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William Stallings • Thomas Case

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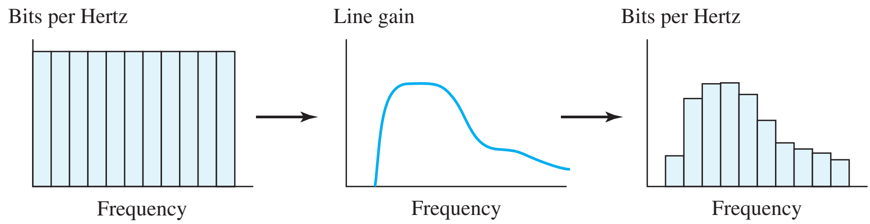


Figure 6.7 DMT Bits per Channel Allocation

Each subchannel can carry a data rate from 0 to 60 Kbps. The figure shows a typical situation in which there is increasing attenuation and hence decreasing signal-to-noise ratio at higher frequencies. As a result, the higher-frequency subchannels carry less of the load.

Present ADSL/DMT designs employ 256 downstream subchannels. In theory, with each 4-kHz subchannel carrying 60 Kbps, it would be possible to transmit at a rate of 15.36 Mbps. In practice, transmission impairments prevent attainment of this data rate. Current implementations operate at 1.5 to 9 Mbps, depending on line distance and quality.

6.4 SYNCHRONOUS TIME-DIVISION MULTIPLEXING

The TDM Mechanism

The other major form of multiplexing is **time-division multiplexing (TDM)**. In this section we examine **synchronous TDM**, which is often simply referred to as TDM.

Time-division multiplexing is possible when the data rate of the transmission medium exceeds the required data rate of signals to be transmitted. A number of digital signals, or analog signals carrying digital data, can be carried simultaneously by interleaving portions of each signal in time. A general case of TDM is shown in Figure 6.3b. In this figure, six signal sources are fed into a multiplexer, which interleaves the bits from each signal by taking turns transmitting bits from each of the signals in a round-robin fashion. For example, the multiplexer in Figure 6.3b has six inputs that might be, say, 9.6 Kbps each. A single line with a capacity of at least 57.6 Kbps accommodates all six sources.

A simple example of TDM is illustrated in Figure 6.8, which shows the transmission of three data signals simultaneously over a transmission medium. In this example, each source operates at 64 Kbps. The output from each source is briefly buffered. Each buffer is typically one bit or one character in length. The buffers are scanned in a round-robin fashion to form a composite digital data stream. The scan operations are sufficiently rapid so that each buffer is emptied before more data can arrive. The scanned data are combined by the multiplexer into a composite data stream. Thus, the data rate transmitted by the multiplexer must at least equal the sum of the data rates of the three inputs ($3 \times 64 = 192$ Kbps). The digital signal produced by the multiplexer may be transmitted digitally or passed through a modem so that an analog signal is transmitted. In either case, transmission is

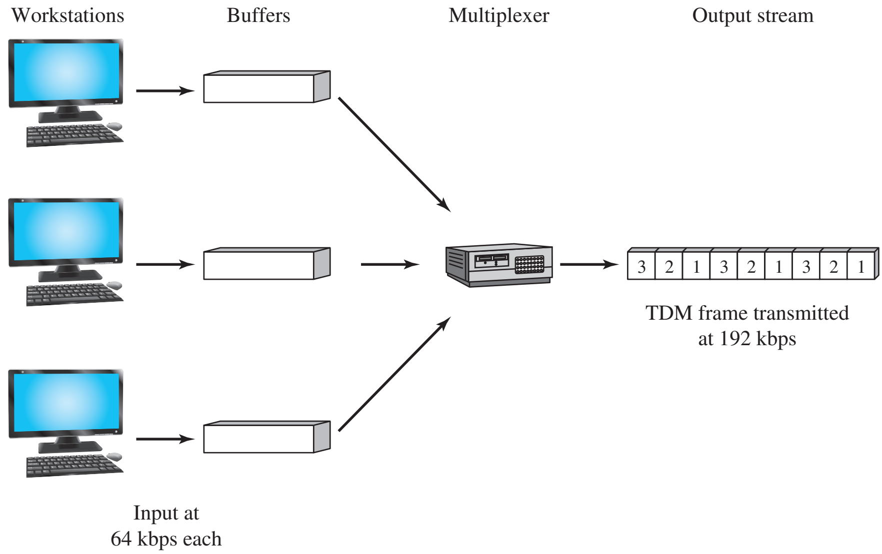


Figure 6.8 Synchronous TDM of Three Data Channels

typically synchronous (as opposed to asynchronous). At the receiving end, the demultiplexing process involves distributing the incoming data among three destination buffers.

