Lecture 5: Telephone Networks, DSL, Modulations, and Internet over Cable

(09/30/2009)

Lecture Outline

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1. Introduction

(1) Nature of classical PSTN: an analog, circuit-switching voice delivery system

a. It is connection-oriented – each connection requires the establishment of a physical circuit from the caller to the receipient. Fig.24 shows the typical circuit route for a medium-distance call.

b. It was built to carry analog voice signals from the beginning of 1870s and has been optimized in many ways since then.

(2) Modern PSTN: there are three main components:

a. The local loop: the analog wires (twisted pairs) going into houses and businesses.

b. The trunks: digital fiber optics connecting switching offices.

c. Switching offices: switches that connecting trunks and move calls from trunks to trunks.

d. When analog transmission is used over the access lines, the total network is known as the PSTN. When digital transmission is used over the access lines, the total network is known as ISDN.

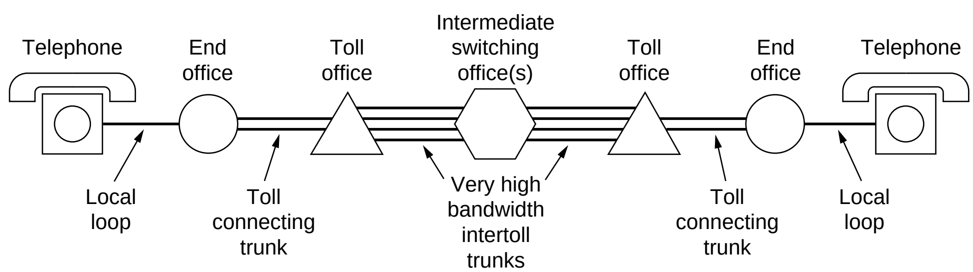

Figure 24: A typical circuit route for a medium-distance call

(3) Architecture of modern PSTN: Fig.2.1, p.93. There three levels:

a. Local access and switching networks.

 (a) A large number of local exchange/end offices

 (b) Local tandem exchange/office

b. Interexchange trunk/carrier networks:

 (a) Reginonal tandem exchange/office

 (b) National tandem exchange/office

c. International networks:

 (a) International gateway exchange/office

 (b) Connections through terrestrial, submarine, and satellite links

(4) Three issues in PSTN:

a. Transmission system

 (a) Local loop (also called customer line, or subscriber line): a twisted-pair wire cable connecting a customer home to an LE/EO. This line is used exclusively by that customer's home.

- For analog applications, the bandwidth utilized is approximately 3.2kHz (200Hz to 3.4kHz).
- Customers who wish to use digital transmissions should *subscribe* to the carrier. The service is known **DSL** (digital subscriber line).
- Customers can also access a number of digital services through PSTN by using modems.

b. Switching system

(a) Each LE/EO contains sufficient switching capacity to support a defined number of simultaneous calls/connections.

(b) A call that involves to homes within the same local area may involve only two interconnected LEs/EOs

(c) A call that involves to homes within the same local area may also involve local tandem exchanges/offices.

(d) Calls may involve regional tandem exchanges/offices, or national tandem exchanges/offices, or even international gateways.

c. Signal system

(a) To establish connections a set of control messages, known as **signaling messages**, are used.

- The signaling messages are used between the called and calling subscribers and their respective LE/EO, as well as between the various exchanges involved.
- The signaling messages used over the subscriber lines are different from those used within the core transmission and trunk network.

(b) The signaling methods for PSTN and ISDN are also different.

(5) Modern history of US PSTN

a. The break-up of AT&T in 1984. The whole AT&T was broken up into 23 BOCs (Bell Operating Companies). The 23 BOCs were grouped into several RBOCs (regional BOCs).

b. LATA (Local Access and Transport Area). The whole US was divided into 164 LATAs. A LATA is roughly the size of an area code. Fig.25.

c. LEC (Local Exchange Carrier). Within a LATA, there was only one allowed LEC that had a monopoly on traditional telephone services.

d. IXC (IntereXchange Carrier). IXCs were companies that handle inter-LATA traffic.

e. POP (Point of Presense). Established by IXCs that wished to serve a LATA. The IXC was required to connect each IXC to every end office (directly or indirectly) within the IXC area.

f. The 1996 law.

   (a) Lifted the restriction of a single LEC within a LATA.

   (b) Cable TV companies, local telephone companies (LECs), long distance carriers (IXCs), and mobile operators were allowed to enter one another's service areas.

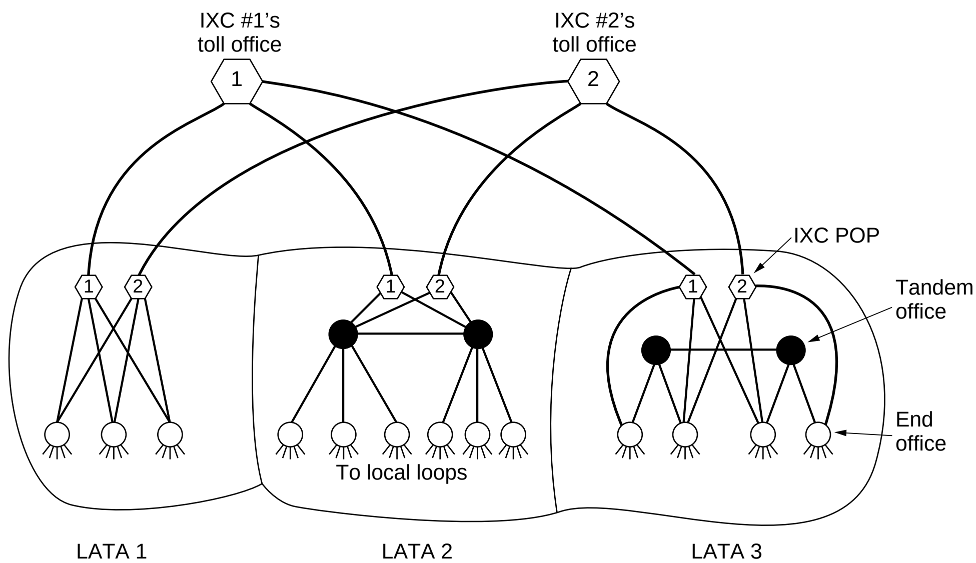

Figure 25: The relationship of LATAs, LECs, and IXCs. All the circles are LEC switching offices. Each hexagon belongs to the IXC whose number is in it.

