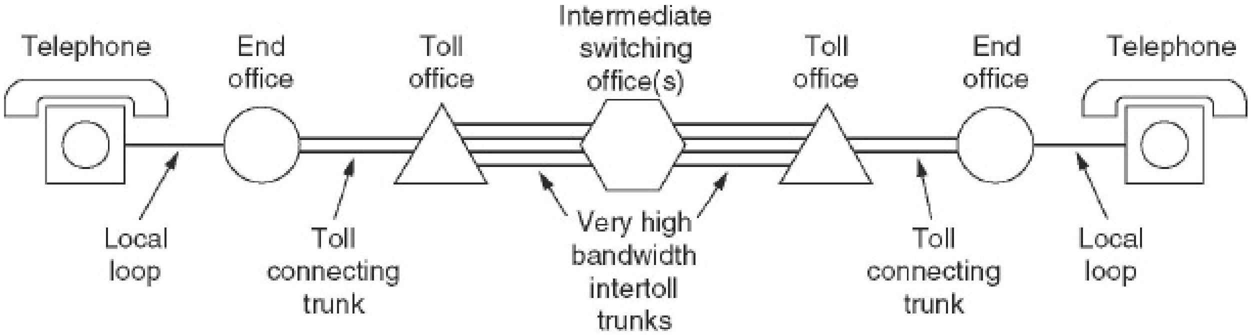
7. ADSL and High-Rate Digital Communication

7. 1 Digital Subscriber Line Technologies

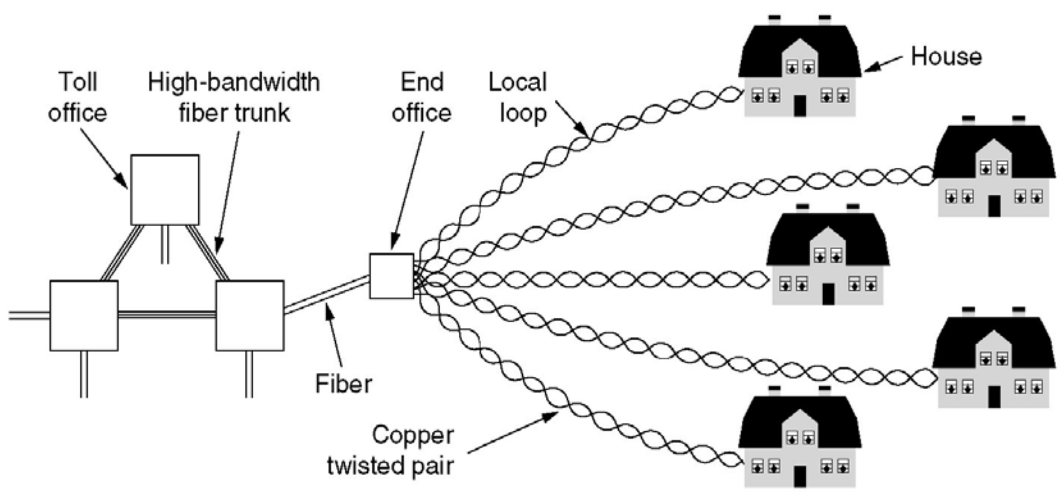
Digital Subscriber Line Technologies (xDSL) is a revitalized transmission technology facilitating simultaneous use of Plain Old Telephone Services (POTS) and data transmission of up to 6.0 Mbits/s over the existing infrastructure of copper wiring. In particular, Asymmetric DSL (ADSL) is a newly standardized technique (ANSI/T1.413). During the past couple of years, xDSL have attracted a great deal of attention as the access solution of the future in both the home and business application environments. Originally, xDSL technologies were proposed as an intermediate access solution for the residential area before the extensive installation of hybrid fiber coax (HFC) or fiber to the home (FTTH). It has become apparent that these last two systems will not be widely accepted in decades so the intermediate solution of xDSL is now seen as a deployment for at least few decades.

Telephone Network or Subscriber Line: For voice and even for data and video transmission, the existing POTS have the following have been configured as follows:



where:

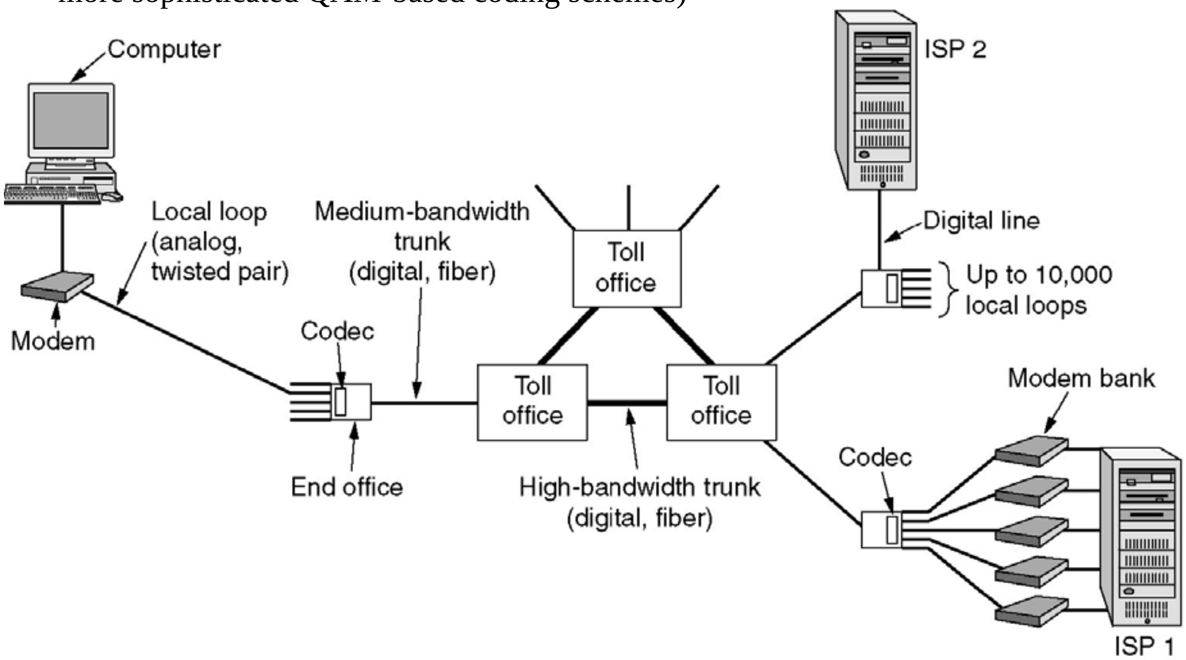
1 Local loop: analog link connecting your home to the toll offices
2 Trunks: Digital fiber optics connecting these toll offices/switching offices etc.
3 Switching offices: calls are moved from one trunk to another to connect the users
4 Except for the local loop, all others are digital.
5 Physical media are shown below.



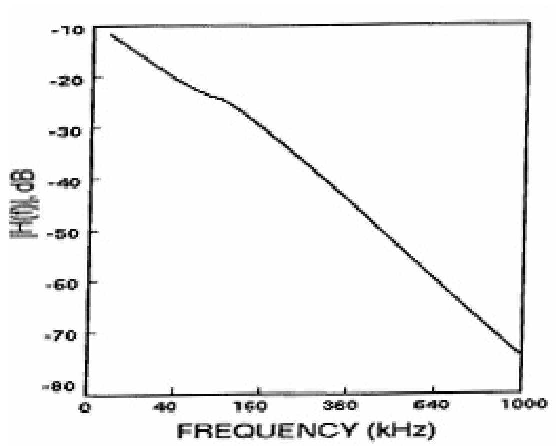
1 With the wide-spread penetration of the internet into our homes, the scenario has been shifted heavy phone usage to data communication. In many cases, it is more than 90% the traffic is internet traffic.
2 For decades, conventional wisdom has held that analog modems would reach (did reach)

56 kbits/s ceiling in terms of maximum possible bandwidth without compression. However, it is worth noting that Shannon's limit: 35,000 bps (assuming analog conversions at both end points).

