8.0 Multiplexing PCM

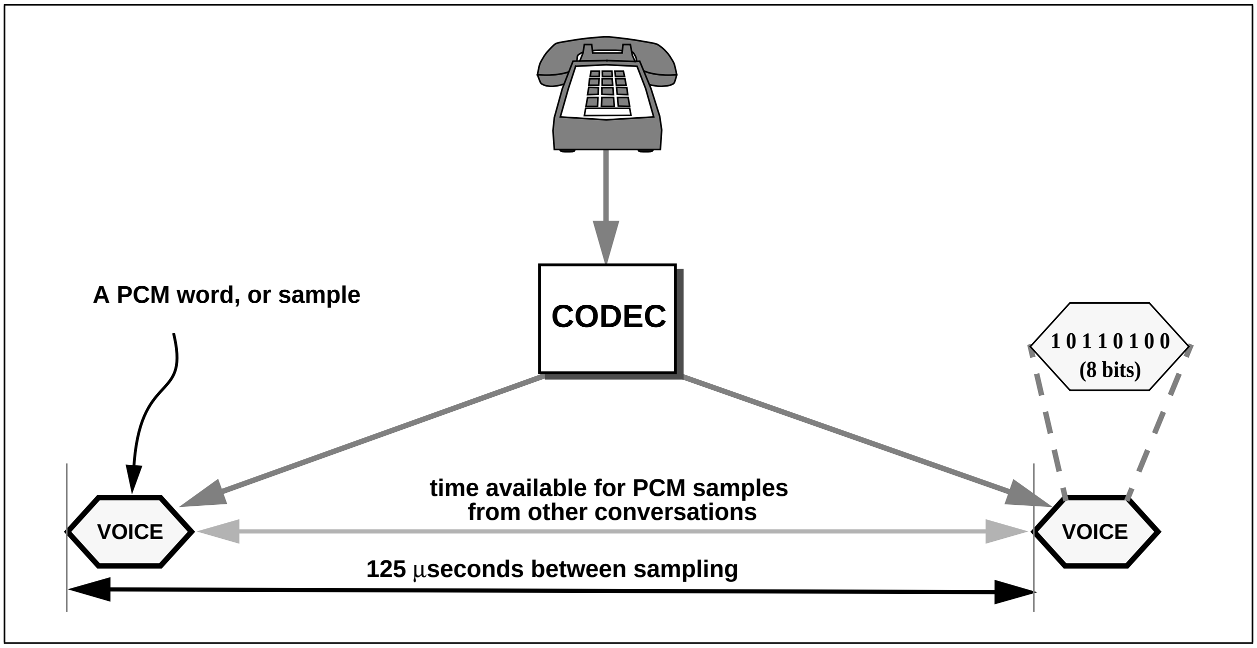

Figure 29: Voice sampling at 8000 times per Second

The CODEC in Figure 29 is fast enough in its processing that it does not require the full 125 μseconds between samples to generate the PCM words. In the wasted time gap between PCM samples, PCM samples from other encoded voices can be placed (Figure 30). Processing time here refers to the ability of the codec to perform A/D and D/A functions. This is not to be confused with the sampling rate, which is fixed at 8000 samples per second.

