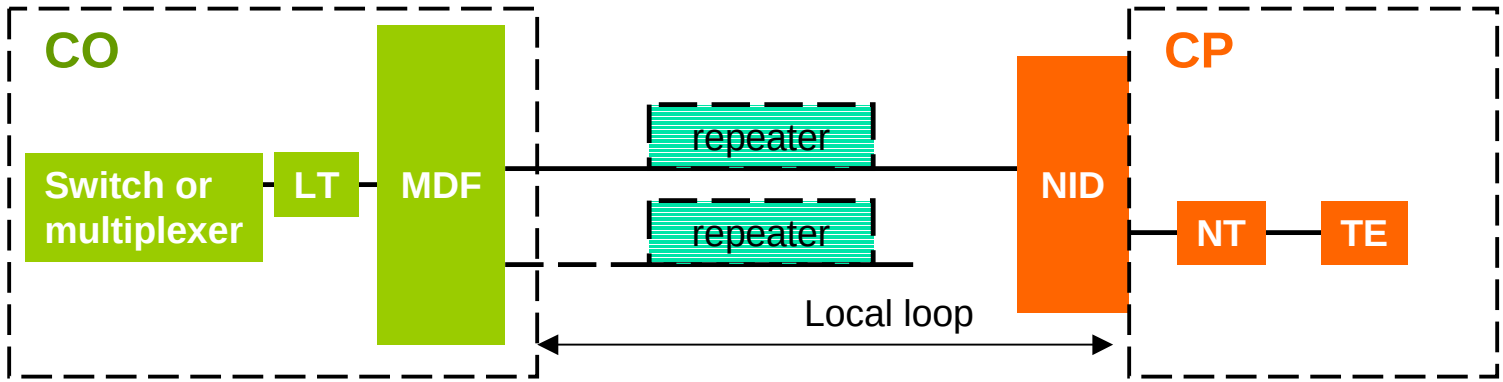


Using DSLAM



POTS: Plain old telephone system

Generic DSL reference model



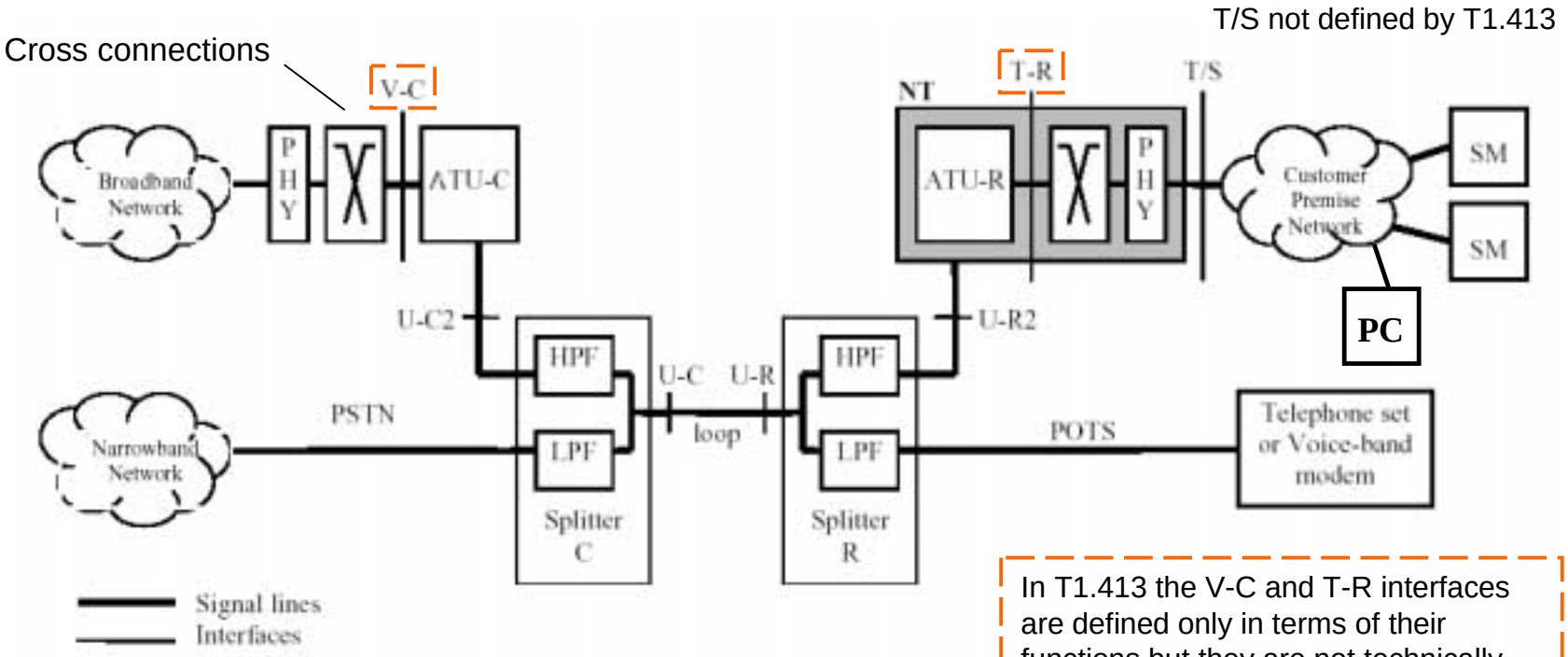
ADSL transceiver units

ATU-R

ATU-C

- **CP**: Customers premises - local loop connects to switch (CO)
- **TE**: Terminal equipment - PC or telephone
- **NT**: Network terminal - DSL modem at CP
- **NID**: Network interface device - all customer's installation reside right from this point and telephone company's to the left in the diagram
- **CO**: Central office
- **MDF**: Main distribution frame - wire cross-connection field connects all loops to CO
- **LT**: Line termination eg DSL modem
- repeater: signal regeneration for transmission introduced impairments
- local loop: in ADSL 2-wire connection between CO and CP

