Introduction to Digital Subscriber Lines

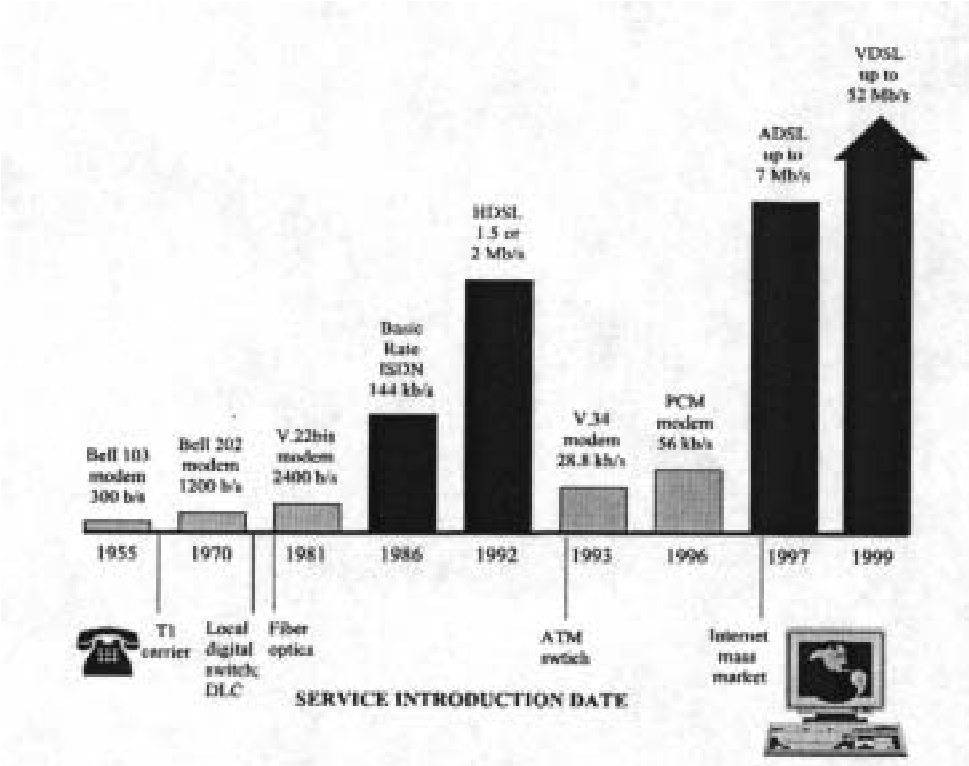
Wen-Rong Wu
Dept. of Communication Engineering
National Chiao Tung University

Contents

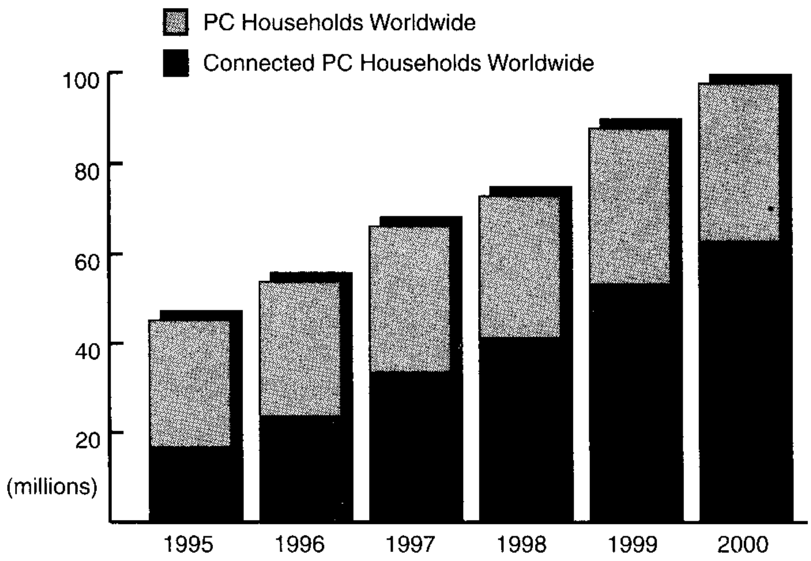
1. Introduction

- Telephone service was first provided by A. G. Bell in 1877. Now, about 740 million subscriber lines exist in the world (according to ITU) and 73% of them are for residential use. In U.S., there are 160 million lines.
- Originally, the public switched telephone network (PSTN) is developed for analog speech signals. Thus, only low-speed digital transmission is allowed.
- However, due to the advance of *silicon* and *digital signal processing* technology, high-speed transmission now is possible.

- Growth of the transmission rate:

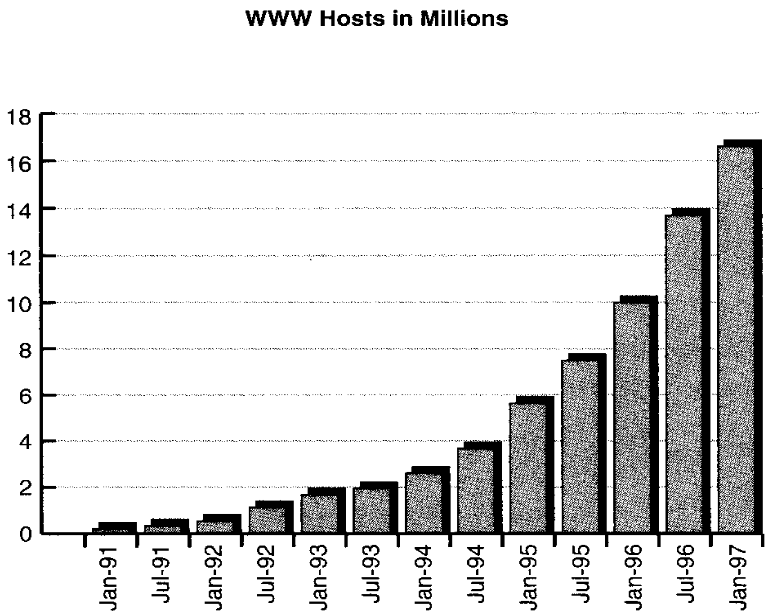


- Motivation for higher bit rates:
  - Growth of PC



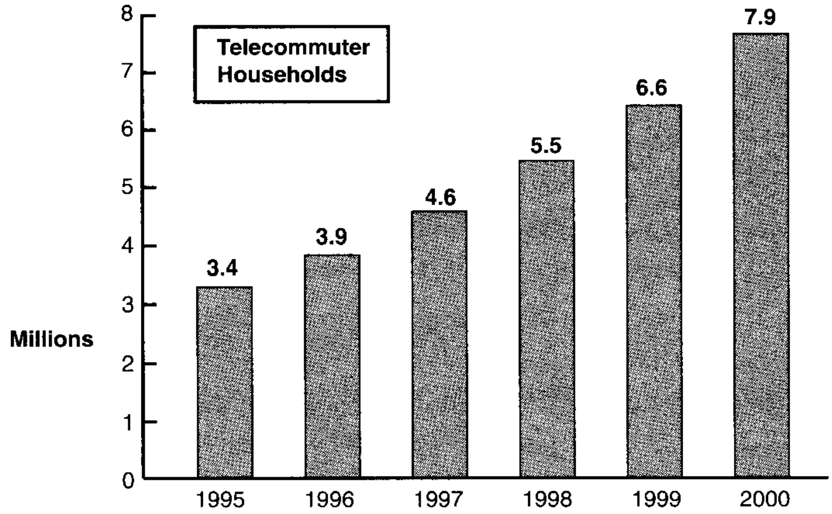
  - Internet access

The growth of Internet hosts (courtesy of Network Wizards, http://www.nw.com/).



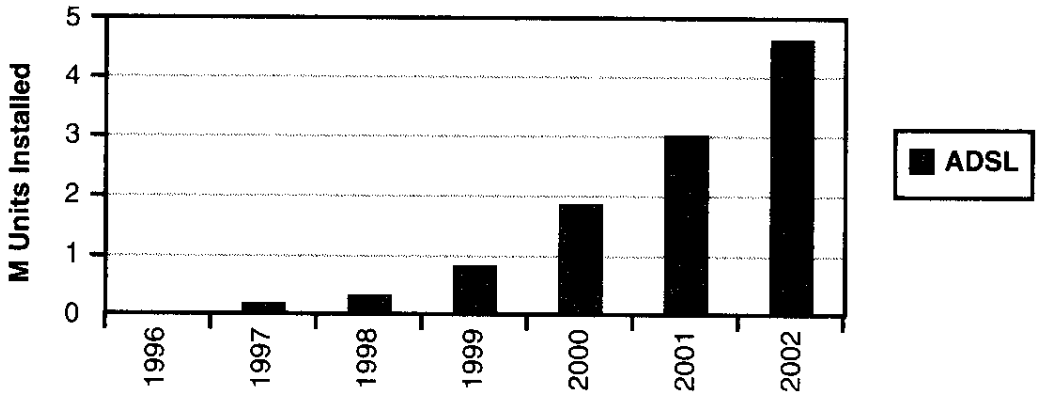
– Small office/Home office (SOHO)

The increasing number of telecommuters in the United States will continue into the year 2000.



