Chapter 1

PDH and T-Carrier: The Plesiochronous Hierarchies

1.1 Pulse Code Modulation

The *pulse code modulation* (PCM) technology (see Figure 1.1) was patented and developed in France in 1938, but could not be used because suitable technology was not available until World War II. This came about with the arrival of digital systems in the 1960s, when improving the performance of communications networks became a real possibility. However, this technology was not completely adopted until the mid-1970s, due to the large amount of analog systems already in place and the high cost of digital systems, as semiconductors were very expensive. PCM's initial goal was that of converting an analog voice telephone channel into a digital one based on the sampling theorem (see Figure 1.2):

The sampling theorem states that for digitalization without information loss, the sampling frequency (f_s) should be *at least twice* the maximum frequency component (f_{max}) of the analog information:

$$f_s > 2 \cdot f_{max}$$

The frequency $2 \cdot f_{max}$ is called the Nyquist sampling rate. The sampling theorem is considered to have been articulated by Nyquist in 1928, and mathematically proven by Shannon in 1949. Some books use the term *Nyquist sampling theorem*, and others use *Shannon sampling theorem*. They are in fact the same theorem.

PCM involves three phases: sampling, encoding, and quantization:

1. In sampling, values are taken from the analog signal every $1/f_s$ seconds (the sampling period).
2. Quantization assigns these samples a value by approximation, and in accordance with a quantization curve (i.e., A-law of ITU-T [1]).
3. Encoding provides the binary value of each quantified sample.

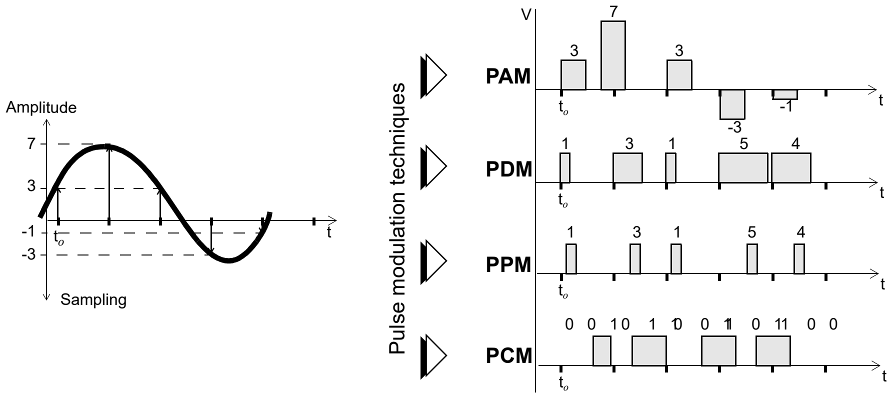

Figure 1.1 Pulse code modulation (PCM) was the technology selected to digitalize the voice in telephone networks. Other pulse techniques are pulse amplitude modulation (PAM), pulse duration modulation (PDM), and pulse position modulation (PPM).

A telephone channel admits frequencies of between 300 Hz and 3,400 Hz. Because margins must be established in the channel, the bandwidth is set at 4 kHz. Then the sampling frequency must be $f_s \geq 2 \cdot 4{,}000 = 8{,}000\ Hz$; equivalent to a sample period of $T = 1/8{,}000 = 125 \mu s$.

In order to codify 256 levels, 8 bits are needed, where the PCM bit rate (v) is:

$$v = 8{,}000_{\ samples/s} \times 8_{bits/sample} = 64Kbps$$

This bit rate is the subprimary level of transmission networks.

1.2 PDH and T-Carrier

At the beginning of the 1960s, the proliferation of analog telephone lines, based on copper wires, together with the lack of space for new installations, led the transmission experts to look at the real application of PCM digitalization techniques and TDM multiplexing. The first digital communications system was set up by Bell Labs in 1962, and consisted of 24 digital channels running at what is known as T1.

1. This is a International Telecommunication Union (ITU-T) ratified audio encoding and compression technique (Rec. G.711). Among other implementations, A-law was originally intended as a phone-communications standard.

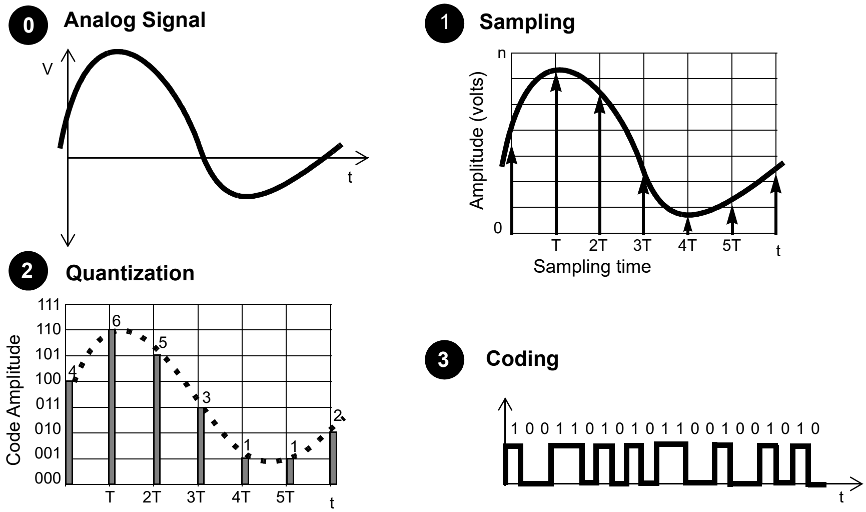

Figure 1.2 The three steps of digitalization of a signal: sampling of the signal, quantization of the amplitude, and binary encoding.

1.2.1 Basic Rates: T1 and E1

In 1965, a standard appeared in the U.S. that permitted the TDM multiplexing of 24 digital telephone channels of 64 Kbps into a 1.544-Mbps signal with a format called T1 (see Figure 1.3). For the T1 signal, a synchronization bit is added to the 24 TDM time slots, in such a way that the aggregate transmission rate is:

$$(24_{channels} \times 8_{bit/channel} + 1_{bit})/125\mu s = 1{,}544 Mbps$$

125 μs is the sampling period

Europe developed its own TDM multiplexing scheme a little later (1968), although it had a different capacity: 32 digital channels of 64 Kbps (see Figure 1.3). The resulting signal was transmitted at 2.048 Mbps, and its format was called E1 which was standardized by the ITU-T and adopted worldwide except in the U.S., Canada, and Japan. For an E1 signal, the aggregate transmission rate can be obtained from the following equation:

$$(30_{channels} \times 8_{bit/channel})/125\mu s = 2{,}048 Mbps$$

1.3 The E1 Frame

The E1 frame defines a cyclical set of 32 time slots of 8 bits. The time slot 0 is devoted to transmission management and time slot 16 for signaling; the rest were assigned originally for voice/data transport (see Figure 1.4).