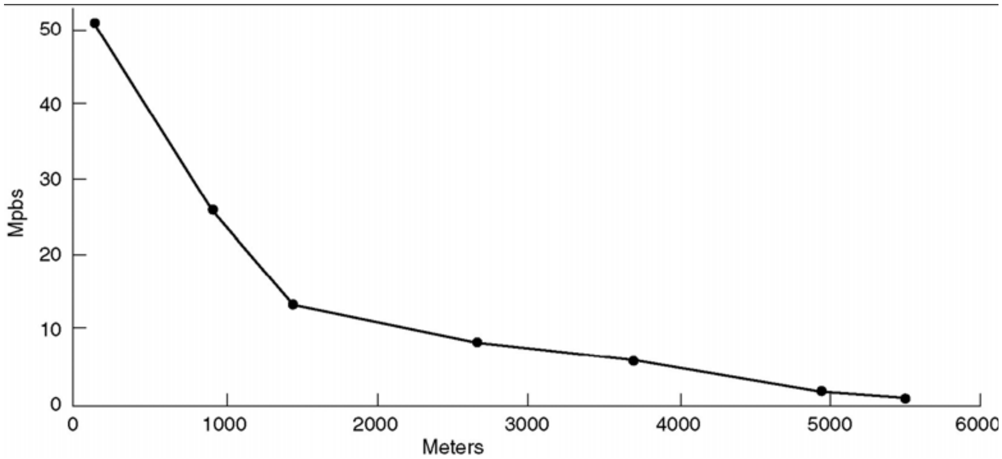
3 By sending more bits per symbol, we can reach higher speeds 56,000 bps (e.g., V.34 bis encoding uses 14 data bits/symbol at 2400 baud to achieve 33600 bps and V.90, V.92 have more sophisticated QAM-based coding schemes)



4 In actuality, the 56 kbits/s magic number refers to only to the amount of bandwidth that is theoretically possible over the audible spectra of frequencies, which is the bottom 4.0 kHz of total spectra available on a typical pair of telephone wire. Below, we present the attenuation characteristics for a typical twisted-pair (12 gauge, 12,000 ft) wire.



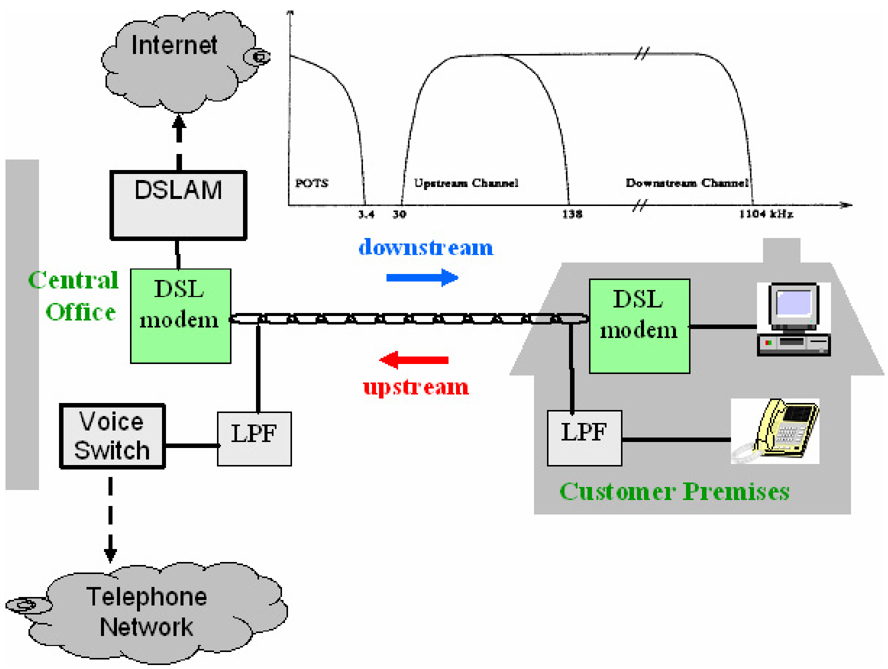
5 More critically, we plot the capacity versus transmission distance under the new regimes used in xDSL technologies.



As it can be seen from the figure that the digital transmission rates of up to 6.0 Mbits/s for distances 6,000 ft or less (1 Km or less) is possible over the majority of the existing twisted-pair copper wire installations throughout the world.

2. How xDSL systems utilize the copper subscriber loop?

ADSL and its technological cousins can be seen as an Orthogonal Frequency-Domain Multiplexing (OFDM) system in which the available bandwidth of a single copper-loop is divided into three parts. In particular, the ADSL spectrum shown here has a splitter to guarantee a ***simultaneous*** POTS channel for the lowest 3.4-4.0 kHz and a digital data channel on the remaining 30-1,104 kHz.



ADSL standard, as the adjective “asymmetric”, allocates 30-138 kHz for the upstream data and the rest to the downstream information sequences in an uneven fashion. However, typical splitters used in home restrict bandwidth to 1.5 Mbps Before we go into the system details let us discuss a few applications for the xDSL technologies.

	G.DMT ADSL	Asymmetric DMT VDSL
Data band	0.025 – 1.1 MHz	0.138 – 12 MHz
Upstream subcarriers	32	256
Downstream subcarriers	256	2048/4096
Target up-stream rate	1 Mbps	3 Mbps
Target down-stream rate	8 Mbps	13/22 Mbps

7. 2 Applications of Digital Subscriber Line Technologies

1. **Intranet Access:** An organization that has already implemented an Intranet will require the higher bandwidth afforded by xDSL to link their office/branch offices and telecommuters to the more demanding business oriented applications.
   Some more terminology:
   IP : Internet Protocol.
   ATU-C: ADSL Terminal Unit for CO.
   ATU-R: ADSL Unit for the remote site.
2. **Low-Cost and High-Throughput, LAN-to-LAN Connectivity**: These emerging xDSL technologies have the potential to prove far more effective in this role than ISDN or traditional leased lines.
3. **Frame Relay Access:** Since xDSL operates at the physical layer, it could emerge as the most cost-effective method of carrying frame relay traffic from the service subscriber to the frame relay network.
4. **ATM Network Access:** As with (3), xDSL can also be used to carry ATM cells to an ATM access device, where they are statistically multiplexed over an ATM backbone.
5. **Leased Line Provisioning:** xDSL can be used to greatly reduce the cost of provisioning T-1/E-1 lines from the central office (CO) to the customer's site.

7.3 Speeds and Feeds for ADSL Systems

ADSL as presently standardized is defined as having (7) transport classes: 4 classes based on multiples of T-1 (1.5 Mbits/s) downstream bandwidth and three classes based on E-1 (2.0 Mbits/s) bandwidth as tabulated below.

Type	Maximum Length of Local Loop	Maximum Downstream Rate	Maximum Upstream Rate
T1	5.5km	1.5 Mbps	384 Kbps
E1*	4.6km	2.0 Mbps	384 Kbps
T2	3.7km	6.1 Mbps	384 Kbps
E2*	2.7km	8.4 Mbps	640 Kbps

There are several digital subscriber loop technologies related to ADSL.

1. **Symmetric DSL (SDSL):** The same amount of BW is allocated to both upstream and downstream links. The price paid for maintaining BW symmetry is lower aggregate BW.

Systems operating at 384 kb/s, 768 kb/s, 1.5 Mb/s (T-1) and 2 Mb/s (E-1) are available. Because of theses restrictions SDSL is not likely to be a serious contender in low-cost markets.

2. **Very-High Rate DSL (VDSL):** Like the ADSL case, it is an asymmetrical transmission scheme operating in the range 30-51 Mb/s over extremely short distances (150-300 m). It is anticipated that VDSL can have market penetration in conjunction with fiber to the curb (FTTC) deployment in its last link between the curb and the user terminal equipment.