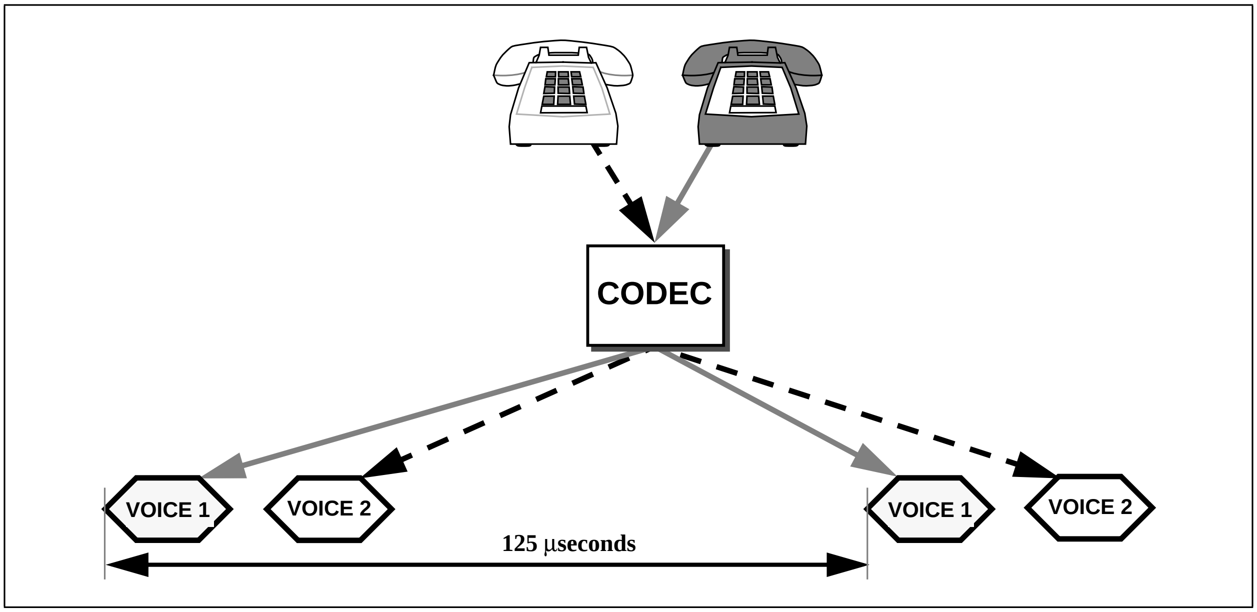

Figure 30: Time Division Multiplexing

If the PCM coding and decoding process is fast enough, many voice conversations can be stuffed into a single stream of PCM words (Figure 31). Putting many conversations onto a single transmission line in this manner is called **Time Division Multiplexing (TDM).**

