UNITED STATES DEPARTMENT OF AGRICULTURE
Rural Electrification Administration

BULLETIN 1751H-405

SUBJECT: **Digital Transmission Systems**

TO: REA Telephone Borrowers
REA Telephone Staff

EFFECTIVE DATE: Date of Approval

EXPIRATION DATE: Seven years from the effective date

OFFICE OF PRIMARY INTEREST: Transmission Branch, Telecommunications Standards Division

PREVIOUS INSTRUCTIONS: This Bulletin replaces the following Bulletin and Telecommunications Engineering and Construction Manual (TE&CM) Sections:

Bulletin 1751H-405, *Digital Span Lines*
TE&CM Section 954, *Digital Terminals & Multiplexers*
TE&CM Section 958, *Digital Cross-Connect & Drop & Insert Systems*

FILING INSTRUCTIONS: Discard the following Bulletin and TE&CM Sections and replace with this Bulletin:

Bulletin 1751H-405, *Digital Span Lines*
TE&CM Section 954, *Digital Terminals & Multiplexers*
TE&CM Section 958, *Digital Cross-Connect & Drop & Insert Systems*

Also file along with 7 CFR 1751 and on REANET.

PURPOSE: To provide information on digital transmission systems, including a description of system components and basic guidelines for the design of transmission systems. The document assumes the reader is familiar with the topics of basic telephony and digital transmission. All information in this bulletin is advisory.

Administrator

5/5/94
Date

TABLE OF CONTENTS

APPENDIX A
CONSIDERATIONS FOR IMPROVED SPAN LINE BIT ERROR RATES

LIST OF FIGURES & TABLES

CHAPTER I: DIGITAL TERMINAL EQUIPMENT

CHAPTER II: DIGITAL SPAN LINES

INDEX:

ABBREVIATIONS & DEFINITIONS

The definitions and abbreviations used in this bulletin are shown below. Definitions for terms related to digital transmission in general may be found in Section 9 of REA Bulletin 1751H-403, Digital Transmission Fundamentals.

-A-

A/D Analog-To-Digital.

ALBO Automatic Line Build Out; a network that automatically compensates for cable attenuation between repeaters. It is used to equalize the cable characteristics to restore the transmitted signal level.

APS Automatic Protection Switch; transmission facility used to switch traffic to alternative facilities in the event of failure or excessive errors.

ARQ Automatic Request for Repeat.

-B-

Backplane Connector blocks and special wiring located on the rear of an equipment mounting shelf.

BER Bit Error Rate; ratio of the number of erroneous bits to the total number of bits transmitted during a given time interval.

-C-

Clear-channel capability No portion of the channel is used for control, framing, or signaling. The entire 64 kb/s channel is used for information transport.

CO Central Office; the location of the switch for a telephone exchange.

Codec Equipment that converts analog signals to digital and vice versa.

COT Central Office Terminal; equipment at the central office that interfaces the switch with a concentrator or subscriber carrier system.

Cross-Connect Mechanical or electronic device that permits the interconnection of separate channels or circuits.

Crosspoints As part of the switch, it is a set of physical contacts that work together to extend voice and data signals in a switching network.

Crosstalk Form of interference due to electromagnetic coupling from one circuit or channel to another; can occur within a single system or between systems.

-D-

D/A Digital-To-Analog.

DACS Digital Access & Cross-Connect System.

dB decibel; a logarithmic measure of the ratio of two signals, either on a voltage or power basis.

DCS Digital Cross-Connect System.

DS1 Digital Signal Level 1; a digitally-encoded signal at a nominal rate of 1.544 Mb/s.

DSX Digital Signal Cross-Connect Frames; often used in the form DSX-m, where m is either a 1, 2 or 3 referring to a DS1, DS2 or DS3 digital signal level.

-E-

EDSX Electronic Digital Signal Cross-Connect.

Engineering Loss Impedance measurement, in dB, of a cable at a frequency of 772 kHz.

-F-

FEC Forward Error Correction.

FEXT Far End Crosstalk; form of electromagnetic noise interference between two transmission systems operating in the same direction where the interference occurs at the distant end from the source.

-I-

Instantaneous Compandor The process of compressing analog signals before they are sampled for quantizing, thus reducing the effect of quantizing noise.

Interleaving Transmitting several digital signals in time division sequence over a single path.

-L-

LEC Local Exchange Carrier.

LIU Line Interface Unit.

-N-

Nailed-up A semipermanent circuit or connection made through a digital switch.

NEXT Near End Crosstalk; a form of electromagnetic noise interference between two transmission systems operating in opposite directions where the interference occurs at the source end of one system and the distant end of the other system.

-P-

PAM Pulse Amplitude Modulation.

PCM Pulse Code Modulation.

PIC Plastic Insulated Cable.

-Q-

Quantizing Process of sampling a signal into discrete levels that are defined by binary digits.

-R-

Regenerator Device that samples and interprets an attenuated digital signal, reconstructs it and then retransmits a new digital signal with the same information content for continued transmission or processing; also referred to as a repeater.

Repeater See regenerator.

RER Residual Error Rate.

Robbed-bit signaling In a DS1 frame, the least significant bit is robbed from the information bits every six frames. This provides for four-state signalling capability. This leaves only 56 kb/s for information transport.

-S-

Screened Cable Outside plant cable constructed with internal metallic shielding around groupings of paired wires to reduce the crosstalk interference among different signals simultaneously transmitted within the cable.

Section Facilities between two repeaters on a span line.

Section Loss Amount of signal attenuation between two repeaters on a span line.

S/N Signal-to-Noise ratio; the ratio of a desired signal to an undesired signal, such as noise or adjacent channel interference; generally expressed in dB.

Span Line String of repeaters between two points on a digital transmission network.

Special Service Circuits that carry specific information for general use such as weather.

Stuff Bit Bits containing no information that are added to bit streams for synchronization.

-T-

T1 A metallic digital transmission system operating at a rate of 1.544 Mb/s and carrying 24 channels. T2 carries 96 channels and operates at 6.312 Mb/s.

TSI Timeslot Interchanger; in time division, channels are divided into time slots and information is transferred between them.

TSPS Traffic Service Position System.

-V-

VF Voice Frequency; analog signal with a nominal 4 kHz bandwidth.

-Z-

Zero-Code Substitution The process of inserting a "1" bit to prevent the transmission of more than eight consecutive "0" bits.

CHAPTER I: DIGITAL TERMINAL EQUIPMENT

1. INTRODUCTION

1.1 This bulletin provides REA borrowers and other interested parties with information and recommendations on digital transmission systems and span lines. In Chapter I, Section 2 discusses channel banks while Section 3 describes the function and operation of multiplex systems. Section 4 discusses digital cross-connect systems and Section 5 describes applications and design examples for drop and insert systems.

1.2 Chapter II covers digital span lines including a description of the components and engineering guidelines. REA Bulletin 1751H-403, *Digital Transmission Fundamentals*, should be referenced for an overview and summary of digital transmission and a glossary of digital transmission terminology.

2. CHANNEL BANKS

2.1 Introduction

2.1.1 This section will discuss the different types of channel banks that have evolved over the years. In addition, several encoding processes will also be discussed briefly. For a discussion on interface requirements for trunk and subscriber carrier systems, refer to REA Specifications PE-60[1] and PE-64[2].

2.1.2 Voice and data signals are processed by D-type channel banks for transmission over digital facilities. A channel bank is part of the terminal equipment that performs the first step of modulation. More specifically, at the near end of a span line, a digital channel bank converts analog signals (voice and data) into a digital bitstream. At the distant end, another channel bank demultiplexes the incoming digital bitstream and converts it into analog signals. Channel banks generally consist of 24 channels or multiples of 24 channels.

2.1.3 Providing an interface between analog circuits on the customer side and a standard DS1 digital signal on the network side is only one of the many functions of a channel bank. Other basic functions include filtering, sampling, quantizing, coding, multiplexing, synchronizing, framing, and formatting.

2.2 Digital Transmission Systems

2.2.1 The first digital transmission system was the Western Electric D1 channel bank (and T1 span line) used for trunk service. From this system, D1A, D1B, D1C, D1D, D2, D3, D4, and D5 channel banks were developed along with a variety of comparable channel banks from different manufacturers. Variations of the D1, D3, and D4 channel banks are used for subscriber service. These earlier versions required manual adjustments.

2.2.2 For many years, the D3-type channel bank was the industry standard and is still being used extensively, particularly for subscriber carrier systems. Today, the D4-type channel bank is the most frequently used terminal. The newest generation is a software controlled D5-type that is an enhanced D4-type with D5 features.

---

1 REA Bulletin 345-50, REA Specification for Trunk Carrier Systems

2 REA Bulletin 345-66, REA Specification for Subscriber Carrier Systems

2.2.3 Although there are several channel banks manufactured by different vendors, they all basically perform the same functions. By using special plug-in cards, these channel banks can be used interchangeably.

2.3 Encoding Techniques

2.3.1 Voice and data signals are modulated before transmission over a digital line. Pulse Code Modulation (PCM) is the technique used in digital processing. This technique is used to reconstruct pulses that have been impaired during transmission. The signal processing required to achieve a suitable line format takes place in the terminal equipment, or channel bank.

2.3.2 The process by which analog signals are represented by a stream of binary pulses is called encoding. Quantizing and instantaneous companding are part of the coding process for voice signals.

2.3.3 PCM involves sampling a signal at 8000 times per second. These samples are quantized to discrete levels and represented by binary digits. (For more information on digital terminology refer to REA Bulletin 1751H-403, Digital Transmission Fundamentals.) Instantaneous companding involves compressing analog signals before they are sampled for quantizing. Then, signals are expanded after decoding on the receiving end. Instantaneous companding and nonlinear coding are used for low amplitude signals to improve the signal-to-noise ratio. More amplitude steps are used to represent small amplitude variations. Consequently, less quantizing noise is generated by small signals than by large signals.

2.3.4 Nonlinear encoding is used to transmit voice signals over digital systems to improve voice quality with fewer coding steps. Earlier systems used instantaneous compandors and linear coders and decoders to provide nonlinear encoding. Today, systems use nonlinear encoders and decoders (codecs) to achieve the same (or improved) results.

2.3.5 A near constant signal-to-noise ratio is desired over a wide range of voice signals for digital systems. In North America, this is achieved by using a method known as the "mu-law". Ideally, the "mu-law" produces an improvement of about 30 dB in signal-to-noise ratio for mu = 255. D2, D3, D4, and D5 channel banks use mu = 255 and D1 channel banks use mu = 100 to determine the nonlinear coding steps.

2.4 Channel Bank Characteristics

2.4.1 D1: The D1 channel bank was the first digital channel bank used. This channel bank processed analog voice signals by feeding them into an instantaneous compandor before encoding. Then, the voice signal was sampled 8000 times per second. The generated PAM signals were compressed using the mu = 100 law and each channel coded into a 7-digit binary word. Each word in a channel includes a signaling bit which the channel bank multiplexed to the encoded signal. Finally, a framing digit was added. Consequently, the total number of digits per sample was:

$$(7 + 1) \times 24 + 1 = 193$$

The block of 193 digits was called a frame. Since there are 8000 frames per second, the words were formatted into the DS1 signal operating at 1.544 Mb/s.

2.4.2 The D1 system used two compandors, feeding channels 1 through 12 into one and channels 13 through 24 into the other. The channel bank interleaved the outputs from the two compandors such that the outgoing channel sequence was 1, 13, 2, 14, 3, 15, etc. This interleaving reduced crosstalk in adjacent time slots.

2.4.3 D1A: The D1 channel bank was later called the D1A channel bank. As previous described, one of the eight bits assigned per channel was used for signaling. Some PCM channels required two signaling bits. With D1A channel banks, a bit normally assigned for voice encoding was used for the additional signaling bit. Consequently, this left only six bits for voice encoding resulting in greater noise and distortion.

2.4.4 D1B: Essentially, the D1B channel bank was the same as the D1A. However, the D1B divided the signaling bit into four segments to provide two signaling channels. As a result, the seven remaining bits could always be used for voice encoding. Manufacturers provided D1 channel banks that could be used for either D1A or D1B signaling.

2.4.5 D1C: The D1C was a special purpose D1 channel bank used in TSPS (Traffic Service Positions System) applications. This channel bank combined the signaling bits for all 24 voice channels into a separate high speed data channel operating at 192 kb/s.