Type	Maximum Length of Local Loop	Maximum Downstream Rate	Maximum Upstream Rate
¼OC-1	1250m	12.96 Mbps	1.6 Mbps
½OC-1	900m	25.92 Mbps	2.3 Mbps
OC-1	300m	51.84 Mbps	2.3 Mbps

3. **Rate-Adaptive DSL (RA-DSL):** Here the line speed is automatically adjusted based on a series of initial tests that determine the maximum speed possible on a given line. This is designed to take the guesswork out of the picture on the gauge of the wire, the variations in length, and the condition of the loop.

4. **High-Bit-Rate DSL (HDSL):** It is the most widely deployed xDSL technology and it has been commercially available for sometime now. Unlike the other xDSL technologies, HDSL uses 2-pairs of copper cable rather than one and does not carry POTS. They provide either 1.5 or 2 Mb/s of symmetrical BW up to 4,000 meters from the CO. It is attractively used in T-1/E-1 provisioning since it eliminates the need for repeaters, loop conditioning, or pair selection. These advantages have been one of the reasons why the lease line prices have come down significantly.

7.4 Selected Other Broadband Systems

Standard	*Meaning*	*Data Rate*	*Mode*	*Applications*
ISDN	Integrated Services Digital Network	144 kbps	Symmetric	Internet Access, Voice, Pair Gain (2 channels)
T1	T-Carrier One (requires two pairs)	1.544 Mbps	Symmetric	Enterprise, Expansion, Internet Service
HDSL	High-Speed Digital Subscriber Line (requires two pairs)	1.544 Mbps	Symmetric	Pair Gain (12 channels), Internet Access, T1/E1 replacement
HDSL2	Single Line HDSL	1.544 Mbps	Symmetric	Same as HDSL except pair gain is 24 channels
G.Lite ADSL	Splitterless Asymmetric Digital Subscriber Line	up to 1.5 Mbps up to 512 kbps	Downstream Upstream	Internet Access, Digital Video
G.DMT ADSL	Asymmetric Digital Subscriber Line	up to 10 Mbps up to 1 Mbps	Downstream Upstream	Internet Access, Digital Video
VDSL	Very High-Speed Digital Subscriber Line (proposed)	up to 22 Mbps up to 3 Mbps up to 13 Mbps	Downstream Upstream Symmetric	Internet Access, Digital Video, Broadcast Video

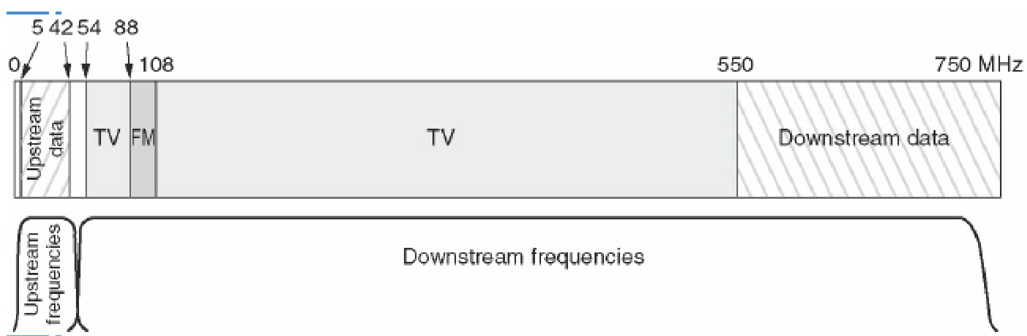
7.5 xDSL Systems vs. Cable Modems

Cable modems designed to provide multi-megabit BW over existing CATV networks is the primary competitor for xDSL family in the residential access market.

2 Cable was designed for pumping lots of channels/data downstream.
3 During the last years of the past decade digital data service offered by cable TV operators.
4 **DOCSIS:** Data Over Cable Service Interface Specifications is the industry norm (not a standard!) for cable modems used by service providers.
5 In theory: Downstream: 27-55 Mbps upstream: 2-10 Mbps
6 Typical: Downstream: 500Kbps-2 Mbps upstream: 200 kbps-2 Mbps
7 Some of the cable companies offer downstream services only and upstream is to be done via telephone services. (Two modems, two service provisions!)

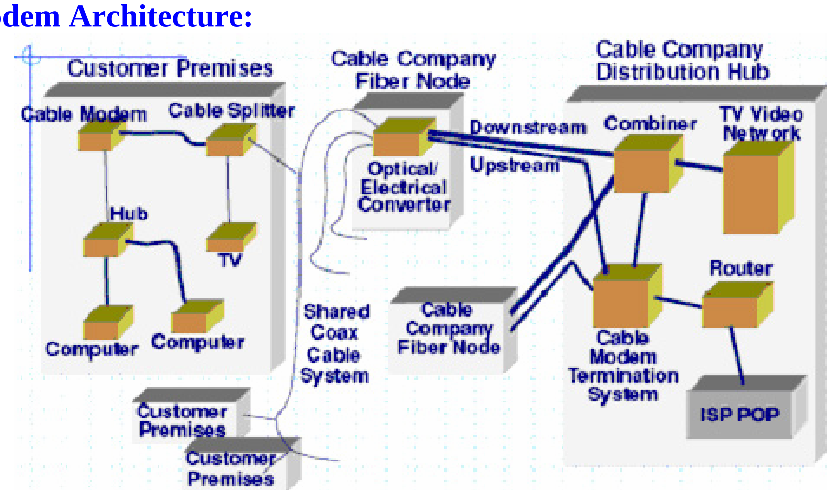
Cable Modem Architecture:

- Cable modems: Because of shared multi-point circuits, all messages on the circuit are heard by all computers, which has security issues.
- 300-1000 customers per cable segment is common load.
- Cable modems are called: **Cable Modem Termination System (CMTS)**
- Combiner: Needed for downstream traffic to combine internet traffic with TV video



Cable Service Providers Spectrum

Basic Cable Modem Architecture:

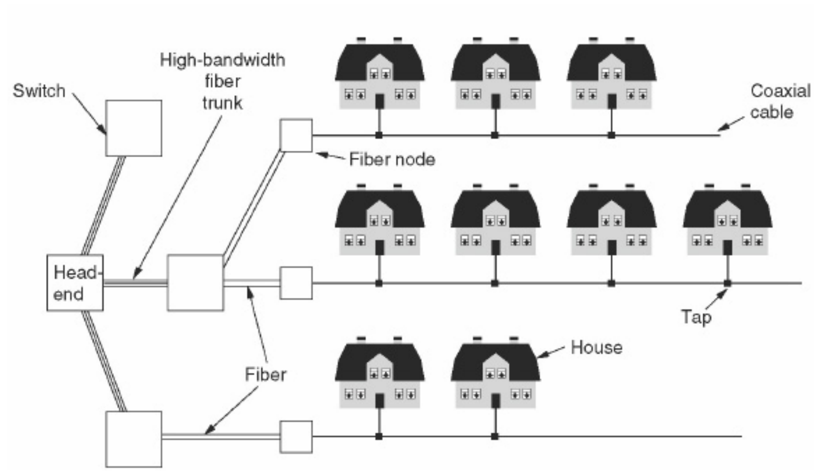


Data services based on CATV's coaxial cable network infrastructure possess a number of shortcomings in comparison with the DSL family products:

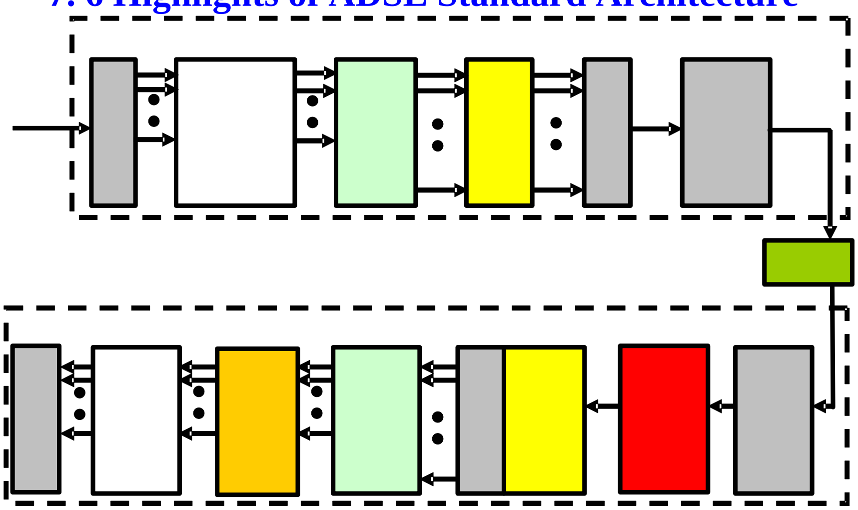
(i) DSP technology is a point-to-point communication technology.