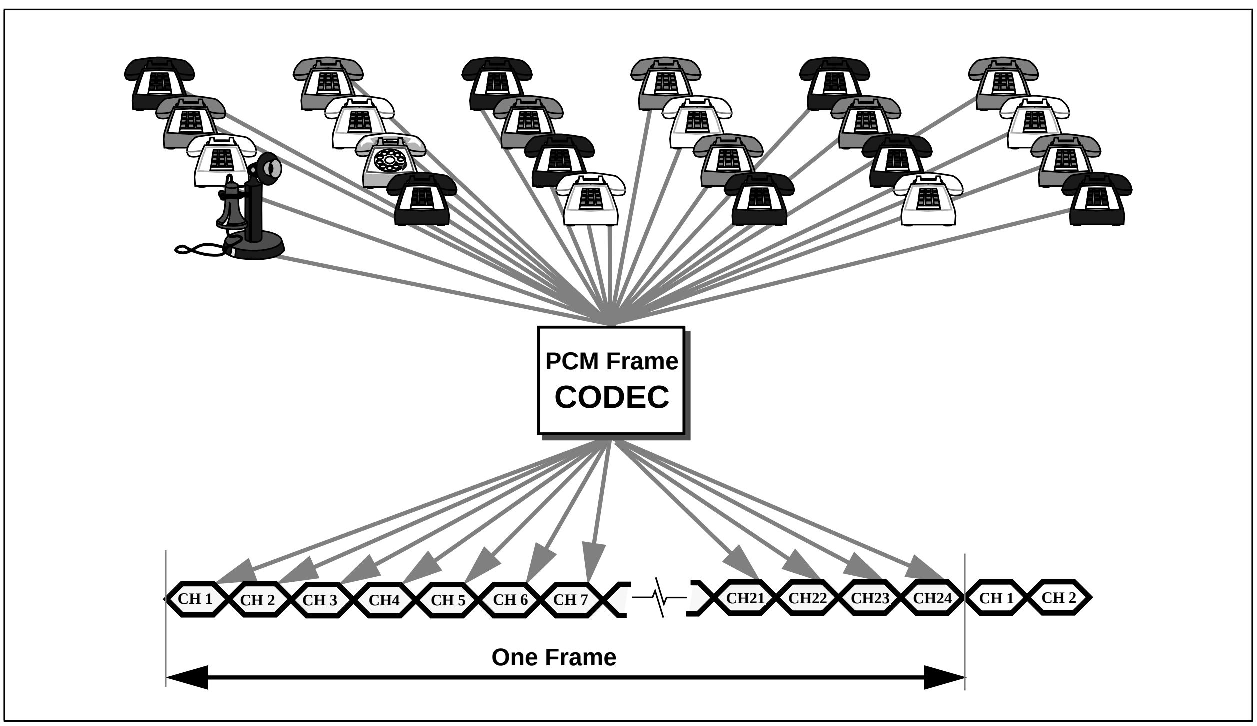

Figure 31: Twenty four (24) conversations in a PCM Frame

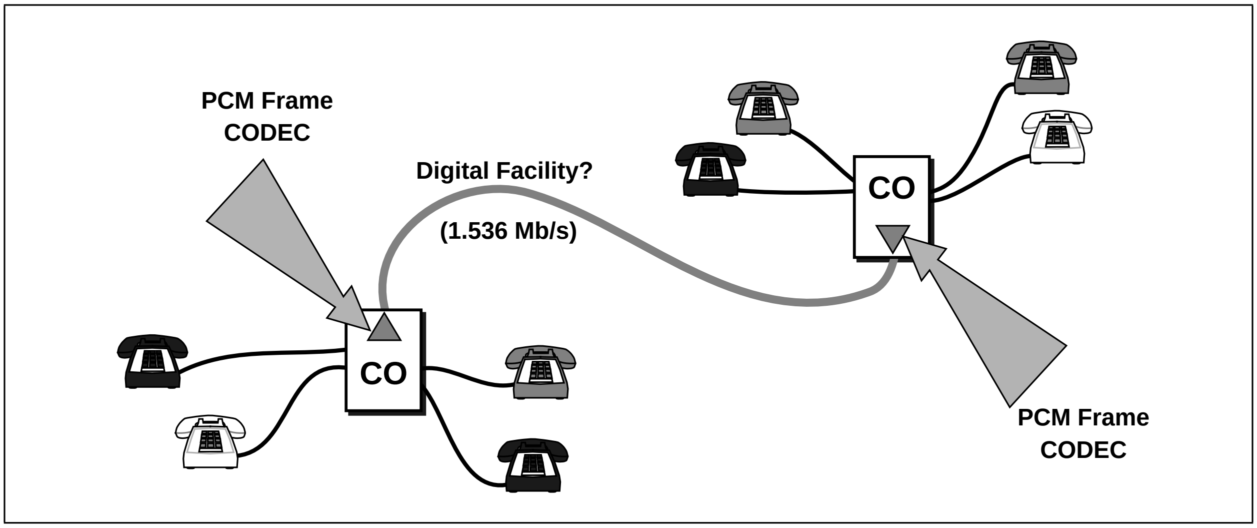

Figure 32: PCM Frame CODEC is *almost* a complete digital transmission system

Voice can be encoded by the PCM frame CODEC, but something essential is missing from this digital signal format that allows the CODEC to decode received PCM samples. In Figure 32, the digital voice transmission system is not complete yet because the receiver has no means of locating where PCM samples start or end within the 1.536 Mb/s bit PCM stream.

9.0 The Channel Bank

To allow the receiver to locate the PCM samples, Bell engineers developing T1 created a special bit, called the 193rd bit, and added it between the 24-channel frames (Figure 33). This special bit is the **framing bit**. The framing bit creates a repeating pattern of 1s and 0s that a receiver uses to identify the 193rd bit. Once the receiver locates the framing bit, it then knows where the PCM samples for each telephone conversation lie. With the addition of this framing bit, all the elements of a viable voice digital transmission format are complete.

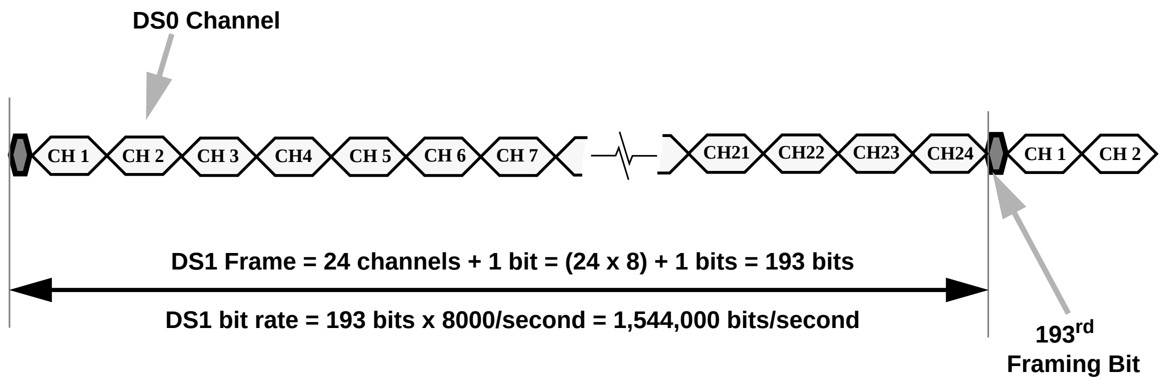

Figure 33: DS1 Format

Twenty-four voice conversations are formatted into a PCM stream that contains an update of the PCM samples 8,000 times per second. The 24 PCM samples and the 193rd bit create a signal format known as **DS1 (Digital Signal level 1)**. Each PCM sample for a given voice signal constitutes a **channel** within the DS1 stream. These channels are referred to as **DS0 (Digital Signal level 0)** channels.

The PCM frame codec device has grown to include the capability of creating and recovering a framing bit. This device, which encodes 24 telephone conversations and multiplexes them into a framed digital signal is called a **channel bank**. It is the channel bank that creates the **T1** signal. Figure 34 shows the completed T1 transmission facility. The addition of the 193rd bit bumps the overall bit rate up to 1,544,000 bps.