2.4.6 D1D: The D1D channel bank was a modified version of the D1 channel bank that had achieved D3 voice quality. This system was developed to use the large quantities of D1 racks and shelves already installed. Manufacturers used D3 channel banks to meet D1D application requirements by changing the channel sequence from 1, 2, 3, 4, etc., for D3, to 1, 13, 2, 14, etc., for D1. This modification was produced by a plug-in card or a change in channel bank backplane wiring depending on the specific type and age of the equipment.

2.4.7 D2: The D2 channel bank provided a higher quality voice circuit for intertoll applications. The D2 channel bank used an 8-bit nonlinear encoding to derive 255 coding levels based on the mu = 255 companding law. The D2 channel bank provided two signaling channels by "robbing" the least significant voice bit from each channel every sixth frame. Channel A signaling was transmitted in the sixth frame and Channel B signaling in the twelfth frame.

2.4.8 The D2 channel bank had 96 channel groups for T1 applications (24 channels) and T2 applications (96 channels). However, D2 channel banks were designed in 24 channel groups. Plug-in cards could change the channel sequence and make most channel banks versatile for D2, D3, and D1D applications.

2.4.9 D3:. The D3 channel bank had 24 channel groups for T1 applications and provided the same voice quality as D2 channel banks. The channel sequence is 1, 2, 3, 4, etc. The D2 channel bank was redesigned to cover both D2 and D3 applications.

2.5 D4 and D5 Channel Banks

2.5.1 The D4 type channel bank is the last of the manually adjusted channel banks but the most versatile. Each D4 channel bank can transmit 48 channels and can be used with T1, T1C, and T2 span lines or dedicated fiber facilities. The D4 channel bank combines two D3 channel banks and offers a reduction in both size and cost relative to the D3 channel bank. Figure 1 illustrates a typical D4 channel bank.

2.5.2 The D4 channel bank offers five possible modes of operation as shown in Figure 2. Following is a brief description of these operating modes. More detailed information on the general operation of the D4 channel bank (encoding, decoding, etc.) is described in REA Bulletin 1751H-403, *Digital Transmission Fundamentals*.

2.5.3 Operating Modes

2.5.3.1 Mode 1: Mode 1 operates at the DS1C level, usually over a T1C span line (3.152 Mb/s), with D4 channel banks at both ends. The DS1C line interface units combine two synchronous DS1 signals and framing bits (64 kb/s) before transmission. The Mode 1 signal cannot be multiplexed to the DS3 level nor demultiplexed to DS1 by an M1C multiplex unit. Consequently, Mode 1 is not widely used.

2.5.3.2 Mode 2: Mode 2 also operates at the DS1C level over a T1C line. However, there is a D4 channel bank at one end and another Mode 2 system or an M1C multiplex unit at the other. The M1C multiplex unit may be connected to a D1D, D2, D3, or D4 bank or to a digital switch. Mode 2 uses an M1C frame format and the 24 channel groups do not require synchronization.

2.5.3.3 Mode 3: Mode 3 allows the D4 channel bank to be used over two T1 span lines. The terminating equipment can be another D4 channel bank, a DCS, or a digital switch. The two sections of the D4 operate independently and can be used for carrier systems to two different offices.

2.5.3.4 Mode 4: Mode 4 takes two D4 channel banks to form a 96 channel transmission signal operating at the DS2 level over a T2 span line (6.312 Mb/s). The distant end can be another D4 channel bank or a Mode 4 terminal. It can also be a M12 multiplexer connecting four of any type of channel bank, all operating over T1 span lines.

2.5.3.5 Mode 5: Mode 5 operation is the same as Mode 4 except the DS2 interface is optical rather than electrical.

2.5.3.6 The D4 channel bank can be equipped with a low bit rate codec for each channel, unlike earlier channel banks where codecs are shared. This provides easy access to the bitstream for high speed data. The 1.544 Mb/s bitstream can be accessed in multiples of 64 kb/s for each voice channel when the channel bank uses "clear-channel capability" or in multiples of 56 kb/s when it uses "robbed-bit signaling".

2.5.3.7 Modes 1, 2, and 4 require multiplexers to operate at DS1C and DS2 rates. These multiplexers are plug-in cards in the D4 channel bank. Changing from one operation mode to another is made possible with few equipment changes. Designing the multiplexers as an integral part of the D4 channel bank is more cost effective than the separate units used with D3 channel banks.

2.5.4 D5: The D5 channel bank is a fifth generation digital transmission system controlled by a microprocessor. This microprocessor automates most maintenance functions and supervises the channel bank's operations. The D5 channel bank consists of 96 channels and can transmit at the DS1 or DS1C level.

3. MULTIPLEX SYSTEMS

3.1 Introduction

3.1.1 Most digital systems transmit information at the DS1 rate of 1.544 Mb/s over T1 span lines. Digital multiplexers combine (multiplex) basic DS1 signals to form a higher rate digital signal increasing transmission efficiency. This section will briefly describe how digital multiplexers combine individual nonsynchronized DS1 signal inputs to form a higher rate synchronized output.

FIGURE 1 - D4 CHANNEL BANK

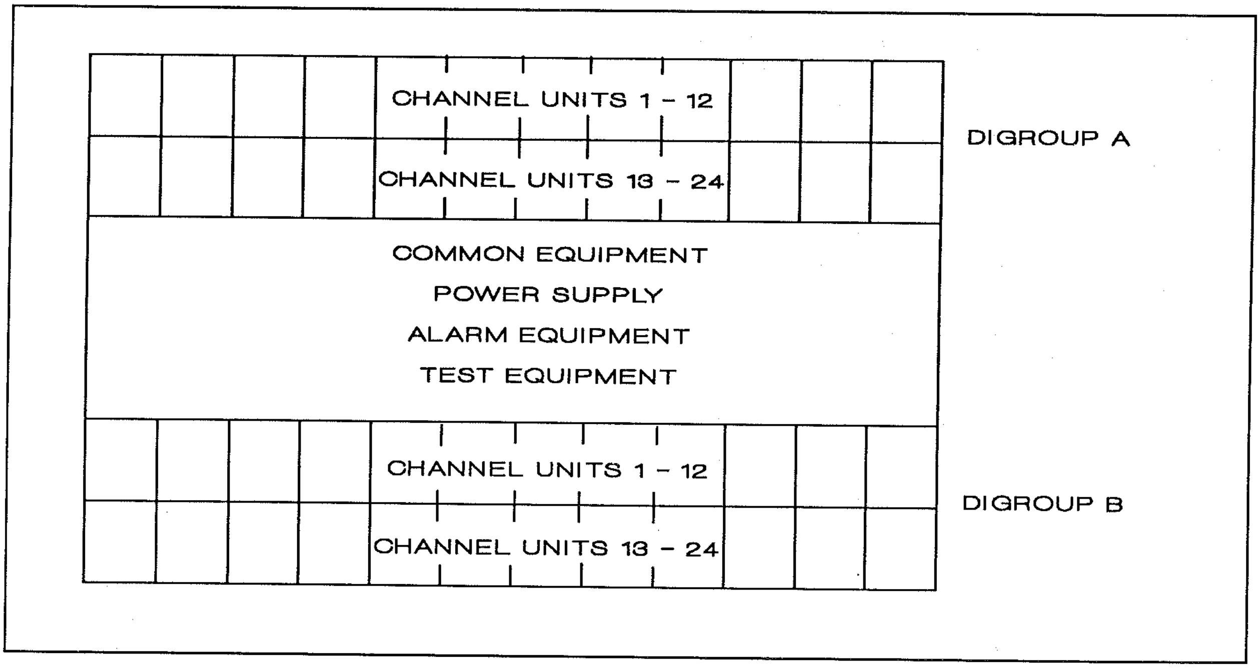
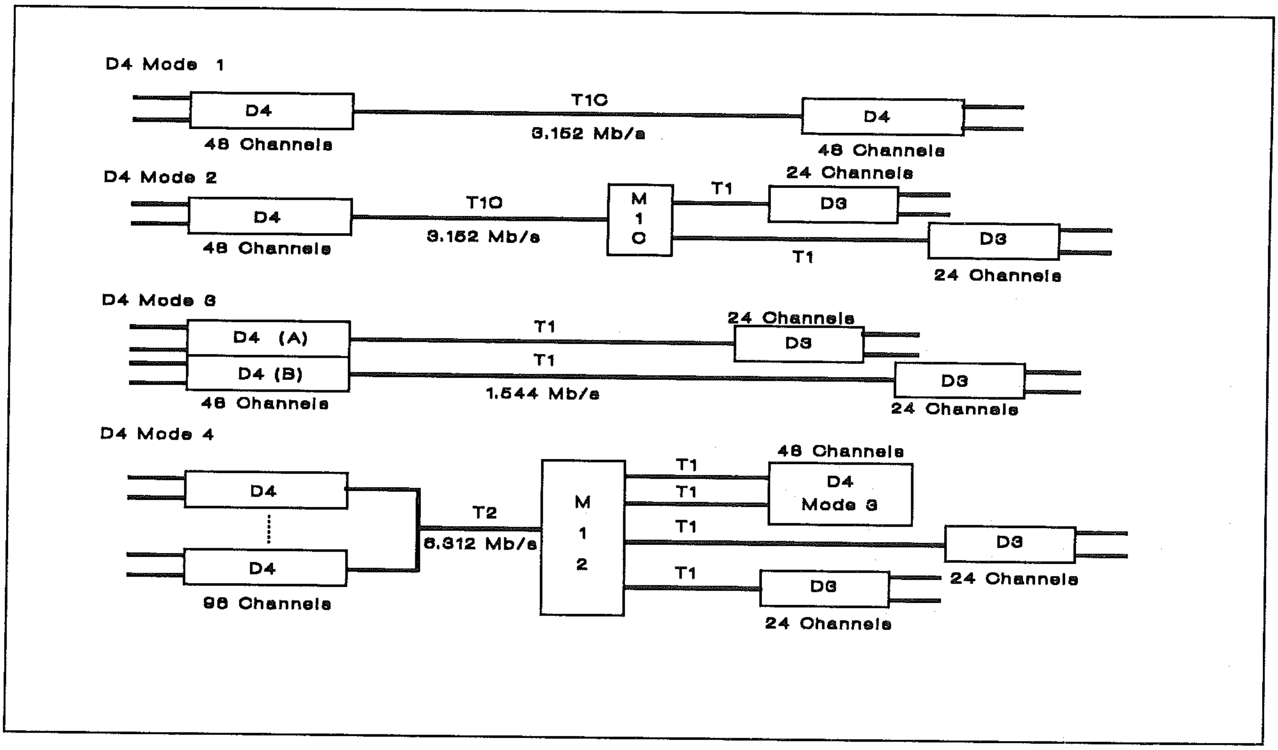


FIGURE 2 - D4 MODES OF OPERATION



3.2 Multiplex Architecture

3.2.1 Multiplexers are designated by the prefix M (for multiplex) followed by a number associated with the digital levels. For example, a M12 multiplexer combines several DS1 signal levels into a DS2 signal, and conversely, demultiplexes a DS2 signal to several DS1 signals. The M12 combines four DS1 inputs to produce a DS2 output. Table 1 lists the multiplex levels for systems in North America. Similarly, the M13 accepts 28 DS1 level inputs to form a DS3 output. The M34 takes 6 DS3 inputs to produce a DS4 output. DS1C is a special case where 2 DS1 signals are multiplexed to form a 48 channel group with a line rate of 3.152 Mb/s.

3.2.2 The higher level line rate is simply a multiple of the lower input rate plus some additional bits. For example, the DS2 line rate is 6.312 Mb/s. The DS1 line rate is 1.544 Mb/s. Four multiplexed DS1s (1.544 * 4) produce a line rate equal to 6.176 Mb/s. Adding 136 kb/s for synchronization and framing will produce a DS2 output with a line rate of 6.312 Mb/s.

TABLE 1 - MULTIPLEX HIERARCHY

System	Level	Bit Rate (Mb/s)	Channels
North America	1	1.544	24
	2	6.312	96
	3	44.736	672
	4	274.176	4032

3.3 Functions

3.3.1 In addition to multiplexing signals to higher levels, digital multiplexers may include zero code substitution, add/drop capability, condition monitoring, performance monitoring, alarm control, internal protection switching, operations interfaces and other related functions.

