Multiplexing and Demultiplexing
Multiplexing

- *Multiplexing* means combining multiple streams of information for transmission over a shared medium.

- *Demultiplexing* performs the reverse function: split a combined stream arriving from a shared medium into the original information streams.
Figure 11.1 The concept of multiplexing in which independent pairs of senders and receivers share a transmission medium.

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Types of Multiplexing

• Frequency Division Multiplexing.
• Wavelength Division Multiplexing.
• Time Division Multiplexing.
• Statistical Time Division Multiplexing.
• Code Division Multiplexing.
Frequency Division Multiplexing (FDM)

- It is the basis for broadcast radio.
- Several stations can transmit simultaneously without interfering with each other provided they use separate carrier frequencies (separate channels).
- In data communications FDM is implemented by sending multiple carrier waves over the same copper wire.
- At the receiver’s end, demultiplexing is performed by filtering out the frequencies other than the one carrying the expected transmission.
- Any of the modulation methods discussed before can be used to carry bits within a channel.
Figure 11.2 Illustration of the basic FDM demultiplexing where a set of filters each selects the frequencies for one channel and suppresses other frequencies.

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• Rather than a single frequency, each channel is assigned a contiguous range of frequencies.
• Channels are separated from each other by guard bands to make sure there is no interference among the channels.
• Why is a range of frequencies assigned rather than a single frequency?
  – Sender can do FDM within its channel to increase the data rate. For example, it can split its channel into $K$ subchannels and transmit $1/K$ of the data over each subchannel. This will result in a K-fold increase of the data rate.
  – Spread spectrum: Transmit the same information over $K$ separate subchannels. If there is interference in one of the subchannels, the receiver can tune in one of the other subchannels.
<table>
<thead>
<tr>
<th>Channel</th>
<th>Frequencies Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 KHz - 300 KHz</td>
</tr>
<tr>
<td>2</td>
<td>320 KHz - 520 KHz</td>
</tr>
<tr>
<td>3</td>
<td>540 KHz - 740 KHz</td>
</tr>
<tr>
<td>4</td>
<td>760 KHz - 960 KHz</td>
</tr>
<tr>
<td>5</td>
<td>980 KHz - 1180 KHz</td>
</tr>
<tr>
<td>6</td>
<td>1200 KHz - 1400 KHz</td>
</tr>
</tbody>
</table>

**Figure 11.4** An example assignment of frequencies to channels with a guard band between adjacent channels.
Figure 11.5 A frequency domain plot of the channel allocation from Figure 11.4 with a guard band visible between channels.

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Wavelength Division Multiplexing

• In optical transmissions, FDM is known as *Wavelength Division Multiplexing* (WDM).
• With light different frequencies correspond to different colors.
• Several transmissions can be send over the same fiber by using different light colors, and combining into a single light stream.
• Prisms are used as multiplexors and demultiplexors.
Figure 11.7 Illustration of prisms used to combine and separate wavelengths of light in wavelength division multiplexing technologies.

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Time Division Multiplexing (TDM)

• It means dividing the available transmission time into time slots, and allocating a different slot to each transmitter.

• One method for transmitters to take turns is to transmit in *round-robin* order.
Figure 11.8 Illustration of the Time Division Multiplexing (TDM) concept with items from multiple sources sent over a shared medium.
Synchronous TDM

- No gaps between items.
- Uses round-robin.
Figure 11.9 Illustration of a Synchronous Time Division Multiplexing system with four senders.
TDM in the telephone system

• An extra bit is inserted at the beginning of each frame. The extra bit alternated between zero and one.

• Used by the demultiplexor to detect a synchronization error.
Figure 11.10 Illustration of the synchronous TDM system used by the telephone system in which a framing bit precedes each round of slots.

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Hierarchical TDM.

• A DS-1 (or T1) phone channel can transmit 24 conversation simultaneously. Data rate = 1.544Mbps.
• A DS-2 (or T2) channel multiplexes 4 DS-1 channels. Data rate = 6.312 Mbps.
• A DS-3 (or T3) channel multiplexes 7 DS-2 channels. Data rate = 44.736 Mbps.
• A DS-4 (or T4) channel multiplexes 6 DS-3 channels. Data rate = 274.176 Mbps.
**Figure 11.11** Illustration of the TDM hierarchy used in the telephone system.

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Unfilled slots in TDM

• In TDM every possible sender has a reserved time slot, whether it needs it or not.
• This may lead to underutilization of the transmission channel.
Figure 11.12 Illustration of a synchronous TDM system leaving slots unfilled when a source does not have a data item ready in time.

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The solution to unfilled slots: Statistical TDM

- Select items for transmission in round-robin order.
- But if a sender’s data is not ready, skip that sender and move to the next one.
- All slots will be filled as long as some sender has some data ready to send.
- But now each slot must also contain an identifier to indicate who is the receiver.
Figure 11.13 Illustration that shows how statistical multiplexing avoids unfilled slots and takes less time to send data.