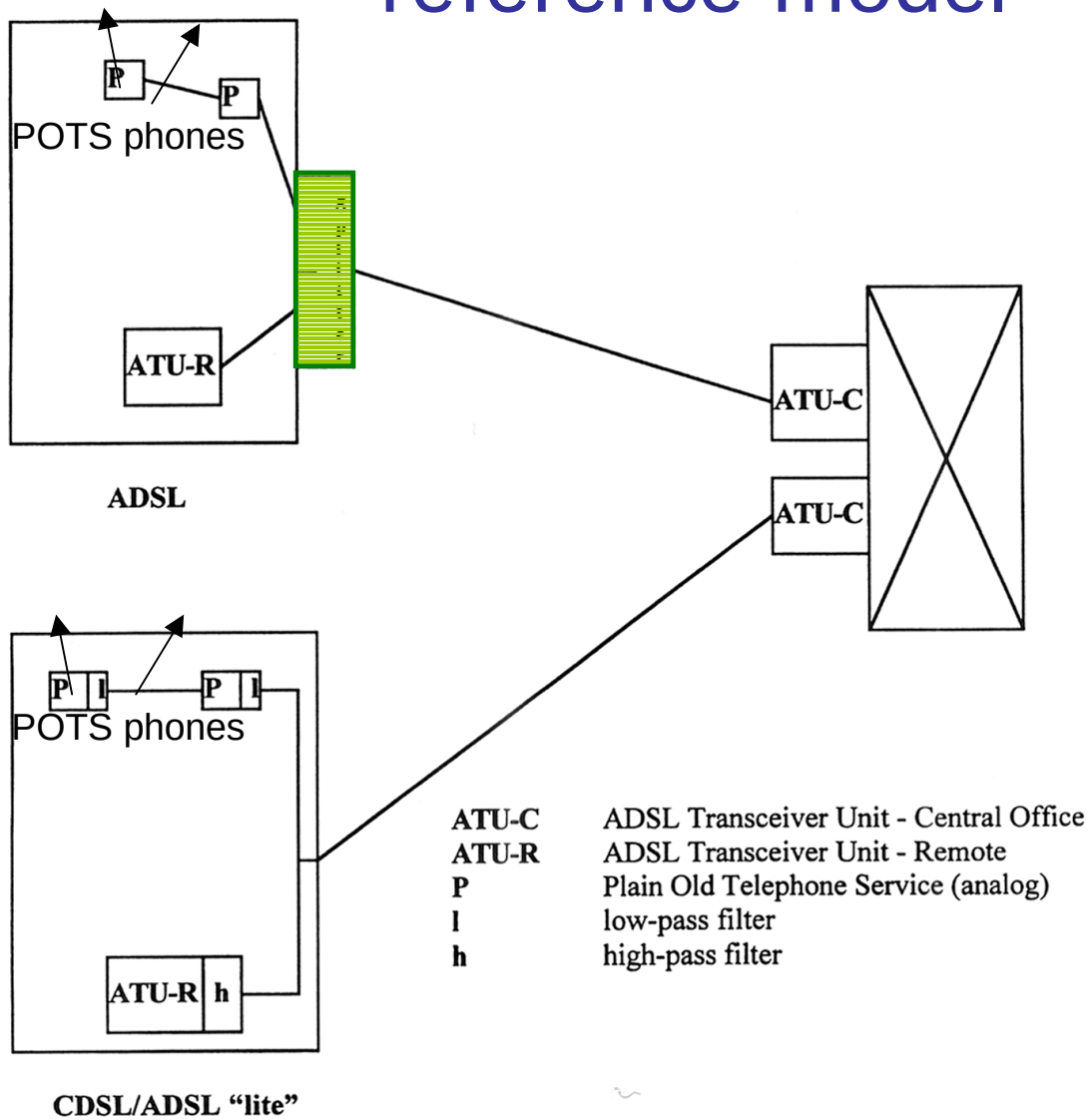
What is specified in ADSL standard? **ANSI T1.413** ADSL reference model:



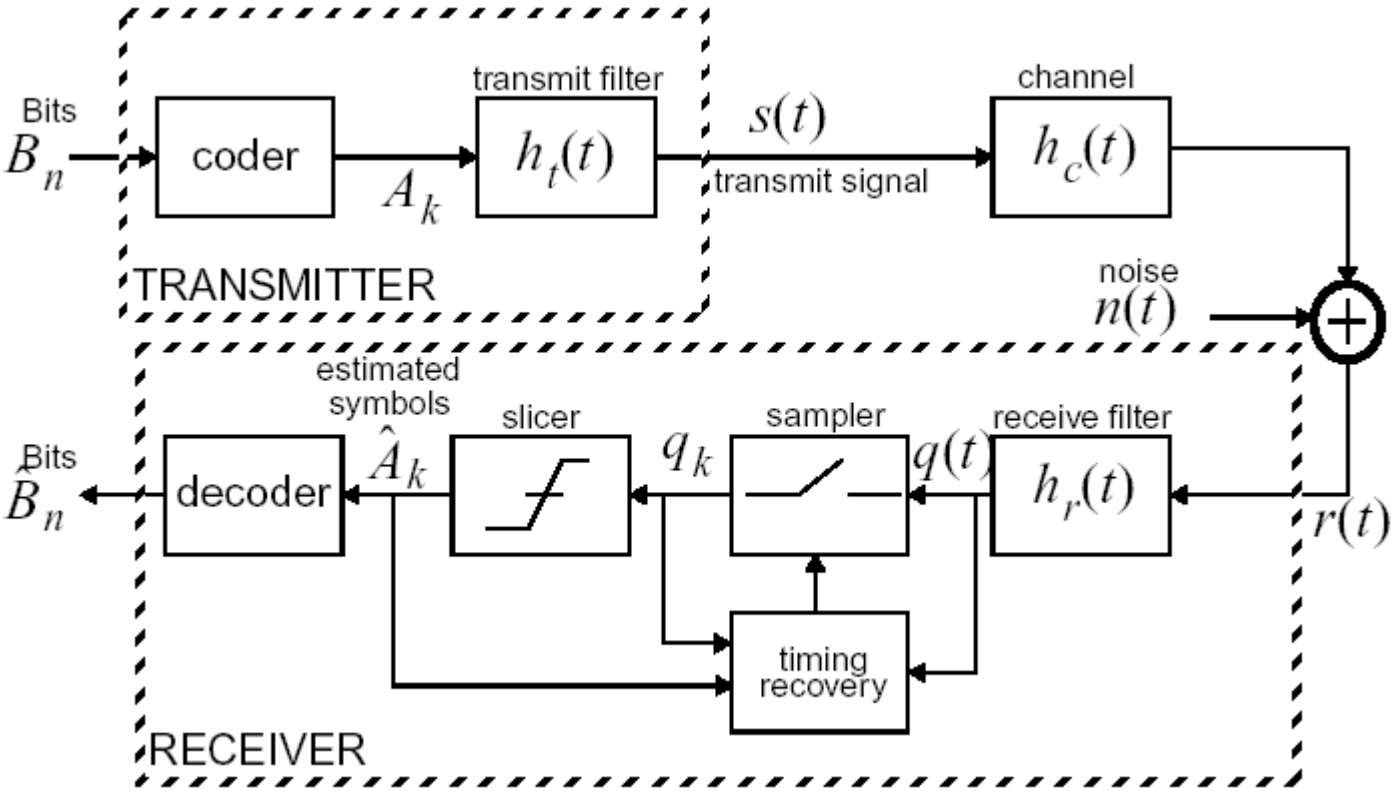
- Standard specifies **interfaces** and **units** as for example
  - ATU-R: ADSL transceiver unit - remote terminal
  - ATU-C: ADSL transceiver unit - central office terminal ← units
  - U-C (2), U-R (2) ← interfaces