3.3.2 Zero code substitution is required to provide sufficient signal energy to keep repeaters synchronized. Add/drop capability allows the extraction and replacement of a lower rate signal from a higher rate signal. Condition and performance monitoring is the detection and collection of any irregularities of the transmitted signal. Alarm control alerts of any internal problems while protection switching prevents system outages. Operations interfaces allow remote observation and control of the facilities.

3.3.3 As mentioned, 64 kb/s is assigned to each of the 24 channels in a channel bank. The channel bank performs the first level of multiplexing by interleaving the individual 8 bit words from the 24 voice channels into a digital pulse stream (DS1). The DS1 level is the basic building block produced by channel banks and digital switches and suitable for universal interface and efficient transmission over paired cables.

3.3.4 Likewise, multiplexers interleave incoming bitstreams on a bit-by-bit or byte (group of bits) basis. Multiplexers generally interface at standard Bell Communications Research (Bellcore) signal levels, e.g., DS1, DS2, DS3, etc. However, they may not all follow the specific signal format or bit rate outlined for standard Bellcore specified M-type multiplexers at both the input and output interfaces. Most multiplexers use similar techniques for scrambling, stuffing, and temporary storage of bits in multiplexing.

3.4 Operation

3.4.1 The function of a multiplexer will be described using the M12 model as an example. The M12 combines four asynchronous DS1 inputs into a DS2 output. Before multiplexing, the multiplexer inverts the second and fourth input signals (ones becomes zeros and zeros become ones) as a first stage of randomizing (scrambling) the multiplexed output. The multiplexer takes twelve bits from each input signal, interleaves them into a single bitstream, and adds one control bit (12+12+12+12+1 = 49 bits). The multiplexer repeats this sequence six times to form a subframe (49 x 6 = 294 bits). The subframe sequence repeats four times to form a frame consisting of 1176 bits (294 x 4). Of these 1176 bits, 1152 are information bits from the four DS1 inputs and 24 are control bits.

3.4.2 To synchronize the four DS1 inputs the system writes each input into a buffer from which the bits can be extracted at the appointed time. Since each input may be operating at a different speed, some of the input buffers may become empty before others. The multiplexer adds extra bits to the incoming bitstreams as required to prevent the stores from becoming empty and thus synchronizing the inputs. The extra bits may be added only at specified locations (time slots) in the outgoing bitstream. Specific control bits identify when the multiplexer adds an extra bit.

3.4.3 The 24 control bits per frame consist of four "M" bits, eight "F" bits, and 12 "C" bits. The M bit pattern (011X) aligns the frame and the subframes and transmits alarm information (X = 0 or 1) between multiplexers. The patterns of F and C bits further align each subframe and possible stuff bit time slots. The C bits also identify whether the multiplexer has transmitted stuff bits. A maximum of about 0.3 percent of the output bitstream may be stuff bits. The clocks driving the individual DS1 inputs do not require high level precision but must remain within specified limits to ensure that the multiplexer does not have to add excessive stuff bits.

3.4.4 The multiplexer output bit rate is the sum of all DS1 inputs plus a fixed number of control and framing bits plus a variable number of stuff bits. The multiplexer processes the output to ensure that it includes no more than five consecutive zeros. Table 2 provides examples of standard Bellcore M-type multiplexers. REA Bulletin 1751H-403, Digital Transmission Fundamentals, describes zero-code suppression techniques.

4. DIGITAL CROSS-CONNECT SYSTEMS

4.1 General

4.1.1 This section describes the operation and application of digital cross-connect systems. This type of equipment can provide effective solutions for various network problems. This section will highlight many of these problems and discuss possible solutions.

4.2 Digital Cross-Connect Types

4.2.1 Until the early 1980s, telephone companies used digital signal cross-connects (DSX) exclusively for traffic routing between network elements and test access points. DSXs are patch panels that provide test access and manual patching at the DS1, DS1C, DS2, and DS3 signal rates. The corresponding cross-connects are DSX1, DSX1C, DSX2, and DSX3. A block diagram of a typical DSX is illustrated in Figure 3.

4.2.2 Automated DSXs are now available with computer controlled connections between the incoming and outgoing connector blocks. A switch matrix consisting of mechanical or solid-state crosspoints makes these metallic connections. Even though these are digital cross-connects, the crosspoints are analog. Craftspersons control the cross-connect states using an administrative interface. Figure 4 illustrates a block diagram of an automated DSX.

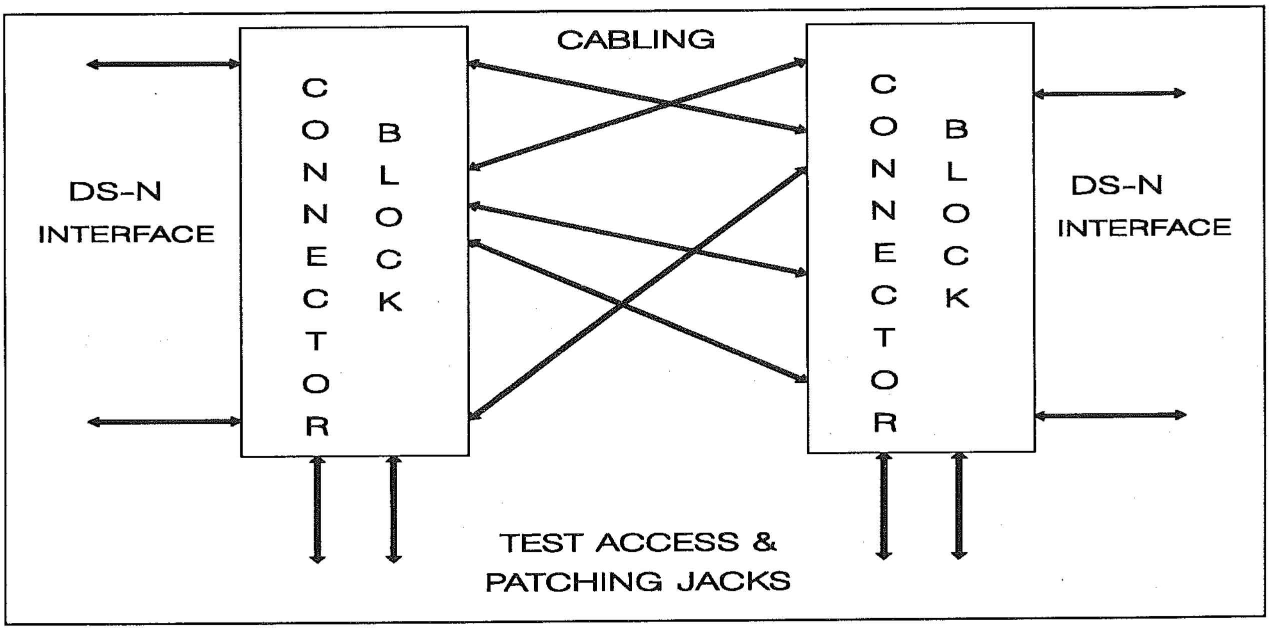
TABLE 2 - STANDARD MULTIPLEXERS

Multiplex	Input	Output	Channels
M1C	2 DS1	DS1C	48
M12	4 DS1	DS2	96
M13	28 DS1	DS3	672
M23	7 DS2	DS3	672
MX3 (See Note)	28 DS1 or 14 DS1C or 7 DS2	DS3	672
M34	6 DS3	DS4	4032

NOTE:

The MX3 multiplexer has inputs for 28 DS1, 14 DS1C, or 7 DS2 streams or a mixture of rates equivalent to 28 DS1s.

FIGURE 3 - MANUAL DIGITAL SIGNAL CROSS-CONNECT



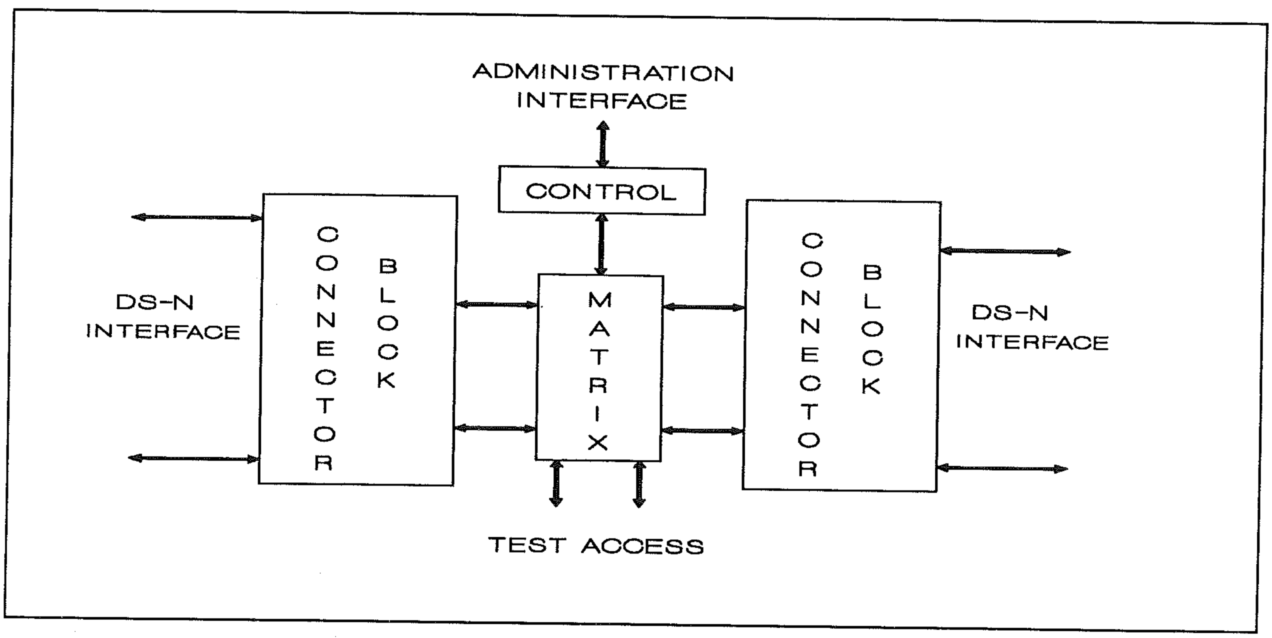
4.2.3 Neither the manual nor the automated DSX has digital signal regeneration. The manual DSX is vulnerable to improper connections caused by maintenance and system reconfigurations. The automated DSX alleviates these problems to a large extent.

4.2.4 In larger central offices, it is often necessary to cross-connect a large number of DS1 and DS3 signals. Neither the manual or the automated DSXs are economical with large applications. In addition, office repeaters are often necessary to regenerate the signals to comply with cross-connect distance specifications.

4.2.5 The DSXs described can only cross-connect signals at the same rate. If the system requires cross-connection of signals at different rates, additional equipment is required. For example, cross-connection of DS0 signals with DS1 signals requires channel banks as shown in Figure 5.

4.2.6 The back-to-back channel arrangement shown in Figure 5 can be very expensive. Furthermore, each time a digital-to-analog (D/A) and subsequent analog-to-digital (A/D) conversion takes place, some transmission degradation occurs.

FIGURE 4 - AUTOMATED DIGITAL SIGNAL CROSS-CONNECT



4.2.7 M13 multiplexers are used to cross-connect DS1 signals with DS3 signals as shown in Figure 6. As described in paragraph 4.2.6, the back-to-back multiplexer configuration can be very costly. In addition, if it is also necessary to cross-connect at the DS0 level, the components from Figure 5 can be added to Figure 6. Of course, the complexity of this configuration would increase the cost and the incidences of connection errors.

4.2.8 Digital cross-connect systems (DCSs) matured and electronic digital signal cross-connects (EDSX) were developed to compensate for the shortcomings found in manual and automated DSXs. An EDSX cross-connects at the interface signal level rate while DCSs cross-connects at the component level rates. The X/Y generic format is used to classify these systems. The X identifies the interface rate and the Y the cross-connect rate.

4.3.2 Using the manual DSX is time consuming, prone to mistakes and costly. The manual DSX becomes unreliable with constant rearrangements which can cause connectors to wear and loosen and cables to break. These faults lead to network failures. These problems increase in magnitude at higher facility speeds, e.g., DS3.

4.3.3 The automated DSX eliminates on-site rearrangements by using a terminal at a central location for reconfiguration. This method is less expensive and more accurate. A terminal at a central location can also control remote test access.

4.4 Digital Cross-Connect System Operations

4.4.1 The following paragraphs describe the basic operation of a 1/0 type digital cross-connect system (DCS). Other types such as 3/1 operate in a similar fashion.