The data transmitted by a synchronous TDM system have a format like that of Figure 6.9. The data are organized into *frames*, each of which contains a cycle of time slots. In each frame, one or more slots are dedicated to each data source. Transmission consists of the transmission of a sequence of frames. The set of time slots dedicated to one source, from frame to frame, is called a *channel*. Note that this is the same term used for FDM. The two uses of the term "channel" are logically equivalent. In both cases, a portion of the transmission capacity is dedicated to signals from a single source; that source sees a constant-data-rate or constant-bandwidth channel for transmission.

The slot length equals the transmitter buffer length, typically a bit or a byte (character). The byte-interleaving technique is used with both asynchronous and synchronous sources. Each time slot contains one byte of data. For asynchronous transmission, the start and stop bits of each character are typically eliminated before transmission and reinserted by the receiver, thus improving efficiency. The bit-interleaving technique is used with synchronous sources.

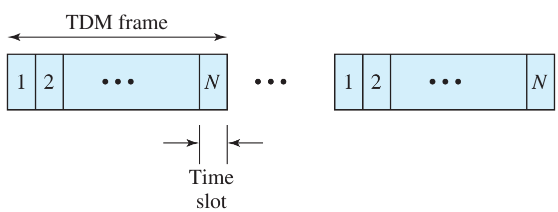


Figure 6.9 TDM Frame Structure

Synchronous TDM is called synchronous not because synchronous transmission is used but because the time slots are preassigned to sources and are fixed. The time slots for a given source are transmitted whether or not the source has data to send. This is, of course, also the case with FDM: A frequency band is dedicated to a particular source whether or not the source is transmitting at any given time. In both cases, capacity is wasted to achieve simplicity of implementation. Even when fixed assignment is used, however, it is possible for a synchronous TDM device to handle sources of different data rates. For example, the slowest input devices could be assigned one slot per frame, while faster devices are assigned multiple slots per frame.

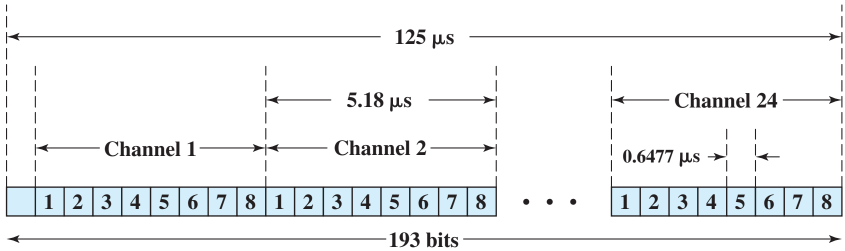
Digital Carrier Systems

The long-distance carrier system provided in the United States and throughout the world was designed to transmit voice signals over high-capacity transmission links, such as optical fiber, coaxial cable, and microwave. Part of the evolution of these telecommunications networks to digital technology has been the adoption of synchronous TDM transmission structures. In the United States, AT&T developed a hierarchy of TDM structures of various capacities; this structure is used in Canada and Japan as well as the United States. A similar, but unfortunately not identical, hierarchy has been adopted internationally under the auspices of ITU-T; it is widely used in Europe and is often referred to as the E-carrier hierarchy, where E stands for European (Table 6.2).