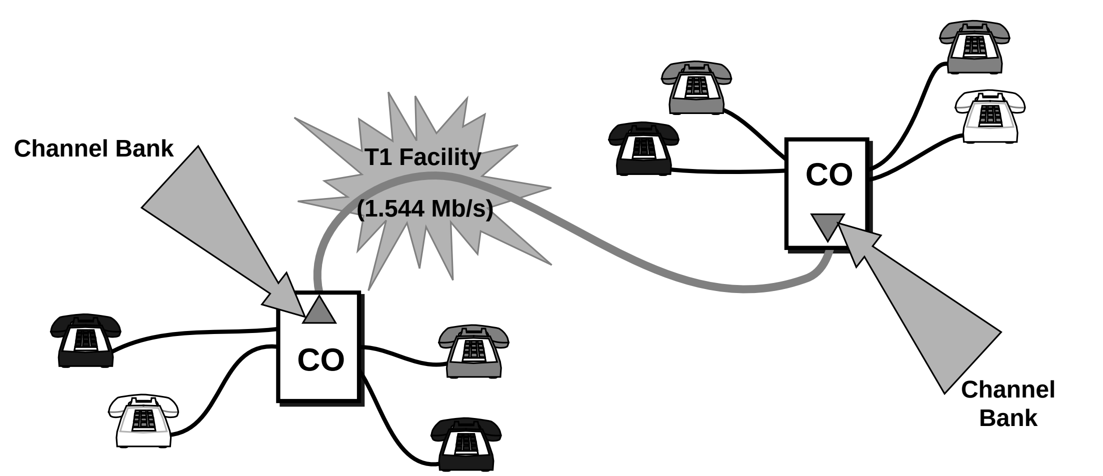

Figure 34: T1 - A transmission format for DS1

T1 is the ubiquitous digital carrier for telecommunications in North America. T1 was developed by Bell Laboratories to carry the DS1 signal. It was first tested in Chicago in 1961. T1 was commercially deployed in New York City in 1962 to improve voice transmission quality and reduce cabling congestion in underground telephone ducts, where space was at a premium.

The T1 bit rate of 1,544,000 bits per seconds was chosen so the T1 repeaters could be positioned at about one mile (6000 foot) intervals along a T1 span. This spacing intentionally coincided with the spacing of voice-frequency load coils, allowing access to both devices at the same location. Also, 1.544 Mb/s was the upper bit repetition rate for digital transmitters built with the electronics that were available in the early sixties. Discrete transistors of the day had a top switching speed of only 6 MHz.

T1 is a balanced-circuit transmission system that uses **100 Ω characteristic-impedance** conductors (typically twisted-pair wire).

9.1 The Beginnings: D1

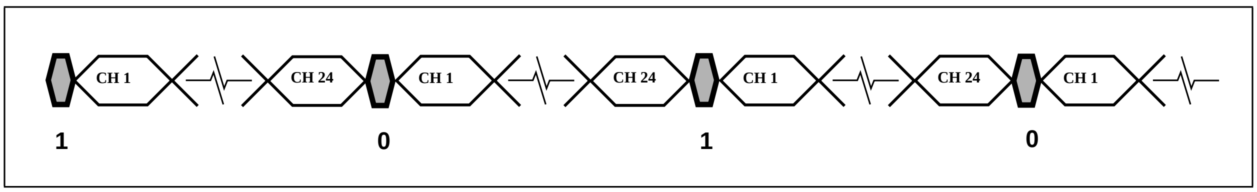

Figure 35: "D1" Original DS1 193rd-bit Framing Pattern

D1 was the first DS1 framing format Bell Laboratories developed. D1 (for Digital, first generation) was also the name given to Western Electric's first channel bank. It used an alternating 1010 pattern in the 193rd bit position (see Figure 35). D1 framing bits were designated as **terminal framing**, or $\mathbf{F_t}$, bits.

D1 was susceptible to framing problems. PCM created by certain tones (1000 Hz, for example) could mimic the alternating one-zero-one-zero F_t pattern. This could allow a channel bank that is attempting to acquire the framing bits on a received T1 signal to lock onto the false framing pattern generated by such a tone and ignore the proper 193 framing bits. A bit sequence that mimics a framing pattern is called a **framing demon**.

9.1.1 Robbed-bit Signaling

A DS1 signal must convey trunk **signaling** information as well as voice signals. Telephone call status such as busy or idle is conveyed by these signaling bits. Instead of adding more bits to the DS1 signal to carry this signaling information, D1 mode took the least significant bit of each PCM channel and reserved it for signaling bits. Since this method required robbing each PCM word of its least-significant bit and replacing it with a signaling bit, this process was given the distinctive name of **robbed-bit** signaling. This signaling scheme allows only 7 bits of a DS0 channel for PCM, as the last bit is used for signaling.

