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Leon W. Couch II

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DIGITAL AND ANALOG COMMUNICATION SYSTEMS

Eighth Edition

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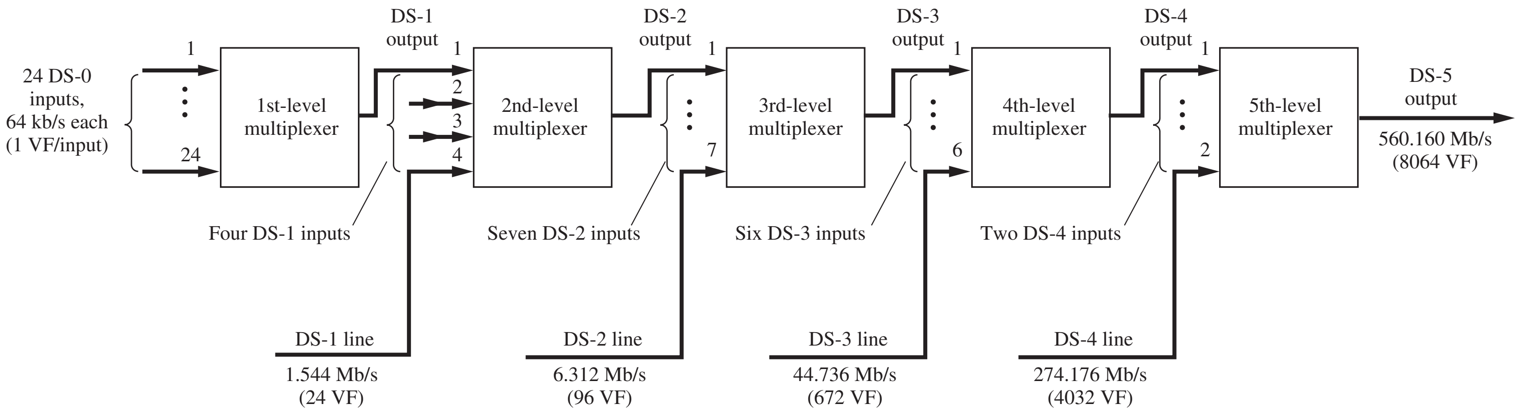


Figure 3–40 North American digital TDM hierarchy.

TABLE 3–8 TDM STANDARDS FOR NORTH AMERICA

Digital Signal Number	Bit Rate, R (Mbits/s)	No. of 64 kbits/s PCM VF Channels	Transmission Media Used
DS-0	0.064	1	Wire pairs
DS-1	1.544	24	Wire pairs
DS-1C	3.152	48	Wire pairs
DS-2	6.312	96	Wire pairs, fiber
DS-3	44.736	672	Coax., radio, fiber
DS-3C	90.254	1344	Radio, fiber
DS-4E	139.264	2016	Radio, fiber, coax.
DS-4	274.176	4032	Coax., fiber
DS-432	432.000	6048	Fiber
DS-5	560.160	8064	Coax., fiber

1989. This SONET standard is shown in Table 3–10. The OC-1 signal is an optical (light) signal that is turned on and off (modulated) by an electrical binary signal that has a line rate of 51.84 Mbits/s. The electrical signal is called the Synchronous Transport Signal—level 1 (STS-1 signal). Other OC-N signals have line rates of exactly N times the OC-1 rate and are formed by modulating a light signal with an STS-N electrical signal. The STS-N signal is obtained by byte-interleaving (scrambling) N STS-1 signals. (More details about fiber-optic systems are given in Sec. 8–7.)

The telephone industry can also provide an all-digital network that integrates voice and data over a single telephone line from each user to the telephone company equipment. One approach is called the *integrated service digital network* (ISDN). Another approach is a digital subscriber line (DSL) technique called G.Lite. This provides an "always-on" 1.5-Mb/s data path (for Internet access) plus a standard VF telephone signal over a single twisted-pair line. (For details on these techniques, see Section 8–3.)

The T1 PCM System

For telephone voice service, the first-level TDM multiplexer in Fig. 3–40 is replaced by a TDM PCM system, which will convert 24-VF analog telephone signals to a DS-1 (1.544-Mbits/s) data stream. In AT&T terminology, this is either a D-type channel bank or a digital carrier trunk (DCT) unit. A T1 line span is a twisted-pair telephone line that is used to carry the DS-1 (1.544 Mbit/s) data stream. Two lines, one for transmiting and one for receiving, are used in the system. If the T1 line is connecting telephone equipment at different sites, repeaters are required about every mile.