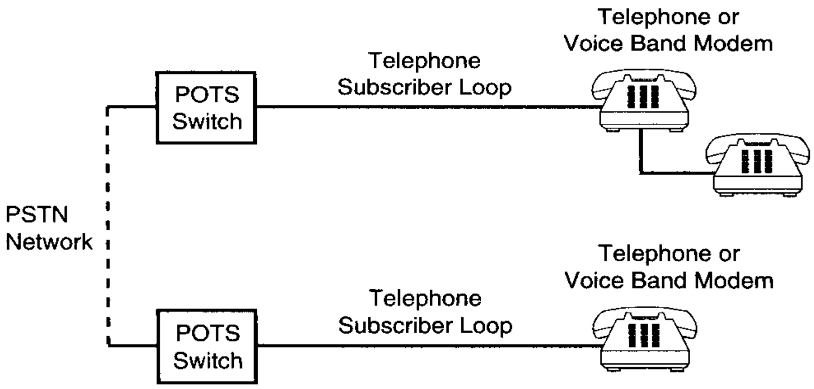
- Why try to use a new technology on old lines?
  – *Because the copper is already there. It is an installed base*.
- Installing a new base of any kind is costly and time-consuming.
- The Market demand:

U.S. xDSL Modem Market - 1996 - 2002

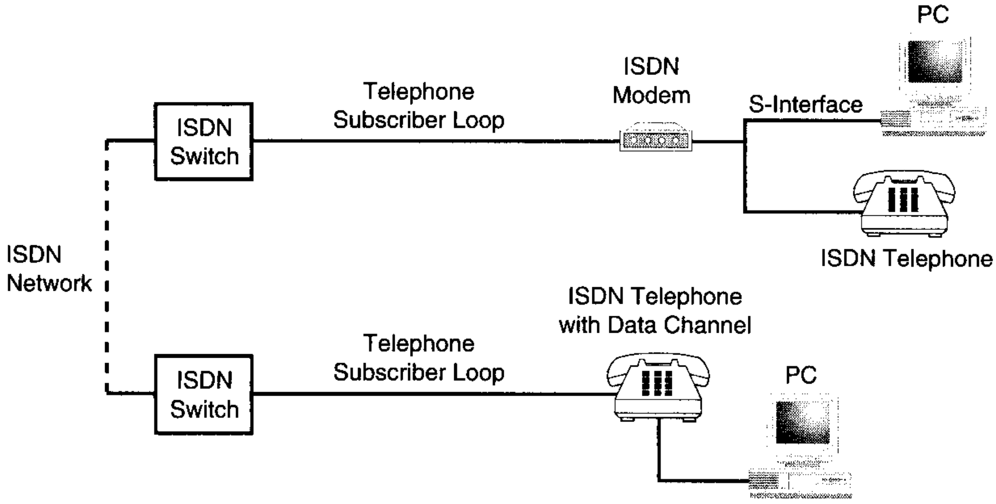


- There are three ways to provide digital access through the telephone subscriber line.

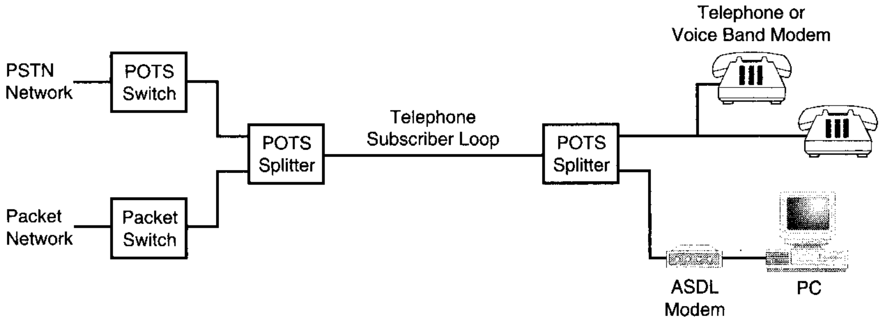
- Analog (modem):

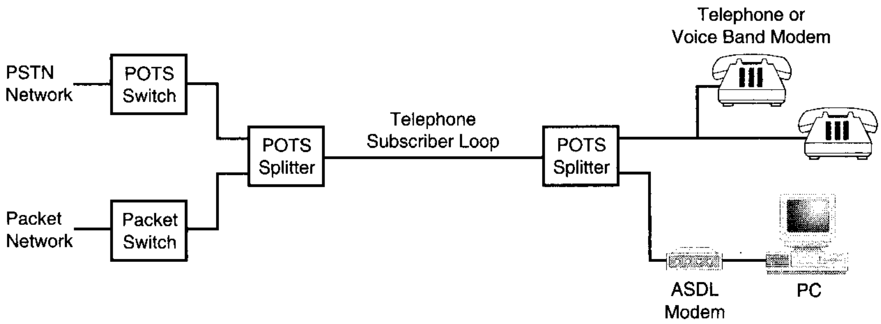


- Digital (ISDN):



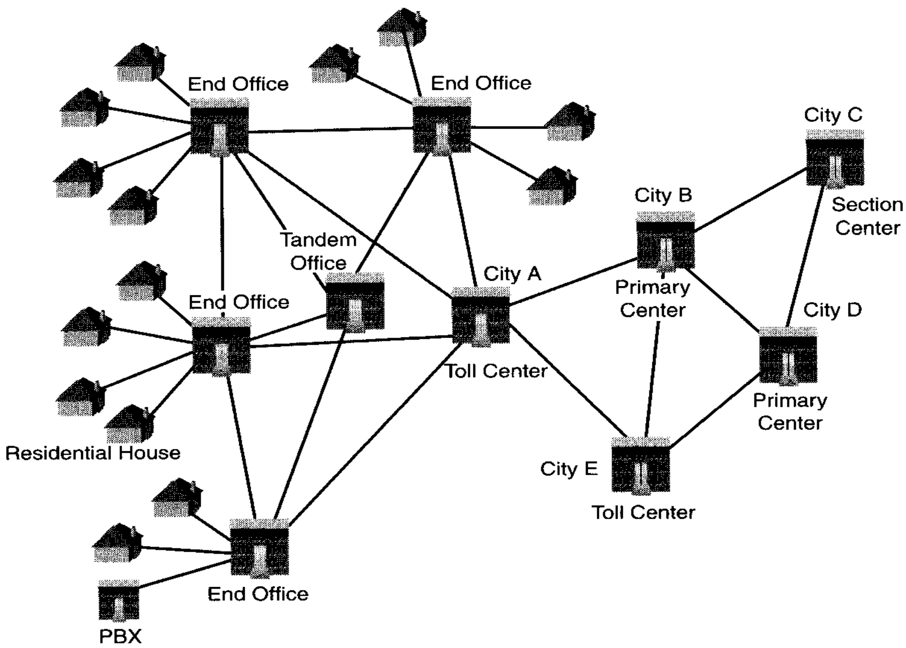
- Both (DSL):



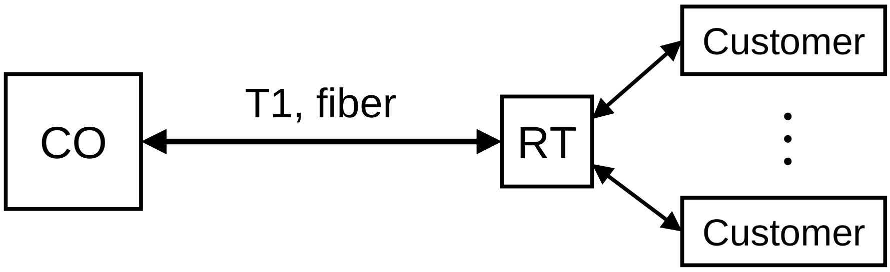


2. Subscribe Loop Environment

- Telephone network:



- A *subscriber loop* is the twisted pair telephone loop connecting a subscriber to the central office (CO).
- Resistance design rule: a maximum loop resistance above 1500 ohms will meets powering, signaling, and transmission requirements.
- To extend the service area and reduce loop deployment cost, the digital loop carrier (DLC) was introduced as an electronic multiplexing device.