This robbed-bit technique reduced the fidelity of the transmitted voice, since voice encoding in a channel was effectively reduced from 64 kb/s (in which all 8 bits per DS0 is used for PCM) to 56 kb/s (in which only 7 bits within a DS0 is used for PCM). Not only did the D1 format reduce the bit rate for voice encoding, but the 8 kb/s robbed for signaling purposes was a waste of information bandwidth. Since trunk signaling required for a telephone call typically only changes states at the start and end of a call, a much lower bit rate could be allocated for signaling purposes. If most of the signaling bandwidth was given back to the voice encoding, a much better balance between voice quality and signaling bandwidth would result. So the Bell scientist and engineers set out to improve their channel bank's performance. The D1 framing and signaling format was scrapped, and replaced with a more efficient, but more complex, DS1 framing structure.

Frame Number	**193rd Bits**		**LSB Content (for each channel in the Frame)**
	Terminal (F_t)	**Multiframe Synchronization (F_s)**	
1	**1**		PCM
2		**0**	PCM
3	**0**		PCM
4		**0**	PCM
5	**1**		PCM
6		**1**	**signaling bit "a"**
7	**0**		PCM
8		**1**	PCM
9	**1**		PCM
10		**1**	PCM
11	**0**		PCM
12		**0**	**signaling bit "b"**

Table 1: D4 Framing

9.2 Superframe

The **superframe** format, with the F_s framing bit, was introduced in 1969 with the advent of the D2 and D1D channel banks. The concepts of 193rd bit for framing and robbed bit signaling are retained, but that is where similarities end. In superframe format, the 193rd

bit is divided into two bits, F_s and F_t. F_t is known as the terminal bit. Its pattern is the old D1 repeating pattern of 1010. F_t allows a receiving channel bank to locate the 193rd bit, and hence find the 24 channels. The F_s bit is interleaved between F_t bits. The F_s bit forms a 6-bit pattern that allows a receiving channel bank to align to a 12-frame structure. These 12 frames are known as a superframe **(SF)**, or a **multiframe**. For simplicity, think of the F_s and F_t bits as forming a single 12-bit repeating pattern that marks off a 12-frame block of PCM frames (see Table 1). Since the SF pattern is not a simple repeating 1010 pattern, it is less likely that digital patterns in a DS0 will create a framing demon.

SF framing format is often referred to as D4, after the channel bank series that popularized this format.

9.2.1 Robbed bit signaling advances with Superframing

The advent of the superframe allowed 12 frames to be distinguished with the superframe. Only the 6^{th} and 12^{th} frames are designated for robbed bit signaling. Figure 36 shows how robbed bit signaling is accomplished in the 6^{th} and 12^{th} frames. SF conveys two signaling bits, the “a” and “b” bits, for each DS0 channel. The PCM encoding used here is sometimes referred to as $7^5/_6$ encoding, since on average over time, $7^5/_6$ bits out of 8 in a DS0 channel are used for voice encoding. The left over bandwidth of $^1/_6$ bit out of 8 is robbed for signaling.