4.4.2 Under software program control, DCSs, also called digital access and cross-connect systems (DACS), connect voice channels of different DS1 bitstreams. Changing the time slot arrangements of an individual DS1 stream (time slot interchange) is also possible. This type of cross-connection does not require D/A or A/D conversion. The DCS cross-connects entirely at the DS0 level. Also, the DCS permits access to individual DS0 channels for monitoring and test purposes.

4.4.3 The electronic computer controlled DCS equipment contains memory maps stored in an environment that is immune to power failure. Consequently, the DCS does not lose cross-connect instructions due to a power interruption. A craftsperson uses a local or remote administration terminal to enter or change these memory maps. DCS equipment can also be changed automatically by program control based on the time of day or a failure in the local network.

4.4.4 Figure 9 illustrates the operation of a typical 1/0 DCS. The following paragraphs describe the operation of transmission in one direction. Transmission in the opposite direction is a mirror image.

4.4.5 Each T1 port of a DCS has an assigned time slot interchange (TSI) which consists of an input buffer, an output buffer, and transfer logic. Each direction of transmission has a separate TSI.

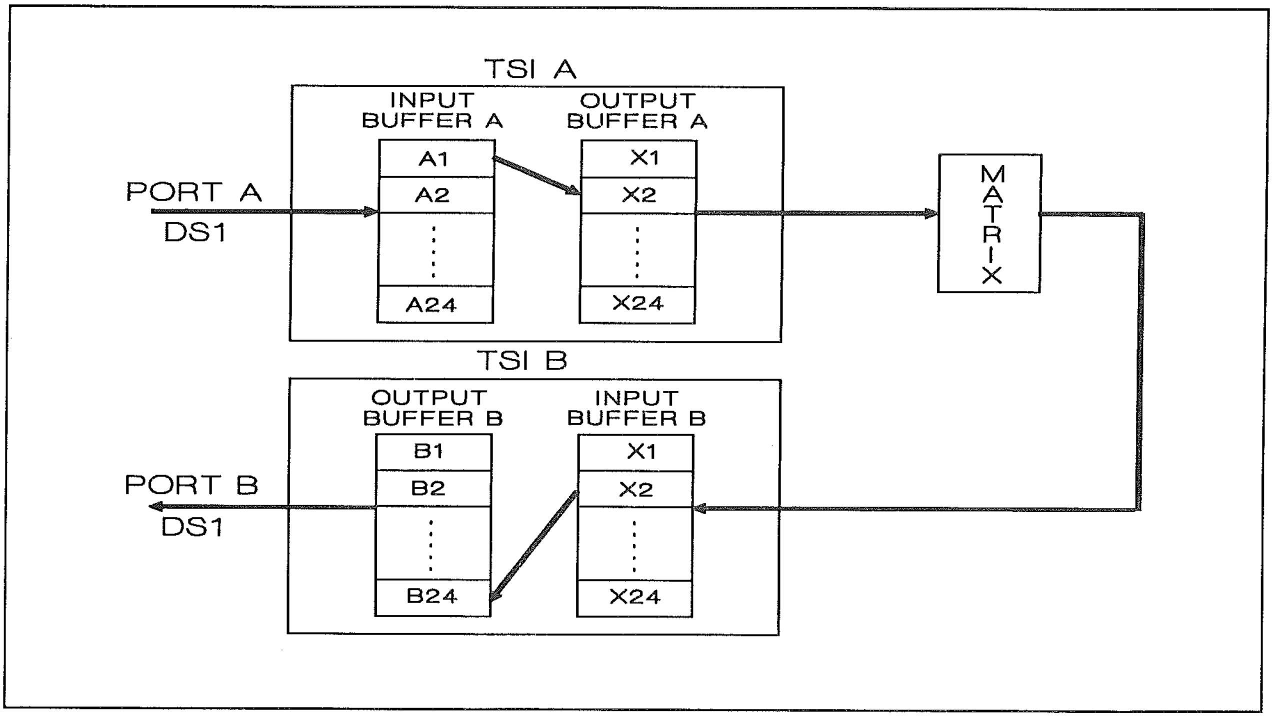
4.4.6 The DCS assigns each of the 24 DS0 channels of a DS1 bitstream to a time slot. The system writes each time slot of an incoming DS1 bitstream to a memory location in the input buffer of the TSI assigned to the incoming T1 port. The central processor assigns an internal time slot to transfer the information from the TSI of the incoming T1 port to the TSI of the appropriate outgoing T1 port via the matrix. In Figure 9, the DCS reads time slot A1 from input buffer A and writes it to time slot X2 of output buffer A. During time slot X2, the system establishes a matrix path between TSI A and TSI B. Thus, the DCS passes information in time slot A1 from output buffer A to input buffer B. Transfer logic in TSI B then transfers the information in time slot X2 of input buffer B to time slot B24 of output buffer B. Therefore, the DCS cross-connects time slot A1 to time slot B24 of the DS1 bitstream outgoing at port B.

4.4.7 The DCS matrix enables any TSI assigned to an incoming T1 port to be cross-connected to any TSI assigned to an outgoing T1 port. The combination of the TSIs and the matrix permits any time slot of any incoming DS1 bitstream to be cross-connected to any time slot of any outgoing DS1 bitstream.

4.4.8 DCS equipment provides special service circuits without requiring nailed-up connections using back-to-back channel banks. In addition, DCS equipment is less costly than back-to-back channel banks and requires less power. Since DCS equipment does not require D/A and A/D conversions, transmission is not degraded.

4.4.9 DSC equipment introduces a delay from 2 to 4 frames (250 to 500 microseconds) into the transmission. DCS equipment also conforms to the Stratum 3 criteria as specified in Bellcore TA-NPL-000436, Digital Synchronization Network Plan, November 1986. This plan defines the stability and accuracy requirements of system clocks.

FIGURE 9 - BASIC DCS OPERATION



4.4.11 DCSs and digital switches are similar in some respects. However, they are distinctly different in several important areas as follow:

4.4.11.1 Holding Times - A typical holding time for a voice call switched through a digital central office is 2 to 3 minutes. Private line and special service circuits of the kind typically connected through a DCS have holding times measured in weeks or months or even longer.

4.4.11.2 Signal Preprocessing - A digital switch requires signal preprocessing for call set-up and translation. A DCS requires either preprogramming with cross-connect information or remote control.

4.4.11.3 Broadband Signals - A DCS can add DS0 channels together to provide broadband signal management whereas current digital switches can only switch at the DS0 level.

4.5 Digital Cross-Connect System Applications

4.5.1 For proper cross-connection, the services on either side of the DCS should have the following characteristics:

1) Same signaling type (or no signaling)

2) Compatible channel banks and channel units

3) Consistent transmission direction, e.g., if the traffic entering the DCS is from an office toward a subscriber, it must continue toward the subscriber upon leaving the DCS.

4) Compatible customer premises equipment

4.5.2 Applications

4.5.2.1 The following describes several major applications for DSCs. An all-inclusive list of applications is not intended. There are certainly other configurations. This section leaves it to the readers' ingenuity and knowledge of their individual network requirements to use DCS equipment to solve any special network problems which they may have.

4.5.2.2 Hubbing - When a telephone company has several central offices, trunk groups usually connect each office as shown in Figure 10. DCS equipment can be used to efficiently route the DS1 (or DS3) circuits via an alternate or tandem route rather than by direct point-to-point circuits between central offices. Figure 10b illustrates such routing of the network shown in Figure 10a. Hubbing creates a flexible and responsive network and eliminates back-to-back channel banks.

4.5.2.2.1 To demonstrate the efficiency produced by hubbing, assume that each of the trunk routes in Figure 10a requires 8 channels. Figure 10b shows the span line between office A and B now carries A-D and A-C traffic in addition to A-B traffic and uses 24 channels. In this case, using a T1 span line is more efficient. The same results can be shown for the span lines between offices C and D and B and D. The original trunk routes not required (shown as dashed lines in Figure 10b) may be used as alternate routes in case of overload or network failures.

4.5.2.3 Grooming - Circuit grooming techniques can be used to segregate and/or concentrate traffic. Special services and voice (message) traffic can be combined onto the same span lines. The DCS separates the two types of traffic onto different span lines increasing the T1 fill. Figure 11 illustrates this application. A DCS can also concentrate traffic and increase the fill of T1 spans without segregating traffic types. This enables nailed-up circuits to be routed on a T1 around a digital switch. This allows the switch to process normal switched traffic.

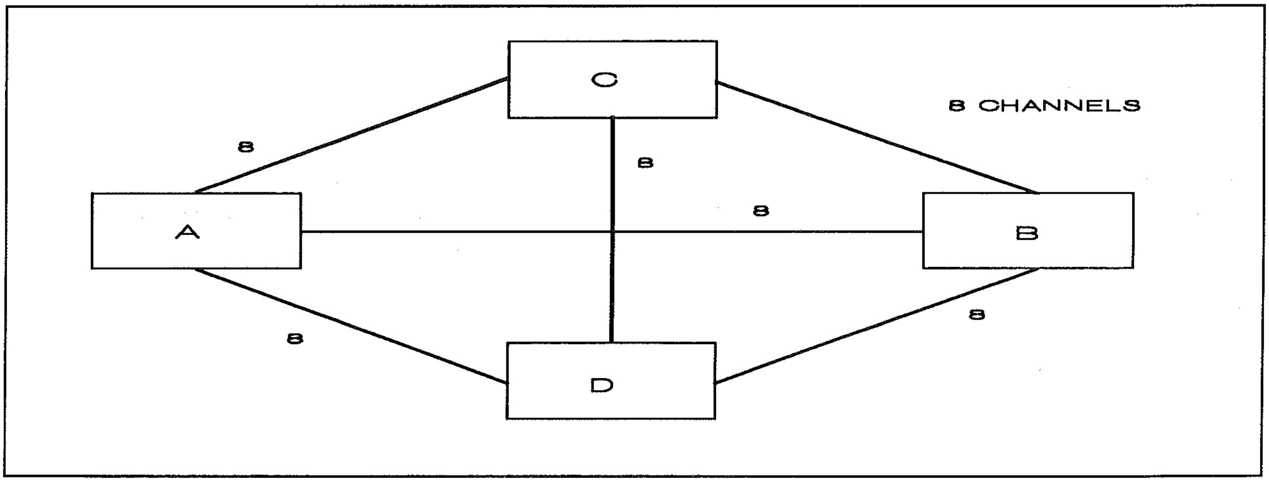
4.5.2.4 Test Access - For testing purposes, DCS equipment allows access to individual DS0 channels within a 24 channel DS1 bitstream or individual DS1 signals within a DS3 bitstream. The accessed channel can be monitored and/or tested. It is possible to perform tests locally or from a remote maintenance center. Figure 12 illustrates this capability. Remote testing can be accomplished without a test device at the remote location. If the DCS system does not perform D/A conversion for analog testing of the dropped channels, then a channel bank or drop and insert system should be used for the conversion.

4.5.3 DCS equipment monitors performance and alarms. The DCS monitors each DS1 or DS3 signal interfaced to it for proper performance including framing losses, frame slips and bit error rate. The system generates carrier group alarms when required for normal carrier operation. DCS equipment also provides external alarms for power and carrier failures.

4.5.4 DCS equipment can be managed and configured from a remote location. Figure 13 illustrates this capability. Figure 14 shows how DCSs can simplify a new facility cutover. Figure 14a shows a copper facility connecting the two DCSs. A new radio or fiber route is turned up. The DCS makes this rearrangement through a remote management center. The two offices are briefly disconnected during the switchover. Figure 14b shows the new arrangement.