The main characteristics of the 2-Mbps frame are described in the following.

1.3.1 Frame Alignment

In an E1 channel, communication consists of sending consecutive frames from the transmitter to the receiver. The receiver must receive an indication showing when the first interval of each frame begins, so that, since it knows to which channel the information in each time slot corresponds, it can demultiplex correctly. This way, the bytes received in each slot are assigned to the correct channel. A synchronization process is then established, and it is known as frame alignment.

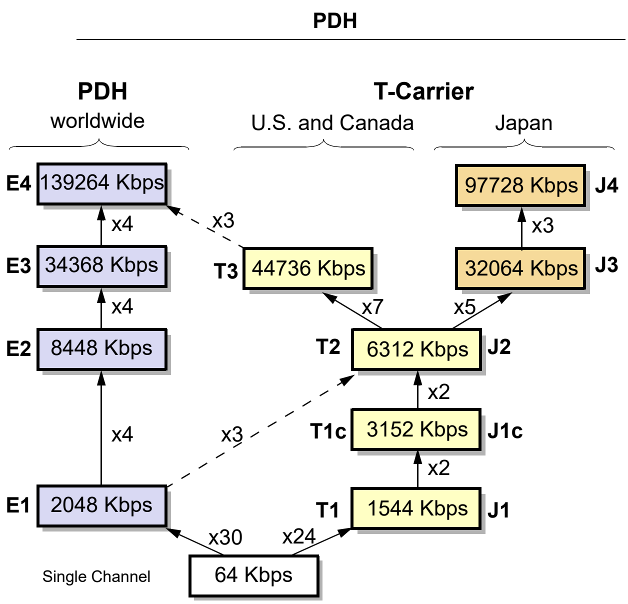

Figure 1.3 The PDH and T-carrier hierarchies, starting at the common 64-Kbps channel and the multiplexing levels. Most of the narrowband networks are built on these standards: POTS, FRL, GSM, ISDN, ATM (asynchronous transfer mode), and leased lines to transmit voice, data, and video.

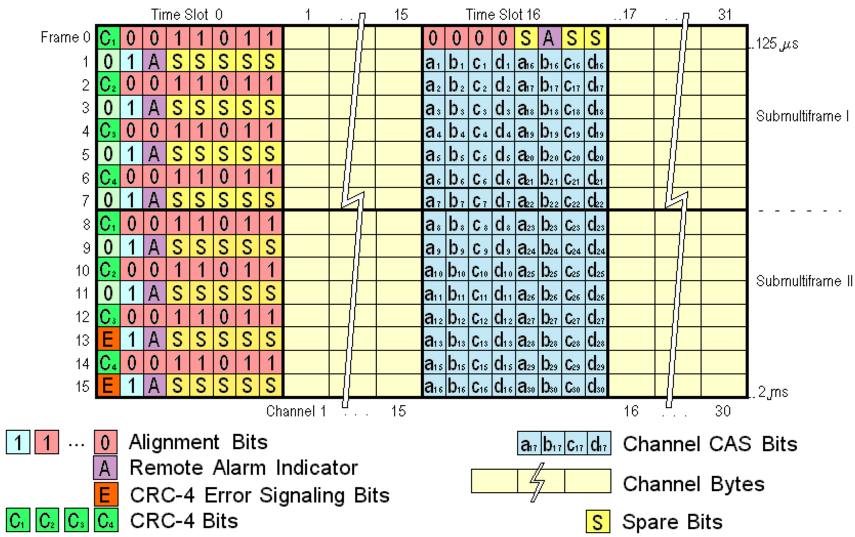

Figure 1.4 The E1 frame is the first hierarchy level, and all the channels are fully synchronous.

1.3.2 Frame Alignment Signal

In order to implement the frame alignment system so that the receiver of the frame can tell where it begins, there is what is called a frame alignment signal (FAS) (see Figure 1.5). In the 2Mbps frames, the FAS is a combination of seven fixed bits ("0011011") transmitted in the first time slot in the frame (*time slot zero* or TS0). For the alignment mechanism to be maintained, the FAS does not need to be transmitted in every frame. Instead, this signal can be sent in alternate frames (in the first, in the third, in the fifth, and so on). In this case, TS0 is used as the synchronization slot. The TS0 of the rest of the frames is therefore available for other functions, such as the transmission of the alarms.

1.3.3 Multiframe CRC-4

In the TS0 of frames with FAS, the first bit is dedicated to carrying the *cyclic redundancy checksum* (CRC). It tells us whether there are one or more bit errors in a specific group of data received in the previous the previous block of eight frames known as submultiframe (see Figure 1.6).

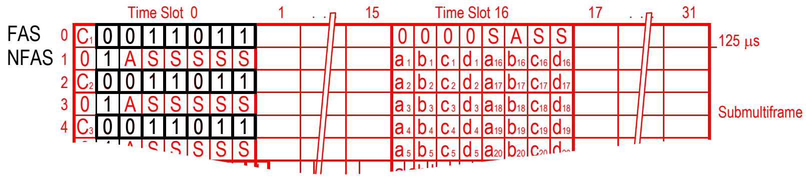

Figure 1.5 The E1 multiframe uses the FAS code only transmitted in even frames. The NFAS frames are the odd ones, using a bit equal to "1" to avoid coincidences.

1.3.3.1 The CRC-4 procedure

The aim of this system is to avoid loss of synchronization due to the coincidental appearance of the sequence "0011011" in a time slot other than the TS0 of a frame with FAS. To implement the CRC code in the transmission of 2-Mbps frames, a CRC-4 multiframe is built, made up of 16 frames. These are then grouped in two blocks of eight frames called submultiframes, over which a CRC checksum or word of four bits (CRC-4) is put in the positions C_i (bits #1, frames with FAS) of the next submultiframe.

At the receiving end, the CRC of each submultiframe is calculated locally and compared to the CRC value received in the next submultiframe. If these do not coincide, one or more bit errors is determined to have been found in the block, and an alarm is sent back to the transmitter, indicating that the block received at the far end contains errors (see Table 1.1).

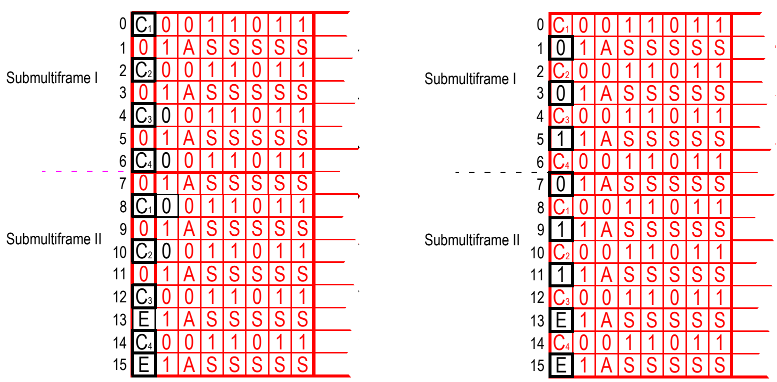

Figure 1.6 The CRC-4 provides error monitoring by means of four Ci bits that correspond to the previous submultiframe. If the receiver detects errors, it sets the E-bit to indicate the error. The "001011"sequence is used to synchronize the submultiframe.