ADSL and ADSL-lite reference model

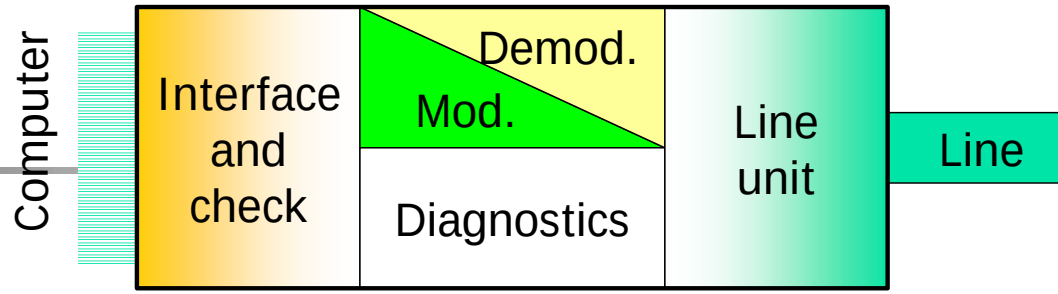
- ADSL and ADSL-lite have the major difference in the missing **FDM splitter**
- This causes lower rates for ADSL-lite but makes it cheaper to install



Reference in physical level: A baseband system



Modem parts



- Analog parts
  - analog transmit and receiver filters
  - DAC, automatic gain control, ADC
- Digital parts
  - modulation/demodulation
  - coding/decoding
    - Reed-Solomon
    - Trellis
  - bit packing/unpacking (compressed transmission)
  - framing
  - scrambling

Modem technology

- Conventional modem modules:
  - Constellation mapping
  - Interleaving (convolutional)
  - Symbol/bit conversion
  - Timing recovery
- Advanced techniques for DSL:
  - Carrierless AM/PM (CAP) or QAM line codes (97% of USA installations apply this method)
  - Fast Fourier Transforms for Discrete Multi-Tone Modulation (DMT) - the dominant method
    - tone ordering -> water pouring bit allocations (adaptation to transfer function) & peak-to-average ratio (PAPR) decrease
    - channel equalization (tone-by-tone different rates)
    - guard intervals (adaptation to channel delay spread)
  - Turbo - coding
  - Adaptive echo canceller

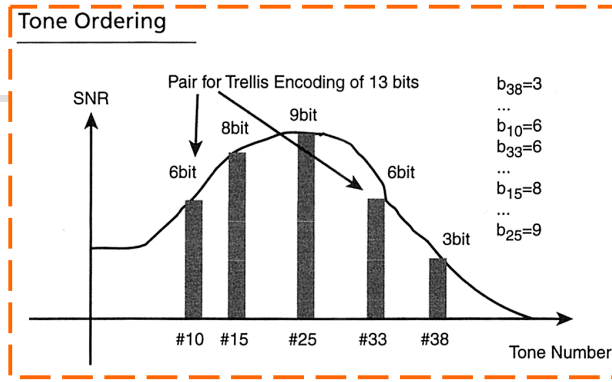
RADSL start-up phases

- RADSL (rate adaptive DSL) modems apply sophisticated **hand shaking** to initiate transmissions that include
  - **Activation**: notice the need for communications
  - **Gain setting/control**: Adjust the power for optimum transmission and minimum emission
  - **Synchronization**: Clocks and frames to the same phases
  - **Echo cancellation** (if used required for both ends)
  - **Channel identification and equalization**
- In DMT modulation during the handshaking active channels are decided and bit rates assigned for them

Multi-tone modulation (cont.)

- In channel activation phase different sub-channels are allocated for their optimum rates (by changing number of levels in modulation)
- DMT-ADSL supports both synchronous transfer modules (STM) of SDH and asynchronous transfer mode (ATM, AS0 used for primary cell stream)
- DMT defines **two data paths**: fast and interleaved
- Fast
  - low latency (2ms)
  - real-time traffic
- Interleaved
  - low error rate
  - Reed-Solomon encoding (concatenated convolutional codes) at the expense of increased latency

ADSL is based on OFDM/DMT



OFDM Transmitter

Binary input

Error correction coding

Interleaving

Modulation (QAM)

Pilot insertion

Serial to Parallel

IFFT

Parallel to serial

Adding Guard interval

Pulse shaping D/A

RF Tx

Channel estimation

Adaptation to burst errors (applied for interleaved data)

DMT modulation

Multipath & BW adaptation

OFDM Receiver

RF Rx

Filter A/D

Deleting Guard interval

Serial to Parallel

FFT

Time and frequency Synchronisation

Parallel to serial

Channel Estimation

Demodulation (QAM…)