- American wire gauge (AWG):

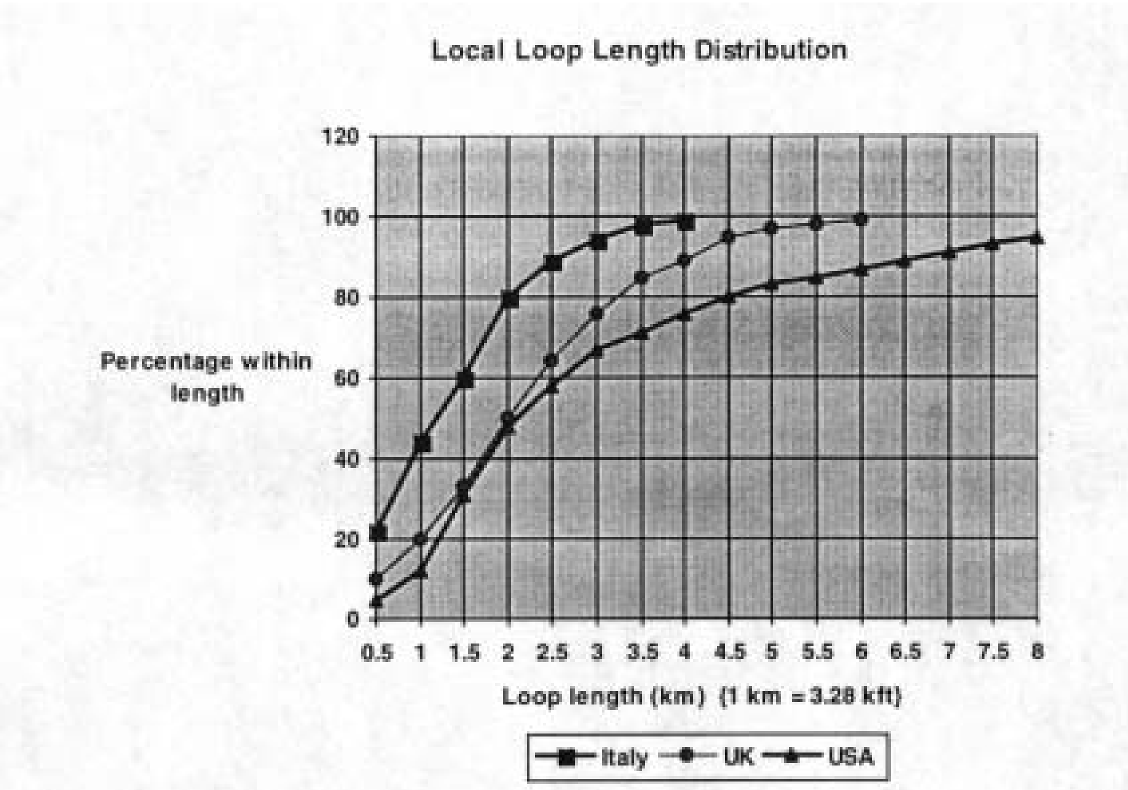
AWG	Metric size (mm)	Loop resistance (Ohms/mile)
28	0.32	685
26	0.4	441
24	0.5	277
22	0.63	174

- Category:

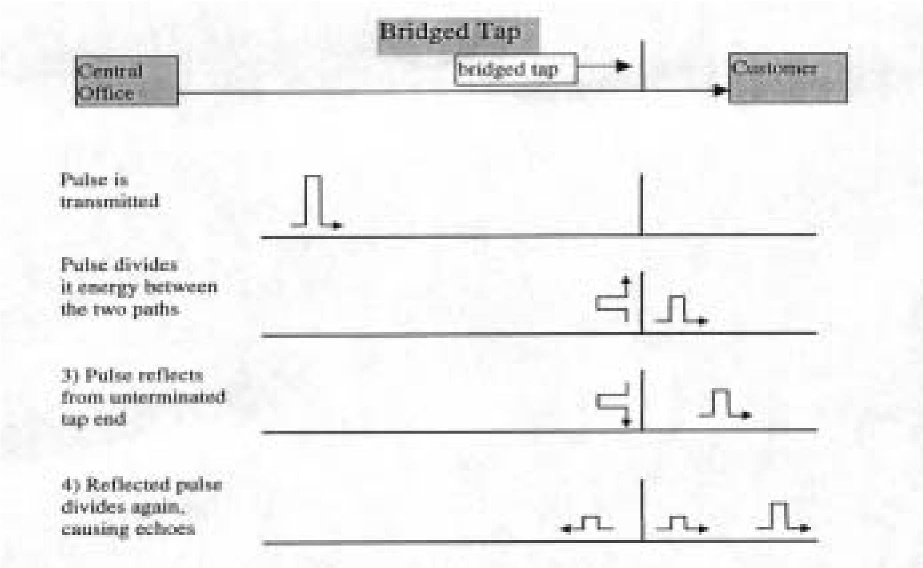
Category	Bit rates	Applications
1	unspecified	
2	1 Mbps	low-speed data circuit (DDS)
3	16 Mbps	16 Mbps 10BaseT and 4 Mbps token ring
4	20 Mbps	10BasedT and 16 Mbps token ring
5	100 Mbps	10/100BasedT, high-speed copper technology

- The carrier serving area (CSA) design rule (for DLC loops) :
  - The maximum CSA loop length is 12 Kft for 24 AWG.
  - The maximum CSA loop length is 9 Kft for 26 AWG.
- Speech signal is digitized at the CO with a rate of 64 Kb/s (8 bits x 8 K).
- Due to the quantization noise, the analog modem speed cannot exceed 56 Kb/s.
- Digital data between COs are usually communicated using optic fibers.

- The loop length distributions:

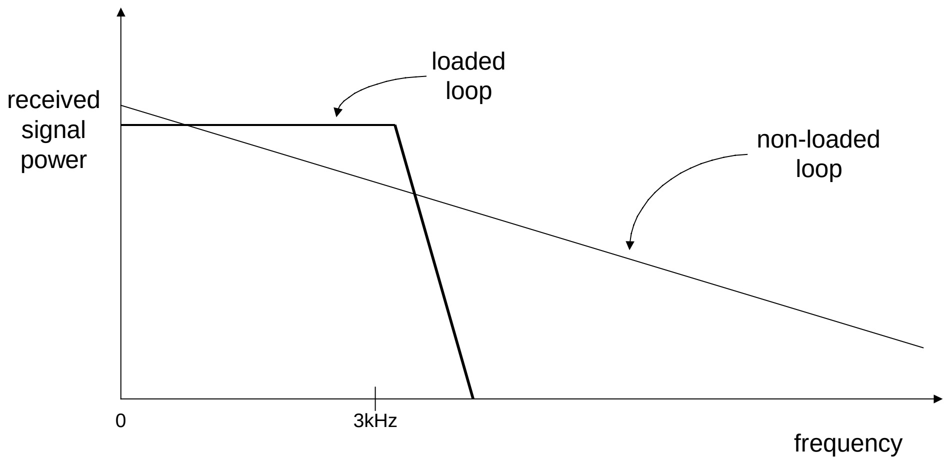


- The feeder and distribution cables are bundled into binder groups 25, 50, and 100 pairs.
- It is common practice to connect a twist-pair from a feeder cable with more than one cables (bridged tap).



- For loops beyond 5.5 Km, the signal loss at frequencies above 1 KHz is unacceptable. Series inductors placed at 1.8 Km result in a flatter spectrum at the voice band (loading coil)

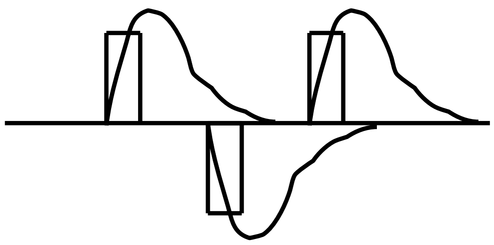
Frequency characteristics of a loop over 18 kft long



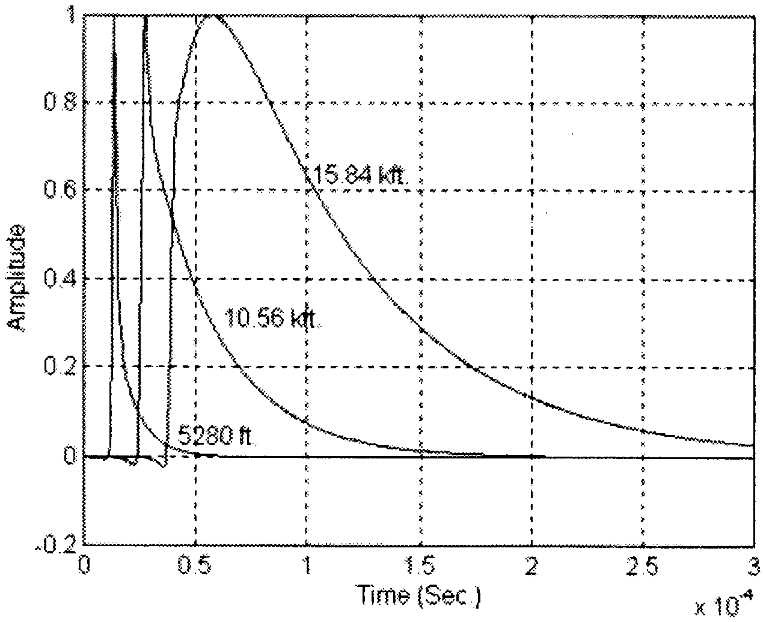
- There are many impairments in the subscriber loops
  - Channel distortion
  - Channel attenuation
  - Crosstalk noise
  - Impulsive noise
  - Background/thermal noise
  - Radio frequency interference
  - Echoes

- The channel distortion (ISI):

Inter-symbol interference:



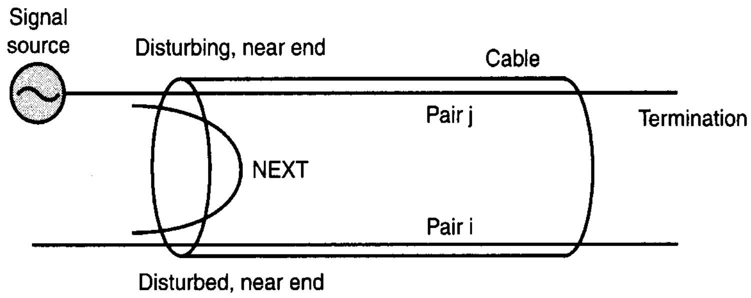
- Channel impulse responses:



- Channel attenuation:

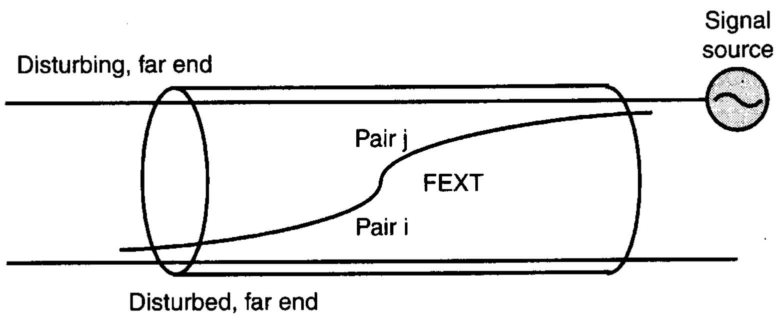
DSL type	Transmission peak (Volts)	Maximum power loss (dB)	Minimum received peak (Volts)
ISDN (144kb/s)	2.5	42	0.02
HDSL (1.5Mb/s)	2.5	35	0.045
ADSL (1.5Mb/s)	15	45	0.085
VDSL (26 Mb/s)	3-4	30	0.09-0.12

- Since telephone subscriber loops are organized in binder group, there is crosstalk between each twisted pair.
- Near end crosstalk (NEXT):



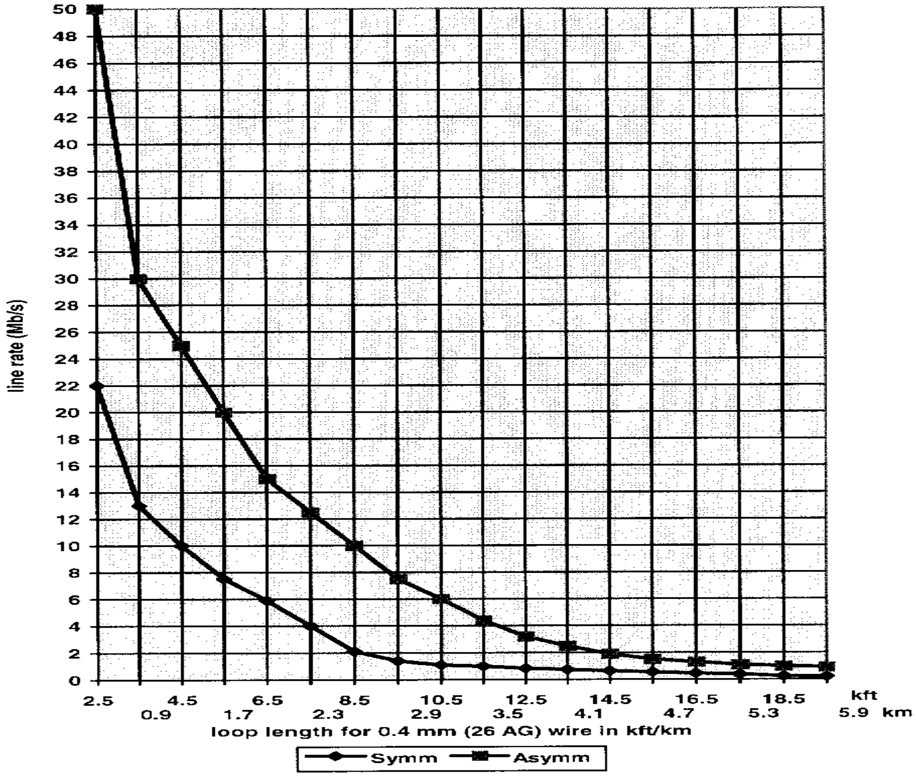
- The crosstalk effect is frequency dependent. It is more apparent for the high frequency signal components.
- It is generally accepted that NEXT is increased with $f^{1.5}$.

- Far end crosstalk (FEXT):



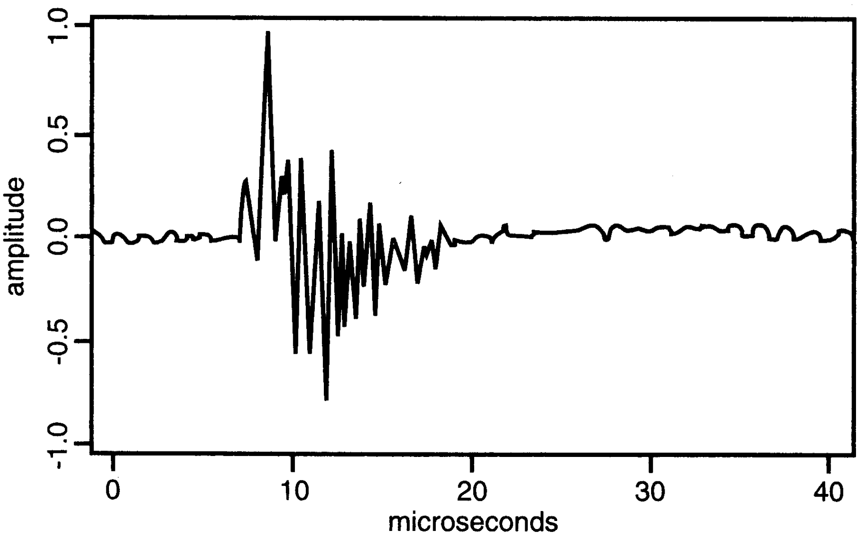
- FEXT is increased with f^{2}. However, since the far-end signal is weak, FEXT is usually less concerned.
- The transmission rate is essentially limited by the NEXT crosstalk noise.

- Rates vs. loop length:

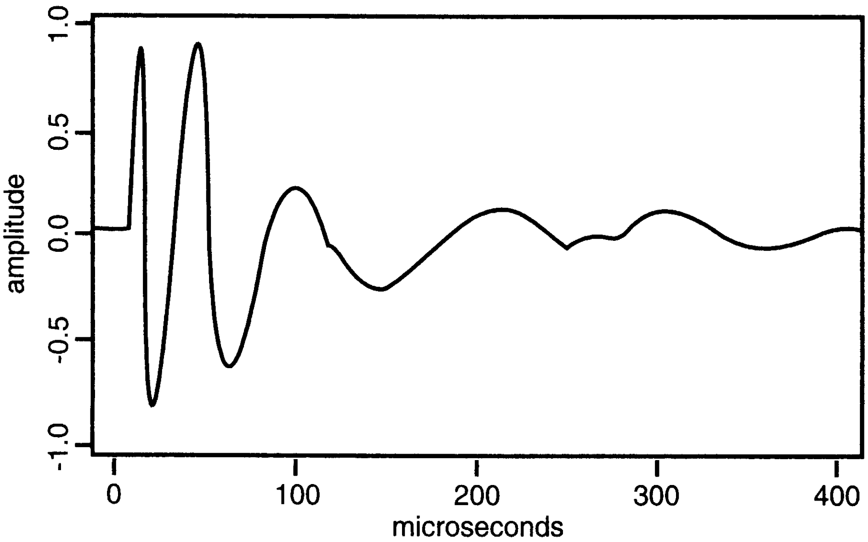


- Impulsive noise can come through connections of telephone lines or from the influence of an electromagnetic filed.
- Impulsive noise is characterized as a random pulse waveform whose amplitude is much higher than the background noise.
- The frequency of impulses is between 1 and 5 per minute and is somewhat related to daily activities.