1.3.3.2 CRC-4 multiframe alignment

The receiving end has to know which is the first bit of the CRC-4 word (C1). For this reason, a CRC-4 multiframe alignment word is needed. Obviously, the receiver has to be told where the multiframe begins (synchronization).

The CRC-4 multiframe alignment word is the set combination “001011,” which is introduced in the first bits of the frames that do not contain the FAS signal.

1.3.3.3 Advantages of the CRC-4 method

The CRC-4 method is mainly used to protect the communication against a wrong frame alignment word, and also to provide a certain degree of monitoring of the *bit error rate* (BER), when this has low values (around 10^{-6}). This method is not suitable for cases in which the BER is around 10^{-3} (where each block contains at least one errored bit).

Another advantage in using the CRC is that all the bits transmitted are checked, unlike those systems that only check seven bits (those of the FAS, which are the only ones known in advance) out of every 512 bits (those between one FAS and the next). However, the CRC-4 code is not completely infallible, since there is a probability of around 1/16 that an error may occur and not be detected; that is, that 6.25% of the blocks may contain errors that are not detected by the code.

1.3.3.4 Monitoring errors

The aim of monitoring errors is to continuously check transmission quality without disturbing the information traffic and, when this quality is not of the required stan-

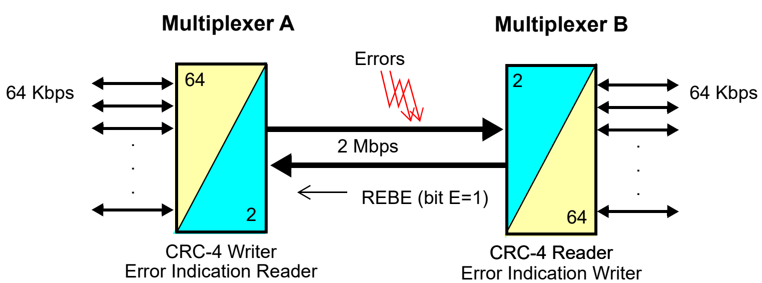

Figure 1.7 The A multiplexer calculates and writes the CRC code, and the multiplexer B reads and checks the code. When errors affect the 2-Mbps frame, the multiplexer B indicates the problem by means of the E-bit of the frame which travels toward the multiplexer B.

dard, taking the necessary steps to improve it. Telephone traffic is two way, which means that information is transmitted in both directions between the ends of the communication. This in its turn means that two 2-Mbps channels and two directions for transmission must be considered.

The CRC-4 multiframe alignment word only takes up six of the first eight bits of the TS0 without FAS. There are two bits in every second block or submultiframe, whose task is to indicate block errors in the far end of the communication. The mechanism is as follows: Both bits (called E-bits) have "1" as their default value. When the far end of the communication receives a 2Mbps frame and detects an erroneous block, it puts a "0" in the E-bit that corresponds to the block in the frame being sent along the return path to the transmitter (see Figure 1.7). This way, the near end of the communication is informed that an erroneous block has been detected, and both ends have the same information: one from the CRC-4 procedure and the other from the E bits. If we number the frames in the multiframe from 0 to 15, the E-bit of frame 13 refers to the submultiframe I (block I) received at the far end, and the E-bit of frame 15 refers to the submultiframe II (block II).

1.3.4 Supervision Bits

The bits that are in position 2 of the TS0 in the frame that does not contain the FAS are called supervision bits and are set to "1," to avoid simulations of the FAS signal.

1.3.5 NFASs - Spare Bits

The bits of the TS0 that do not contain the FAS in positions 3 to 8 make up what is known as the *non-frame alignment signal* or NFAS. This signal is sent in alternate frames (frame 1, frame 3, frame 5, etc.). The first bit of the NFAS (bit 3 of the TS0) is used to indicate that an alarm has occurred at the far end of the communication. When operating normally, it is set to "0," while a value of "1" indicates an alarm.

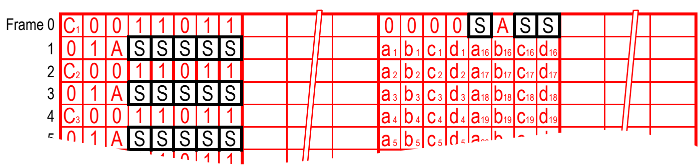

Figure 1.8 Spare bits in the E1 frame.

The bits in positions 4 to 8 are spare bits (see Figure 1.8), and they do not have one single application, but can be used in a number of ways, as decided by the telecommunications carrier. In accordance with the ITU-T Rec. G.704, these bits can be used in specific point-to-point applications, or to establish a data link based on messages for operations management, maintenance or monitoring of the transmission quality, and so on. If these spare bits in the NFAS are not used, they must be set to "1" in international links.

1.3.6 NFAS - Alarm Bit

The method used to transmit the alarm makes use of the fact that in telephone systems, transmission is always two way (see Figure 1.9). Multiplexing/demultiplexing devices (known generically as multiplex devices) are installed at both ends of the communication for the transmission and reception of frames. An alarm must be sent to the transmitter when a device detects either a power failure or a failure of the coder/decoder, in its multiplexer; or any of the following in its demultiplexer: *loss of the signal* (LOS), *loss of frame alignment* (LOF), or a BER greater than 10^{-3}.

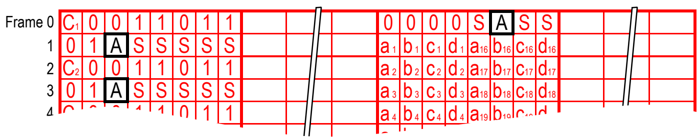

Figure 1.9 The alarm indication signal is used to send alarms to the remote end to indicate a power fault, loss of incoming signal, loss of frame, coder/decoder fault or a high bit error rate, among others.

The *remote alarm indication* (RAI) is sent in the NFAS of the return frames, with bit 3 being set to "1." The transmitter then considers how serious the alarm is, and goes on generating a series of operations, depending on the type of alarm condition detected (see Table 1.1).

1.3.7 Signaling Channel

As well as transmitting information generated by the users of a telephone network, it is also necessary to transmit signaling information. Signaling refers to the protocols that must be established between exchanges so that the users can exchange information between them.