(ii) Cable Modems are configured for **"Shared Bandwidth Access:"** All users in the service area must share the available bandwidth. Even though, cable modems can provide raw BW up to aggregate rate of 51 MB/s, each time a subscriber is added in a given service area, the BW available to each user is decreased. For instance, if 100 subscribers are in a service area, then effectively each user has 300 kb/s if the overall rate were 30 Mb/s.

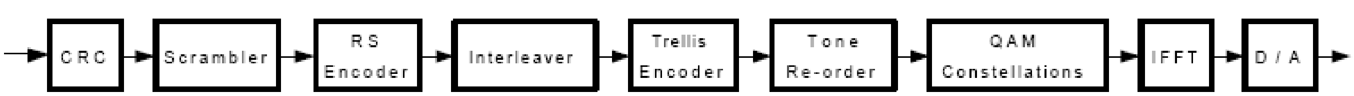
(iii) Cable modem services lack penetration in commercial areas.
(iv) Cable modem services lack penetration in rural areas.
(v) Security.
(vi) Cable modem services do not have sizeable and organized CATV infrastructure outside North America and Japan to build a viable price-competitive technology in the long run.
(vii) Price of ADSL services is coming down drastically (US$14.95-19.95/monthly in Southern California, but cable companies are somewhat higher with an initial cable hookup charge of $40+/month)
(viii) Cable companies lack experience in network management, and most critically
(ix) **"Shared Bandwidth Access:"** All users in the service area must share the available bandwidth. Even though, cable modems can provide raw BW up to aggregate rate of 51 MB/s, each time a subscriber is added in a given service area, the BW available to each user is decreased. For instance, if 100 subscribers are in a service area, then effectively each user has 300 kb/s if the overall rate were 30 Mb/s.



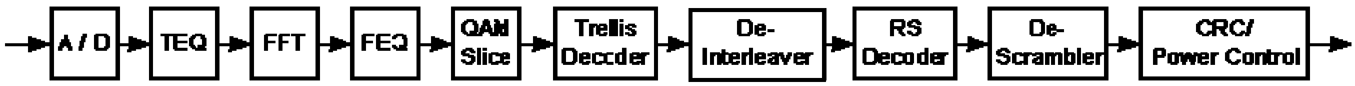
7. 6 Highlights of ADSL Standard Architecture



Transmitter Blocks:



Receiver Blocks:

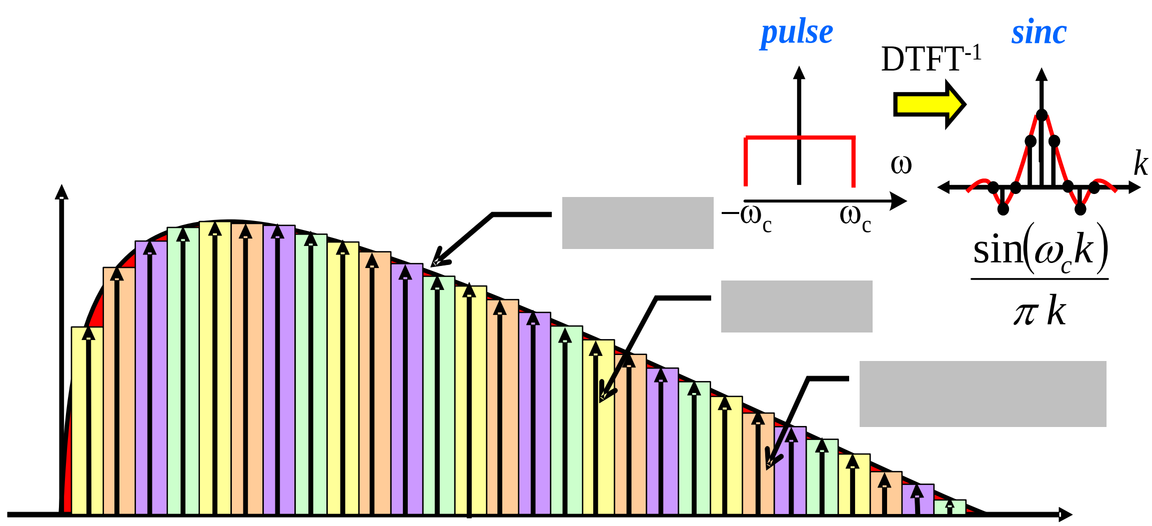


Decomposed and routed data from the digital network is connected to an ATU-C (Transceiver Unit-Central Office) where the data is converted into analog signals. The analog signals are then multiplexed and carried with POTS signals to the remote end. ATU-C also receives and decodes data coming from customer premises sent by ATU-R (Remote.) In addition to combining or separating, the splitter also protects POTS from voice-band interference generated by both ATU's. Similarly, it protects ATU's from POTS-related signals as well.

Discrete Multitone DSL Standards

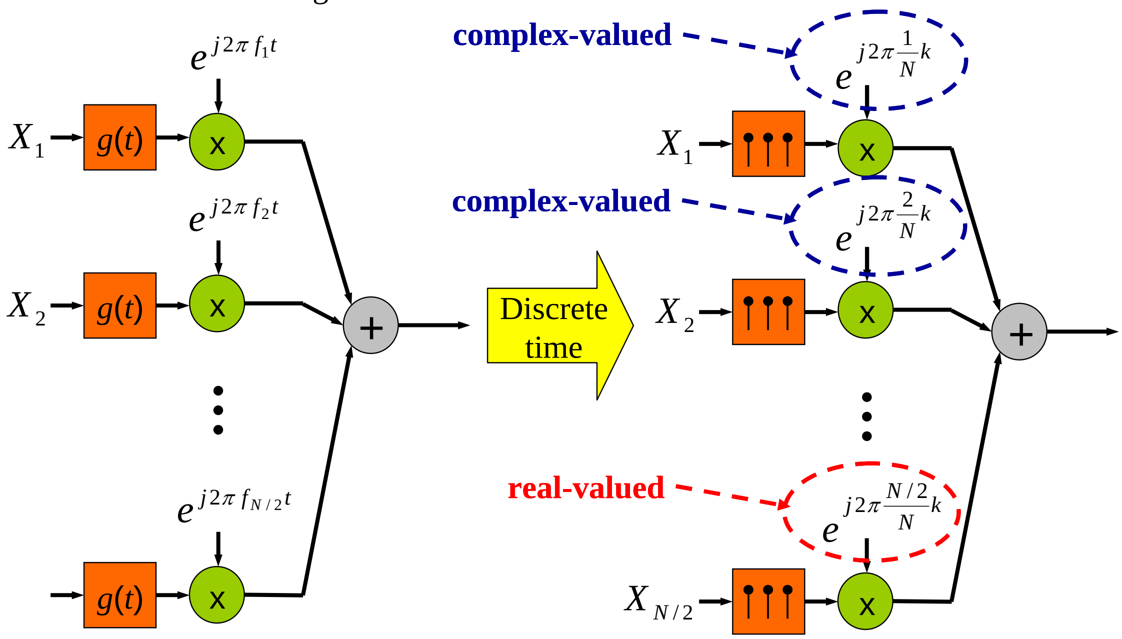
Multi-carrier Modulation: Transmitter has a multi-carrier modulator. At the operational bit rates sophisticated equalizers for each tone are needed, which are normally based on LMS algorithm due to B. Widrow at Stanford.