2. <u>Transmission systems</u>

(1) Telephone basics

   a. Components in a telephone: Fig.2.2(a), p.97

   b. 4-wire to 2-wire hybrid: Fig.2.2(b): to filter out own voice when speaking.

   c. DTMF (dual-tone multi-frequency) keying: Fig.2.2(c)

(2) Remote concentrator units: Fig.2.3, p.99

   a. The distance between a LE/EO and a subscriber's premise is limited to no more than several kilometers.

b. A RCU is located close to subscriber's primises.

c. The link between a RCU and an LE/EO is digital.

d. In theory if the number of subscribers is N, then the link should provide at least data rate $N \times 64$ kbps.

e. In practice, as the number M of concurrent callers is much smaller than N, the actual data rate needed by that link is usually $M \times 64$ kbps. N/M is usually 8/1.

3. <u>PSTN modems and modulations</u>

(1) The need of signal modulations

a. The range of signal frequencies that can pass PSTN is roughly between 200Hz and 3400Hz.

b. The baseband digital signals from computers are DC signals. They exhibit the familiar square wave patterns.

(a) Such square wave signals have broad frequency spectrum (cf. discussions in previous section).

(b) According to previous discussions about problems with signal transmissions such square wave signals suffers from severe attenuations and distortions. The problem is particularly severe when such signals are transmitted on analog telephone lines. Thus the baseband digital signal can only be transmitted reliably within a very short distances and at low speeds.

c. Modulations: Fig.2.5, p.103, and Fig.27

(a) Intuitively speaking, modulations are techniques that change the way the baseband (digital) signals are transmitted and sampled over analog transmission channels (PSTN). The main purposes of modulations are to provide higher data rate and transmission multiplexing.

(b) Due to the problems of sending DC square wave signals, AC signals are transmitted. More specifically, a continuous tone of AC signals in the frequency range 1000Hz to 2400Hz, called *sine wave carrier*, is produced by the sending side.

(c) By manipulating (called *modulation*) the amplitude, frequency, or phase, called **amplitude modulation, frequency modulation**, and **phase modulation** respectively, of the sine wave carrier, more information (i.e. bits) per signal sample can be achieved. They are also called **amplitude-shift keying (ASK)**, **frequency-shift keying (FSK)**, and **phase-shift keying (PSK)**, respectively.

(d) Combinations of the above three modulations can often be used.

(2) Modems

a. The circuit that converts the binary data into a form suitable for transmission in an analog channel is called a **modulator**. The circuit that performs the reverse operation is called a *demodulaor*. Hence the term **modem**: Fig.2.4, p.101.

(a) A modem contains both a MOdulator and DEModulator (hence the term modem) that perform the previously discussed modulation task.

(b) Most modems also perform error control and compressions.

(c) The normal 2-wire analog subscriber line: Fig.2.4(a). The two analog signals that carry transmitted and received bitstreams must share the use of the single twisted-paie subscriber line. A hybrid transformer is used.

(d) For leased lines, normally a 4-wire (2-pair) line is used: Fig.2.4(b). The leased line by-passes the normal switching equipment (exchange) in the PSTN.

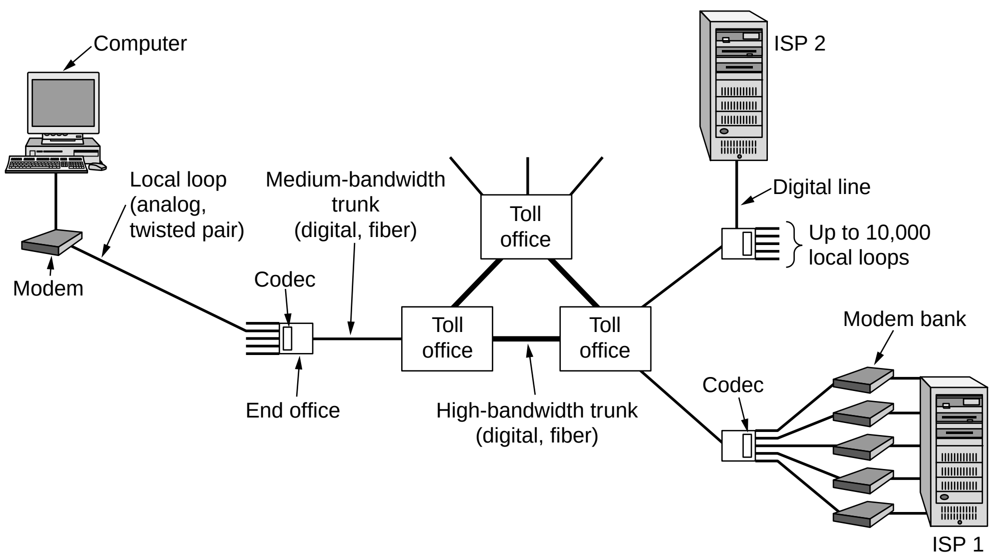

Figure 26: The use of both analog and digital transmission for a computer to computer call. Conversion is done by the modems and codecs.