There are signals that indicate when a subscriber has picked up the telephone, when he or she can start to dial a number, and when another subscriber calls, as well as signals that let the communication link be maintained, and so on.

In the E1 PCM system, signaling information can be transmitted by two different methods: the *common channel signaling* (CCS) method and the *channel associ-*

ated signaling (CAS) method. In both cases, the time slot TS16 of the basic 2-Mbps frame is used to transmit the signaling information (see Figure 1.10).

For CCS signaling, messages of several bytes are transmitted through the 64-Kbps channel provided by the TS16 of the frame, with these messages providing the signaling for all the channels in the frame. Each message contains information that determines the channel that is signaling. The signaling circuits access the 64-Kbps channel of the TS16, and they are also common to all the channels signaled. There are different CCS systems that constitute complex protocols. In the following section and by way of example, channel associated signaling will be looked at in detail. CAS is defined in the ITU-T Rec. G.704, which defines the structure of the E1 frame.

In CAS signaling, a signaling channel is associated with each information channel (there is no common signaling channel), meaning that the signaling circuits are personalized for each channel.

1.3.8 CAS Signaling Multiframe

In the case of channel associated signaling, each 64Kbps telephone channel is assigned 2 Kbps for signaling. This signaling is formed by a word of 4 bits (generically known as a, b, c, and d) that is situated in the TS16 of all the frames sent. Each TS16 therefore carries the signaling for two telephone channels.

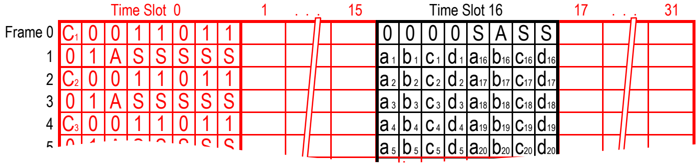

Figure 1.10 When the CAS method is used, each of the channels has an associated 2-Kbps channel (a_i b_i c_i d_i) in the time slot 16. This multiframe also has an alignment signal “0000”; spare and alarm bit to be used specifically by the signaling multiframe.

Given that there are only four signaling bits available for each channel, to transmit all the signaling words from the 30 PCM channels that make up a 2-Mbps frame (120 bits), it is necessary to wait until the TS16 of 15 consecutive frames have been received. The grouping of frames defines a CAS signaling multiframe, which consists of a set of the TS16 of 16 consecutive E1 frames.

1.3.8.1 CAS multiframe alignment signal

In order to synchronize the CAS multiframe, that is to identify where it begins, a *multiframe alignment signal* (MFAS) is defined, made up of the sequence of bits "0000" located in the first four bits of the TS16 of the first frame of the CAS multiframe.

1.3.8.2 CAS non-multiframe alignment signal

The remaining four bits of the interval are divided between one alarm bit and three spare bits, making up the *non-multiframe alignment signal* (NMFAS). In short, the signaling information for the 30 channels is transmitted in 2 ms, which is fast enough if we consider that the shortest signaling pulse (the one that corresponds to dialing the number) lasts for 100 ms.

The alarm bit in the NMFAS is dealt with in a similar way to the NFAS. In this case, the alarms are transmitted between multiplex signaling devices connected to the 64-Kbps circuits that correspond to signaling (TS16). The alarm is sent when the CAS multiplexer detects:

- A power failure;
- Loss of incoming signaling;
- Loss of CAS multiframe alignment.

An indication must be sent to the multiplex signaling device at the far end (see Table 1.1), setting bit 6 of the TS16 in the return frame 0 to "1." Additionally, the value "1" is applied to all the signaling channels (see Figure 1.14).

Example: A remote multiplexer is considered to have lost multiframe alignment when it receives two consecutive MFAS words with error, that is, with a value other than "0000." In this case, bit 6 of the TI16 of the frame 0 that this multiplexer transmits to the near-end multiplexer is set to "1." When it receives this indication of loss of multiframe alignment at the far end, the near end multiplexer sends a signal made up entirely of bits at "1," known as AIS64 (*alarm indication signal* - 64 Kbps) in the TS16 (64-Kbps channel).

1.4 THE PLESIOCHRONOUS DIGITAL HIERARCHY

Based on the E1 signal, the ITU-T defined a hierarchy of plesiochronous signals that enables signals to be transported at rates of up to 140 Mbps (see Figure 1.11). This section describes the characteristics of this hierarchy and the mechanism for

Table 1.1
2-Mbps events: Alarms, errors, and event indications.

ID	*Explanation*
AIS	Alarm indication signal. It is detected if there are two or less zeros (ITU-T G.775).
LOF	Loss of frame alarm. It is raised after three consecutive frames with FAS error or three consecutive signalling bits (ITU-T G.706).
LOS	Loss of frame signal alarm.
RAI	Remote alarm indication. It is detected after three consecutive frames with the A bit equals to 1 (ITU-T G.732).
FAS error	Frame alignment signal error, indicating an incorrect bit in the alignment word.
Bit error	Bit sequence mismatch (when the transmitted pattern is known).
Code error	Violation on coding sequence.
CRC-LOM	Cyclic redundancy checksum - loss of multiframe. It is activated if there is LOF and deactivated after one correct FAS and two correct CRC-MFAS (ITU-T G.706).
CAS-LOM	Channel associated signaling-loss of multiframe. It is raised after two consecutive MFAS errors or two multiframes with time-slot 16 bits equal to 0 (ITU-T G.732).
CAS-MRAI	Channel associated signaling-multiframe remote alarm indication. Detected after two consecutive frames with the MRAI bit equal to 1 (ITU-T G.732).
CAS-MAIS	Channel associated signaling-multiframe alarm indication signal. It is detected if there are less than three zeros in the time slot 16 during two consecutive multi-frames.
CRC error	Cyclic redundancy check error. It is raised whenever one or more bits are erroneous, whenever CRC-LOM is off (ITU-T G.706).
REBE	Remote end block error. It is erased if the first bit of the frames 14 and 16 is 0 (ITU-T G.706).

dealing with fluctuations in respect to the nominal values of these rates, which are produced as a consequence of the tolerances of the system.

1.4.1 Higher Hierarchical Levels

As is the case with level 1 of the plesiochronous digital hierarchy (2 Mbps), the higher levels of multiplexing are carried out bit by bit (unlike the multiplexing of 64-Kbps channels in a 2-Mbps signal, which is byte by byte), thus making it impossible to identify the lower level frames inside a higher level frame. Recovering the tributary frames requires the signal to be fully demultiplexed.

The higher hierarchical levels (8,448, 34,368, and 139,264 Mbps, etc.; referred to as 8, 34, and 140 Mbps for simplicity) are obtained by multiplexing four lower level frames within a frame whose nominal transmission rate is more than four times that of the lower level (see Table 1.2), in order to leave room for the permitted variations in rate (justification bits), as well as the corresponding FAS, alarm, and spare bits (see Figure 1.11).