- Impulse noise #1 used in test:

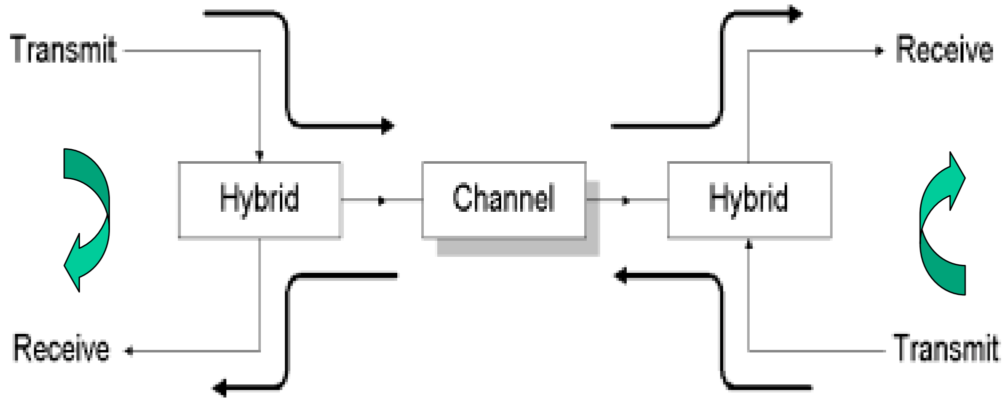


- Impulse noise #2 used in test:



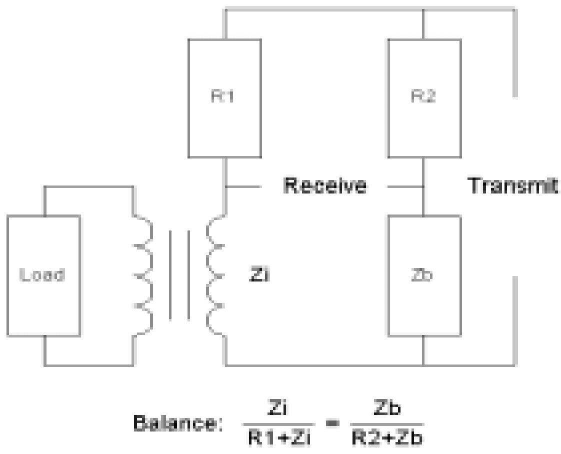
- If the receiver is properly designed and implemented, the thermal noise level can be smaller than the background noise.
- The background noise level for the twist-pair telephone loop plant is around -140 dBm/Hz (dBm=10 x log10(watts x 1000)).
- The radio frequency interference comes from AM MV, AM SM, and HAM. This problem is more serious for very high speed DSL.

- Echoes arises in a full-duplex transmission in a telephone loop.



- Due to the impedance mismatch problem, echoes thus arise.
- Note that the echo power is usually much stronger than that of the receiver signal.

- The basic structure of a hybrid:



- Since the balance condition cannot be met in practice, echoes always exist.

3. Transmission and Signal Processing

- A typical digital transmission system:

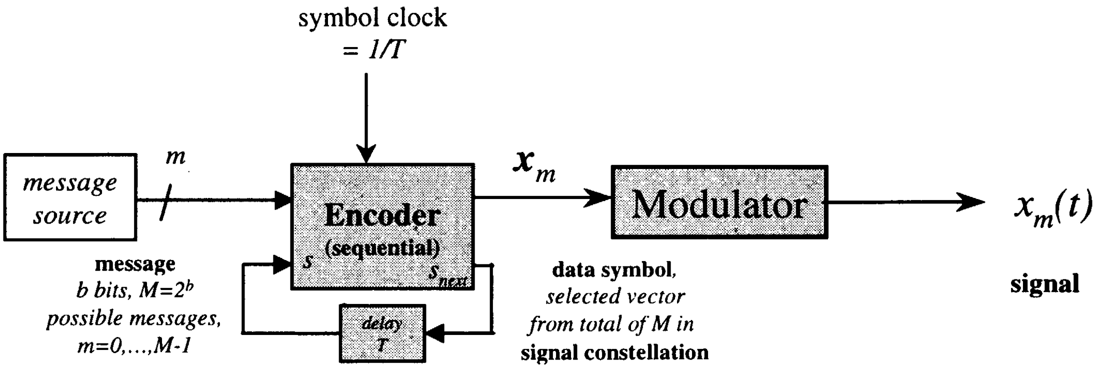
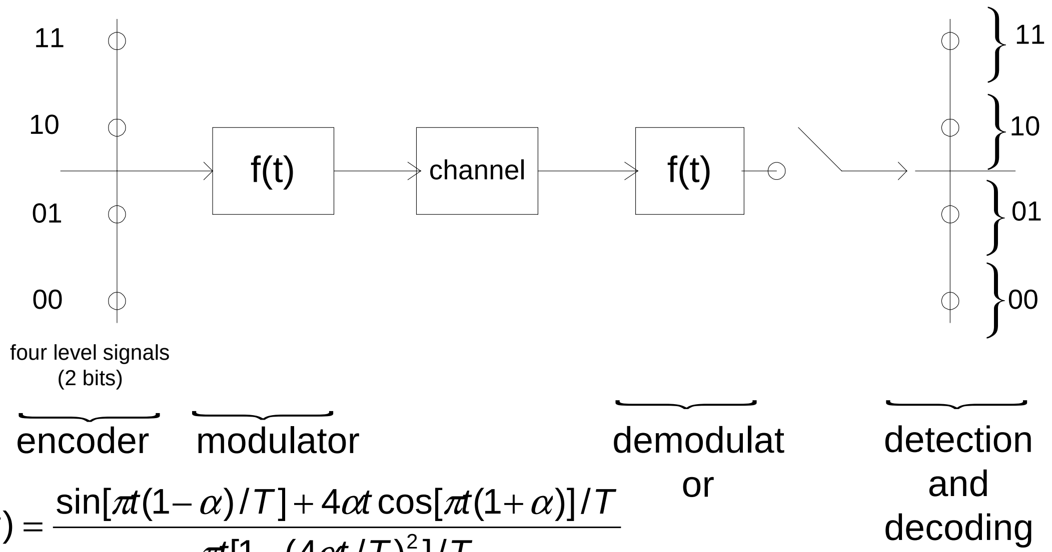


Figure 6.1 Transmitter of a digital transmission system.

- Modulation is the process converting each data symbol vector into a continuous-time signal (for transmission).

- The 2B1Q line code (ISDN and HDSL):
  - "2 bits per one quartenary" symbol



$$f(t) = \frac{\sin[\pi t(1-\alpha)/T] + 4\alpha t\cos[\pi t(1+\alpha)]/T}{\pi t[1-(4\alpha t/T)^2]/T}$$

α: the roll-off factor

This is called the square-root raised consine (SRRC) filter

- Quadrature amplitude modulation (QAM):

$$\varphi_1(t) = \sqrt{2/T}\,\psi(t)\cos(2\omega_c t)$$
$$\varphi_2(t) = \sqrt{2/T}\,\psi(t)\sin(2\omega_c t)$$

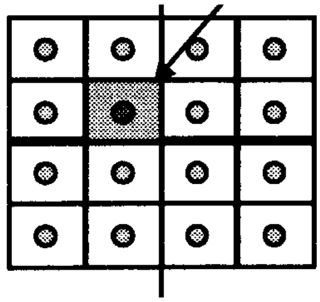
where $\psi(t)$ is a baseband function such as the square-root raised cosine one.

- A successive QAM signal:

$$x(t) = \sqrt{\frac{2}{T}}\sum_k x_{1,k}\psi(t-kT)\cos(\omega_c t) - x_{2,k}\psi(t-kT)\sin(\omega_c t)$$

- Note that the sinusoidal signals are not shifted by *kT* on the *k*-th symbol. The basis functions are not periodic.

- In the complex plane:

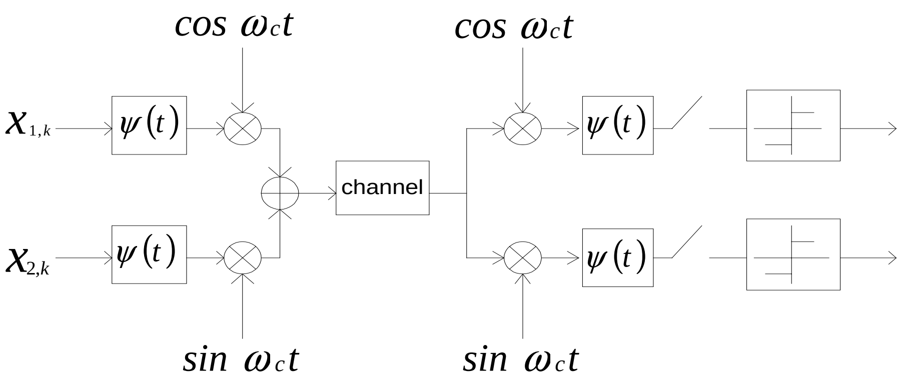


- Carrierless amplitude/phase modulation (CAP):
  - Using the complex representation, we can have QAM as

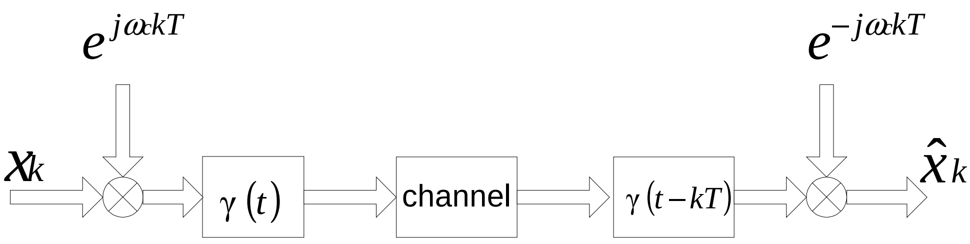
$$x(t) = \mathrm{Re}\left\{\sum_k x_k \psi(t-kT) e^{j\omega_c t}\right\}$$

$$= \mathrm{Re}\left\{\sum_k x_k e^{j\omega_c kT} \psi(t-kT) e^{j\omega_c (t-kT)}\right\}$$

- Original QAM:



- An alternative QAM



$$\gamma(t) = \psi(t-kT) e^{j\omega_c (t-kT)}$$

- The CAP system is the result of removing the phase rotator and the phase de-rotator in a QAM system.