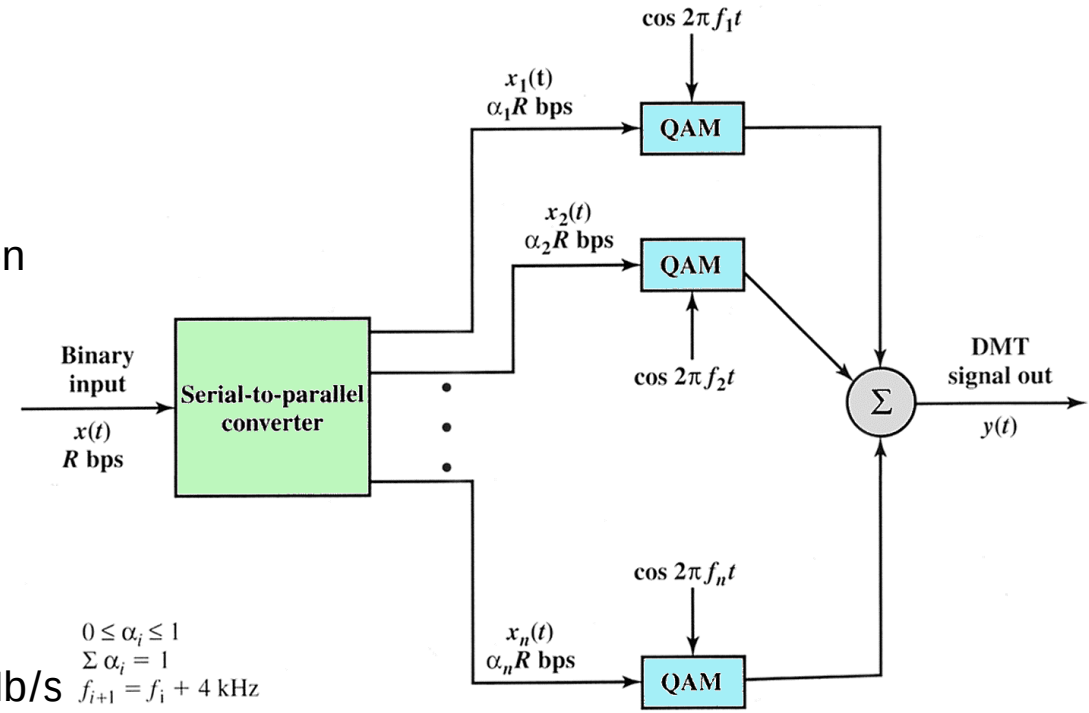
Interleaving

Error correction coding

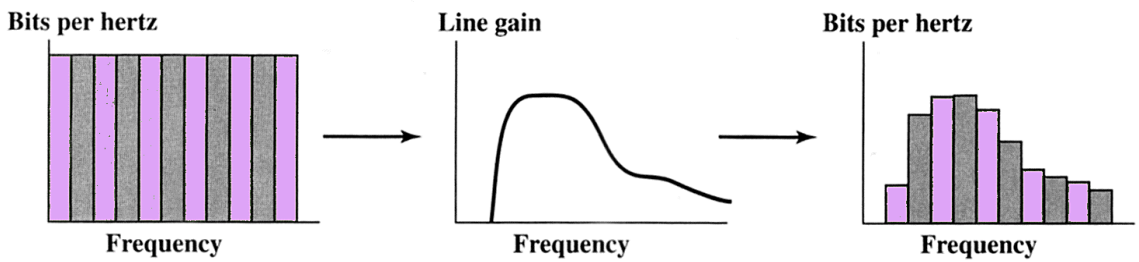
Binary Output

DMT modulation principle [4]

- Transmission band divided into 4 kHz subchannels
- Tone ordering: On initialization test-tone determines number levels in QAM for each subchannel (each can carry 0 - 60 kb/s)
- Number of subchannels is 256 - theoretical maximum rate 15.36 Mb/s
- Current rates 256 kb/s ... 8 Mb/s depending on line conditions and operator specifications in ADSL



Discrete Multi-tone (DMT) modulation

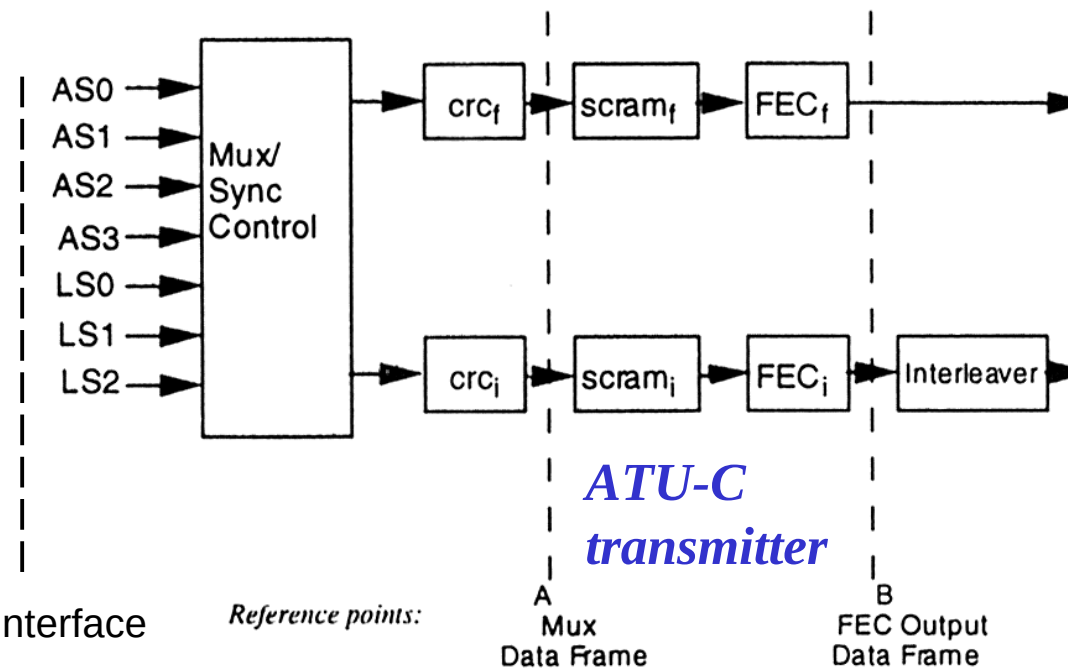


Tone ordering (bit-loading)