b. Internet with modems: Fig.26

(3) Amplitude-shift keying (ASK)

a. Principle illustration: Fig.27(b) and part of Fig.2.5, p.103

(a) Fig.2.5(a): the circuit with modulator and demodulator

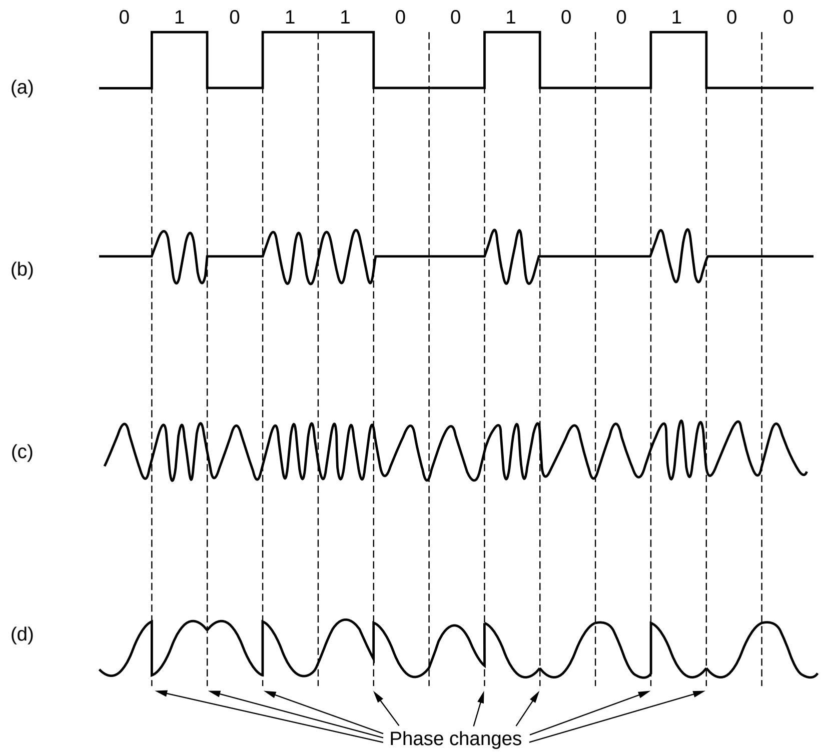

Figure 27: (a) A binary signal. (b) Amplitude modulation. (c) Frequency modulation. (d) Phase modulation.

(b) Fig.2.5(b): example transmission of a binary data sequence

b. Mathematical explanation: ASK is equivalent to multiplying the carrier signal by the binary data signal.

(a) The carrier signal is simply expressed as:

$$v_c(t) = cos\omega_c t$$

(b) Assume the binary data sequence is unipolar with unit amplitude. According to previous discussion, a unipolar data sequence can be represented as:

$$v_d(t) = \frac{1}{2} + \frac{2}{\pi}\{cos\omega_0 t - \frac{1}{3}cos3\omega_0 t + \frac{1}{5}cos5\omega_0 t - \cdots\}$$

(c) ASK can be represented as:

$$v_{ASK}(t) = v_c(t).v_d(t)$$

After some mathematical simplification, we can obtain:

$$v_{ASK}(t) = \tfrac{1}{2}cos\omega_c t + \tfrac{1}{\pi}\{cos(\omega_c - \omega_0)t + cos(\omega_c + \omega_0)t - \tfrac{1}{3}cos(\omega_c - 3\omega_0)t - \tfrac{1}{3}cos(\omega_c + 3\omega_0)t + \cdots\}$$

(d) Therefore we can deduce that an ASK signal is equivalent to the original binary data signal translated up in frequency by the carrier signal ω_c. This translated signal has frequency components for the fundamental: $-(\omega_c - \omega_0)$ and $(\omega_c + \omega_0)$, and two for the harmonics $-(\omega_c - \omega_0)$ and $(\omega_c + \omega_0)$. All components are equally spaced either side of the carrier and are known as **sidebands**: Fig.2.18(c).

(e) Significance:

- To receive the worst-case sequence 101010, which has a fundamental frequency component f_0 (in Hz) which is equal to half of the bit rate, the minimum bandwidth required for ASK is equal to the bit rate (in Hz), $2f_0$.
- To receive the 3rd harmonic components, three times the bit rate (in Hz) $6f_0$ is needed.

c. Use of ASK

(a) Old PSTN networks rarely used ASK. Those old PSTN had to rely on analog lines to carry signals over long distance. Attenuations can easily change signal amplitude and make ASK difficult to use.

(b) Newer PSTN now often only uses analog line to carry signal on the local-loop segment and uses digital circuits after that for long distance transmission. ASK is more usable here.

(c) Example (From 4th ed. of 1st textbook, Section 2.7, p.61) Assuming ASK is used and assuming (a) the fundamental frequency component of the sequence 101010... is to be received and (b) three cases of the fundamental frequency plus 3rd harmomics: 300bps, 1200bps, and 4800bps. Estimate the bandwidth required for a channel to perform the above transmissions.

Bit rate	300 bps	1200 bps	4800 bps
Fundamental freq component	150 Hz	600 Hz	2400 Hz
3rd harmonic component	450 Hz	1800 Hz	7200 Hz
Bandwidth with fundamental only	300 Hz	1200 Hz	4800 Hz
Bandwidth with fundamental and 3rd harmonic	900 Hz	3600 Hz	14400 Hz

For normal PSTN lines the usable bandwidth is 3000Hz. Hence the 300bps rate can be obtained with the 3rd harmonic. A rate of 1200bps can be done but with only the fundamental freq component. A rate 4800bps cannot be done with ASK only.

(4) Frequency-shift keying (FSK)

a. Principle illustration: Fig.27(c), and part of Fig.2.5, p.103.