- **ADSL – Asymmetric DSL (G.DMT)**
  - *Asymmetric*: 8 Mbps downstream and 1 Mbps upstream
  - *Data band*: 25 kHz – 1.1 MHz
  - Maximum data rates possible in standard (ideal case)
    - Echo cancelled: 14.94 Mbps downstream, 1.56 Mbps upstream
    - Frequency division multiplexing: 13.38 Mbps downstream, 1.56 Mbps up
  - Widespread deployment in US, Canada, Western Europe, Hong Kong
    - Central office providers only installing frequency-division ADSL
    - ADSL modems have about 1/3 of market, and cable modems have 2/3



- **VDSL – Very High Rate DSL**
  - *Asymmetric*: either 22/3 or 13/3 Mbps downstream/upstream
  - *Symmetric*: 13, 9, or 6 Mbps each direction
  - *Data band*: 1 – 12 MHz
  - DMT and single carrier modulation supported
  - DMT VDSL essentially higher speed version of G.DMT ADSL

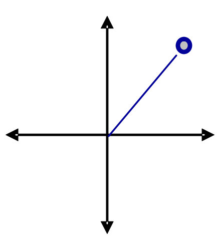
Multi-carrier Modulation using **Inverse FFT Filter Bank**:

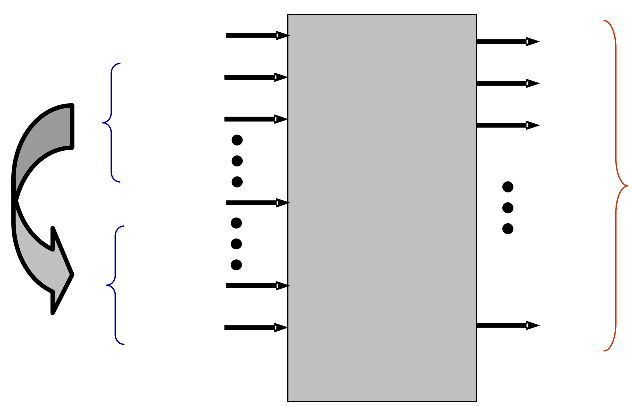


$g(t)$: pulse shaping filter $\quad$ X_i : i^{th} subsymbol from encoder

Modulation of N/2 symbols, in general complex-valued and:

1 **Training Mode:** ADSL uses 4-level Quadrature Amplitude Modulation (QAM)
2 **Data Transmission Mode:** ADSL uses QAM of 22, 23, 24, …, 215 levels



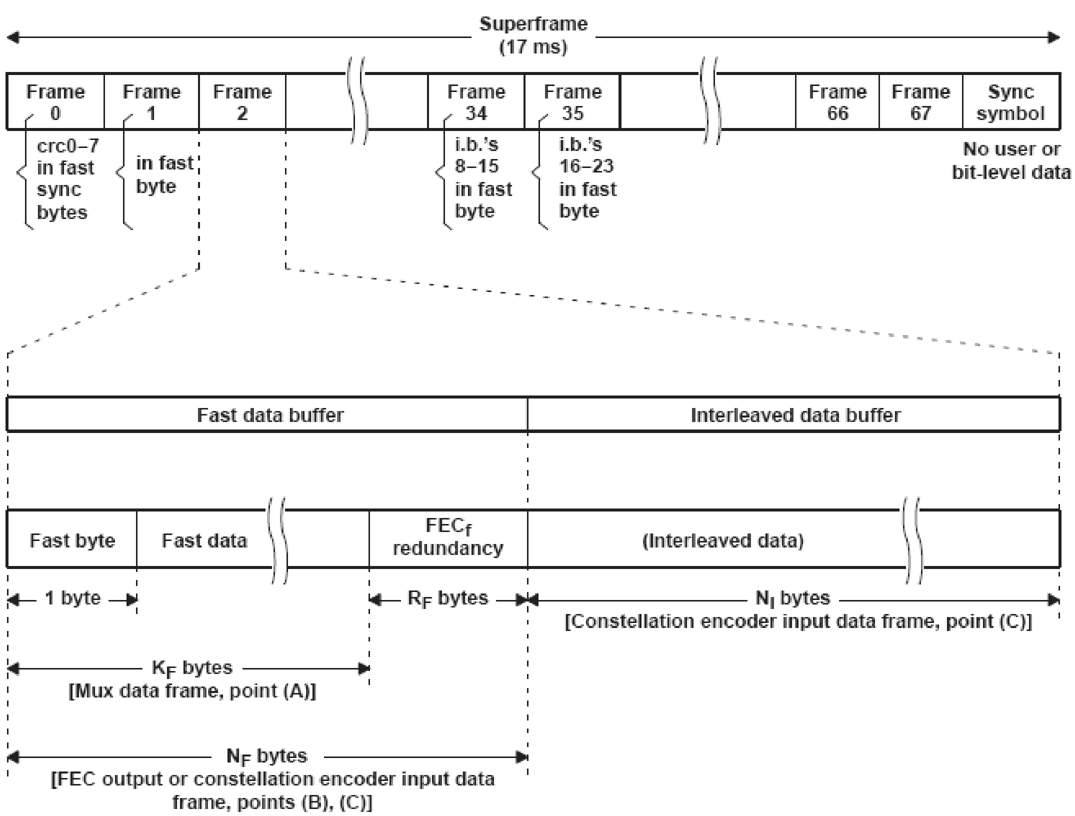


Framing Structure: The downstream and upstream data channels are synchronized to the 4.0 kHz ADSL Discrete Carrier (Tone) (DMT) symbol rate, and multiplexed into two separate data buffers called "fast" and "interleaved." It uses a superframe structure shown below.

Framing Modes:

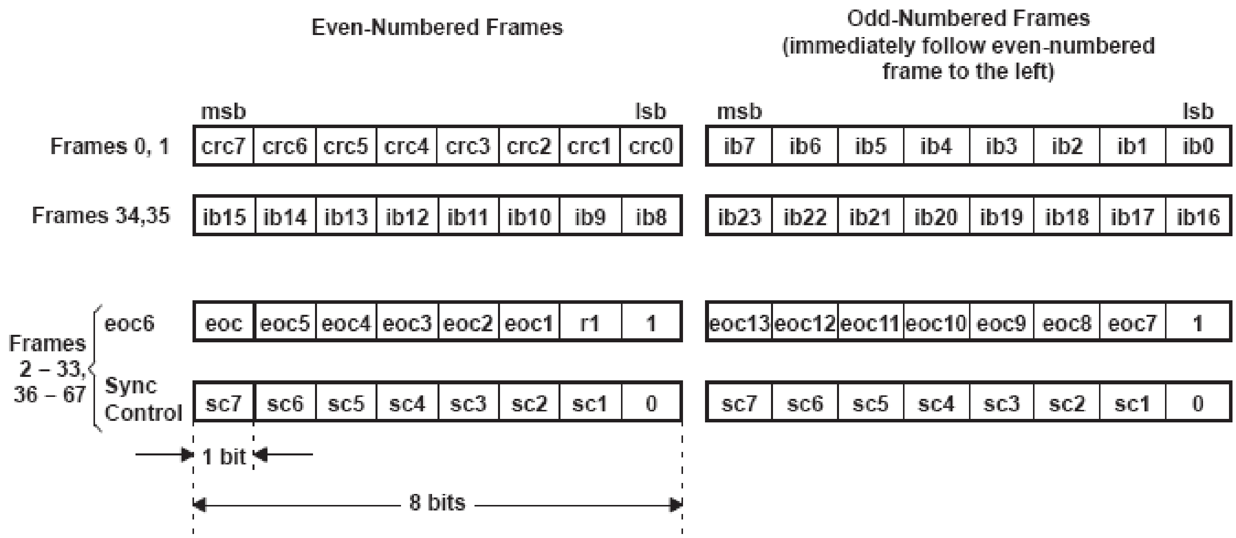
Framing Structure	Description
0	Full overhead framing with asynchronous bit-to-modem timing. (i.e., enabled synchronization control mechanism)
1	Full overhead framing with synchronous bit-to-modem timing. (i.e., disabled synchronization control mechanism)
2	Reduced overhead framing with separate fast and sync byte in fast and interleaved latency buffer respectively. (i.e., 64K bits framing overhead)
3	Reduced overhead framing with merged fast and sync byte, using either the fast or the interleaved latency buffer. (i.e., 32K bits framing overhead)

1. Each ADSL superframe is composed of 68 ADSL data frames and
2. One synchronization symbol, which are encoded and modulated into DMT symbols.
3. The period for whole superframe transmission is 68/4KHz=17ms.
4. From the bit-level and user data perspective, the DMT symbol rate is 4,000 bauds with a symbol period of 250 s. Since one sync symbol is inserted to the end of each superframe.
5. The resulting transmitted symbol rate is $(69/68)*4000$ bauds.