Discrete multi-tone (DMT) modulation [3]

- **ANSI T1.413** specifies DMT modem for ASDL applications
- Downstream:
  - 2.208 MHz sampling rate, 256 tones 0 … 1.104 MHz
  - Symbol rate 4000 symbols /s. Each sub-channel is 4.3 kHz wide
  - max rate 32 kb/s per channel (compare to V.90 modem)
- Upstream:
  - 275 kHz sampling rate, 32 tones 0 … 138 kHz

ASx: high-speed,downstream simplex nx1.54 Mb/s
LSx: low-speed, duplex channels 160…576 kb/s
crc: cyclic redundancy check
FEC f,i: (fast,interleaved): forward error correction
scram f,i: scrambling
ATU-C: ADSL transmitter unit - central office



Usage of subchannels (ANSI T1.413)

- **Downstream simplex** bearer rates in different transport classes (CO->CP):

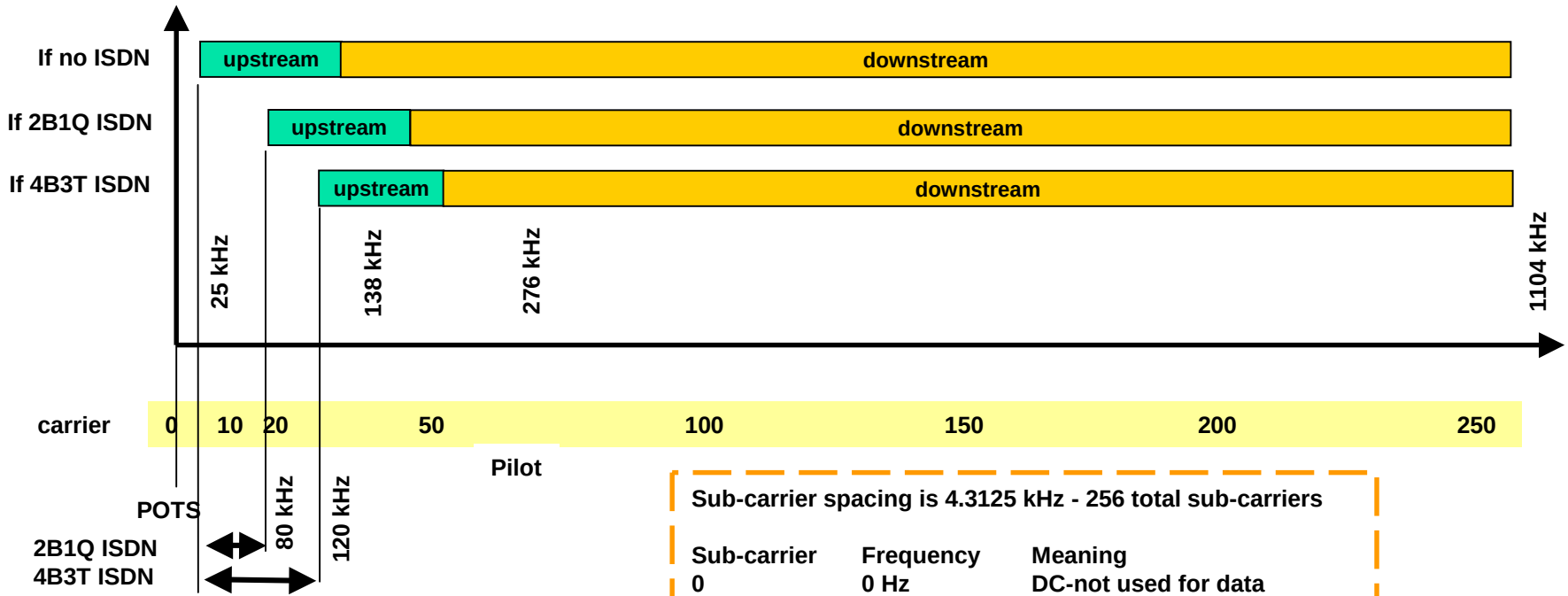
Transport class		1	2	3	4
Maximum capacity Mb/s	■	6.144	4.608	3.072	1.536
Bearer channel Mb/s options:	■	1.536	1.536	1.536	1.536
	■	3.072	3.072	3.072	
	■	4.608	4.608		
	■	6.144			
Maximum active subchannels		**AS0 -AS3**	**AS0 -AS2**	**AS0 -AS1**	**AS0**

Usage of subchannels (ANSI T1.413)

- **Duplex** bearer rates:

Transport class	1	2	3	4
Maximum capacity Mb/s	0.640	0.608	0.608	0.176
Bearer channel Mb/s options:	0.576	0.576	0.576	0.160
	0.384	0.386	0.384	0.016
	0.160	0.160	0.160	
	0.064	0.064	0.064	
Maximum active subchannels	**LS0 -LS2**	**LS0 -LS1**	**LS0 -LS1**	**LS0 -LS1**

DMT spectra / ISDN linecodes [2]



Sub-carrier spacing is 4.3125 kHz - 256 total sub-carriers

Sub-carrier	Frequency	Meaning
0	0 Hz	DC-not used for data
5	25 kHz	lower limit for upstream data
18	80 kHz	Approx limit for 2B1Q ISDN
28	120 kHz	Approx. Limit for 4B3T ISDN
32	138 kHz	upper limit for upstream data
64	276 kHz	Pilot - not used for data
256	1104 kHz	Nyqvist - not used for data