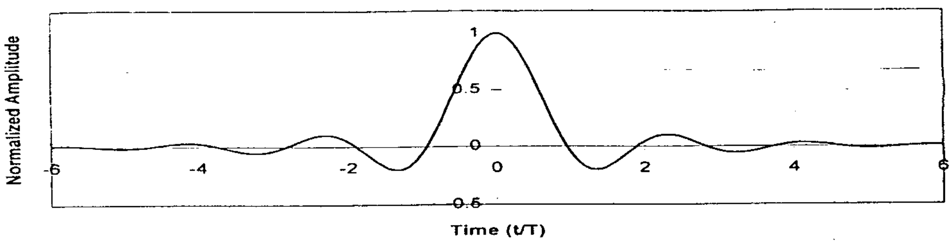
$$x(t)=\sqrt{\frac{2}{T}}\sum_k x_{1,k}\psi(t-kT)\cos(\omega_c(t-kT))-x_{2,k}\omega(t-kT)\sin(\omega_c(t-kT))$$

- Thus, there is no carrier and ω_c is simply a parameter that indicates the center of the transmission passband.
- CAP and QAM are fundamentally equivalent in performance - only implementation is different.
- The probability of bit error for QAM/CAP

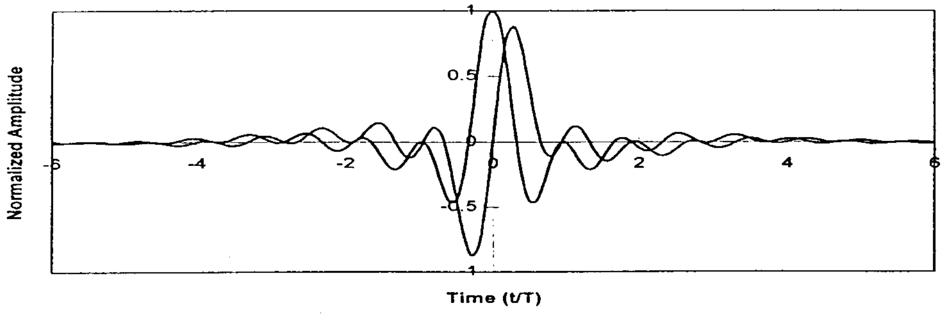
$$P_b \cong \frac{2\left(1-L^{-1}\right)}{\log_2 L} Q\left[\sqrt{\left(\frac{2\log_2 L}{L^2-1}\right)SNR}\right]$$

L : the number of amplitude level (1-D)

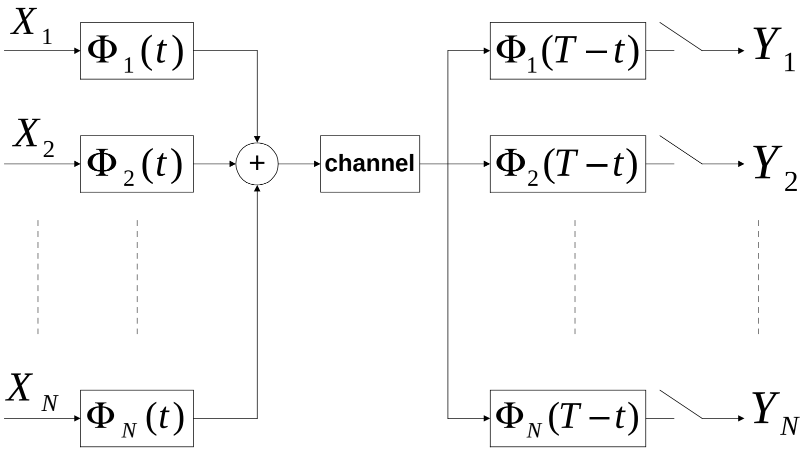
- The CAP basis functions:



Impulse Response g(t) of a Square-root Raised Cosine Shaping Filter.



- The basic multichannel (muticarrier) transmission:



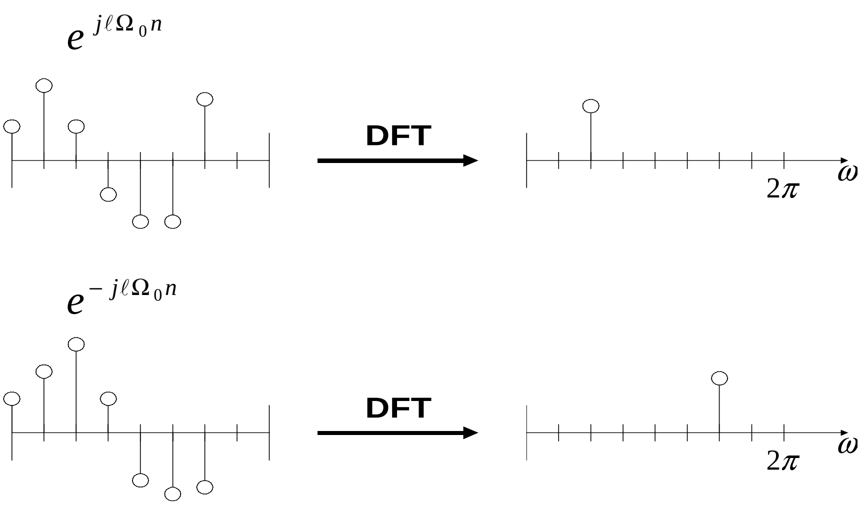
- Note that if $\Phi_i(t)$'s occupies different frequency bands, the orthogonal conditions can be satisfied.

- The simplest $\Phi_i(t)$ function is the sinusoid having a single frequency. Consider the sampled $\Phi_i(t)$.

$$\Phi_k(n) = e^{jk\Omega_0 n}, \qquad \Omega_0 = \frac{2\pi}{N}, \quad k = 0,1,\cdots,N-1$$

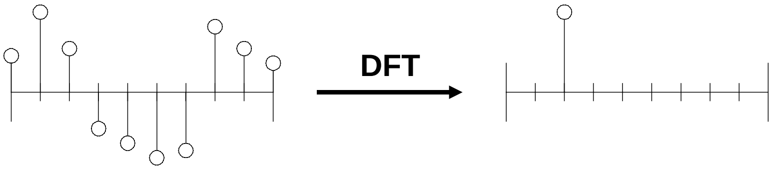
- Property:

$$\frac{1}{N}\sum_{n=0}^{N-1} e^{j(k-m)\Omega_0 n} = \begin{cases} 1, & k = m \\ 0, & k \neq m \end{cases}$$

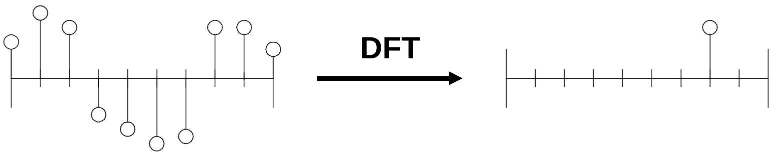


- Thus, we can use the property to perform modulation.

$Ae^{j(\ell\Omega_0 n+\theta)}$ $\quad$ $Ae^{j\theta} = a+bj$



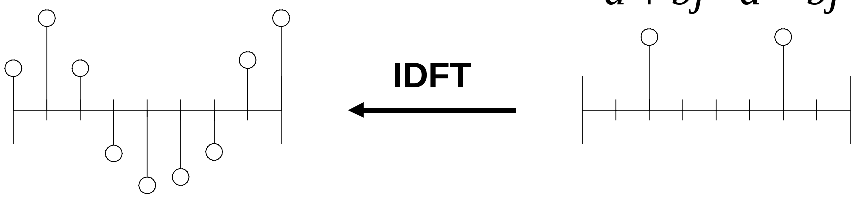
$Ae^{-j(\ell\Omega_0 n+\theta)}$ $\quad$ $Ae^{-j\theta} = a-bj$



- Thus, we can define symbols in the frequency domain.