(a) It uses two different carrier frequencies, one for 0, another for 1. The difference between the two carriers is called **frequency shift**.

(b) More frequencies can be used. For example 4 frequencies, one for 0, 2nd for 1, 3rd for 2 and another for 3.

b. In theory, FSK is equivalent to adding together the outputs of the individual carrier signals:

$$v_{FSK}(t) = cos\omega_1 t.v_d(t) + cos\omega_2 t.v_d'(t)$$

where ω_1 and ω_2 are two carrier signals $-(\omega_c - \Delta\omega)$ and $(\omega_c + \Delta\omega)$, and $v_d'(t)$ is the complement of the original data signal $v_d(t)$. Mathematically $v_d'(t) = 1 - v_d(t)$. Assume the data signal has a fundamental frequency ω_0, then

$$\begin{aligned} v_{FSK}(t) =& cos\omega_1 t\{\tfrac{1}{2} + \tfrac{2}{\pi}(cos\omega_0 t - cos3\omega_0 t + ...)\} \\ &+cos\omega_2 t\{\tfrac{1}{2} - \tfrac{2}{\pi}(cos\omega_0 t - cos3\omega_0 t + ...)\} \end{aligned}$$

i.e.

$$\begin{aligned} v_{FSK}(t) =& \tfrac{1}{2}cos\omega_1 t + \tfrac{1}{\pi}\{cos(\omega_1 - \omega_0)t + cos(\omega_1 + \omega_0)t \\ &-\tfrac{1}{3}cos(\omega_1 - 3\omega_0)t - \tfrac{1}{3}cos(\omega_1 + 3\omega_0)t+\} \\ &+\tfrac{1}{2}cos\omega_2 t + \tfrac{1}{\pi}\{cos(\omega_2 - \omega_0)t + cos(\omega_2 + \omega_0)t \\ &-\tfrac{1}{3}cos(\omega_2 - 3\omega_0)t - \tfrac{1}{3}cos(\omega_2 + 3\omega_0)t+\} \end{aligned}$$

Therefore we can deduce: the bandwidth required for FSK is simply the sum of two separate ASK-modulated carriers of frequencies ω_1 and ω_2.

c. FSK modulates a binary 1 and binary 0 with two separate carrier bits. Therefore the minimum bandwidth required for each carrier is half of the bit rate. Namely for FSK the highest fundamental frequency component for each carrier, f_0, is one half of that for ASK.

(5) Phase-shift keying (PSK)

a. Principle illustration: Fig.27(d) and part of Fig.2.5, p.103

(a) In PSK, the amplitude and frequency of the carrier signal are unchanged. The carrier is shifted in phase every time a bit is transmitted.

(b) There are two types of PSK techniques.

· **Phase coherent PSK** uses two fixed signals to represent a binary 0 and 1 with a 180^o phase difference between them. These two singals are the inverse of each other.

· **Diffential PSK** shift phases at each bit transition. The basic DPSK shifts at 90^o and 270^o.

b. Mathematical explanation: almost the same as ASK except the phase shift changes the polarity of the signal. Hence the bandwidth requirement for PSK is the same as for ASK.

c. **QPSK (quadrature PSK)**, also called **4-PSK**: Fig.2.6(a), p.105.

(a) There are four phase changes at $-0^0, 90^0, 180^0 and 270^0$. There are four possibilities. Hence each phase change represents two bits.

(b) In theory, higher bit rates can be achieved using larger number of phase changes.

(c) For practical implementations, we should minimize the number of phase changes required. Separate carriers are used, each of which is modulated separately.

d. **Constellation diagram**: a diagram that illustrates the phase changes: Fig.2.6(b), p.105.

(a) For 4-PSK, two carries of same frequencies are used. They differ 90^0 in phase.

· The two are known as **in-phase** (I) and the **quadrature carrier** (Q).

· The two modulated carriers are transmitted concurrently.

(6) Multilevel modulation methods.

a. Often a single modulation may not adequate for some applications. The three afore discussed modulations can be used together.

b. **QAM (quadrature amplitude modulation)**: 16-QAM is shown in Fig.2.6(b), p.105.

(a) It has four different amplitudes and eight phase shifts.

(b) For reliability consideration each phase only uses two out of the four amplitudes, resulting a 16 combinations, which can express 4-bit in each combination.

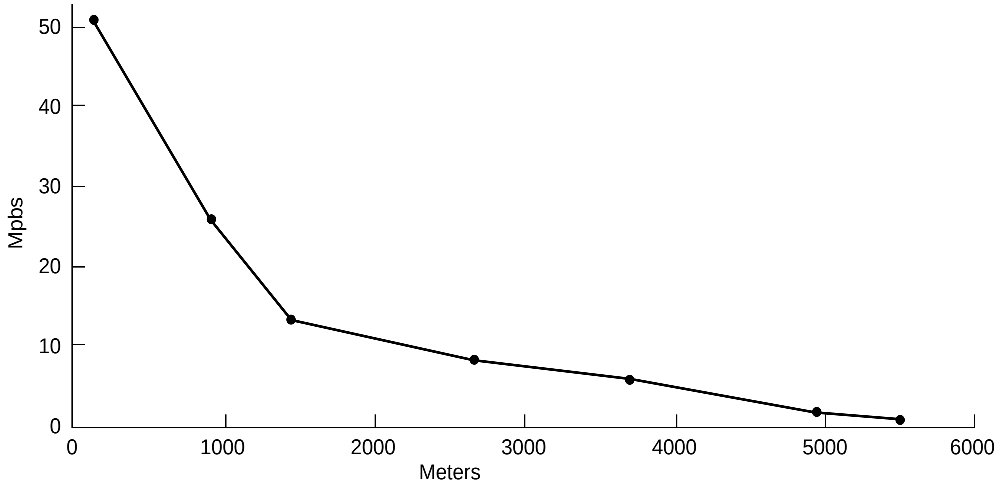

Figure 28: Bandwidth versus distance over category 3 UTP for DSL.