ADSL system total data rate

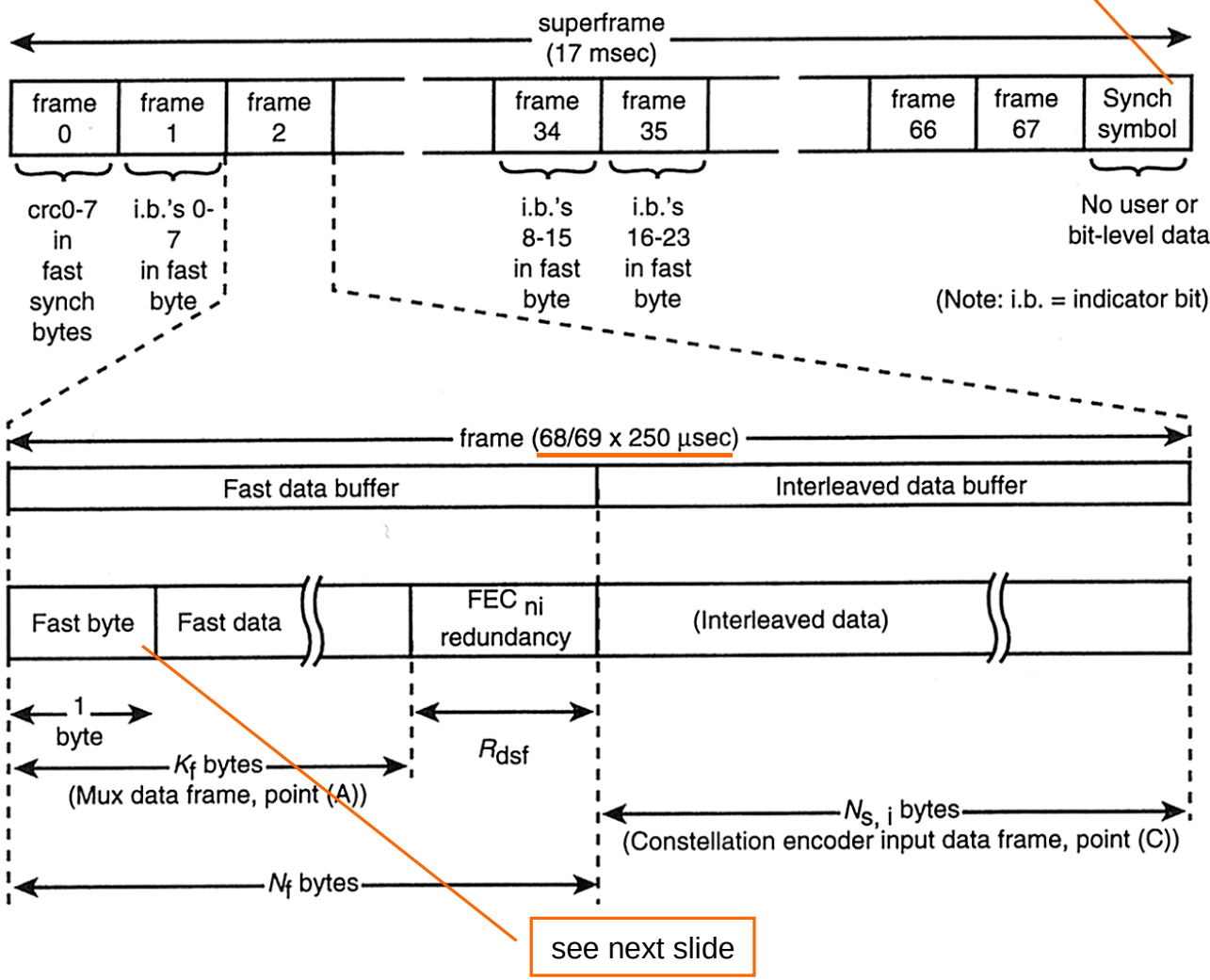
- Total data rate=Net data rate + System overheads
- The net data rate is transmitted in the ADSL bearer channels
- ADSL system overheads
  - an ADSL embedded operations channel, eoc
  - an ADSL overhead control channel, aoc
  - crc check bytes
  - fixed indicator bits for O&M*
  - Reed-Solomon FEC redundancy bytes
- These data streams are organized into ADSL frames and super-frames for the downstream and upstream data

O&M: error detection, corrected errors, loss of signal, remote defects ...

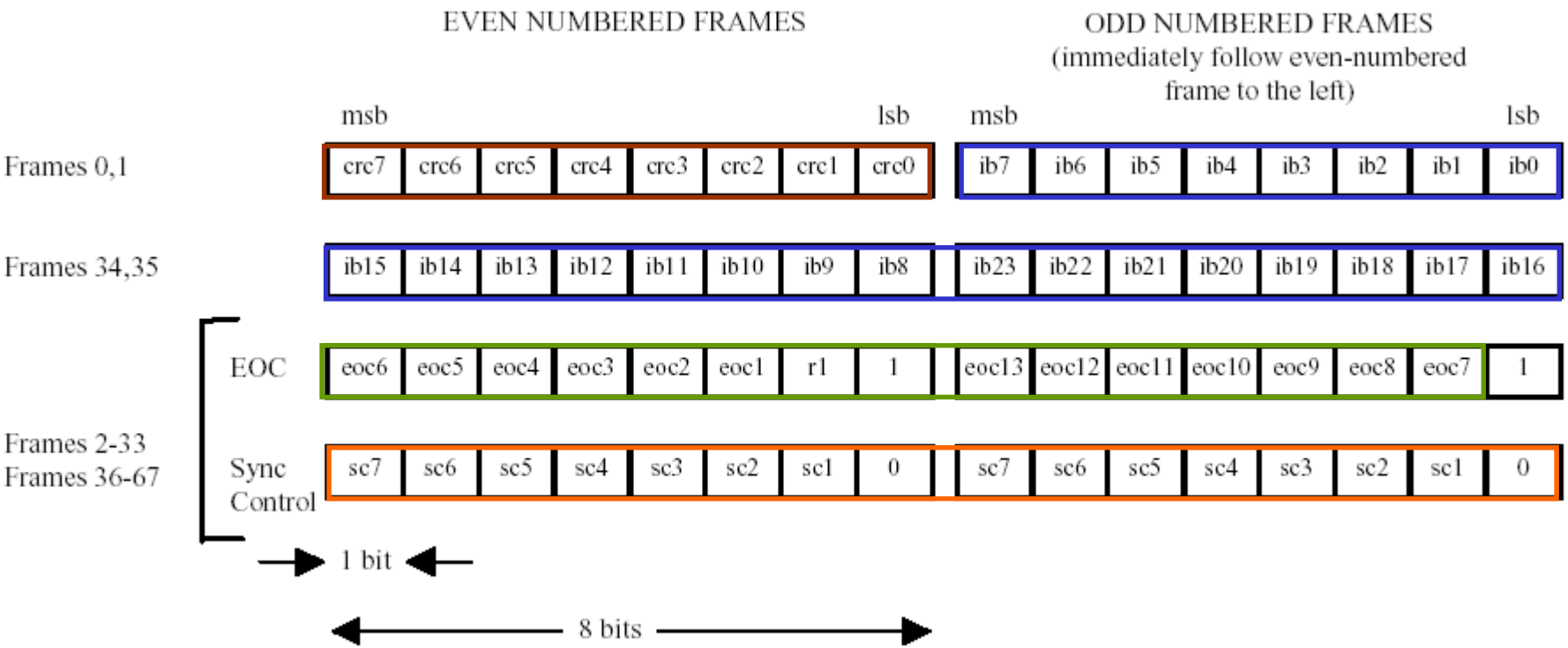
ADSL frames [3]