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Figure 11.14 Illustration of inverse multiplexing in which a single high-speed digital input is distributed over lower-speed connections for transmission and then recombined to form a copy of the input.

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Code division multiplexing (CDM)

• Used in the cellular phone system and in some satellite communications.
• Each sender is assigned a unique binary code: its chip sequence (with -1 representing 0).
• Chip sequences for different senders are orthogonal vectors.
• A one is sent as a chip sequence. A zero is sent as the opposite of the chip sequence.
• Lower delay than TDM in high utilization networks.
Access and Interconnection Technologies
Internet Access Technology: Upstream vs Downstream

• Internet subscriber (home or business) connects to an Internet Service Provider (ISP).
• Most Internet users follow an asymmetric pattern: they download more data than they upload.
• Downstream is the data traveling from the provider to the subscriber.
• Upstream is the data traveling from the subscriber to the provider.
Figure 12.1 Definition of upstream and downstream directions as used in access technologies.
Narrowband vs Broadband Access Technologies

• Narrowband: up to 128 Kbps
• Broadband: at least 1 Mbps
• In between the two: call it what you will.
### Figure 12.2  The main narrowband technologies used for Internet access.

<table>
<thead>
<tr>
<th>Narrowband</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dialup telephone connections</td>
</tr>
<tr>
<td>Leased circuit using modems</td>
</tr>
<tr>
<td>Fractional T1 data circuits</td>
</tr>
<tr>
<td>ISDN and other telco data services</td>
</tr>
<tr>
<td><strong>Broadband</strong></td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>DSL technologies</td>
</tr>
<tr>
<td>Cable modem technologies</td>
</tr>
<tr>
<td>Wireless access technologies</td>
</tr>
<tr>
<td>Data circuits at T1 speed or higher</td>
</tr>
</tbody>
</table>

**Figure 12.3** The main broadband Internet access technologies.
The local loop

• The *local loop* is the pair of wires (twisted pair) connecting a telephone subscriber to a *central office* (CO).

• Only frequencies from 0 to 4 KHz are used to carry voice.

• Frequencies above 4 KHz can be used to carry data using FDM. This is the basis for DSL technology.
Digital Subscriber Line (DSL)

- DSL is a technology used to provide high-speed data communications over a local loop.
- The most common form is ADSL (Asymmetric Digital Subscriber Line). It is asymmetric because the downstream is faster than the upstream.
<table>
<thead>
<tr>
<th>Name</th>
<th>Expansion</th>
<th>General Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADSL</td>
<td>Asymmetric DSL</td>
<td>Residential customers</td>
</tr>
<tr>
<td>ADSL2</td>
<td>Asymmetric DSL version 2</td>
<td>Approximately three times faster</td>
</tr>
<tr>
<td>SDSL</td>
<td>Symmetric DSL</td>
<td>Businesses that export data</td>
</tr>
<tr>
<td>HDSL</td>
<td>High bit rate DSL</td>
<td>Businesses up to 3 miles away</td>
</tr>
<tr>
<td>VDSL</td>
<td>Very-high bit rate DSL</td>
<td>Proposed version for 52-Mbps</td>
</tr>
</tbody>
</table>

Figure 12.4  Main variants of DSL that are collectively known as xDSL.

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Figure 12.5 An illustration of how ADSL divides the available bandwidth of the local loop.

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Local Loop Characteristics

• ADSL sounds simple in concept, but it is complex in practice, because of the different characteristics of local loops.
• The ability of a local loop to carry signals depends on:
  – Distance to CO.
  – Diameter of the wiring.
  – Level of electrical interference.
• Because interference is frequency dependent, it is impossible to pick a single carrier frequency that will work well with all the local loops.
Adaptation. Discrete Multi Tone Modulation

• ADSL is *adaptive*. ADSL modems probe the line and choose an optimal set of frequencies.

• ADSL uses *Discrete Multi Tone modulation* (DMT) that combines FDM and inverse multiplexing.

• 286 frequencies are used: 255 for downstream and 31 for upstream. These frequencies are called *subchannels*.

• The frequencies are spaced 4.1325 KHz apart so that they don’t interfere with each other.
ADSL data rate

- Varies with distance to CO, quality of wiring, and electrical interference.
- Maximum downstream data rate: 8.448 Mbps.
- Maximum upstream data rate: 640 Kbps.
- The ADSL data rate applies only to the connection between the subscriber and the CO, not to the Internet as a whole. For example, connecting to a slow Web server somewhere on the Internet may result in lower effective data rates.
Figure 12.6  Illustration of a splitter and the wiring used with ADSL.