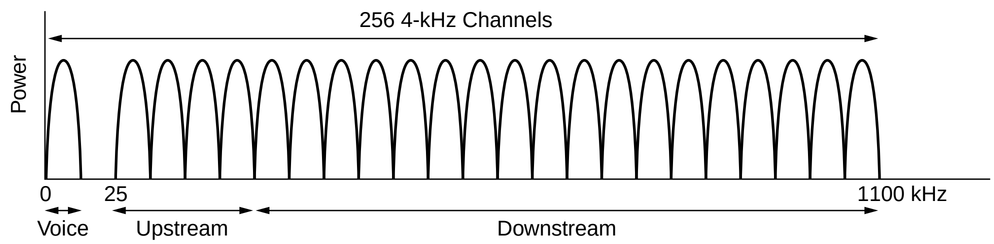

Figure 29: Operation of ADSL using discrete multitone modulation.

4. <u>DSL and ADSL</u>

(1) Principles

a. The 3000Hz limit

(a) PSTN was started to carry voice signal only

(b) Voice signals only need bandwidth around 3000Hz

(c) The entire PSTN had been optimized for voice signal transmission. The end offices of PSTN usually place a filter to filt out signals outside frequency range 300Hz to 3400Hz.

(d) The local loop normally uses category 3 UTP. Its supported bandwidth depends on the distance, as shown in Fig. 28.

b. DSL: when a customer subscribes a DSL service, the carrier will lift the 3000Hz limit at the end office connecting to the local loop of the customer. The whole available bandwidth will be shared between the normal phone services and DSL service.

c. There are various kinds of xDSL offers on the market. They differ in how they allocate the available bandwidth between the phone and DSL services.

(2) Goals and issues

a. DSL services must work over the existing category 3 UTP local loops.

b. They should not affect the existing phone and fax services of their customers.

c. They offer data service that is much faster than the current 56kbps dial-up services.

d. DSL data services should always be on (in order to compete with cable modem services) and charges are monthly, not based on per-minute usage.

(3) ADSL (asymmetric DSL)

a. ADSL divides the total available bandwidth between the phone and DSL services unevenly: it allocates the majority of the bandwidth to DSL and only leaves a small portion to phone service as it only requires a bandwidth around 3000Mz.

b. Most ADSL supports a total 1.1MHz bandwidth from the local loop. Some can support up to 10MHz.

c. There are different ADSL implementations which differ from each other on (i) the ratio of phone bandwidth and DSL width, (ii) the downstream bandwidth and upstream bandwidth. These two bandwidths are not asymmetric in ADSL (hence the name). Normally 80% to 90% of the data bandwidth are allocated to downstream control (downloading is more important for average users).

d. ADSL standard (ANSI T1.413 and ITU G.992.1): up to 8 Mbps downstream, 1 Mbps upstream. Typical standard ADSL services provides 512 Kbps downstream and 64 Kbps upstream. Premium ADSL services can provide 1 Mbps downstream and 256 Kbps upstream.

(4) The DMT (discrete multitone) based ADSL

a. Bandwidth allocation (Fig. 29). The total 1.1MHz bandwidth is divided into 256 independent channels of 4312.5Hz each.

b. Channel 1 (0-4312.5Hz) is used for POTS (plain old telephone service). Channel 1-5 (4313-25875Hz) are left unused to separate POTS from data service for better service quality.

c. Among the 250 channels allocated for data service, one is used for upstream traffic, the rest 249 channels can be used for downstream control.

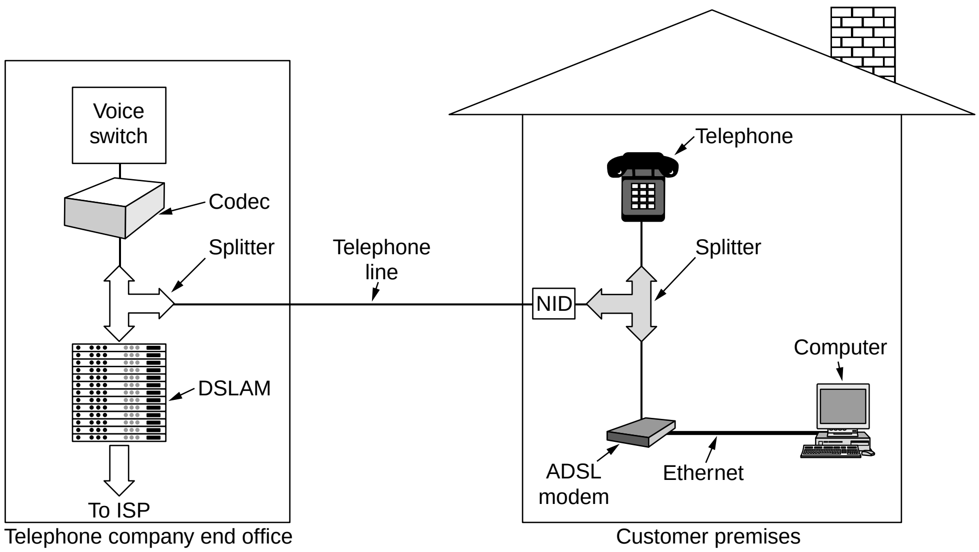

Figure 30: A typical ADSL equipment configuration.