68 DMT data symbols, -> symbol rate ~4000/sec

- bearer channel allocation during initial setup determines ratio of interleaved and fast data frames (Nf,Ns)
- 8 crc bits (crc0-7) supervise fast data transmission
- 24 indicator bits (ib0-ib23) assigned for O&M functions

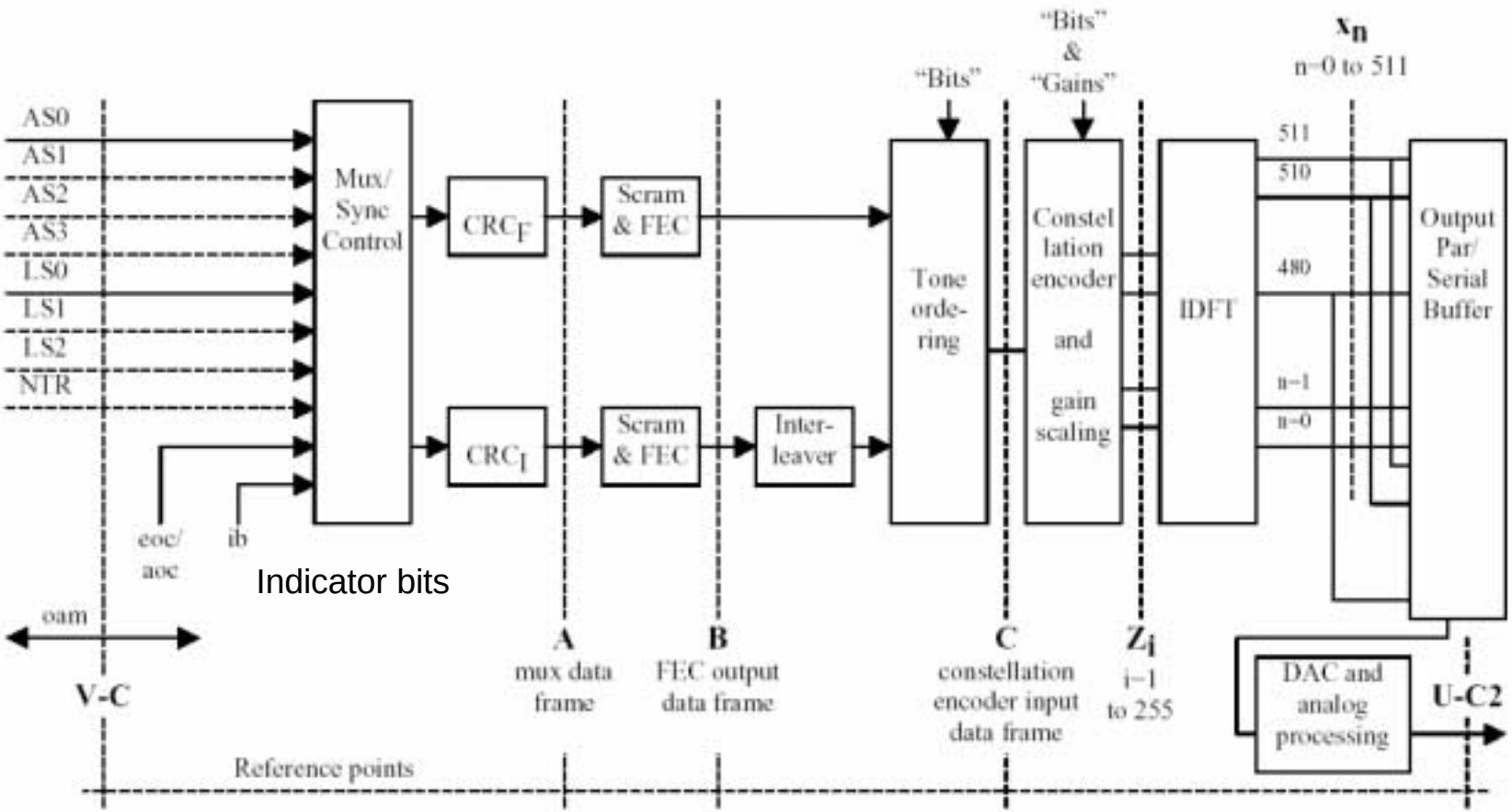


Fast sync - byte [3]



- crc: cyclic redundancy check
- ib: indicator bits (O & M)
- eoc: embedded operations channel (O & M of ATU-C and ATU-R)
- sc: synchronization control

ATU-C transmitter reference model for STM* transport [3]



Asx: any one of the simplex bearer channels AS0, AS1, AS2 or AS3
LSx: any one of the duplex bearer channels LS0, LS1 or LS2
NTR: Network Timing Reference: 8 kHz reference transmitted downstream
aoc: ADSL overhead control channel
eoc: embedded operations channel

*Synchronous transfer module of SDH (Synchronous Digital Hierarchy)

xDSL- systems

- **HDSL** -- High Bit Rate DSL
  - 1.544 Mbps (T1) or 2.048 Mbps (E1) symmetrical
  - channel associated signaling
  - 2- or 4-wire connections
- **ADSL** -- Asymmetric DSL
  - up to 8 Mbps downstream and 640 Kbps upstream
  - ATM / STM compatible
  - 2-wire compatible
  - requires splitter and separate phone line from box to wall
- **CDSL** -- Consumer DSL/ADSL-lite
  - ATM (Q.2931) signaling only
  - up to 1.555 Mbps downstream and 512 Kbps upstream
  - reduced options, performance, cost, easy to install

xDSL- systems (cont.)