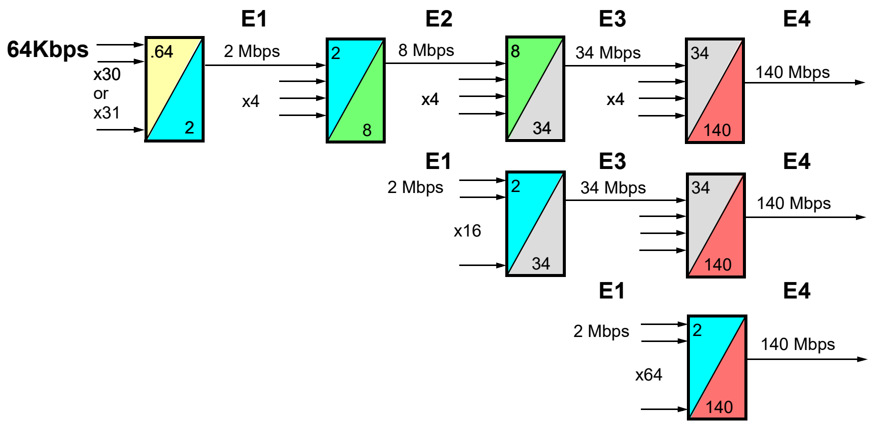

Figure 1.11 The PDH hierarchy, with four levels from 2 to 140 Mbps. A bit-oriented justification process is used to fit tributaries created with different clocks in the second, third, and fourth hierarchy. The first hierarchy, 2 Mbps, is the only fully synchronous frame.

1.4.2 Multiplexing Level 2: 8 Mbps

The 8-Mbps frame structure is defined in the ITU-T Rec. G.742 (see Figure 1.12). The frame is divided into four groups:

- Group I contains the FAS, with sequence "1111010000"; the A-bit (remote alarm); the S-bit (spare); and 200 T-bits (tributary) transporting data.
- Groups II and III contain a block of four J-bits (justification control) and 208 T-bits transporting data.
- Group IV contains a block of four J-bits, a block of R-bits (justification opportunity), one per tributary, and 204 T-bits. To check whether R-bits have been used, the J-bits are analyzed in each of the groups II, III, and IV (there are three per tributary). Ideally the R-bit does not carry useful information on 42.4% of the occasions. In other words, this percentage is the probability of justification or the insertion of stuffing bits.

1.4.3 Multiplexing Level 3: 34 Mbps

The structure of this frame is described in the ITU-T Rec. G.751 (see Figure 1.12). As in the previous case, the frame is divided into four groups:

- Group I contains the FAS, with sequence "1111010000"; the A-bit (remote alarm); the S-bit (spare); and 372 T-bits (tributary) transporting data.

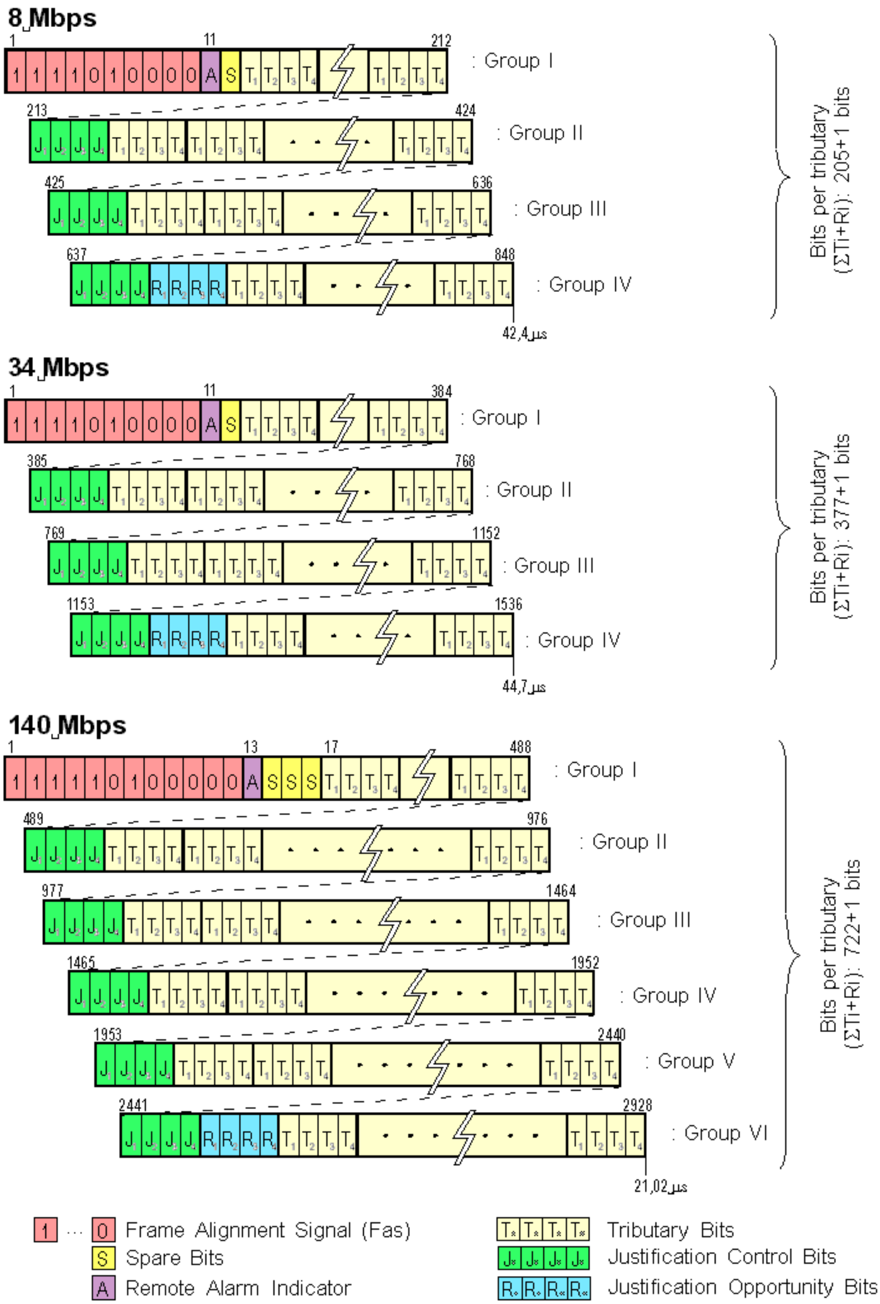

Figure 1.12 The PDH higher hierarchies. A bit-oriented justification process is used to fit tributaries created with clock impairments.