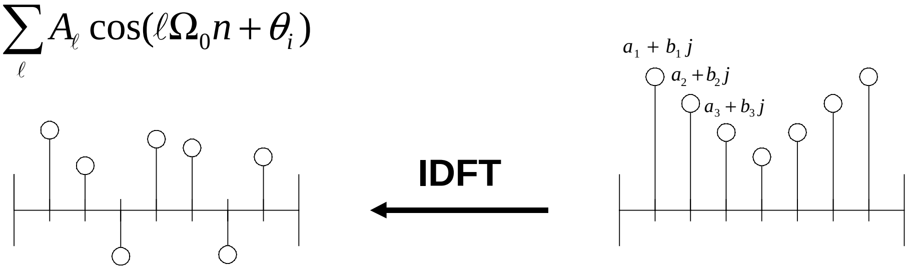
- For example:

$A\cos(\ell\Omega_0 n+\theta)$ $\quad$ $a+bj \quad a-bj$



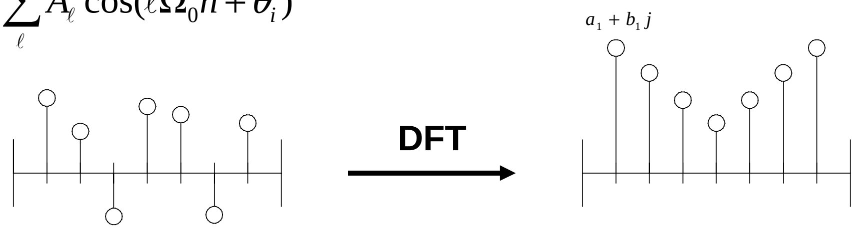
- For multitones (multichannels/muticarriers), we can have

$\sum_{\ell} A_\ell \cos(\ell\Omega_0 n+\theta_i)$

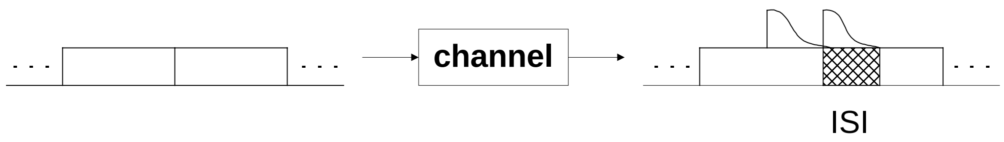


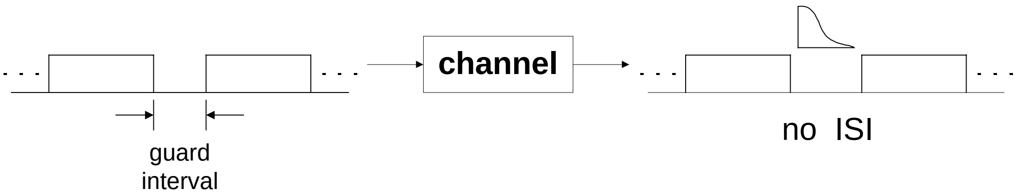
- In the receiver, we then have

$$\sum_{\ell} A_{\ell} \cos(\ell \Omega_0 n + \theta_i)$$

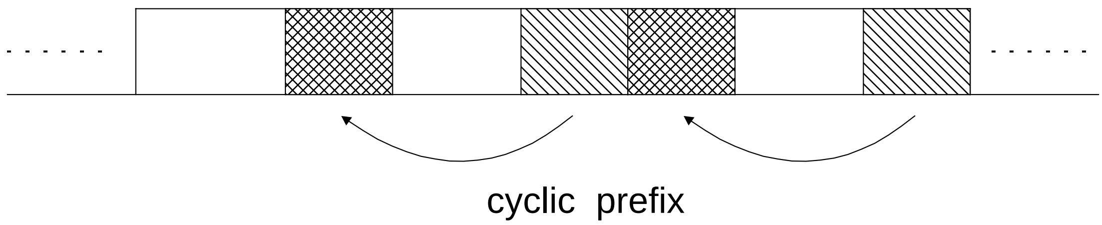


- ISI:





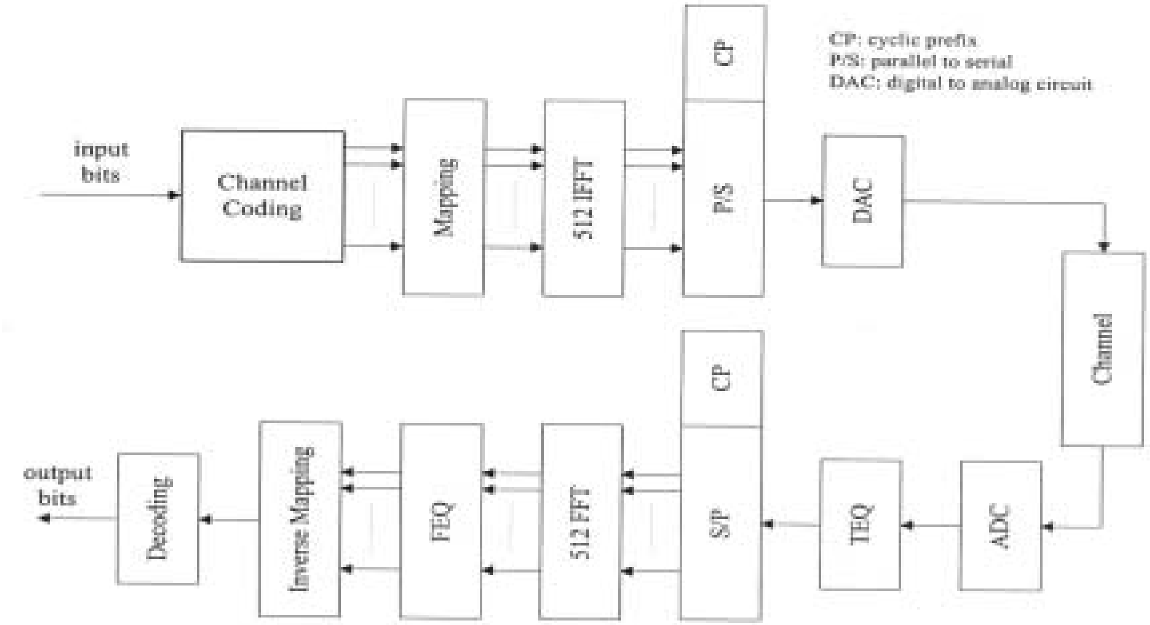
- To compensate the channel effect in frequency domain (circular convolution), the guard interval is



- If the channel response is known (shorter than CP), then

$$y^m(n) = x^m(n) \otimes h(n)$$
$$\Rightarrow X^m(e^{j\omega_k}) = \frac{Y^m(e^{j\omega_k})}{H(e^{j\omega_k})}$$

- The discrete multitone (DMT) system (ITU g.dmt, ANSI T1.413):



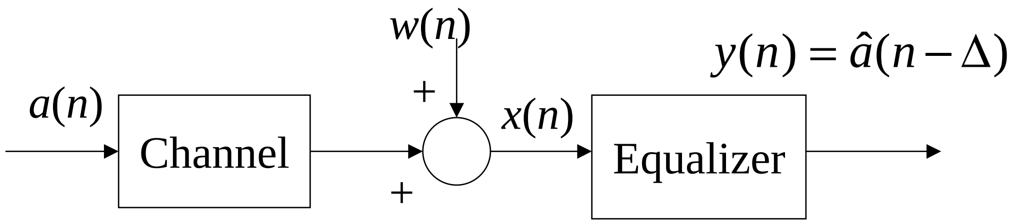
- The DMT downstream parameters:

Symbol rate	4 kHz
FFT size	512 samples
Cyclic prefix	32 samples
Sampling rate	2.208 MHz
Frequency spacing	4.3125 KHz

- The DMT upstream parameters:

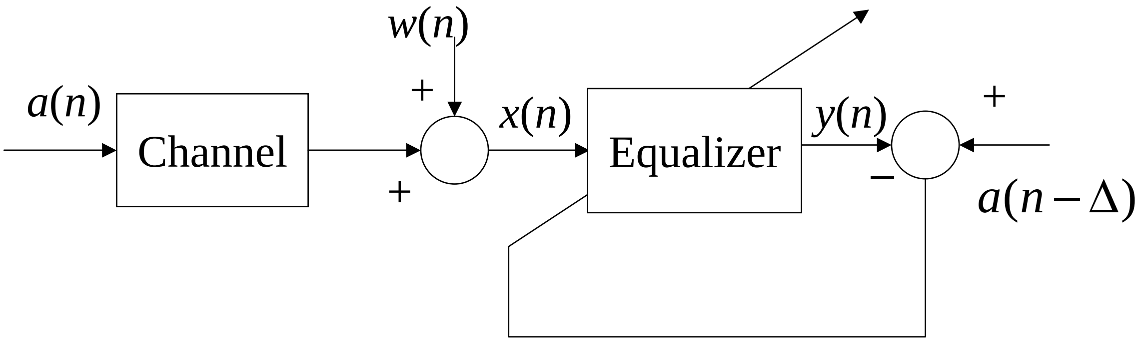
Symbol rate	4 kHz
FFT size	64 samples
Cyclic prefix	4 samples
Sampling rate	276 KHz
Frequency spacing	4.3125 KHz

- An equalizer is a commonly used device to compensate for the channel effect.