ADSL Super Frame Structure

6. During each ADSL superframe in full overhead mode, the first byte of the fast data buffer (“fast byte”) carries the CRC check bits in frame 0 and the OAM indicator bits in frames 1, 34, and 35, where $(ib_0 - ib_{23})$ are assigned for OAM functions (Operation, administration, and maintenance).
7. The fast byte in other frames is assigned in even-/odd-frame pairs to either the EOC or to synchronization control of the bearer channels assigned to the fast buffer. As a result, out of 68 data frames in a superframe in 17ms period, 64 frames (except frame 0,1,34, and 35) can carry an EOC byte in full overhead mode.



Fast Synchronization Byte (“fast byte”) Format in Full Overhead Mode

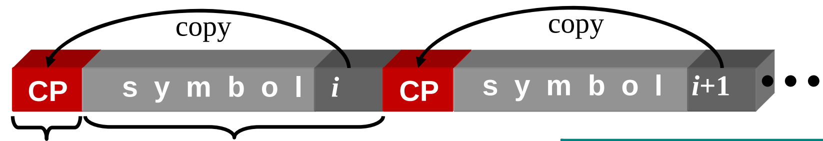
8. One EOC message is composed of 13 bits, which are carried by two data frames’ fast data buffer (refer to Table 2). When bit5=0, the EOC message is set to autonomous transfer (clear EOC) . Bit 6~13, totally 8 bits are payload among 13 bits of an EOC message. Assuming all EOC bandwidth is occupied by clear EOC, **64frame/2*8bits payload/17ms=15Kbps** is EOC maximum capability in full overhead mode.

Field No.	Bit (s)	Description	Notes
1	1, 2	Address field	Can address 4 locations
2	3	Data (0) or opcode (1) field	Data used for read/write or when an autonomous data message is sent
3	4	Byte parity field Odd (1) or even (0)	Byte order indication for multi-byte transmission
4	5	Autonomous message field: ATU-C ❑ set to 1 for ATU-C commands sent to ATU-R ❑ set to 0 for autonomous transfers ATU-R ❑ set to 1 for response to ATU-C command ❑ set to 0 for autonomous transfers	Set to 0 by ATU-R to send dying gasp message or autonomous data transfers
5	6–13	Information field	One out of 58 opcodes or 8 bits of data

EOC Message Fields

9. Each user data stream is assigned to either fast or the interleaved buffer during initialization.

- **Frame is sent through D/A converter and transmitted**
  - Frame is the symbol with cyclic prefix prepended
  - Cyclic prefix (CP) consists of last ν samples of the symbol



ν samples N samples

- CP reduces throughput by factor of $\frac{N}{N+\nu} = \frac{16}{17}$

ADSL G.DMT Values		
	Down stream	Up stream
ν	32	4
N	512	64

- **Linear convolution of frame with channel impulse response**
  - Is circular convolution if channel length is CP length plus one or shorter
  - Circular convolution ⇨ frequency-domain equalization in FFT domain
  - Time-domain equalization to reduce effective channel length and ISI

Scrambling and Forward Error Correction (FEC):

If the n^{th} output from the fast or interleaved buffer is d_n and $d_n^{'}$ is the n^{th} output from the corresponding scrambler, data streams from both the fast or interleaved buffers are scrambled separately according to:

$$d_n^{'} = d_n \oplus d_{n-18}^{'} \oplus d_{n-23}^{'} \qquad (7.1)$$

Forward error correction is based on Reed-Solomon coding, which we have studied in Chap 5. In the ADSL terminology, the size of the RS codeword is defined by $N = K + R$, in which the number of check bytes are R and the codeword size is N depending on the number of bits assigned to either fast or interleaved buffer.

- RS codewords in the interleave buffer are convolutionally interleaved and the interleaving depth values are either 16, 32, or 64 for 1.5 Mb/s-based systems and they are 32 or 64 for 2 Mb/s-based systems.

.Constellation Encoding:

Constellation encoding can be implemented with or without “trellis coding.” However, for high rates it is unavoidable. It is based on an improved version of Ungerboeck Codes due to Wei. It is has 4-dimensional trellis coder with 16-states.

1. For a given sub-channel, the encoder selects an odd point (X,Y) from the square-grid based on b bits: $\{v_{b-1}, v_{b-2}, \cdots v_1, v_0\}$.
2. These b bits are identified with an integer label whose binary representation is given by: $(v_{b-1}, v_{b-2}, \cdots v_1, v_0)$. For instance: for b=2, the 4 constellations are labeled 0,1,2,3 as shown below.

3. Even values of b: Higher order constellations are obtained from the 2-bit ones above by replacing each label by the 2x2 block of labels: $\begin{Bmatrix} 4n+1 & 4n+3 \\ 4n & 4n+2 \end{Bmatrix}$
4. Odd values of b: Using the 3-bit labeling as basis, the two MSB of X and the two MSB of Y

are determined by the five MSBs of the b bits. For instance, the 7-bit constellation is obtained by replacing each label n by the same 2x2 labeling scheme given above.

ADSL DMT Modulation Details:

- Downstream channels are divided into 256 4kHz-wide tones.
- Upstream channels are divided into 32 sub-channels.
- Pilot: Carrier-64 ($f = 276\,kHz$) is reserved for a pilot tone. The data modulated into the pilot sub-carrier is a constant 0,0. Use of this pilot allows resolution of sample timing in a receiver modulo-8 samples.
- The carrier at the Nyquist frequency (256) may not be used for data.

Let $\{a_k[n]\}$ and $\{b_k[n]\}$ be two real-valued sequences of length M to be transmitted over a bandlimited channel. We assume that these are operating at a sampling rate F_S.

- Define a new set of complex sequence of length N=2M by:

$$\alpha_k[n] \equiv \begin{cases} 0 & k = 0 \\ a_k[n] + jb_k[n] & 1 \le k \le (N/2) - 1 \\ 0 & k = N/2 \\ a_{N-k}[n] - jb_{N-k}[n] & (N/2) + 1 \le k \le N - 1 \end{cases} \qquad (7.2)$$

It is worth noting that this definition guarantees a real-valued signal due to the Hermitian symmetry above.