The basis of the TDM hierarchy (in North America and Japan) is the DS-1 transmission format (Figure 6.10), which multiplexes 24 channels. Each frame contains 8 bits per channel, 24 channels, plus a framing bit. Hence, each frame is 193 bits (24 channels $\times$ 8 bits per channel $+$ 1 framing bit $=$ 193 bits). For voice transmission, the following rules apply. Each channel of each frame contains one byte (8 bits) of digitized voice data. The original analog voice signal is digitized using pulse code modulation (PCM) at a rate of 8000 samples per second. Therefore, each channel slot and hence each frame must repeat 8000 times per second. With a frame length of 193 bits, we have a data rate of 8000 frames per second $\times$ 193 bits per frame $=$ 1.544 Mbps. For five of every six frames, 8-bit PCM samples are used. For every sixth frame, each channel contains a 7-bit PCM byte plus a signaling bit. The signaling bits form a

Table 6.2 North American and International TDM Carrier Standards

North American			International (ITU-T)		
Designation	**Number of Voice Channels**	**Data Rate (Mbps)**	**Level**	**Number of Voice Channels**	**Data Rate (Mbps)**
DS-1	24	1.544	1	30	2.048
DS-1C	48	3.152	2	120	8.448
DS-2	96	6.312	3	480	34.368
DS-3	672	44.736	4	1920	139.264
DS-4	4032	274.176	5	7680	565.148



Notes:

1. The first bit is a framing bit, used for synchronization.
2. Voice channels:
   - 8-bit PCM used on five of six frames.
   - 7-bit PCM used on every sixth frame; bit 8 of each channel is a signaling bit.
3. Data channels:
   - Channel 24 is used for signaling only in some schemes.
   - Bits 1–7 used for 56 kbps service
   - Bits 2–7 used for 9.6, 4.8, and 2.4 kbps service.

Figure 6.10 DS-1 Transmission Format

stream for each voice channel that contains network control and routing information. For example, control signals are used to establish a connection or terminate a call.

The same DS-1 format is used to provide digital data service. For compatibility with voice, the same 1.544-Mbps data rate is used. In this case, 23 channels of data are provided. The twenty-fourth channel position is reserved for a special sync byte, which allows faster and more reliable reframing following a framing error. Within each channel, 7 bits per frame are used for data, with the eighth bit used to indicate whether the channel, for that frame, contains user data or system control data. With 7 bits per channel, and because each frame is repeated 8000 times per second, a data rate of 56 Kbps can be provided per channel. Lower data rates are provided using a technique known as subrate multiplexing.[2]

Finally, the DS-1 format can be used to carry a mixture of voice and data channels. In this case, all 24 channels are utilized; no sync byte is provided.

Above this basic data rate of 1.544 Mbps, higher-level multiplexing is achieved by interleaving bits from DS-1 inputs. For example, the DS-2 transmission system combines four DS-1 inputs into a 6.312-Mbps stream. Data from the four sources are interleaved 12 bits at a time. Note that $1.544 \times 4 = 6.176$ Mbps. The remaining capacity is used for framing and control bits.

The designations DS-1, DS-1C, and so on refer to the multiplexing scheme used for carrying information. AT&T and other carriers supply transmission facilities that support these various multiplexed signals, referred to as carrier systems. These are designated with a "T" label. Thus, the T-1 carrier provides a data rate of 1.544 Mbps and is thus capable of supporting the DS-1 multiplex format and so on for higher data rates.

[2]For this technique, an additional bit is robbed from each channel to indicate which subrate multiplexing rate is being provided. This leaves a total capacity per channel of $6 \times 8000 = 48$ Kbps. This capacity is used to multiplex five 9.6-Kbps channels, ten 4.8-Kbps channels, or twenty 2.4-Kbps channels. For example, if channel 2 is used to provide 9.6-Kbps service, then up to five data subchannels share this channel. The data for each subchannel appear as six bits in channel 2 every fifth frame.

T-1 Facilities

The T-1 facility is widely used by companies as a way of supporting networking capability and controlling costs. The most common external use (not part of the public telephone network) of T-1 facilities is for leased dedicated transmission between customer premises. These facilities allow the customer to set up private networks to carry traffic throughout an organization. Examples of applications for such private networks include:

- **Private voice networks:** When there is a substantial amount of intersite voice traffic, a leased private network can provide significant savings over using dial-up facilities.
- **Private data network:** Similarly, high data volumes between two or more sites can be supported by T-1 lines.
- **Video teleconferencing:** Allows high-quality video to be transmitted. As the bandwidth requirement for video declines, private video conferencing links can share T-1 facilities with other applications.
- **High-speed digital facsimile:** Permits rapid transmission of facsimile images and, depending on the facsimile load, may be able to share the T-1 link with other applications.
- **Internet access:** If a high volume of traffic between the site and the Internet is anticipated, then a high-capacity access line to the local Internet service provider is needed.