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Cable Modem Technology

• Again based on FDM.
• Some frequency bands in the cable carry TV. Other frequency band can be used to carry data.
• However there are too many subscribers to allocate a separate data channel to each.
• Instead, a single data channel is shared among many subscribers (sort of like Ethernet, which we will study later).
• Each subscriber is assigned a unique address.
• Each packet carries the address of the subscriber it is intended to.
• Max data rates:
  – Downstream: 52 Mbps
  – Upstream: 512 Kbps
• Effective data rate depends on how many subscribers are using the shared channel at the same time.
Hybrid Fiber Coax

• Combination of optical fibers and coaxial cables.
• A **trunk** is a high-capacity connection between the cable office and each neighborhood. Uses optical fibers.
• A **feeder circuit** runs form a curbside box to the individual subscribers. Uses coaxial cable.
• Max trunk length approx. 15 miles.
• Max feeder circuit length approx. 1 mile.
Figure 12.7 Illustration of a Hybrid Fiber Coax access system.

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Fiber based access technologies

<table>
<thead>
<tr>
<th>Name</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTTC</td>
<td>Fiber To The Curb</td>
</tr>
<tr>
<td>FTTB</td>
<td>Fiber To The Building</td>
</tr>
<tr>
<td>FTTH</td>
<td>Fiber To The Home</td>
</tr>
<tr>
<td>FTTP</td>
<td>Fiber To The Premises</td>
</tr>
</tbody>
</table>

**Figure 12.8** Names of additional access technologies that use optical fiber.

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Head-End and Tail-End modems.

• The cable modem at the subscriber’s location is called a *tail-end modem*.
• The cable modem at the provider’s location is called a *head-end modem*.
• A large number of head-end modems are usually combined into a single unit that can be configured, controlled and monitored together.
• The technical name for these sets of head-modems is *Cable Modem Termination System* (CMTS).
• An industry standard called *Data Over Cable System Interface Specifications (DOCSIS)* specifies the format of the data and messages send to the CMTS’s.
High-Capacity Connections at the Internet Core

• DSL and Cable Modem Technologies do not provide enough capacity to handle the traffic from the Providers to the Internet Routers or between Internet Routers.

• The technologies used to support high capacity connections are known as core technologies.

• The capacity of core connections is measured in Gbps, whereas the capacity of DSL and Cable is measured in Mbps.

• Core capacity is provided by point-to-point digital circuits leased from the phone companies.
Figure 12.10 Aggregate traffic from the Internet to a provider assuming the provider has 5,000 customers each downloading 2 Mbps.
Telephone Standards for Digital Circuits

• In the US we use the \textit{T standards}. In Europe the \textit{E standards} are used.

• There is a related set of standards, the \textit{Digital Signal Level Standards}, or DS standards. They are used interchangeably. Thus T1 and DS1 are the same thing.

• \( T2 = 4 \times T1 \)

• \( T3 = 7 \times T2 \)
<table>
<thead>
<tr>
<th>Name</th>
<th>Bit Rate</th>
<th>Voice Circuits</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic rate</td>
<td>0.064 Mbps</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>1.544 Mbps</td>
<td>24</td>
<td>North America</td>
</tr>
<tr>
<td>T2</td>
<td>6.312 Mbps</td>
<td>96</td>
<td>North America</td>
</tr>
<tr>
<td>T3</td>
<td>44.736 Mbps</td>
<td>672</td>
<td>North America</td>
</tr>
<tr>
<td>E1</td>
<td>2.048 Mbps</td>
<td>30</td>
<td>Europe</td>
</tr>
<tr>
<td>E2</td>
<td>8.448 Mbps</td>
<td>120</td>
<td>Europe</td>
</tr>
<tr>
<td>E3</td>
<td>34.368 Mbps</td>
<td>480</td>
<td>Europe</td>
</tr>
</tbody>
</table>

**Figure 12.11** Examples of digital circuits and their capacity.
STS Standards (Highest Capacity Circuits)

- STS stands for *Synchronous Transport Signal*. It is set of standards used in the trunks (high-capacity circuits) of the phone companies.
## STS circuits

<table>
<thead>
<tr>
<th>Copper Name</th>
<th>Optical Name</th>
<th>Bit Rate</th>
<th>Voice Circuits</th>
</tr>
</thead>
<tbody>
<tr>
<td>STS-1</td>
<td>OC-1</td>
<td>51.840 Mbps</td>
<td>810</td>
</tr>
<tr>
<td>STS-3</td>
<td>OC-3</td>
<td>155.520 Mbps</td>
<td>2430</td>
</tr>
<tr>
<td>STS-12</td>
<td>OC-12</td>
<td>622.080 Mbps</td>
<td>9720</td>
</tr>
<tr>
<td>STS-24</td>
<td>OC-24</td>
<td>1,244.160 Mbps</td>
<td>19440</td>
</tr>
<tr>
<td>STS-48</td>
<td>OC-48</td>
<td>2,488.320 Mbps</td>
<td>38880</td>
</tr>
<tr>
<td>STS-192</td>
<td>OC-192</td>
<td>9,953.280 Mbps</td>
<td>155520</td>
</tr>
</tbody>
</table>

**Figure 12.12** Data rates of digital circuits according to the STS hierarchy of standards.

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