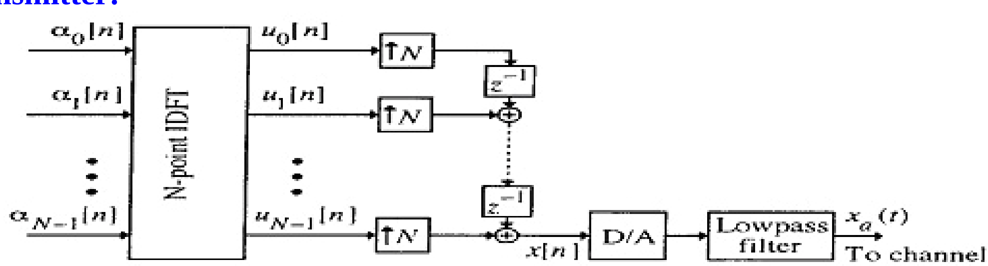
- Let us apply an inverse DFT(IDFT) to for a new set of N signals:

$$u_l[n] = (1/N).\sum_{k=0}^{N-1} \alpha_k[n].W_N^{-lk} \quad for\ l = 0,1,\cdots,N-1 \qquad (7.3)$$

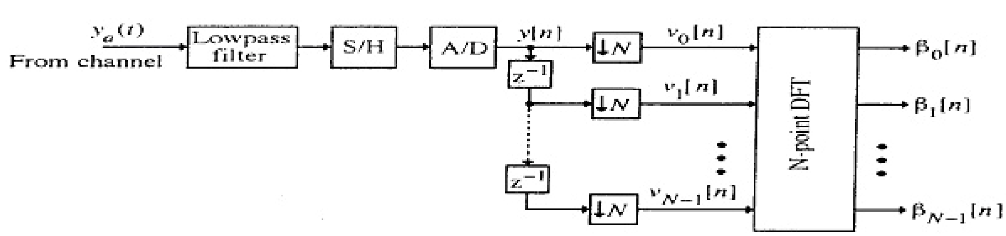
where $W_N = \exp\{-j\frac{2\pi}{N}\}$ is the N-point DFT kernel.

- Each of these N signals is then up-sampled by a factor of N and time-interleaved to generate a composite signal $\{x[n]\}$ operating at a rate: $N.F_S = 2.F_c$.
- The composite signal is converted into an analog signal $x_a(t)$ by passing it through a D/A followed by a synthesizing LP filter. The analog signal is then transmitted over the channel.

DMT Transmitter:



DMT Receiver:



- At the receiver, the received possibly corrupted signal $y_a(t)$ pre-processed and digitized at a rate $NF_S = 2F_C$.
- They are de-interleaved by a delay chain of N-1 units whose outputs are then downsampled by a factor N to generate the signal set $\{v_l[n]\}$.
- Applying DFT to these N-signals will result in

$$\beta_k[n] = \sum_{l=0}^{N-1} v_k[n].W_N^{lk} \quad for\ l = 0,1,\cdots,N-1 \tag{7.4}$$

- If we assume the frequency the frequency response of the channel is flat passband, and the processes between IDFT and DFT operations are lossless then we can show that

$$y[n] = x[n]$$

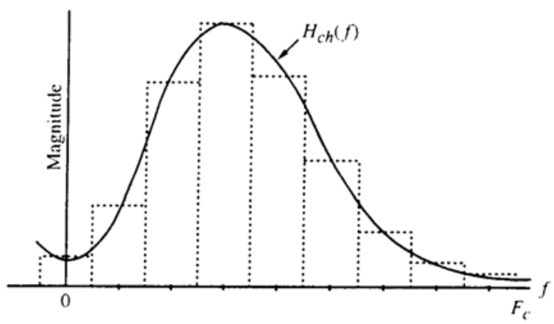


Figure 11.64 Frequency response of a typical bandlimited channel.

- Since the transmission channels have a bandpass frequency response $H_{ch}(f)$ with a magnitude response falling to zero at some frequency F_C, we need to use a channel equalizer for reliable transmission as discussed earlier.
- For large DFT length, as the case in ADSL systems, the channel can be treated as a composition of a series of contiguous narrow bandwidth bandpass sub-channels with flat top (dotted lines.)
- In this case, each sub-channel can be approximated by a single complex number given by the value of its frequency response at $w = 2\pi k / N$. These values can be determined by first transmitting a known signal to train the system as mentioned in ADSL structures above. The actual data samples are then divided by these complex numbers at the receiver to compensate for channel distortion.

ATU-C Modulation by the Inverse Discrete Fourier Transform (IDFT):

If a particular data sequence is assigned the i^{th} point on the 2-D constellation with coordinates:

$$(X_i, Y_i) \quad \Rightarrow \quad Z_i = X_i + jY_i \tag{7.5}$$

and if the encoder output is multiplied by a fine gain adjuster:

$$Z_i^{'} = g_i . Z_i \tag{7.6}$$

Then modulating transform determines between these weighted complex values the 512 real values:

$$x_k = \sum_{i=0}^{511} Z_i^{'}.\exp(j\frac{\pi ki}{256}) \quad for\ k = 0,1,\cdots,511 \tag{7.7}$$

In order to generate real values of x_k we must augment them to have Hermitian symmetry:

$$Z_i^{'} = conj[Z_{512-i}^{'}] \quad for\ i = 257,\cdots,511 \tag{7.8}$$

Synchronization Symbols: Synchronization symbol permits recovery of the frame boundary after micro-interruptions that might otherwise necessitate retraining, which could be costly.

- Symbol rate: $f_{sym} = 4{,}000$; Sub-carrier separation : $\Delta f = 4{,}312.5\,Hz$
- IDFT Size: $N = 512$ then a cyclic prefix of (40) samples could be used:

$$(512 + 40)x4000 = (512x4312.5) = 2{,}208{,}000 \tag{7.9}$$

- The cyclic prefix, however, is shortened to (32) samples and a synchronization symbol with a nominal length 544 is inserted after every 68 data samples:

$$(512 + 32)x69 = (512 + 40)x68$$

- Data pattern used in the synchronization symbol is a pseudo-random sequence with a specific generation structure and a seed.
- The last (32) samples of the output of the IDFT is appended to the block of 512 samples and read out to the DAC in sequence: $x_{480}, x_{481}, x_{482}, \cdots, x_{511}, x_0, \cdots, x_{511}$.

ATU-R Modulation by the Inverse Discrete Fourier Transform (IDFT):

- Maximum number of sub-carriers is 31 and carrier_16 is reserved for pilot.
- Modulating transform is adjusted to reflect that:

$$x_k = \sum_{i=0}^{63} Z_i^{'}.\exp(j\frac{\pi ki}{32}) \quad for\ k = 0,1,\cdots,63 \tag{7.10}$$

The encoder generates only 31 complex values of $Z_i^{'}$ plus zero at DC and one real value if Nyquist frequency is used. In order to generate real values from (7.10), this time the Hermitian symmetry condition is changed to:

$$Z_i^{'} = conj[Z_{64-i}^{'}] \quad for\ i = 33,\cdots,63 \tag{7.11}$$

- For synchronization and cyclic prefix there are similar modifications to reflect that.
- Symbol rate: $f_{sym} = 4{,}000$; Sub-carrier separation : $\Delta f = 4{,}312.5\,Hz$
- IDFT Size: $N = 64$ then a cyclic prefix of (5) samples could be used:

$$(64 + 5)x4000 = (64x4312.5) = 276{,}000$$

- The cyclic prefix, however, is shortened to (4) samples and a synchronization symbol with a nominal length 68 is inserted after every 68 data samples:

$$(64 + 4)x69 = (64 + 5)x68$$

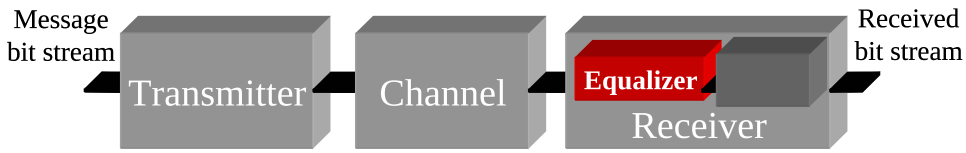
- Data pattern used in the synchronization symbol is a pseudo-random sequence with a specific generation structure and a seed.
- The last (4) samples of the output of the IDFT is appended to the block of 64 samples and read out to the DAC in sequence: $x_{60}, x_{61}, x_{62}, x_{63}, x_0, \cdots, x_{63}$.