- Groups II and III contain a block of four J-bits (justification control) and 380 T-bits transporting data.
- Group IV contains a block of four J-bits, a block of R-bits (justification opportunity) one per tributary, and 376 T-bits. To check whether R-bits have been used, the J-bits are analyzed in each of the groups II, III, and IV (there are three per tributary). Ideally the R-bit does not carry useful information on 43.6% of the occasions.

1.4.4 Multiplexing Level 4: 140 Mbps

The structure of this frame is described in the ITU-T Rec. G.751 (see Figure 1.12). In this case, the frame is divided into six groups:

- Group I contains the FAS, with sequence "111110100000;" the A-bit (remote alarm); the S-bit (spare); and 472 T-bits (tributary) transporting data.
- Groups II, III, IV, and V contain a block of four J-bits (justification control) and 484 T-bits transporting data.
- Group VI contains a block of four J-bits, a block of R-bits (justification opportunity), one per tributary, and 376 T-bits. To check whether R-bits have been used, the J-bits are analyzed in each of the groups II, III, IV, V, and VI (there are five per tributary). Ideally the R-bit does not carry useful information on 41.9% of the occasions.

Table 1.2
The PDH hierarchy, with four levels from 2 to 140 Mbps. A bit-oriented justification process is used to fit tributaries created with different clocks in the second, third, and fourth hierarchy.

Standard	*Binary Rate*	*Size*	*Frame/s*	*Code*	*Amplitude*	*Attenuation*
G.704/732	2,048 Kbps±50 ppm	256 bits	8,000	HDB3	2.37-3.00V	6 dB
G.742	8,448 Kbps±30 ppm	848 bits	9,962.2	HDB3	2.37V	6 dB
G.751	34,368 Kbps±20 ppm	1536 bits	22,375.0	HDB3	1.00V	12 dB
G.751	139,264 Kbps±15 ppm	2928 bits	47,562.8	CMI	1.00V	12 dB

1.4.5 Service Bits in Higher Level Frames

In any of the groups containing the FAS in the 8-, 34-, and 140-Mbps frames, alarm bits and spare bits are also to be found. These are known as service bits. The A-bits (alarm) carry an alarm indication to the remote multiplexing device, when certain breakdown conditions are detected in the near-end device. The spare bits are designed for national use, and must be set to "1" in digital paths that cross international boundaries.

1.4.6 Plesiochronous Synchronization

As far as synchronization is concerned, the multiplexing of plesiochronous signals is not completely trouble free, especially when it comes to demultiplexing the circuits. In a PCM multiplexer of 30 + 2 channels, a sample of the output signal clock (1/32) is sent to the coders, so that the input channels are synchronized with the output frame. However, higher level multiplexers receive frames from lower level multiplexers with clocks whose value fluctuates around a nominal frequency value within certain margins of tolerance. The margins are set by the ITU-T recommendations for each hierarchical level. The signals thus formed are almost synchronous, except for differences within the permitted margins of tolerance, and for this reason they are called plesiochronous (see Figure 1.13).

1.4.7 Positive Justification

In order to perform bit-by-bit TDM, each higher-order PDH multiplexer has elastic memories in each of its inputs in which the incoming bits from each lower level signal line or tributary are written. Since the tributary signals have different rates, they are asynchronous with respect to each other. To prevent the capacity of the elastic memories from overflowing, the multiplexer reads the incoming bits at the maximum rate permitted within the range of tolerances. When the rate of the incoming flow in any of the tributary lines is below this reading rate, the multiplexer cannot read any bits from the elastic memory, and so it uses a stuffing bit or justification

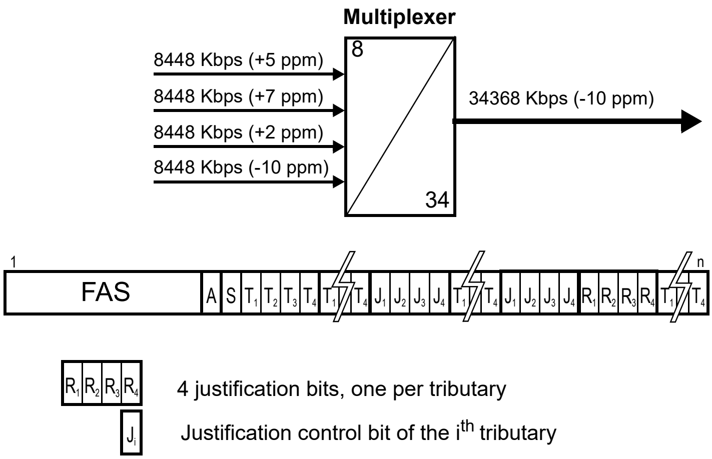

Figure 1.13 The PDH and the T-carrier hierarchies are not synchronous and variations can be expected in the bit rate clock, shown in this figure as parts per million (ppm). The justification mechanism is implemented in the E2, E3, and E4 frames. If all J_i=1, then R_i is a justification bit that does not contain information. If all J_i=0, then R_i contains information. If all are not 0 or 1, the decision is based on the majority.

bit (called justification opportunity) in the output aggregate signal. Its task is that of adapting the signal that enters the multiplexer to the rate at which this signal is transmitted within the output frame (its highest clock value). This type of justification is called positive justification.

Justification bits, together with other overhead bits, make the output rate higher than the total of the input signals.

1.4.7.1 Justification opportunity bits

The task of the *justification opportunity bits* (R-bits) is to be available as extra bits that can be used when the rate of the incoming tributaries is higher than its nominal value (within the margin specified by ITU-T) by an amount that makes this necessary. In this case, the opportunity bit is no longer mere stuffing, but becomes an information bit instead.

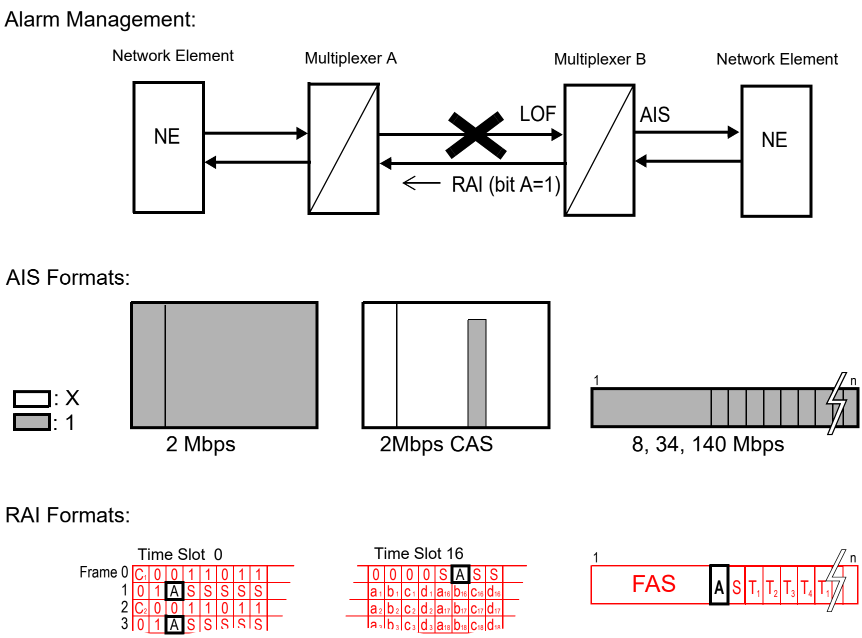

Figure 1.14 When a multiplexer detects an LOS or LOF, it sends a remote alarm indication (RAI) to its partner multiplexer and forwards an AIS to the next network element, because it has not been possible to recover any information.