(5) Typical ADSL arrangement: Fig.30.

a. **NID** (network interface device). Installed by the provider. It marks the end of customer property and start of the provider's property.

b. The **splitter**. This is a filter that extracts the analog signal generated for POTS and the ADSL data signal. ADSL signals are fed to the ADSL modem.

c. The ADSL modem. This is a digital signal processor. It is a 250 QAM modem that operates in parallel on different frequencies.

   (a) Most current ADSL modems are external. Such an external ADSL modem is connected to the computer's Ethernet port to form a 2-node Ethernet.

   (b) USB ports are used for some implementations. Internal DSL modems should be possible in the near future.

d. **DSLAM** (DSL Access Multiplexer). It is located in the provider's end office. The splitter in the end office provides the same function as the one in the customer's home.

5. <u>Internet over cable</u>

(1) Cable television system

a. History

(a) Community antenna television: started in 1940s as a way of providing better TV reception to people living in rural mountainous areas: Fig.31.

- Antennas picked up redio signals
- **Headend** is an amplifier that strengthens the received signal and send it along a coaxial cable.
- By 1970 thousands of independent antenna television systems existed.

(b) 1974, Time Inc. started HBO service that carries movies only feeding to antenna television systems. Many other specialized channels started shortly afterward.

(c) The cable industry subsequently consolidated many rounds leading to today's cable television system.

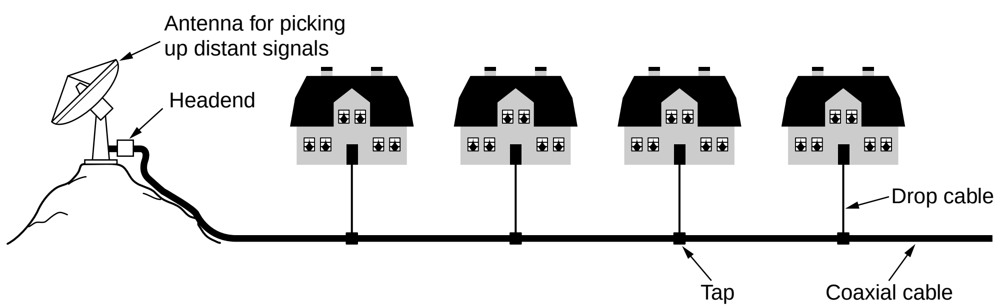

Figure 31: An early cable television system.

(2) Internet over cable: Fig.32

a. Traditional cable systems are purely coaxial cable systems.

b. Upgrade of the classical cable system: use of optical fiber for long haul transmissions. Such a cable system is called **HFC (hybrid fiber coax)** system.

(a) **Fiber nodes**: the electro-optical converters that interface between the optical and electrical parts of the cable system.

(b) The high bandwidth of fibers allows a fiber node to feed many multiple coaxial cables.

c. Noticeable differences of cable systems and telephone systems:

(a) The cable system is a broadcasting system. Programs are broadcast by a fiber node to its entire coaxial cable segment. Cable Internet users can affect each other.

(b) Telephone systems are point-to-point. There is a dedicated local-loop connection to its end office. Because the fiber that leading an end office out provides very high bandwidth, users of ADSL can hardly affect each other.

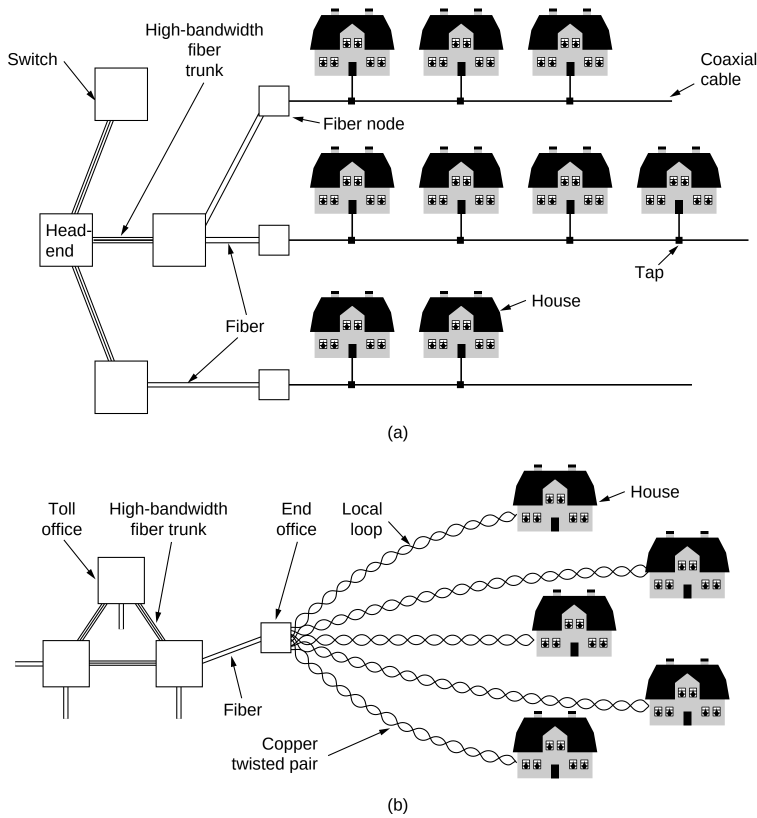

Figure 32: (a) CAble television. (b) The fixed telephone system.

(3) Spectrum (available bandwidth) allocation: Fig.33

a. Cable systems can have a bandwidth of about 750MHz (0-750MHz).

b. 54-88MHz, and 108-550MHz are used for (downstream) TV programs. These channels are 6MHz wide (including guard bands).

c. 88-108MHz is reserved for FM radio.

d. 5-42MHz is for upstream Internet traffic, 550-750MHz is for Internet downstream traffic.

e. The coaxial cable segments can be long. Transmitting digital signals over long coaxial cables has the same problems of sending them over analog lines. Analog modulation techniques have to be used.