Open Issues for Multicarrier Modulation:

- Advantages
  - Efficient use of bandwidth without full channel equalization
  - Robust against impulsive noise and narrowband interference
  - Dynamic rate adaptation
- Disadvantages
  - *Transmitter:* High signal peak-to-average power ratio
  - *Receiver:* Sensitive to frequency and phase offset in carriers
- Open issues
  - Pulse shapes of subchannels (*orthogonal, efficient realization*)
  - Channel equalizer design (*increase bit rate, reduce complexity*)

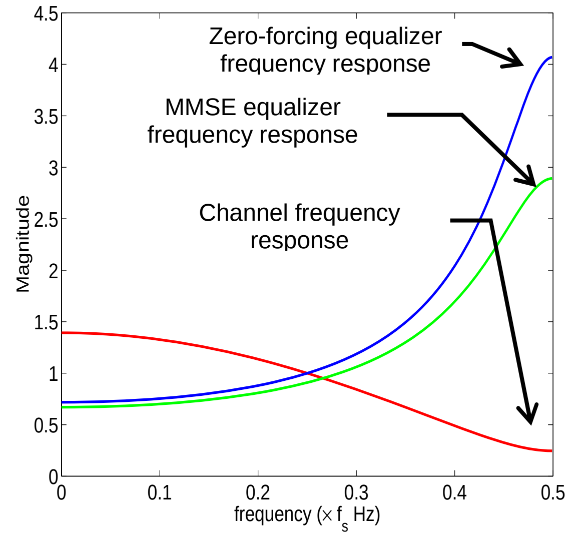
- Synchronization (*timing recovery*, *symbol synchronization*)
- Bit loading (*allocation of bits in each subchannel*)
- Echo cancellation

ADSL Equalizers:



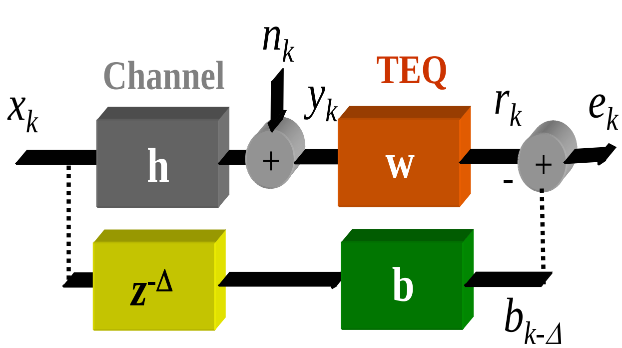
Combating ISE in ADSL Family is a must:

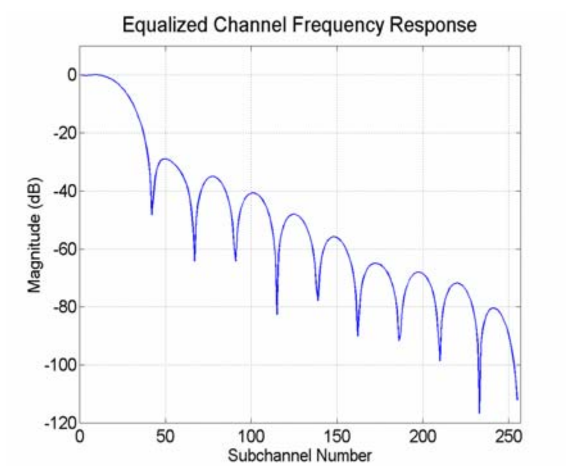
- Equalization because channel response is not flat
- Zero-forcing equalizer
  - Inverts channel
    - Flattens freq. response
    - Amplifies noise
  - MMSE equalizer
    - Optimizes trade-off between noise amplification and ISI
  - Decision-feedback equalizer
    - Increases complexity
    - Propagates error



Minimum Mean Squared Error Transversal Equalizer (TEQ) Design: (Original standard)

- Set aside 1024 frames (~.25s) for TEQ estimation
- Reserved ~16,000 frames for channel and noise estimation for the purpose of SNR calculation
- TEQ is estimated before the SNR calculations
- Noise power and channel impulse response can be estimated before time slot reserved for TEQ if the TEQ algorithm needs that information





Task: Minimize $E\{e_k^2\}$:

- Chose length of **b** (e.g. n+1) to shorten length of $h * w$
- b is eigenvector of minimum eigenvalue of symmetric channel-dependent matrix:

  $R_\Delta = R_{XX} - R_{XY} R_{YY}^{-1} R_{YX}$ where R_{XX}, R_{YY}, R_{XY} are autocorrelation and cross-correlation matrices, respectively.
- Minimum MSE occurs when $R_{YY} w = R_{XY}.b$ where $w \neq 0$.

Single-FIR Time-Domain Equalizer Design Methods

- *All methods below perform optimization at TEQ output*
- Minimizing the mean squared error
  - Minimize mean squared error (MMSE) method [Chow & Cioffi, 1992]
  - Geometric SNR method [Al-Dhahir & Cioffi, 1996]
- Minimizing energy outside of shortened (equalized) channel impulse response
  - Maximum Shortening SNR method [Melsa, Younce & Rohrs, 1996]
  - Divide-and-conquer methods [Lu, Evans, Clark, 2000]
  - Minimum ISI method [Arslan, Evans & Kiaei, 2000]
- Maximizing bit rate [Arslan, Evans & Kiaei, 2000]
- Implementation
  - Geometric SNR is difficult to automate (requires human intervention)
  - Maximum bit rate method needs nonlinear optimization solver
  - Other methods implemented on fixed-point digital signal processors

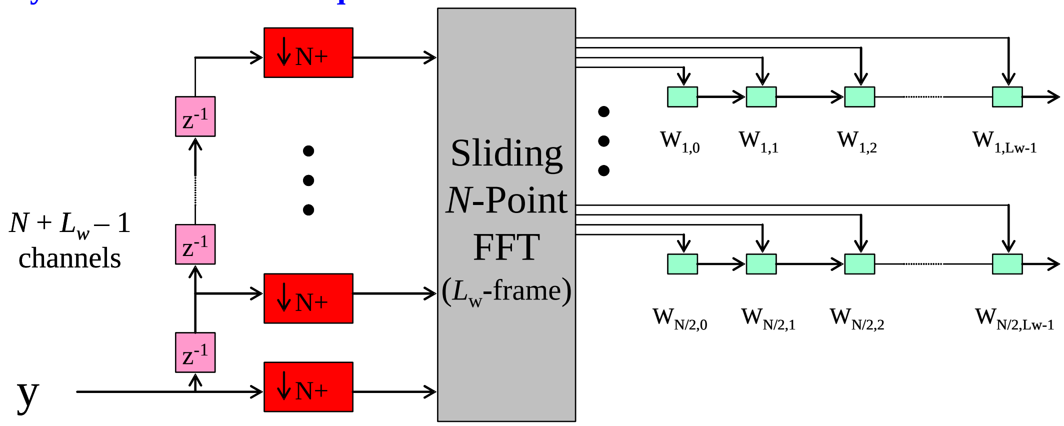
Problems with Single FIR TEQ:

- Equalizes all tones in combined fashion
- Does not consider *bit rate*
- Deep notches in equalized frequency response
- Output of conventional equalizer for a particular tone *i* (carrier *i*) computed using sequence of linear operations: $Z_i = D_i.row_i(Q_N).Y * w$

  where:

  - D_i is the complex scalar value of one-tap equalizer for tone *i*.
  - Q_N is the *NxN* complex-valued FFT matrix
  - Y is *NxLw* real-valued Toeplitz matrix of received samples and
  - w is a *Lwxl* column vector of real-valued TEQ taps.

Frequency-Domain Per Tone Equalizer:



- Rewrite equalized FFT coefficient for each of *N*/2 tones:

$$Z_i = D_i.row_i(Q_N).Y * w = row_i(Q_N Y)(wD_i) = row_i(Q_N Y)w_i$$

- Take a sliding FFT to produce *N*x*Lw* matrix product $Q_N Y$
- Design w_i for each tone.

Example: Motorola CopperGold ADSL Chip

- Announced in March 1998
- 5 million transistors, 144 pins, clocked at 55 MHz
- 1.5 W power consumption
- DMT processor consists
  * Motorola MC56300 DSP core
  * Several application specific ICs
    -- 512-point FFT
    -- 17-tap FIR filter for time-domain channel equalization based on MMSE method (20 bits precision per tap)
- DSP core and memory occupies about 1/3 of chip area