FIGURE 10 - HUBBING

(A) HUBBING - DIRECT TRUNKING



(B) HUBBING - DCS HUB

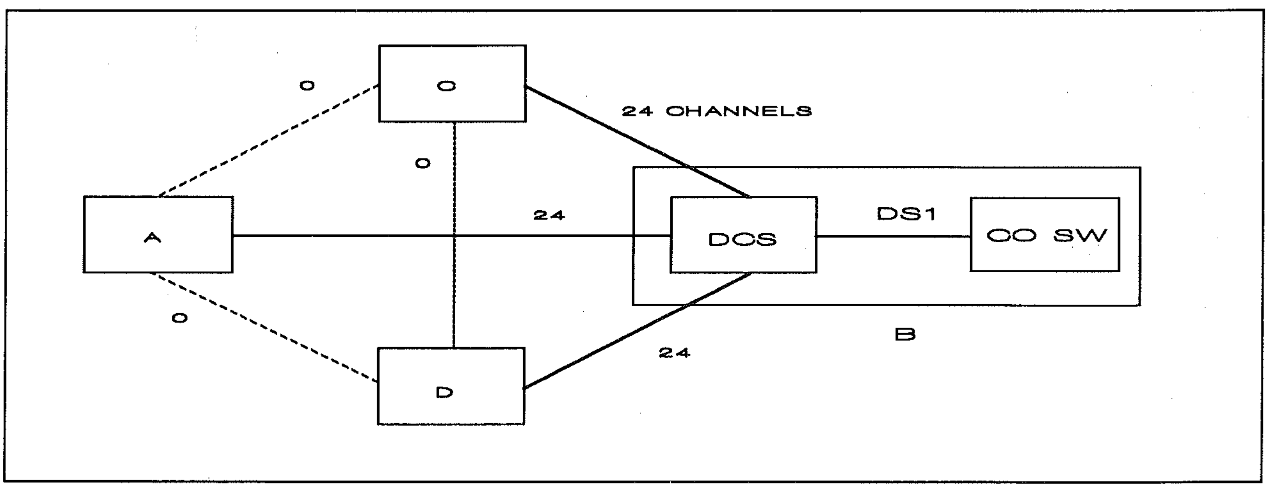


FIGURE 11 - GROOMING

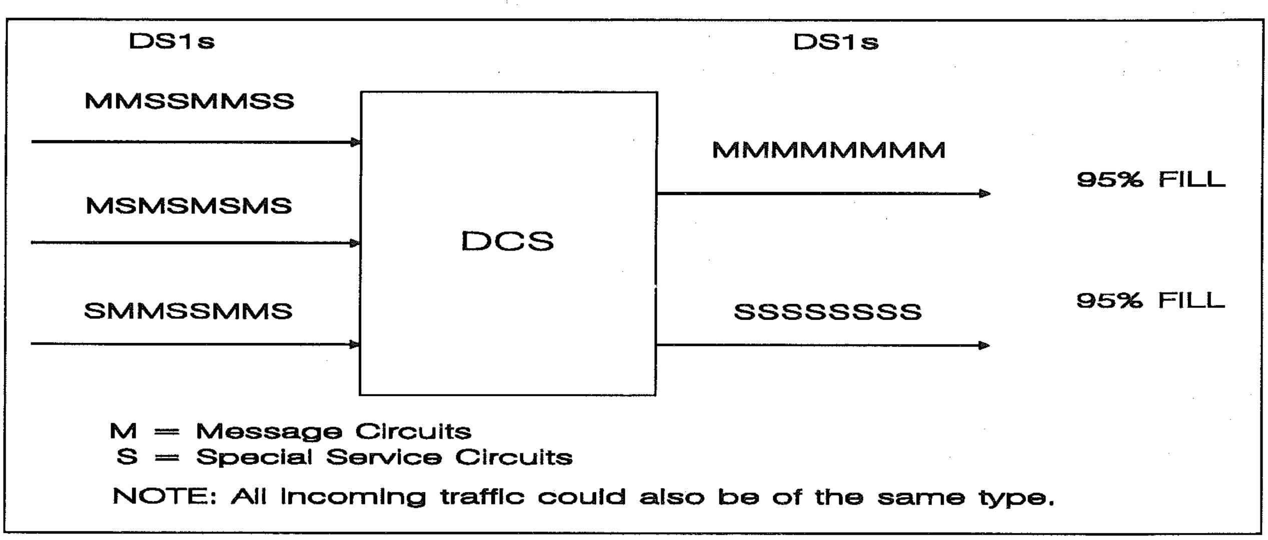


FIGURE 12 - REMOTE AND LOCAL TESTING

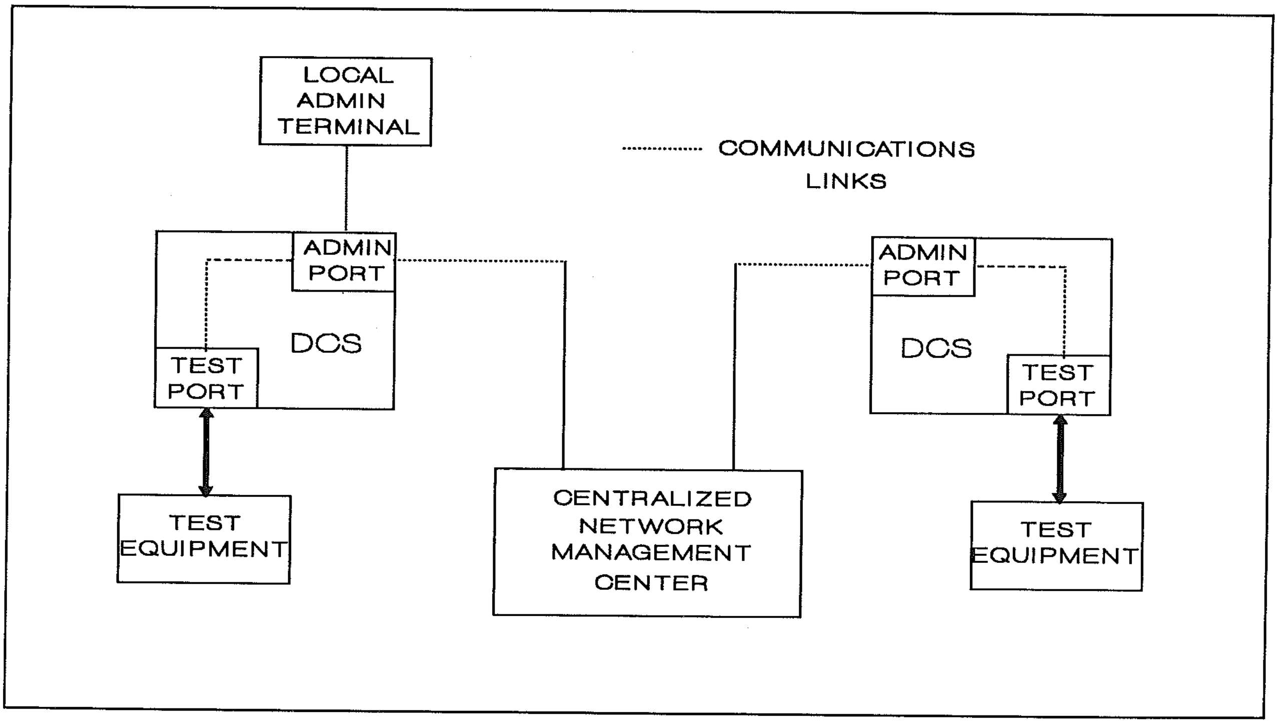


FIGURE 13 - REMOTE NETWORK MANAGEMENT

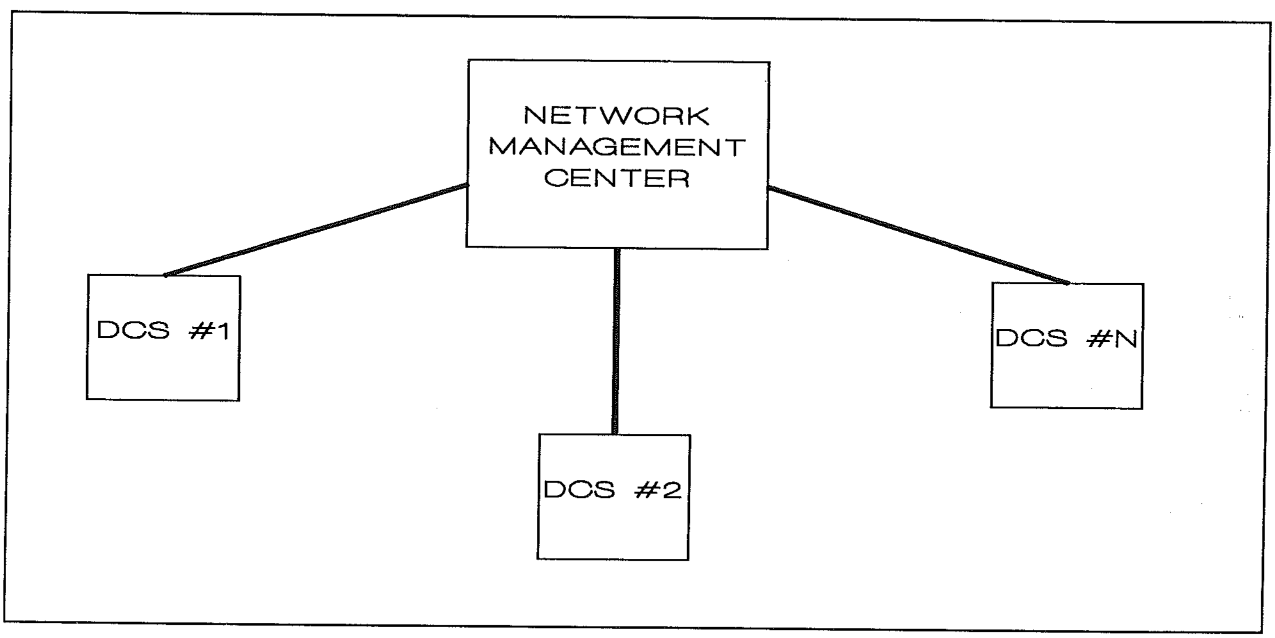
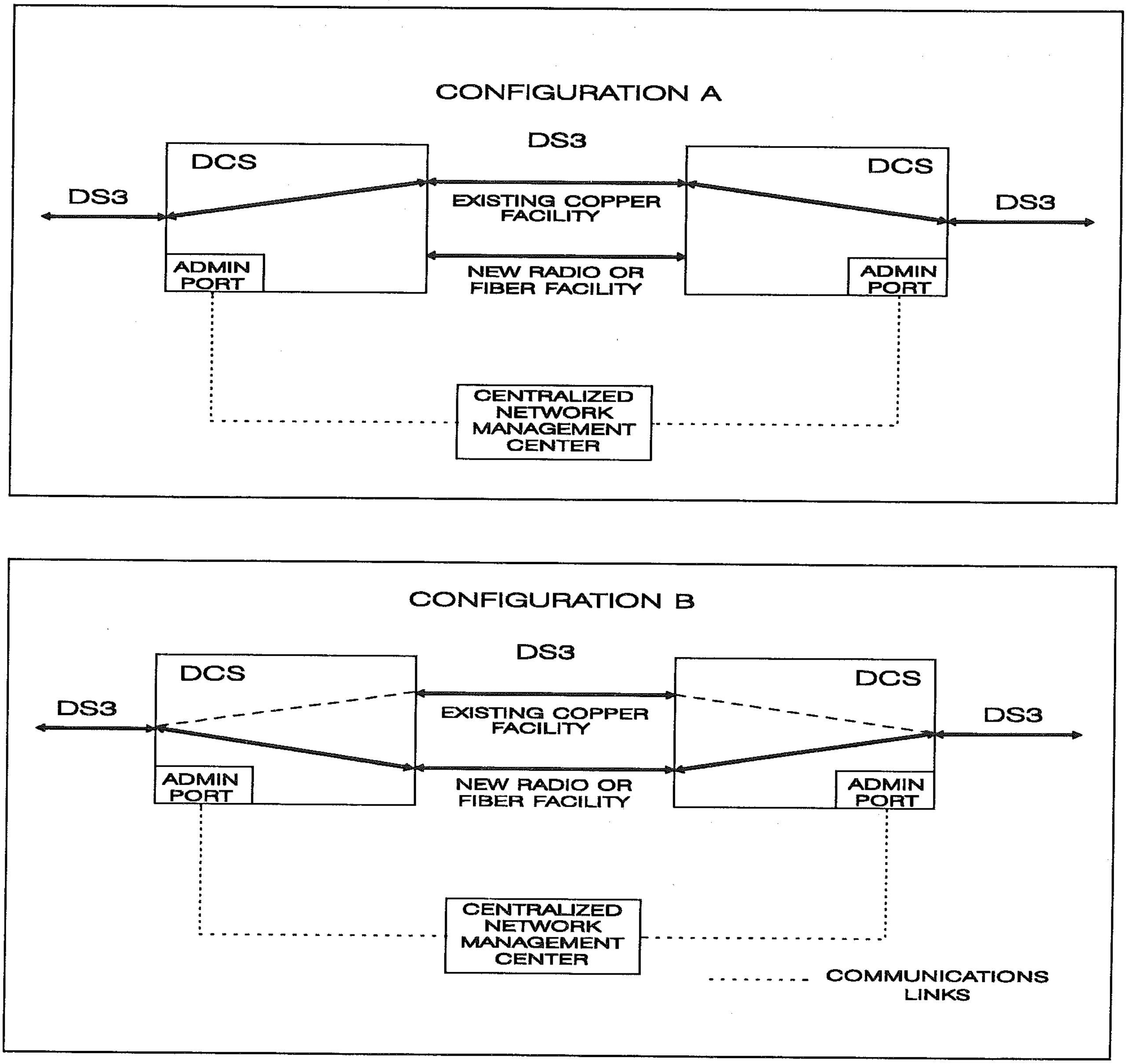


FIGURE 14 - FACILITY PROVISIONING



4.5.5 Many types of DCS equipment have additional features such as subrate data capability and digital multipoint bridging.