The T1 system was developed by Bell Laboratories for short-haul digital communication of VF traffic up to 50 mi. The sampling rate used on each of the 24-VF analog signals is 8 kHz, which means that one frame length is $1/(8 \text{ kHz}) = 125\ \mu\text{s}$, as shown in Fig. 3–42. Currently, each analog sample is nominally encoded into an 8-bit PCM word, so that there are $8 \times 24 = 192$ bits

TABLE 3–9 SPECIFICATIONS FOR T-CARRIER BASEBAND DIGITAL TRANSMISSION SYSTEMS

System	Rate (Mbits/s)	System Capacity: Digital Signal No.	System Capacity: Voice Channels	Medium	Line Code	Repeater Spacing (miles)	Maximum System Length (miles)	System Error Rate
T1	1.544	DS-1	24	Wire pair	Bipolar RZ	1	50	10^{-6}
T1C	3.152	DS-1C	48	Wire pair	Bipolar RZ	1	—	10^{-6}
T1D	3.152	DS-1C	48	Wire pair	Duobinary NRZ	1	—	10^{-6}
T1G	6.443	DS-2	96	Wire pair	4-level NRZ	1	200	10^{-6}
T2	6.312	DS-2	96	Wire pair[a]	B6ZS[b] RZ	2.3	500	10^{-7}
T3	44.736	DS-3	672	Coax.	B3ZS[b] RZ	[c]	[c]	[c]
T4	274.176	DS-4	4032	Coax.	Polar NRZ	1	500	10^{-6}
T5	560.160	DS-5	8064	Coax.	Polar NRZ	1	500	4×10^{-7}

[a] Special two-wire cable is required for 12,000-ft repeater spacing. Because T2 cannot use standard exchange cables, it is not as popular as T1.

[b] BnZS denotes *binary* n-*zero substitution*, where a string of *n* zeros in the bipolar line code is replaced with a special three-level code word so that synchronization can be maintained [Fike and Friend, 1984; Bic, Duponteil, and Imbeaux, 1991].

[c] Used in central telephone office for building multiplex levels; not used for transmission from office to office.

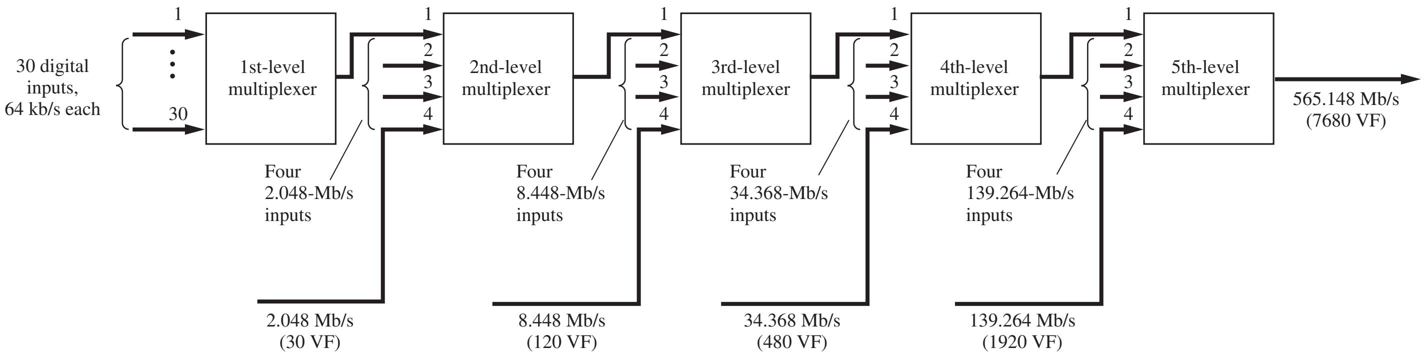
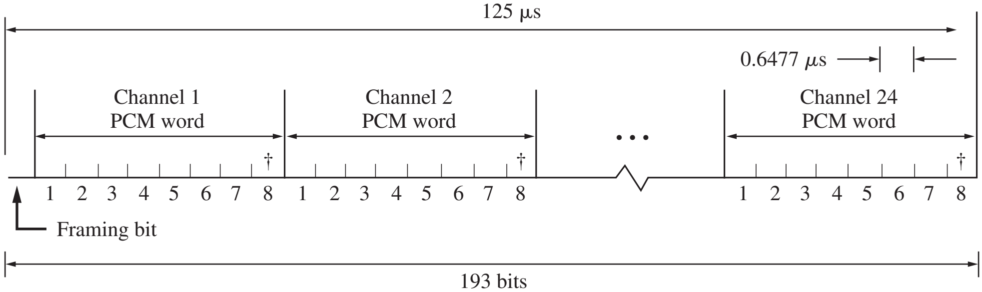


Figure 3–41 CCITT digital TDM hierarchy.