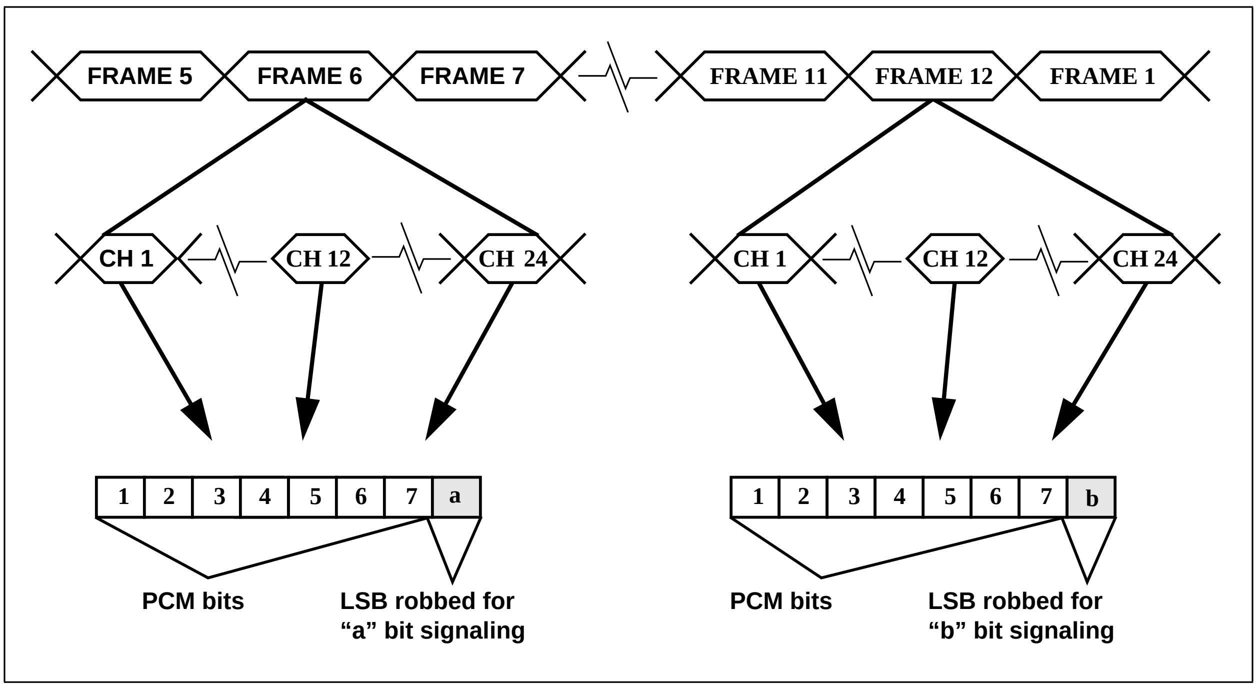

Figure 36: D4/SF Robbed Bit Signaling

9.3 Extended Superframe

An enhancement of the superframe concept led to the **Extended Superframe (ESF)** format. ESF is another DS1 framing format. It expands the superframe to 24 frames. The ESF 193rd framing bit is called the $\mathbf{F_e}$ bit. As Table 2 shows, there are three types of 193rd bits, F_e, FDL, and CRC-6, within the extended superframe.

9.3.1 Facility Data Link

Not all the 193rd bits are required to create the framing pattern sequence, so not the 193rd bits are F_e bits. In addition to F_e framing bits, the 193rd bit position contains a **Facility Data Link (FDL)** bit, which is denoted by *m* bits. FDL is used for alarm signaling and performance monitoring, and is available for data transmission to the customer (customer-supplied protocol).

9.3.2 Cyclic Redundancy Check

The third type of information contained in the 193rd bit is the **Cyclic Redundancy Check (CRC)** bits. CRC is a means of detecting bit errors in an extended superframe. It is not an error correction scheme, but it does allow monitoring of T1 line performance on an ESF link.

ESF uses a cyclic redundancy check with six bits, so the CRC code is referred to as CRC-6.

The ESF framer which creates the 193rd framing bit also creates a CRC-6 code word for each extended superframe. Each transmitted extended superframe contains the CRC-6 code word for the previously transmitted extended superframe. (Since the framer needs to know the value of each of the 4632 bits in an extended superframe to create the CRC-6 code word, it cannot generate the CRC-6 code word until it has completely transmitted the 24 frames of the extended superframe. Hence, the CRC-6 code word created for one extended superframe is sent out along with the *next* extended superframe to be transmitted.)

The receiving ESF framer, which locates the ESF framing pattern, also reads the CRC-6 code word sent from the far end of the T1 span. The receiving framer has also created its own CRC-6 code word for the previously received extended superframe it previously received. The two CRC-6 code words are compared. If they are identical, the receiver concludes no bit errors occurred within the extended superframe during its journey across the T1 span. If the CRC-6 code words do not match, the receiver assumes at least one bit in the extended superframe was corrupted. The receiver reports this as a bit error. After hours or days of collecting CRC-6 code word mismatches, the receiver can report an accurate description of that particular T1 span’s ability to correctly transmit information.

CRC-6 codes are created by a polynomial generator in the following steps.

1. All 193rd bits within the extended superframe to be analyzed are set to 1. This leaves 4632 bits from which to calculate a CRC-6 code word.

2. These 4632 bits are used to create a polynomial in X such that the first bit is the coefficient of term X^{4631} while the last bit is the coefficient of the X^0 term. The polynomial is $(\text{bit }1)X^{4631} + (\text{bit }2)X^1 + \ldots + (\text{bit }4632)X^0$.
3. The polynomial is divided by the factor X^6.
4. The remainder is modulo-2 divided by another polynomial, $X^6 + X + 1$. The six coefficients of the remainder become the CRC-6 bits *C1* through *C6.*

9.3.3 Robbed bit signaling with ESF

ESF supports robbed-bit signaling. Like D4 framing, every 6^{th} frame has the least-significant bit of each channel robbed to allow a signaling bit to be inserted. Since ESF has 24 frames in its multiframe, it can support four signaling bits: *a, b, c* and *d.* These bits are placed respectively in the 6^{th}, 12^{th}, 18^{th} and 24^{th} frames of the Extended Superframe. Note that even though signaling now has four distinct bits available, the PCM encoding format of $7^5/_6$ still applies. The *a* and *b* bits occur half as often now, to make room for the *c* and *d* bits.