In order for the device that receives the multiplexed signal to be able to determine whether a justification opportunity bit contains useful information (i.e., information from a tributary), *justification control bits* (J-bits) are included in the frame. Each group of control bits refers to one of the tributaries of the frame. All of them will be set to "0" if the associated opportunity bit is carrying useful information; otherwise they will be set to "1." Several bits are used instead of just one, to provide protection against possible errors in transmission. On examining the control bits received, if they do not all have the same value, it is decided that they were sent with the majority value (a "1" if there are more 1s than 0s, for instance; it is assumed that there has been an error in the bits that are at 0).

It can be seen that there is a dispersion of the control bits referring to a tributary that causes them to be located in separate groups. Spreading out the J-bits (control bits), reduces the probability of errors occurring in them, and a wrong decision being made as to whether or not they have been used as a useful data bit. If the wrong decision is made, there is not only an error in the output data, but also a slip of one bit; that is, the loss or repetition of one bit of information.

1.5 Managing Alarms in Higher Level Hierarchies

The A-bit of the FAS in 8-, 34-, and 140-Mbps frames enables the multiplexers that correspond to these hierarchies to transmit alarm indications to the far ends (see Figure 1.14) when a multiplexer detects an alarm condition (see Table 1.3).

In addition, 140-Mbps multiplexers also transmit an alarm indication when faced with the loss of frame alignment of the 34-Mbps signals received inside the 140-Mbps signals, as well as in the NFAS of the 34-Mbps signal that has lost its alignment (bit 11 of group I changes from “0” to “1”) in the return channel (see Figure 1.13).

Table 1.3
PDH events: Alarms, errors, and event indications.

ID	*Explanation*
AIS	Alarm indication signal. This is detected if less than six zeros in a frame in the case of 140 Mbps, or less than three zeros in 34 Mbps, and 8 Mbps (ITU-T G.751 and ITU-T G.742).
LOF	Loss of frame alarm. It is raised after four consecutive frames with FAS error (ITU-T G.751 and ITU-T G.742).
LOS	Loss of frame signal alarm.
RAI	Remote alarm indication. It is detected after two consecutive frames with the A bit equal to 1 (ITU-T G.751 and ITU-T G.742).
FAS error	Frame alignment signal error. One or more incorrect bits in the alignment word.

1.6 The T-Carrier Hierarchy

As is the case of the PDH, the T-carrier higher levels multiplexing is carried out bit by bit (unlike the multiplexing of 64-Kbps channels in a DS1 frame, which is byte by byte), thus making it impossible to identify the lower level frames inside a higher level frame. Recovering the tributary frames requires the signal to be fully demultiplexed (see Figure 1.15).

1.6.1 The DS1 Frame

The DS1 frame is made up of 24 byte-interleaved DS0s, the 64-Kbps channels of eight bits, plus one framing bit that indicates the beginning of the DS1 frame. The DS0 channels are synchronous with each other, and are then time division multiplexed in the DS1 frame. Depending on the application, the DS1 frames are grouped in *superframe* (SF), 12 consecutive DS1 frames, and *extended superframe* (ESF), 24 consecutive frames (see Figure 1.16). Depending on the application, the DS1 signal is coded in AMI or in B8ZS.

Frame bit

The F-bit delimits the beginning of the frame and has different meanings. Using ESF, the F-bit sequence has a pattern for synchronization, but if ESF is used, then there is a synchronization pattern, CRC control, and a data link control channel of 4 Kbps.

Signaling

When in-band signaling is used, the signaling goes in the least significant channel bit of every sixth DS1 frame (SF and ESF framing), leaving the effective throughput of those channels at 56 Kbps, to keep distortion minimal. Although in-band is still in use, signaling (call setup, teardown, routing, and status) is generally carried out of band over a separate network using a protocol called *signaling system 7* (SS7).

1.6.2 The DS2 Frame

As long as the DS1 frames are asynchronous from each other, each DS1 line is treated as a bit stream rather than individual frames, and the DS2 signal is formed by bit interleaving of four DS1 signals. Stuffing bits are added to the DS2 to com-

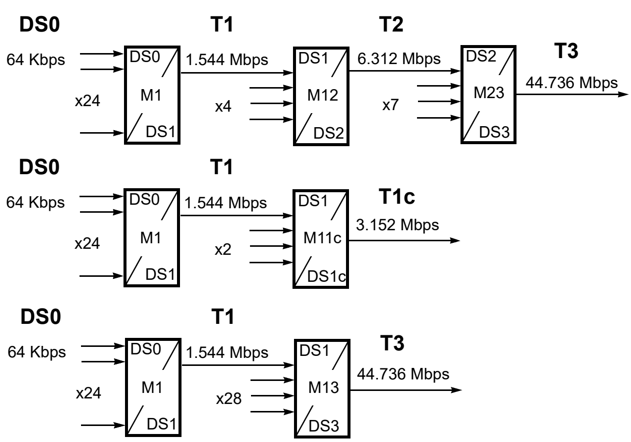

Figure 1.15 T-carrier multiplexing hierarchy. M1 is a TDM; the rest (M12, M23, M11c, and M13) are bit interleaving multiplexers.