TABLE 3–10 SONET SIGNAL HIERARCHY

			Equivalent Number of		
Optical OC Level	Electrical STS Level	Line Rate (Mbits/s)	DS-3s	DS-1s	DS-0s
OC-1	STS-1	51.84	1	28	672
OC-3	STS-3	155.52	3	84	2,016
OC-9	STS-9	466.56	9	252	6,048
OC-12	STS-12	622.08	12	336	8,064
OC-18	STS-18	933.12	18	504	12,096
OC-24	STS-24	1,244.16	24	672	16,128
OC-36	STS-36	1,866.24	36	1,008	24,192
OC-48	STS-48	2,488.32	48	1,344	32,256
OC-192	STS-192	9,953.28	192	5,376	129,024
OC-768	STS-768	89,813.12	768	21,504	516,096
OC-3072	STS-3072	159,252.48	3,072	86,016	2,064,384

of data, plus one bit that is added for frame synchronization, yielding a total of 193 bits per frame. The T1 data rate is then (193 bits/frame)(8,000 frames/s) = 1.544 Mbits/s, and the corresponding duration of each bit is 0.6477 μs. The signaling is incorporated into the T1 format by replacing the eighth bit (the least significant bit) in each of the 24 channels of the T1 signal by a signaling bit in every sixth frame. Thus, the signaling data rate for each of the 24 input channels is (1 bit/6 frames)(8,000 frames/s) = 1.333 kbits/s. The framing bit used in the even-numbered frames follows the sequence 001110, and in the odd-numbered frames it follows the sequence 101010, so that the frames with the signaling information in the eighth bit position (for each channel) may be identified. The digital signaling on the T1 line is represented by a bipolar RZ waveform format (see Fig. 3–15) with peak levels of ±3 V across a 100-Ω load. Consequently, there is no DC component on the T1 line regardless of the data pattern. In encoding the VF PAM samples, a $\mu = 255$-type compression characteristic is used, as described earlier in this chapter. Because the T1 data rate is 1.544 Mbits/s and the line code is bipolar, the first zero-crossing



† On every sixth frame this VF PCM bit is replaced by a signaling bit for this channel.

Figure 3–42 T1 TDM format for one frame.

bandwidth is 1.544 MHz and the spectrum peaks at 772 kHz, as shown in Fig. 3–16d. If the channel filtering transfer function was of the raised cosine-rolloff type with $r = 1$, the absolute channel bandwidth would be 1.544 MHz. In the past, when twisted-pair lines were used for analog transmission only, *loading* coils (inductors) were used to improve the frequency (amplitude) response. However, they cause the line to have a phase response that is not linear with frequency, resulting in ISI. Thus, they must be removed when the line is used for T1 service.

The T1G carrier is described in Table 3–9. Instead of binary levels, it uses $M = 4$ (quaternary) multilevel polar NRZ signaling, where +3 V represents the two binary bits 11, +1 V represents 01, −1 V represents 00, and −3 V represents 10 [Azaret et al., 1985]. Thus, a data rate of 6.443 Mbits/s is achieved via 3.221-Mbaud signaling, giving a 3.221-MHz zero-crossing bandwidth, which is close to the 3.152-MHz zero-crossing bandwidth of the T1C system. This bandwidth can be supported by standard twisted-pair wires (one pair for each direction) with repeaters spaced at one-mile intervals.

Fiber-optic cable systems have phenomenal bandwidths and are relatively inexpensive on a per-channel basis. For example, the FT-2000 fiber-optic TDM system (see Tables 8–2 and 8–6) has a capacity of 32,256 VF channels, and the WaveStar system has a capacity of 6.25 million VF channels.

3–10 PACKET TRANSMISSION SYSTEM

TDM is a *synchronous transfer mode* (STM) technology. That is, a data source is assigned a specific time slot with a constant (fixed) data rate. In a number of applications, this fixed data rate assignment is not cost effective, since stuff bits are inserted to match the assigned data rate when the source does not have any data to send. For example, a user might send a large file (for which a large data rate is needed) and then type in some parameters (for which a low data rate is needed). This type of bursty data source is not efficiently accommodated by an STM system, but can be efficiently accommodated by a packet system.

A *packet transmission system* partitions the source data into data packets, each of which contains a destination address header. Many users share the high-speed channel by merging their packets into a high-speed data stream. Routers along the network read the header information on the packets and route the packet to the appropriate destination. To accommodate high-speed sources, more packets are sent from these sources over a given time interval, compared with only a few packets that are merged onto the network from low-speed sources.

A packet network efficiently assigns network resources when the sources have bursty data. However, there is network overhead caused by the transmission of the packet header information. STM networks are more efficient when the sources have a fixed data rate (i.e., when they are not bursty).

It is emphasized that *packet switched* transmission systems (such as the Internet, where internet protocol is used with IP numbers) are dominating transmission systems. This is especially true when compared with *circuit switched* transmission systems (such as TDM, as described in Sec. 3–9). The upcoming and cost-effective way to implement telephone systems is to use VoIP (Voice over the Internet with IP packets).