Frame Number	193^{rd} Bits			LSB Content (for each channel in the Frame)
	F_e	FDL	CRC	
1		**m**		PCM
2			**C1**	PCM
3		**m**		PCM
4	**0**			PCM
5		**m**		PCM
6			**C2**	**signaling bit “a”**
7		**m**		PCM
8	**0**			PCM
9		**m**		PCM
10			**C3**	PCM
11		**m**		PCM
12	**1**			**signaling bit “b”**
13		**m**		PCM
14			**C4**	PCM
15		**m**		PCM
16	**0**			PCM
17		**m**		PCM
18			**C5**	**signaling bit “c”**
19		**m**		PCM
20	**1**			PCM
21		**m**		PCM
22			**C6**	PCM
23		**m**		PCM
24	**1**			**signaling bit “d”**

Table 2: Extended Superframe format

10.0 T1 Carrier

DS1 describes a protocol for combining PCM samples and the 193rd bits into a contiguous stream, based on an 8 kHz sampling rate for voice signals. T1 describes the actual electrical signal format used to transmit the DS1 information stream. T1 is the first level of the North American **T-carrier** network. Higher bit-rate T-carriers do exist. The T-carrier hierarchy is shown in Table 3.

Digital Signal level	T-Carrier	DS1 Capacity	DS0 Capacity	Transmission	
				Rate	Typical Facility
DS0	--	--	1	64 kb/s	Twisted pair or Coaxial cable
DS1	T1	1	24	1.544 Mb/s	
DS1C	T1C	2	48	3.152 Mb/s	
DS2	T2	4	96	6.312 Mb/s	Fiber Optic cable or Microwave link
DS3	T3	28	672	44.736 Mb/s	
DS4	T4	168	4032	274.176 Mb/s	

Table 3: T-Carrier Hierarchy

10.1 Simplex Span Power

The repeaters in Figure 37 are positioned at intervals along the length of the T1 span, and may be far away from any source of power. A DC current can be passed down the T1 wire line to power these remote repeaters. This is called simplex current, or simplex power. The term simplex refers to the configuration of the current: only one leg of the current path is used by any repeater in the span.

Two repeaters, one for each direction of transmission on a T1 span, are typically housed in a single container. This repeater housing will have simplex current in both directions flowing through it. Each repeater consumes power, so the central office T1 source, where the simplex power is fed onto the T1 lines, must be engineered to provide the correct voltage so that the repeaters along the T1 span have sufficient power to operate. The more repeaters there are to power, the more DC voltage must be applied to the T1 span to power those repeaters. This voltage can range from 20 to 30 volts for a short T1 span with few repeaters, to a deadly 135 volts for a maximum length span with numerous repeaters.

Simplex power is applied to the T1 span in **common mode**. Both wires in a twisted pair carry the same voltage potential for simplex power, while the T1 digital signal is transmitted in **differential mode** down a single twisted wire pair.

At the T1 customer's site (the building on the right of Figure 37), a T1 terminating device called a network interface unit (NIU) provides the loop around at the end of the T1 span for the simplex current. The NIU also isolates the customer's interior T1 equipment (channel banks, data multiplexers, etc.) from the rigors of outside T1. In addition to isolating the customer from the potentially high voltage of the simplex powering, the NIU also provides protection against voltage surges on the T1 line due to lightning strikes, and provides a sensitive receiver to regenerate the incoming T1 signal, which may be weak.

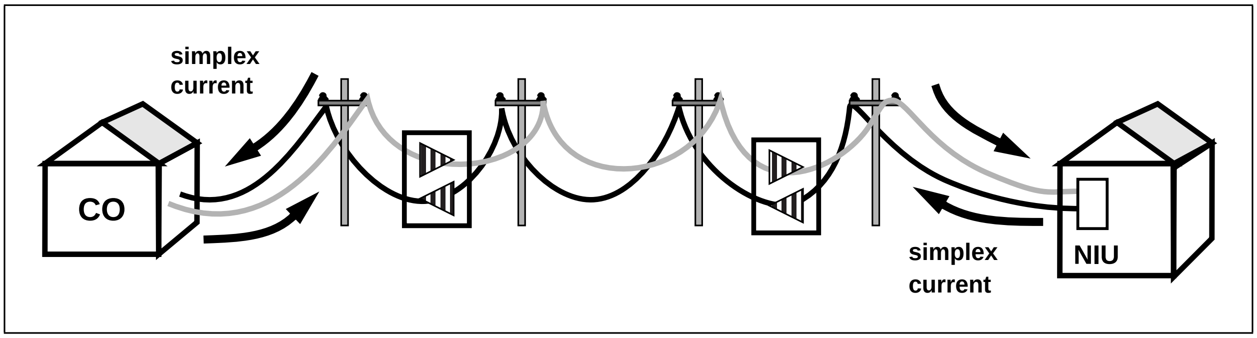

Figure 37: Simplex current powers Repeaters

The NIU is considered expendable in the event of a lightning strike. Should a powerful electrical surge, such as that created by a lightning strike, travel down a T1 span, the NIU acts as a fuse, of sorts. While it may be burned out and destroyed from the power surge, it spares a customer's more expensive T1 equipment the same fate.