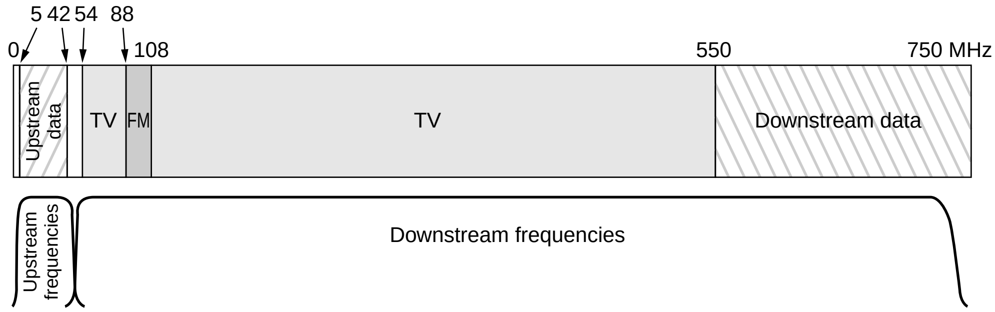

Figure 33: Frequency allocation in a typical cable TV system used for Internet acccess.

(4) Cable modems

a. Cable modems connect computers at Internet users' homes to the cable coaxial segments.

   (a) Early cable modems used proprietary modems.

   (b) The **DOCSIS (data over cable service interface specification)** standard has been gradually accepted as cable modem standard.

b. The modem-to-computer interface: it is simply a 10-Mbps Ethernet. USB interface has also been used.

c. Operation of the headend for upstream control

   (a) The headend interacts with cable modems through *minislots*. The length of the minislots is network dependent. The typical payload for minislots is 8 bytes.

   (b) The headend announces the start of a new round of minislots periodically. Due to propagation delay, cable modems may receive this announcement at different time instances.

   (c) Each upstream packet from any modem must fit in one or more minislots. During modem initialization the headend will assign a minislot to the modem to use for requesting upstream bandwidth.

   (d) Contension is possible because multiple modems can be assigned the same minislot. When a modem accepts a packet from its computer for upstream transmission, it first requests necessary number of minislots for the packet. The headend may acknowledge the request by allocating the requested number of minislots. The headend may also keep silience regarding to the request, implying no current allocation is possible.

(e) Contension is resolved using a binary-exponential backoff algorithm similar to the one used in Ethernet.

d. Cable modem power-up

(a) The modem scans the downstream channels to look for a special packet sent periodically by the headend that provides system parameters to newly powered up modems.

(b) Once finding this packet, the modem notify the headend its presence. The headend responds by assigning the modem to appropriate upstream and downstream channnels.

(c) The modem then performs **ranging** operation, which measures the round-trip time between the modem and the headend. Accurate measurement of this time is important for the modem's operation (so that the modem will know the actual start time instance of the first minislot in the current round of minislots).

e. Operation of the headend for downstream control

(a) It is much simpler. Downstream traffic is much larger than upstream. A packet of 204 bytes (with a 184 byte payload) is used for downstream.

(b) Downstream traffic has no contension. The headend is the only sender.

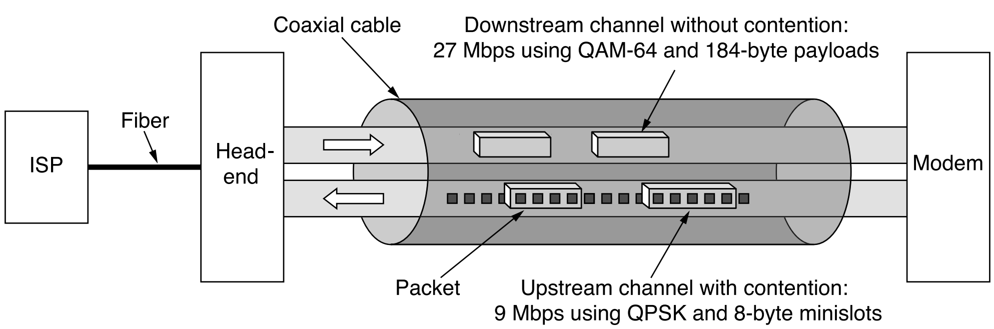

Figure 34: Typical details of the upstream and downstream channels in North America.

(5) Comparison of ADSL and cable modems

Issue	ADSL	Cable
Always online	Yes	Yes
Guaranteed predicable performance	Yes	No
High peak performance	No	Possible
Broadcasting	No	Yes
Peformance impact of more download & upload applications	No	Yes
Reliability	Better	Not as reliable
Security	Better	Encryption has to be used

6. Multiplexing

(1) Physical transmission trunks and multiplexing

a. These are high bandwidth transmission channels such as optical fiber paths and satellite links. Installing higher bandwidth trunks cost almost the same as lower bandwidth links.

b. These high bandwidth channels have to be shared by multiple applications simultaneously. This is called multiplexing.

(2) Frequency division multiplexing (FDM)

a. The whole available frequency bandwidth is divided into multiple channels that can be used by individual applications.

b. Principle illustration: Fig.35

c. Standardized FDM schemes

(a) Twelve 4000-Hz voice channels are multiplexed as a **group** into the 60 to 108 KHz band.

(b) Five groups (60 voice channels) form a **supergroup**.

(c) Five or ten supergroups (300 or 600 voice channels) form a **mastergroup**.