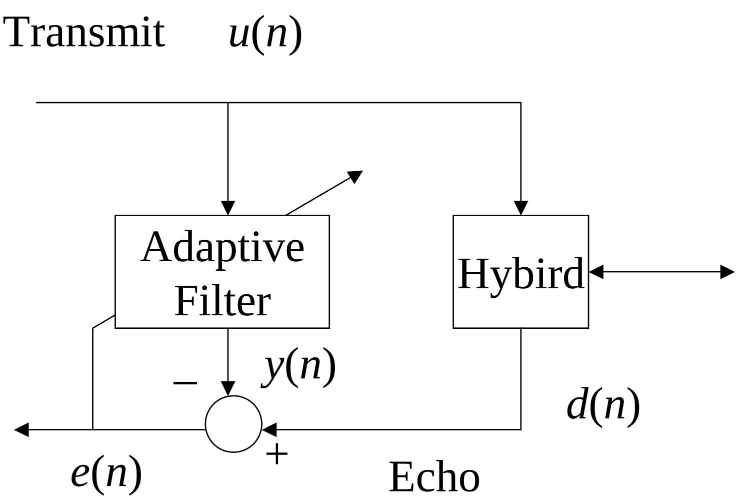


$(H(z))$ $\quad$ (If no noise, $E(z) = \frac{1}{H(z)} z^{-\Delta}$)

- Adaptive equalizer :

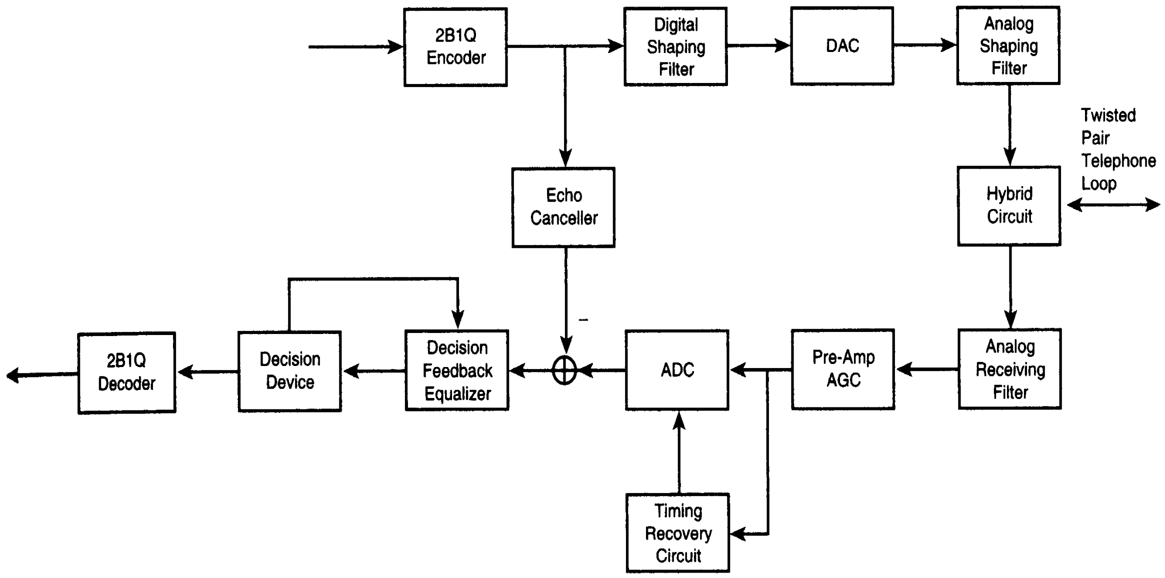


- Adaptive echo canceller :



- Timing recovery:
  - The purpose of timing recovery is to recover a symbol rate clock, which is used in the far-end transmitter D/A device, from the received waveform.

- A general HDSL transceiver:



4. Standards

- ISDN: integrated services digital network. This can be seen as the first DSL service (since 1986).

  B channel $(64 \times 2 = 128\text{ K})$: for data transmission

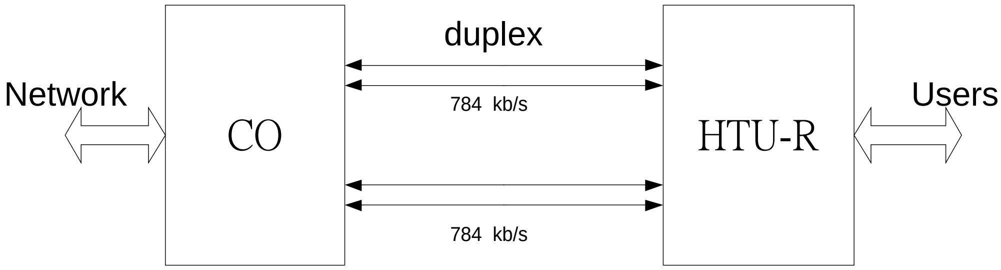
  D channel (16 K) : for signaling and user data packet

  Framing and line control (16K)

  Total 160 Kb/s

- The low data rate ultimately become a major drawback of this DSL technology.
- Nevertheless, many ISDN lines still deployed (1.7 million in 1994 and 6 million in 1996)

- HDSL (high-bit rate digital subscriber loop)
- HSDL was essentially up-scaled the ISDN designs. The first HDSL service was placed in 1992.
- It is now used to replace the T1 and E1 services for cost reduction. This benefit is mainly due to the elimination of mid-space repeaters.



2 pairs wires : 1.544 Mb/s

3 pairs wires : 2.048 Mb/s

- 2B1Q and CAP are the de-facto standards in North America.
- 2B1Q and CAP have the same performance.
- 2B1Q is the selected line code for ETSI standard.
- ADSL (Asymmetric DSL)
- The ADSL concept evolves during the early 1990. At first, ADSL was considered at a fixed rate 1.5 Mb/s downstream and 16 Kb/s upstream for MPEG-1.
- Recently, ADSL finds wide applications with the internet access.

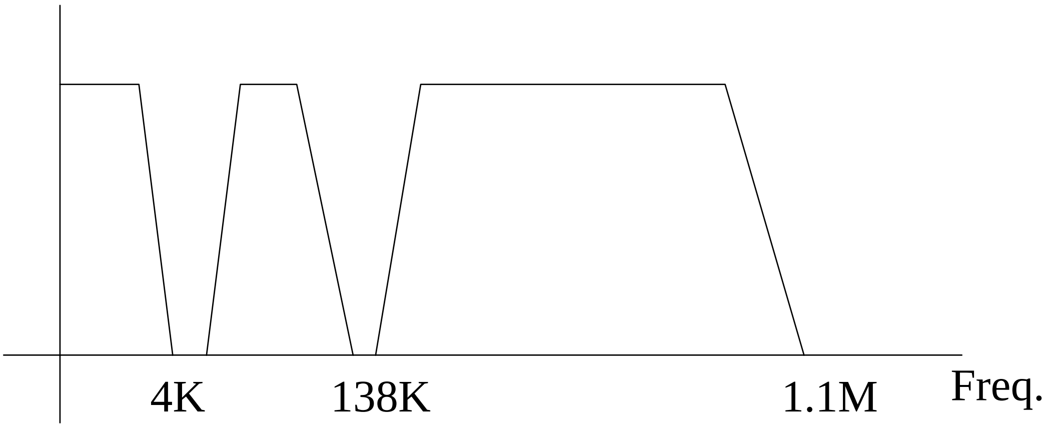
Downstream : up to 9 Mb/s

Upstream : up to 1Mb/s

Simultaneously provides POTS service

One pair of wires

- The conceptual definition of ADSL began in 1989 and the ITU gave preliminary approval to a set of ADSL recommendations in 1998.
- ADSL spectrum:

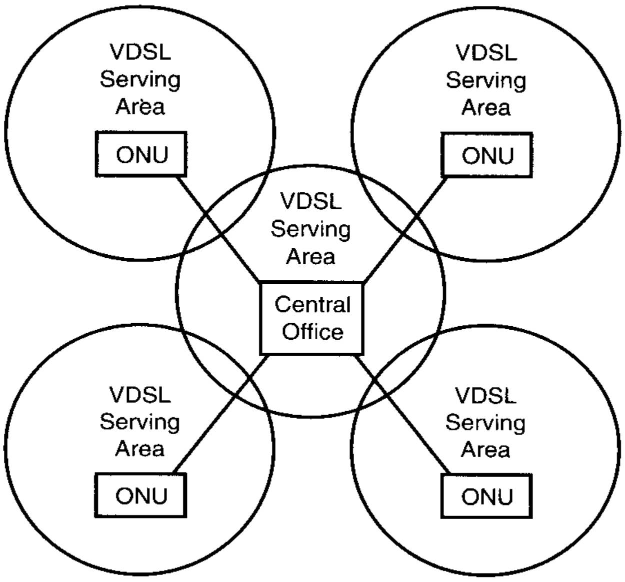


- DMT was selected as the ANSI standard in 1993.

- VDSL (Very-high-bit rate DSL):
- VDSL is an extension of ADSL technology to higher rates up to 52 Mb/s downstream (26 Mb/s two ways)
- Discussion of VDSL in standard committee began in 1994. VDSL is intended to support all applications, voice, data, video (even HDTV).
- VDSL will be primarily used for loops fed from an optical network unit (ONU) which is typical located less than a KM from the customer.
- Both QAM and DMT have been proposed for the standard candidates.

- VDSL service area:

Coverage area of VDSL when deployed from remote ONUs.



- VDSL service range:

Range and reach of VDSL from a central location.