- **RDSL** -- Rate-Adaptive DSL
  - adjusts transmission rates in both directions to obtain the best speed under prevailing conditions
  - otherwise like ADSL
- **SDSL** -- Symmetric DSL
  - one pair of copper wire used, 774 kbps
  - channel associated signaling or Q.921
- **VDSL** -- Very-High-Bit-Rate DSL
  - speeds up to 13- 52 Mbps DL, 1.5-2.3 Mbps UL, but for only short distances, applies ATM

xDSL systems (cont.)

- BRI ISDN (Basic Rate ISDN interface)
  - uses existing ISDN equipment, but in 'always on' mode instead of as a dial-up service. Yields 2B+D
  - up to 128 kbps + 16 kbps or X.25 with 160 kbps
  - signaling Q.921/Q.931
  - designed for speech networks
- V.90
  - 56 kbps DL, 33.6 kbps UL
  - signaling analog
  - for speech network

xDSL systems/rates/repeater spacing

ADSL	**Asymmetric Digital Subscriber Line**	Asymmetric: Downstream: 1.5Mbps -> 8Mbps Upstream: 16Kbps -> 640Kbps Range : 5400 m - 1.544Mbps 4800 m - 2.048Mbps 3600 m - 6.312Mbps 2700 m - 8.448Mbps	Internet access VoD and video access services Remote LAN access Interactive multimedia
VDSL	**Very High Data Rate Digital Subscriber Line**	Asymmetric: Downstream: 13Mbps -> 52Mbps Upstream: 1.6Mbps -> 2.3Mbps Range: 1350 m - 12.96Mbps 900 m - 25.82Mbps 300 m - 51.84Mbps	Same as ADSL and HDTV

DSL	**Digital Subscriber Line**	Duplex: 160K (2B+D+Management)	ISDN service Voice and data communications
HDSL	**High Data Rate Digital Subscriber Line**	Duplex: 2 x T.1 (1.544Mbps) / 2 x E.1 (2.048Mbps) 2 to 4 pairs of copper-wire Range : 3600 meter	T.1 and E.1 service
SDSL	**Single Line Digital Subscriber Line**	Duplex:2 x T.1 (1.544Mbps) / 2 x E.1 (2.048Mbps) 1 pair of copper-wire Range : 3000 meter	Premises access for synchronous services

Standards

ADSL standards

Semiconductors & devices: www.adsl.com

International/national standardization: ITU, ETSI, ANSI ...

Standards Body	Working Group	Standard	Purpose
ADSL Forum	Many, including UAWG SNAG	TR-00x	Industry Advisory Papers
ANSI T1	T1E1.4	T1.413, Issue 2	Basic ADSL Standard
ETSI	TM6		Close interworking with ANSI
ITU-T	Study Group 15	G.992.1	International Standards
		G.992.2	
		G.994.1	
		G.995.1	
		G.996.1	
		G.997.1	

G.full
G.lite

UAWG: Universal ADSL working group - strives to make ADSL more commercially adaptable
SNAG: Service network architecture group

Hierarchy of standards

- International level — -examples: ITU: International Telecommunications Union - yields recommendations that may be adapted by companies
- Regional/national level — -examples: ANSI (American Standards Institute) /ETSI (European Technical Standards Institute)
- Multi-corporate level — -examples: ADSL forum/ATM forum
- Corporate level — -open or proprietary standard created by a company

See also:
http://www.ktl.com/testing/telecoms/xdsl-standards.htm

Peak to T1.413 table of contents

4	**Reference models**		**9**
	4.1	System reference model	9
	4.2	ATU-C transmitter reference models	10
		4.2.1 ATU-C transmitter reference model for STM transport	10
		4.2.2 ATU-C transmitter reference model for ATM transport	11
	4.3	ATU-R transmitter reference models	12
		4.3.1 ATU-R transmitter reference model for STM transport	12
		4.3.2 ATU-R transmitter reference model for ATM transport	13
5	**Transport capacity**		**14**
	5.1	Transport of STM data	14
	5.2	Transport of ATM data	15
	5.3	ADSL system overheads and total data rates	16
	5.4	Classification by ATU options	18
6	**ATU-C functional characteristics**		**19**
	6.1	STM Transmission Protocol Specific functionalities	19
		6.1.1 ATU-C input and output V-C interfaces for STM transport	19
		6.1.2 Downstream simplex bearer channels – bit rates	19
		6.1.3 Downstream/upstream duplex bearer channels – bit rates	19
		6.1.4 Payload transfer delay	20
		6.1.5 Framing structure for STM transport	20
	6.2	ATM Transport Protocol Specific functionalities	20
		6.2.1 ATU-C input and output V-C interface for ATM transport	20
		6.2.2 Payload transfer delay	21

6.3	Network timing reference	23
6.3.1	Need for NTR	23
6.3.2	Transport of the NTR	23
6.3.3	Accuracy requirements	24
6.4	Framing	24
6.4.1	Data symbols	25
6.4.2	Synchronization	33
6.4.3	Reduced overhead framing	36
6.5	Scramblers	37
6.6	Forward error correction	38
6.6.1	Reed-Solomon coding	39
6.6.2	Interleaving	39
6.6.3	Support of higher downstream bit rates with S=1/2	40
6.7	Tone ordering	40
6.8	Constellation encoder (with trellis coding)	42
6.8.1	Bit extraction	42
6.8.2	Bit conversion	43
6.8.3	Coset partition and trellis diagram	45
6.8.4	Constellation encoder	48
6.9	Constellation encoder (without trellis coding)	52
6.9.1	Bit extraction	52
6.9.2	Constellation encoder	52
6.10	Gain scaling	53
6.11	Modulation	53

References

[1] T. Starr, J.M. Cioffi, P.J. Silverman: Understanding Digital Subscriber Line Technology, Prentice-Hall

[2] W.Y. Chen: DSL Simulation Techniques and Standards - Development for Digital Subscriber Line Systems, MacMillan Tech. Publishing

[3] C.K. Summers: ADSL - Standards, Implementation and Architecture, CRC Press

[4] William Stallings: Data and Computer Communications (7th Ed), Prentice Hall

[5] ANSI T1.413, issue 2 standard