4.5.5.1 The subrate data feature cross-connects data circuits within a single DS0 voice channel. This eliminates the need for back-to-back digital data system equipment.

4.5.5.2 Digital multipoint bridging enables the bridging of DS0 voice channels for voice conferencing and the broadcasting of multipoint voice and data circuits. This feature replaces costly analog voice bridges and the associated channel banks.

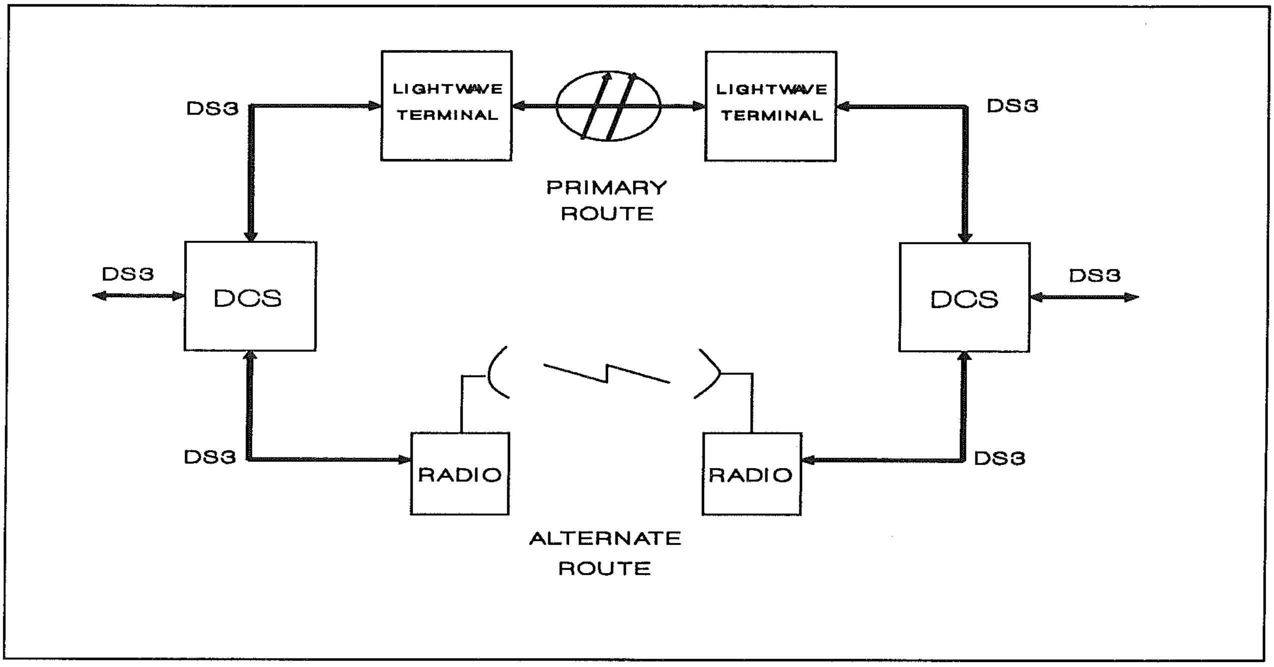
4.5.6 Some types of DCS equipment provide extended superframe (ESF) capability and bipolar 8-bit zero suppression (B8ZS) for clear channel operation. Refer to Bulletin 1751H-403, Digital Transmission Fundamentals, for details on these features.

4.6 Network Restoral

4.6.1 Network providers recognize that service restoral is an essential component to system operation. DCSs lend themselves well to various types of system restoration configurations including route diversity and ring arrangements.

4.6.2 Figure 15 illustrates a route diversity arrangement. This technique for maintaining service continuity requires a large amount of terminal equipment and cable to protect against facility failure. In effect, route diversity is analogous to carrier protection switching.

FIGURE 15 - ROUTE DIVERSITY



4.6.3 The dedicated ring arrangement shown in Figure 16 protects against node failures and facility disruption, such as cable cuts or failures. This arrangement requires more bandwidth since the same facility carries the traffic from all of the nodes in the ring.

5. DROP & INSERT SYSTEMS

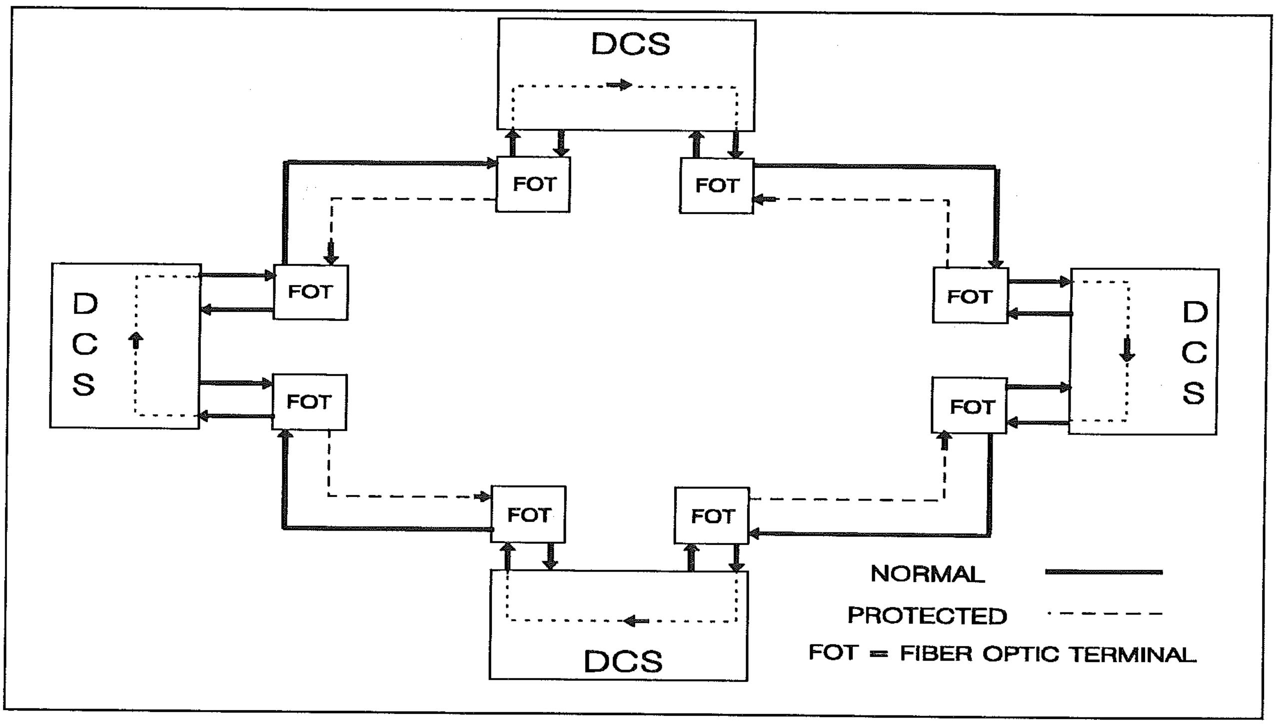
5.1 General

5.1.1 Drop and insert (DI) systems allow individual DS0 channels of a 24 channel DS1 bitstream to be dropped from and/or inserted into the bitstream. DI systems can also serve as end terminals similar to the traditional centralized subscriber carrier. DI systems contain channel units for 2-wire and 4-wire voice frequency interface such as E & M, foreign exchange (FX), transmission only (TO), and duplex (DX). Channel units are also available for asynchronous, synchronous, and subrate data including high speed data which could provide Integrated Services Digital Network (ISDN) capabilities. Also available are special 5 kHz, 7.5 kHz, 8 kHz, and 15 kHz program units which can transmit and receive audio broadcast signals.

5.1.2 DI systems, on a limited scale, can perform many of the same functions as digital cross-connect systems. In many ways, a DI system can also be considered to be analogous to a distributed subscriber carrier system.

5.1.3 Back-to-back channel banks have been used to drop and/or insert individual voice frequency channels from or into a DS1 bitstream as shown in Figure 17a. In this application, a channel bank demultiplexes all 24 channels of the DS1 bitstream and converts them from digital to analog. Then, another channel bank converts the channels back to digital and remultiplexes them. The disadvantages of this arrangement are the same as described previously (expensive, larger power consumption, transmission degradation, and larger size).

FIGURE 16 - RING CONFIGURATION - NORMAL



5.1.4 Figure 17b illustrates a DI system performing the same function. In this case, the DI system performs digital to analog conversion only on the dropped channels and analog to digital conversion on the inserted channels. Other channels pass through the DI system unchanged with a minor delay. This method is less costly and requires less power. In addition, there is no significant transmission degradation in the channels which pass through the system because there is no D/A and A/D conversions.

5.1.5 Based on the network requirements, DI systems can be arranged in several configurations, in a one-way or two-way system, and can be configured as a drop only or an insert only system. Figure 18 illustrates these various configurations.

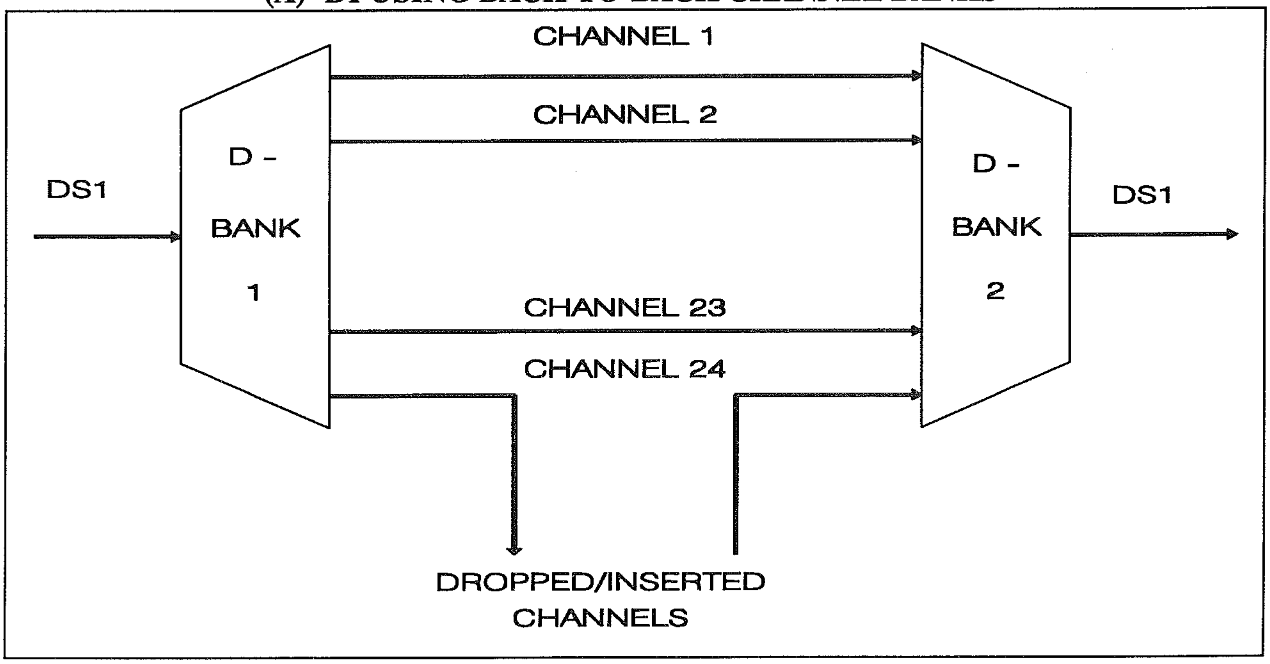
5.2 Drop & Insert System Applications

5.2.1 Dropping/Inserting Special Services - Individual DS0 channels can be inserted into and/or dropped from a DS1 bitstream. This allows the insertion (and removal) of special services circuits to or from a DS1 bitstream; for example, audio programs, data service, foreign exchange services, etc. Figure 19 shows this application. The DI can be used to bypass a digital switch. When a digital switch provides nailed-up connections, it uses valuable call processing time and resources to handle this traffic. As shown in Figure 19, a DI system can be used to bypass this nonswitched traffic around the digital switch. This allows the digital switch to be used for normal switched traffic.