(3) Wavelength division multiplexing (WDM)

a. This is FDM for fiber optical channels.

b. Principle illustration: Fig.36

(4) Time division multiplexing (TDM)

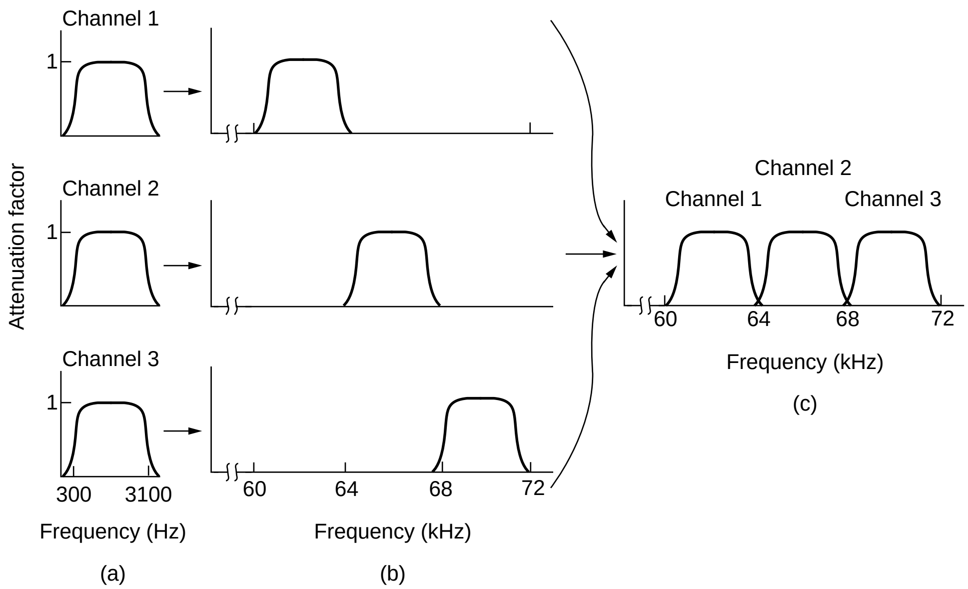

Figure 35: Frequency division multiplexing. (a) The original bandwidths. (b) The bandwidths raised in frequency. (c) The multiplexed channel.

a. WDM only works well for fiber optical channels and does not work well for copper wires. FDM works only for copper media that carry analog signals. TDM is a technique that allows the sharing of copper media, which carry digital signals, by multiple applications.

b. Principle illustration: Fig.37, the T1 carrier

   (a) The T1 carrier consists of 24 voice channels multiplexed together. During a transmission upto 24 connections can use the 24 channels by inserting 8 bit of its data.

   (b) A frame consists 193 bits $(8 \times 24 + 1)$, among them is an extra bit for framing. Such a frame is sent in 125μ seconds. This gives an $8000 \times 192 = 1.544$ Mbps gross data rate.

(5) Code division multiplexing (CDM)

a. Data from different connection sessions are coded differently so that a single comm. medium can be shared among them.

b. The CDMA (CDM Access) standard.

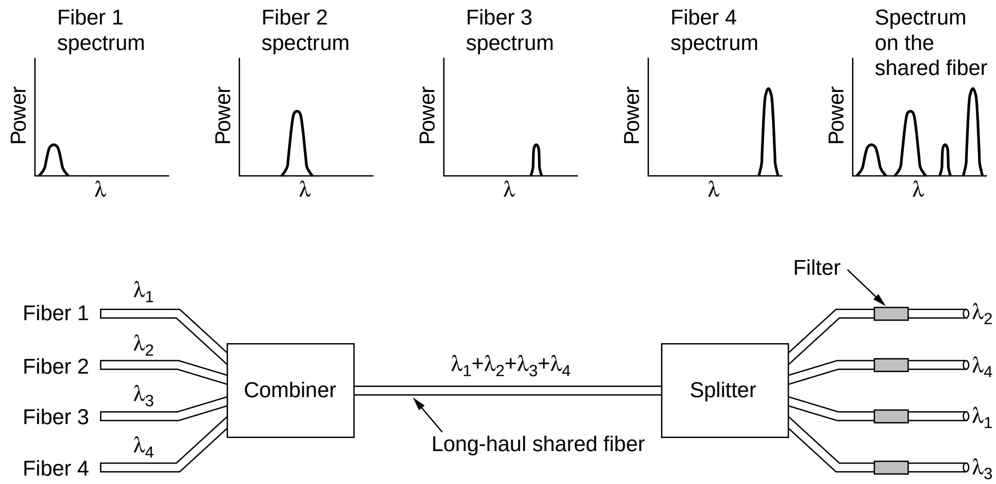

Figure 36: Wavelength division multiplexing.

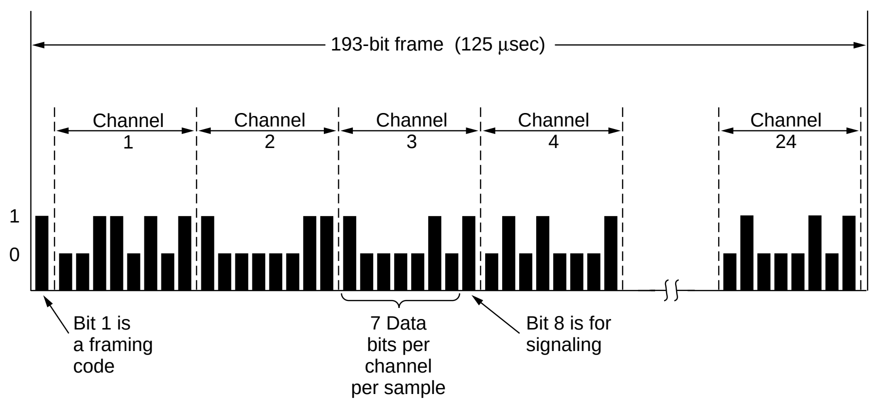

Figure 37: The T1 carrier (1.544 Mbps).