For users with substantial data transmission needs, the use of private T-1 networking is attractive for two reasons. First, T-1 permits simpler configurations than the use of a mix of lower-speed offerings (such as multiple dedicated 56 Kbps links), and second, T-1 transmission services are less expensive.

Another popular use of T-1 is to provide high-speed access from the customer's premises to the telephone network. In this application, a local area network or PBX on the customer's premises supports a number of devices that generate sufficient off-site traffic to require the use of a T-1 access line to the public network.

Sonet/SDH

Synchronous Optical Network (SONET) is an optical transmission interface that was originally designed for the public telephone network. It began to be deployed in the 1980s and is still widely used. It has been standardized by ANSI for voice, long-haul data, and/or video traffic applications. A compatible version, referred to as Synchronous Digital Hierarchy (SDH), has been published by ITU-T in Recommendations G.707, G.708, and G.709.[3]

SONET is intended to provide a specification for taking advantage of the high-speed digital transmission capability of optical fiber. Similar to Ethernet, SONET provides a physical layer (layer 1 in the OSI model) interface technology that is

[3]In what follows, we will use the term *SONET* to refer to both specifications. Where differences exist, these will be addressed.

capable of carrying multiple higher level application protocols. For example, IP packets can be configured for transmission over SONET circuits.

Signal Hierarchy The SONET (Synchronous Optical Network) specification defines a hierarchy of standardized digital data rates (Table 6.3). The lowest level, referred to as STS-1 (Synchronous Transport Signal level 1) or OC-1 (Optical Carrier level 1),[4] is 51.84 Mbps. This rate can be used to carry a single DS-3 signal or a group of lower-rate signals, such as DS1, DS1C, DS2, plus ITU-T rates (e.g., 2.048 Mbps).

Multiple STS-1 signals can be combined to form an STS-N signal. The signal is created by interleaving bytes from N STS-1 signals that are mutually synchronized. For the ITU-T Synchronous Digital Hierarchy, the lowest rate is 155.52 Mbps, which is designated STM-1. This corresponds to SONET STS-3.

The most common data transmission speeds over SONET ranges between 155 Mbps and 2.5 Gbps. To build these data streams, SONET multiplexes lower-speed channels (with bandwidths as low as 64 Kbps) into STS frames.

Frame Format The basic SONET building block is the STS-1 frame, which consists of 810 octets and is transmitted once every 125 μs, for an overall data rate of 51.84 Mbps (Figure 6.11a). The frame can logically be viewed as a matrix of 9 rows of 90 octets each, with transmission being one row at a time, from left to right and top to bottom.

The first three columns ($3 \text{ octets} \times 9 \text{ rows} = 27 \text{ octets}$) of the frame are devoted to overhead octets, called section overhead and line overhead, which relate to different levels of detail in describing a SONET transmission. These octets convey not only synchronization information but network management information.

Table 6.3 SONET/SDH Signal Hierarchy

SONET Designation	ITU-T Designation	Data Rate	Payload Rate (Mbps)
STS-1/OC-1	STM-0	51.84 Mbps	50.112 Mbps
STS-3/OC-3	STM-1	155.52 Mbps	150.336 Mbps
STS-9/OC-9		466.56 Mbps	451.008 Mbps
STS-12/OC-12	STM-4	622.08 Mbps	601.344 Mbps
STS-18/OC-18		933.12 Mbps	902.016 Mbps
STS-24/OC-24		1.24416 Gbps	1.202688 Gbps
STS-36/OC-36		1.86624 Gbps	1.804032 Gbps
STS-48/OC-48	STM-16	2.48832 Gbps	2.405376 Gbps
STS-96/OC-96		4.87664 Gbps	4.810752 Gbps
STS-192/OC-192	STM-64	9.95328 Gbps	9.621504 Gbps
STS-768	STM-256	39.81312 Gbps	38.486016 Gbps
STS-3072		159.25248 Gbps	1.53944064 Gbps

[4]An OC-N rate is the optical equivalent of an STS-N electrical signal. End-user devices transmit and receive electrical signals; these must be converted to and from optical signals for transmission over optical fiber.