5.2.2 Distributed Pair Gain System - A DI system can be utilized to drop/insert individual DS0 channels at various sites along a T1 route as shown in Figure 20.

FIGURE 17 - DROP & INSERT SYSTEMS

(A) DI USING BACK-TO-BACK CHANNEL BANKS



(B) DIGITAL DI SYSTEM

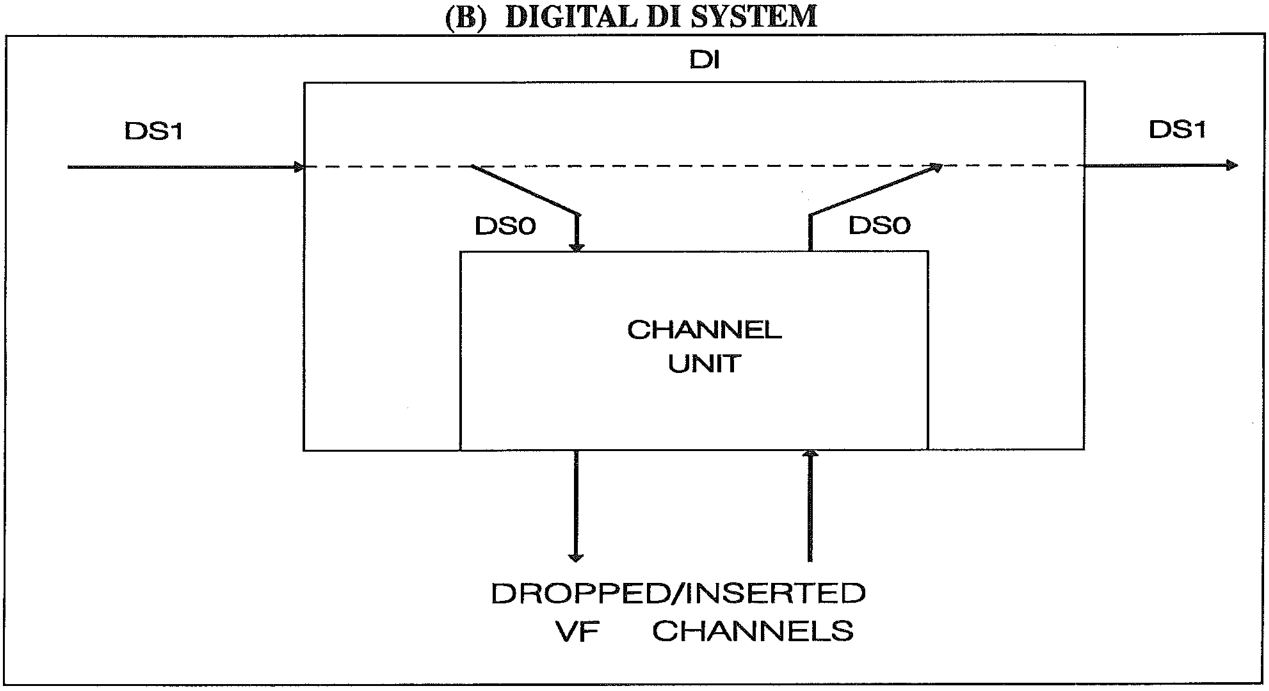


FIGURE 18 - DROP & INSERT CONFIGURATIONS

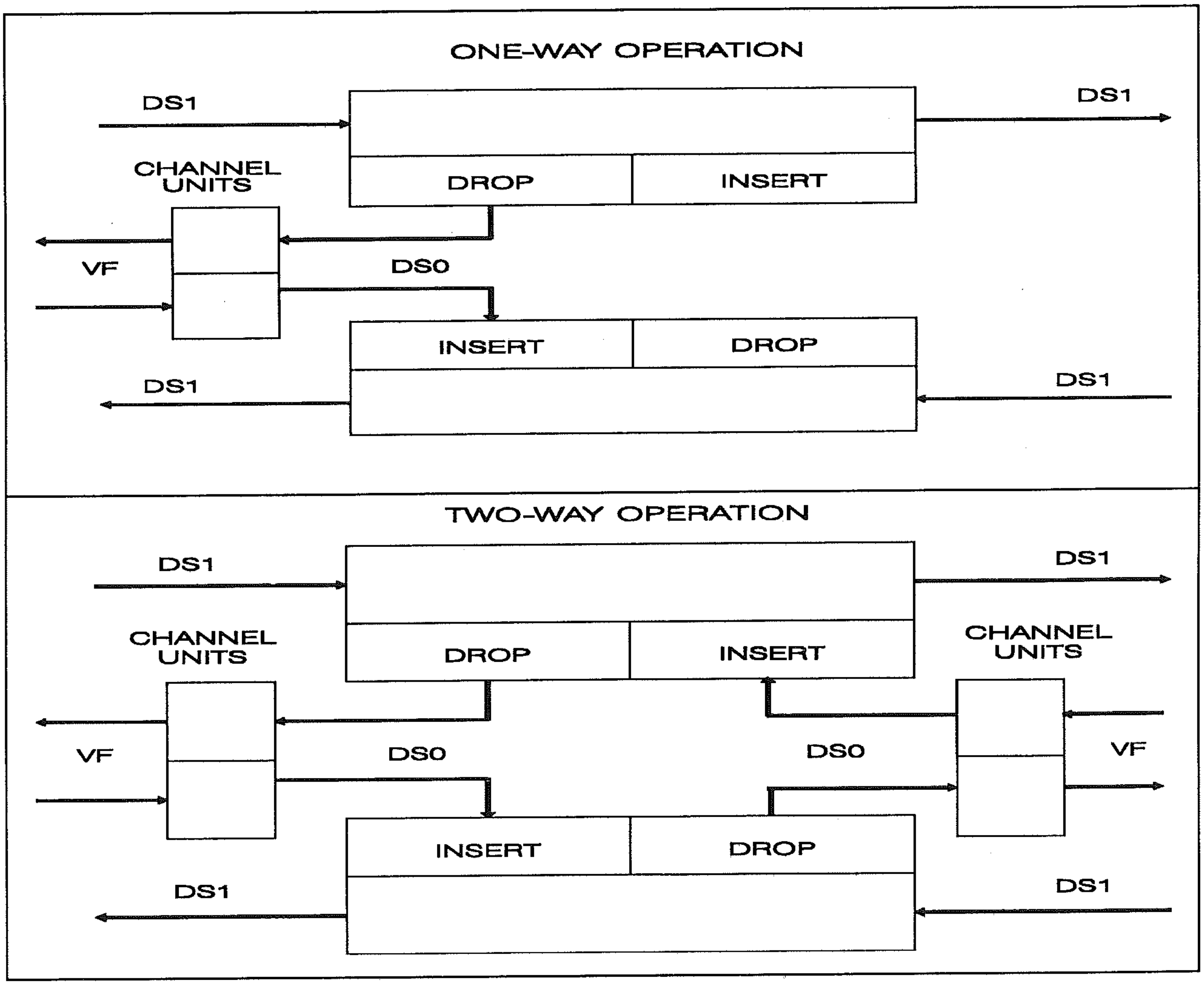


FIGURE 19
DI SPECIAL SERVICES AND DIGITAL SWITCH BYPASS

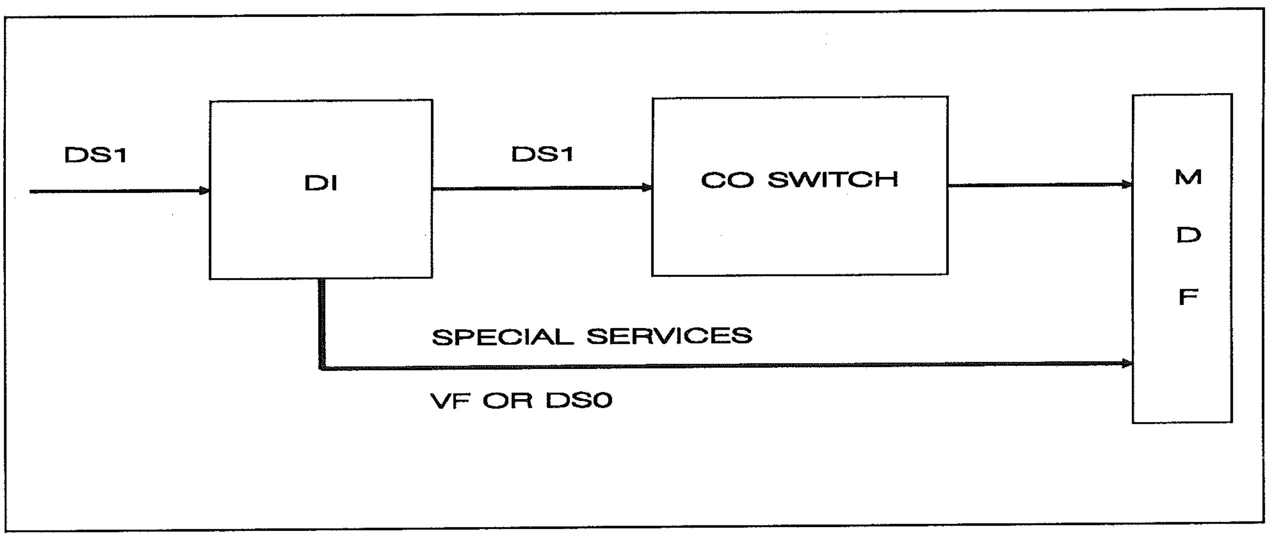
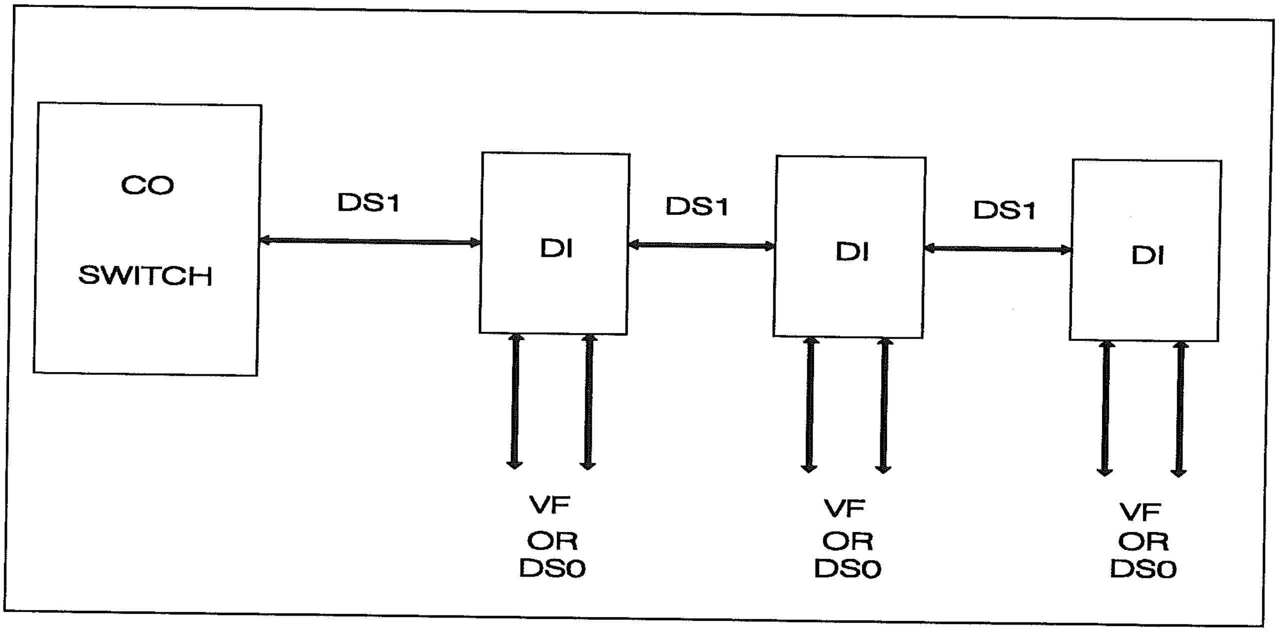
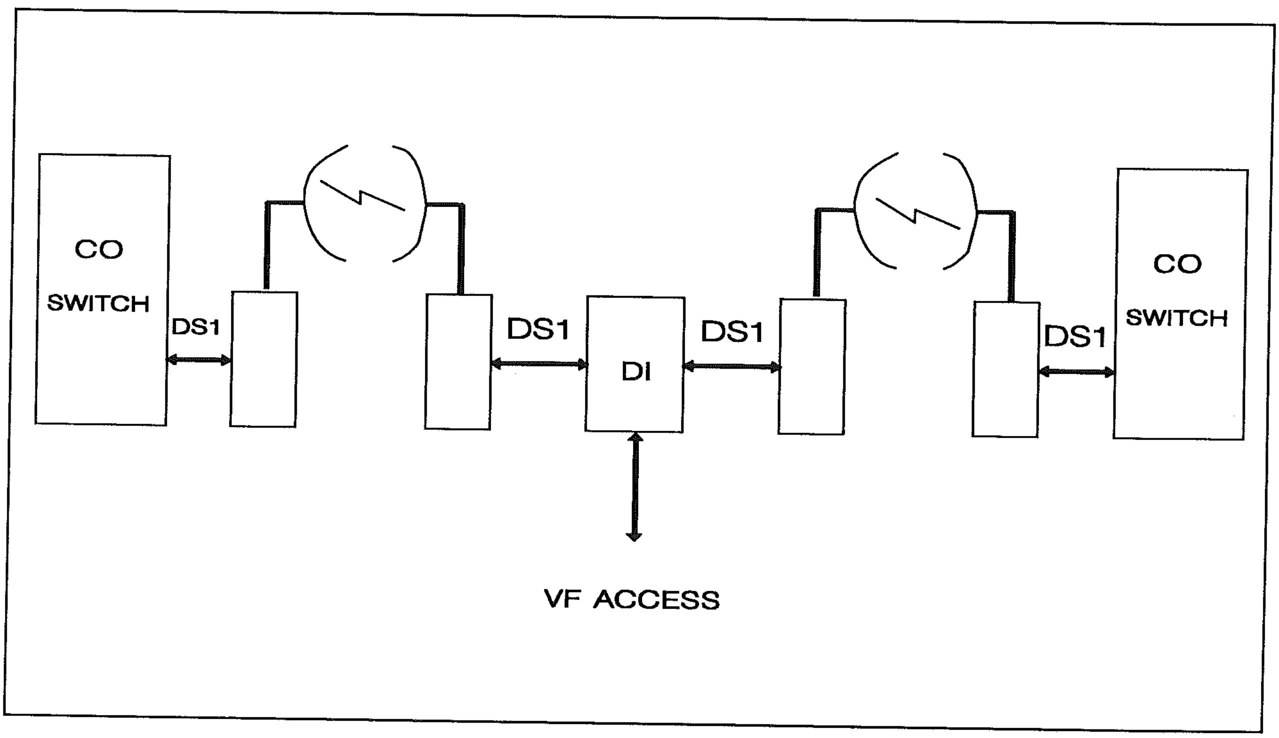