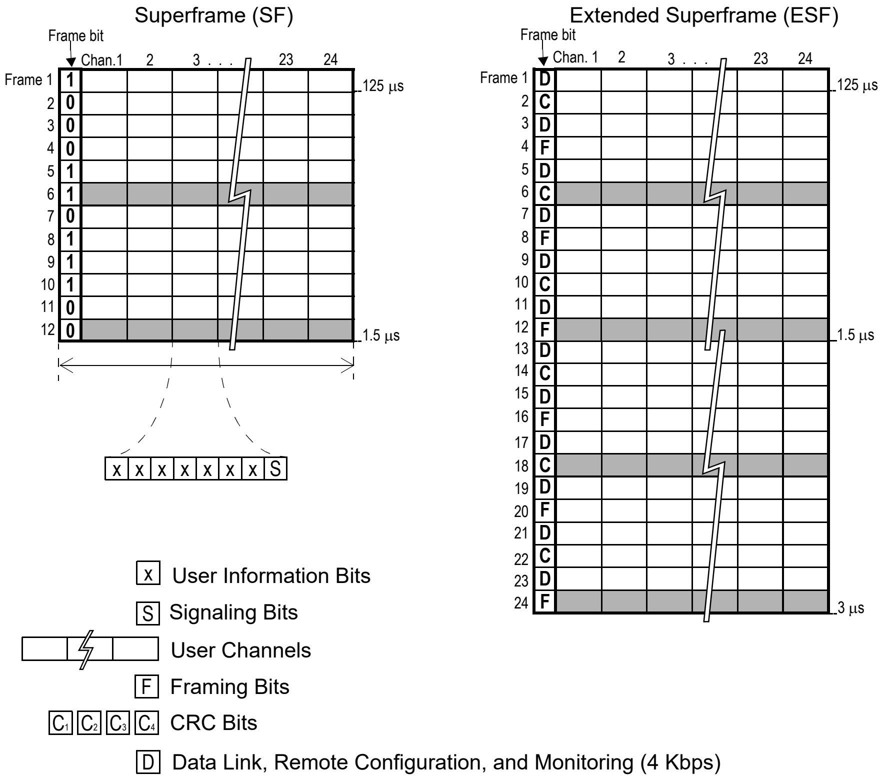

Figure 1.16 The T1 frame and superframe. Depending on the application, the frame bit has different interpretations.

pensate for the slightly different rates. Framing, signaling, alarm, frame alignment, and parity are also added to the frame (see Figure 1.17).

1.6.3 The DS3 Frame

A DS3 frame is formed by bit-interleaving 28 DS1 frames or seven DS2 frames. There are two framing formats, called M13 or C-bit parity (see Figure 1.17), described in the following:

1. *M-13*, multiplexing DS1 to DS3, is done in two steps: (a) the first four DS1 frames form a DS2 frame using M12 multiplexing; (b) the second seven DS2 frames form a DS3 frame using M23 multiplexing. M13 multiplexing uses bit stuffing to bring each asynchronous DS1/DS2 line up to a common data rate

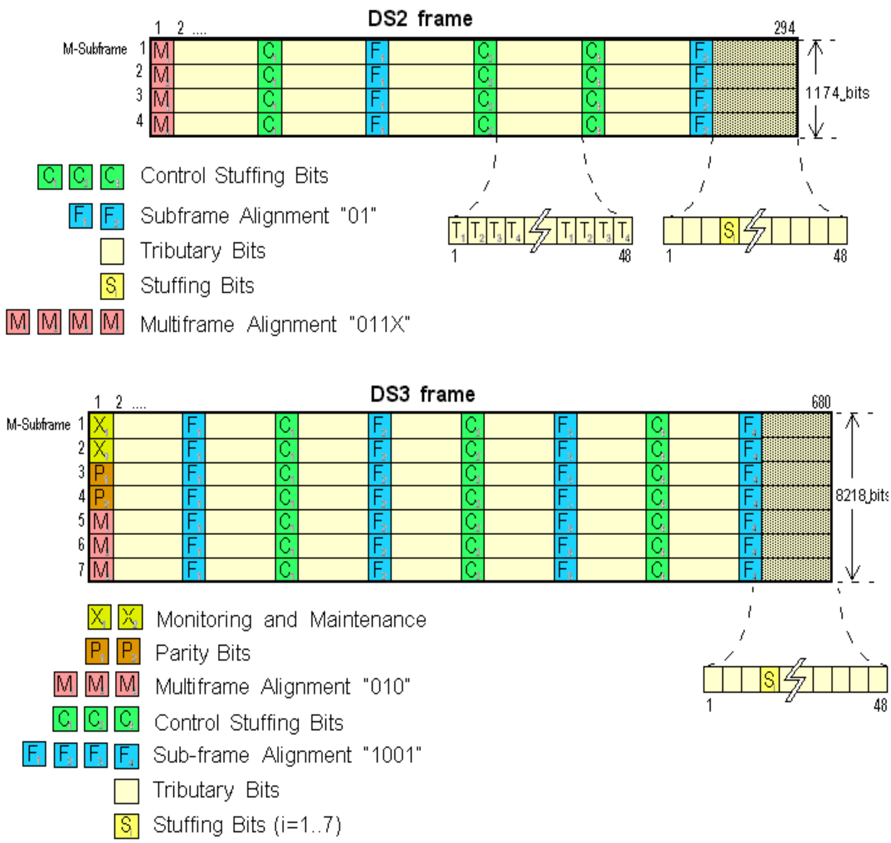

Figure 1.17 (a) The DS2 frame or M12 multiplexing.
(b) The DS3 frame. If C-bit parity framing is used, the C_i bits are not necessary for stuffing, and they are used for end-to-end signaling instead.

for transmission.

2. *C-12*, multiplexing DS1 to DS3, is done in one step: The stuffing control bits (C-bits) at the M23 multiplexing level are not required and can be used for a maintenance link between the end points, applications like *far-end alarm and control* (FEAC) and *far-end block error* (FEBE).

If C-bit parity framing is used, the Ci-bits in the DS3 frame take on signaling definitions as described in the ANSI T1.107 (see Table 1.4).

Table 1.4
C-bit parity: alarm and status signal codes.

Code	*Event Type*	*Explanation*
00110010 11111111	DS3 equipment failure	Service affecting (SA), requires quick attention
00011110 11111111	DS3 equipment failure	Non-service affecting (NSA)
00000000 11111111	DS1 equipment failure	Service affecting (SA), requires quick attention
00001010 11111111	DS1 equipment failure	Non-service affecting (NSA)
00011100 11111111	DS3 LOS	Loss of signal
00101010 11111111	Multiple DS1 LOS	Multiple loss of frame in the DS1 tributaries
00111100 11111111	Single DS1 LOS	Alarm indication signal received from a DS1
00000000 11111111	DS3 OOF	Out of frame in the DS3 signal
00101100 11111111	DS2 AIS	Alarm indication signal received from a DS2

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- ANSI T1.107, Digital hierarchy formats.
- ITU-T Rec. G.703 (10/98), Physical/electrical characteristics of hierarchical digital interfaces.
- ITU-T Rec. G.704 (10/98), Synchronous frame structures used at 1,544, 6,312, 2,048, 8,448 and 44,736 Kbit/s hierarchical levels.
- ITU-T Rec. G.742 (11/88), Second order digital multiplex equipment operating at 8,448 Kbit/s and using positive justification.
- ITU-T Rec. G.751 (11/88), Digital multiplex equipment operating at the third order bit rate of 34,368 Kbit/s and the fourth order bit rate of 139,264 Kbit/s and using positive justification.