10.2 Alternate Mark Inversion

T1 uses a pulse transmission scheme called **alternate mark inversion**, or **AMI**. Figure 38 is a string of 1s, encoded in AMI format. In T1, each pulse is about 3 volts nominal amplitude, either positive or negative about a 0 volt potential. Positive and negative pulses both represent the same information: a "1". Pulses alternate in polarity to prevent undesirable DC biases from being transmitted down the line (do not confuse this undesirable differential mode DC bias from the common mode DC bias applied by simplex powering). This saves power and makes the pulse recovery simpler at the far end. Notice the difference from the digital signal depicted in Figure 10, which would create a DC bias.

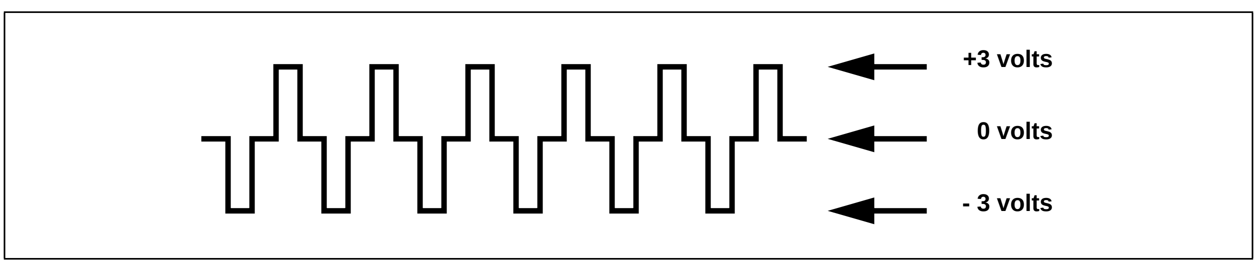

Figure 38: Alternate Mark Inversion encoding

T1 uses a **return-to-zero (RZ)** pulse format. Note that there is a gap between each pulse where the signal returns to the zero volt level before creating the next pulse. This interdigit gap creates a buffer zone between pulses. This buffer zones allows the pulses to “smear” out in time, without interfering with each other. This pulse smearing is known as **dispersion**, and it is a form of distortion an electrical signal suffers as it is transmitted down a wire line.

10.3 Bipolar Violations

Figure 39 is an AMI encoded signal that contains both 1s and 0s (Figure 38 contains only 1s). No pulse where a pulse could fit represents a 0. The down-pointing arrows in Figure 39 show the positions of 0s in this particular AMI signal. T1 is a **ternary** signal, as it contains three states (3 volts, 0 volts, and -3 volts).

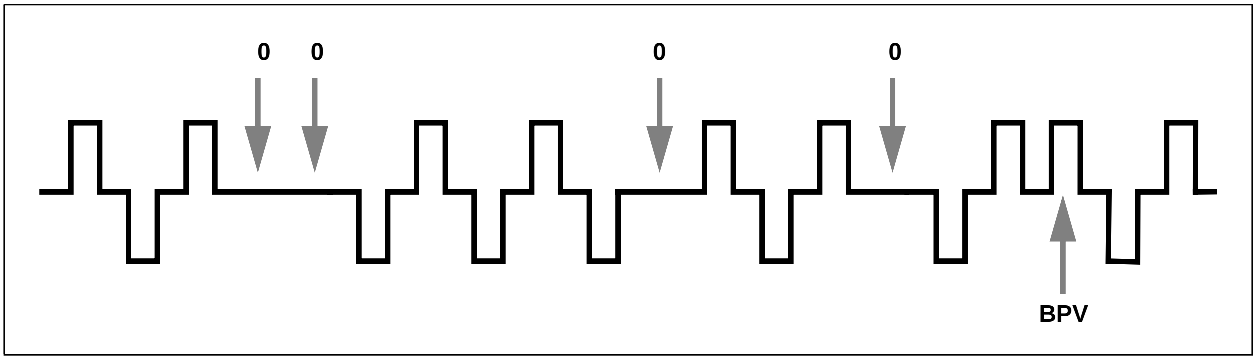

Figure 39: Zeroes in an AMI Signal

Figure 39 also contains two pulses of the same polarity, one following the other. When two consecutive 1s have the same polarity this is called a **bipolar violation (BPV)**. Alternate mark inversion does not care if there are 0s in between 1s. Regardless of any intervening 0s, any 1 should be the opposite polarity of the 1 that occurred previously. A BPV normally indicates an error on a T1 line.