FIGURE 20 - DISTRIBUTED PAIR GAIN SYSTEM



5.2.3 Microwave Radio Access - As shown in Figure 21, a DI system can be used to provide voice frequency (VF) access to a digital microwave radio backbone without using back-to-back channel banks.

FIGURE 21 - MICROWAVE RADIO ACCESS



5.2.4 End Terminal Capability - DI systems can be used as stand-alone voice/data terminals (end terminals) providing the same function as standard D-channel banks.

5.2.5 Digital Tandeming - DI systems can tandem digital circuits through an analog office without D/A and A/D conversions, i.e., the systems do not require back-to-back channel banks.

5.2.6 Most DI systems provide alarm monitoring and transmit terminal-to-terminal alarms such as the "yellow alarm" through the DI sites without disrupting communications between two different DI sites. Some DI systems can also bypass through circuits in the event of DI equipment failure.

5.3 Design Examples

5.3.1 The following paragraphs describe several design examples using DCS and DI equipment to solve network problems.

5.3.2 Example 1 - Analog office A has three incoming T1 span lines each carrying a mixture of message and special services traffic. The message traffic is to be routed to office B and the special services traffic to office C.

5.3.2.1 Figure 22a illustrates this network arrangement. This method provides back-to-back channel banks. A separate channel bank (1, 2, and 3 in Figure 22a) connects each of the incoming T1 span lines. Channel banks 4 and 5 extend the message and special services traffic to offices B and C, respectively. D/A conversion and demultiplexing are performed by channel banks 1, 2, and 3. A physical cross-connect frame connects all VF channels carrying message traffic to channel bank 4. A similar arrangement connects special services VF channels to channel bank 5. Channel banks 4 and 5 then convert the analog traffic to digital and multiplex the DS0 channels into the outgoing DS1 bitstreams.

5.3.2.2 Figure 22b shows an alternative method. This method uses a DCS to separate the message and special services traffic received on the incoming T1 span lines and connect the traffic to the appropriate outgoing T1 span lines. This method requires no D/A or A/D conversions.

5.3.2.3 Although channel banks are less expensive than DCS, five channel banks are required for the method shown in Figure 22a. However, the DCS method is more economical because less power and space is required, and better transmission quality is provided.

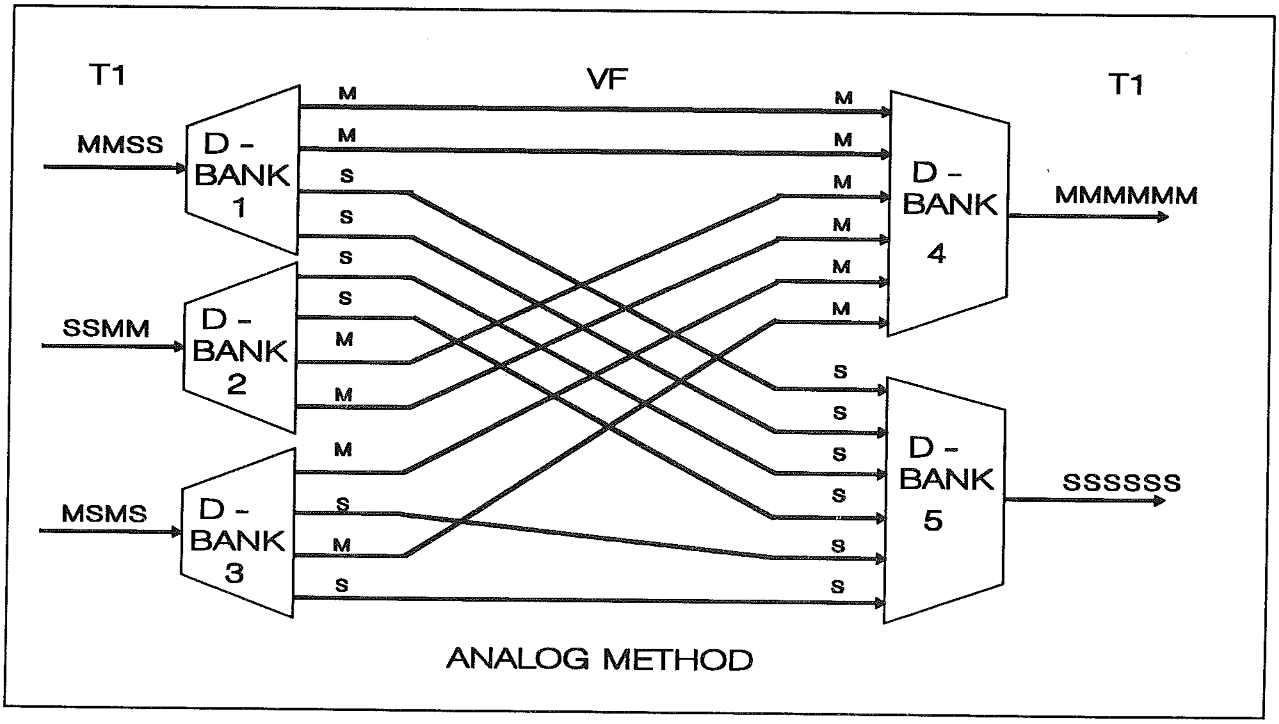
5.3.3 Example 2 - Analog office A has an incoming T1 span line with a single channel to be dropped at office A. The remaining channels are extended to office B and a VF channel is inserted into the DS1 bitstream at office A.

5.3.3.1 Referring back to Figure 17a, two back-to-back channel banks could be used. Channel bank 1 converts the DS1 bitstream into individual analog VF channels. Channel bank 2 performs A/D conversion on the VF channels that extend to office B. Channel bank 1 connects the VF channel to be dropped at office A to its required termination.

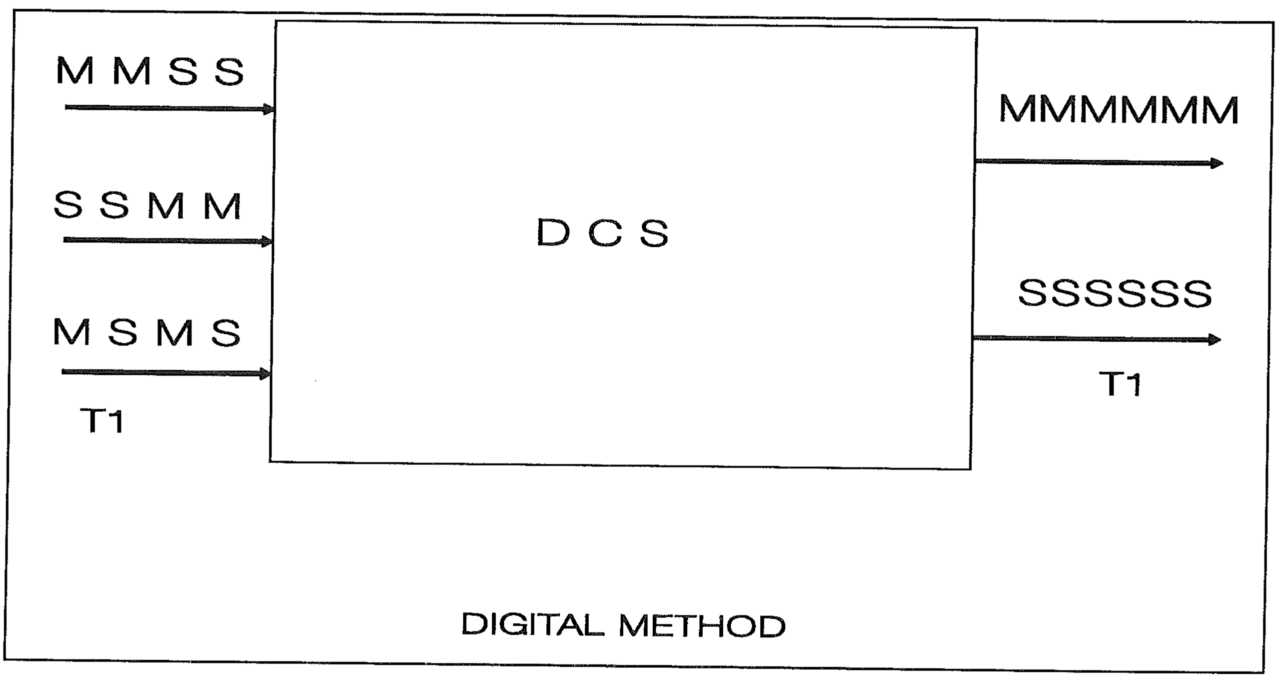
5.3.3.2 In Figure 17b, a DI system is used to provide the required network functions. The DS0 channels are extended to office B requiring no D/A or A/D conversions. The DI system demultiplexes the DS0 channel dropped from the incoming DS1 bitstream in office A and performs D/A conversion. The DI system also performs A/D conversion on the VF channel inserted at office A and multiplexes it into the outgoing DS1 bitstream.

FIGURE 22 - DCS DESIGN EXAMPLE

(A) - ANALOG METHOD



(B) - DIGITAL METHOD



5.3.3.3 As shown, the DI system is more economical than the back-to-back channel bank design. Generally speaking, channel banks are more expensive than a typical DI system.

CHAPTER II: DIGITAL SPAN LINES

1. INTRODUCTION

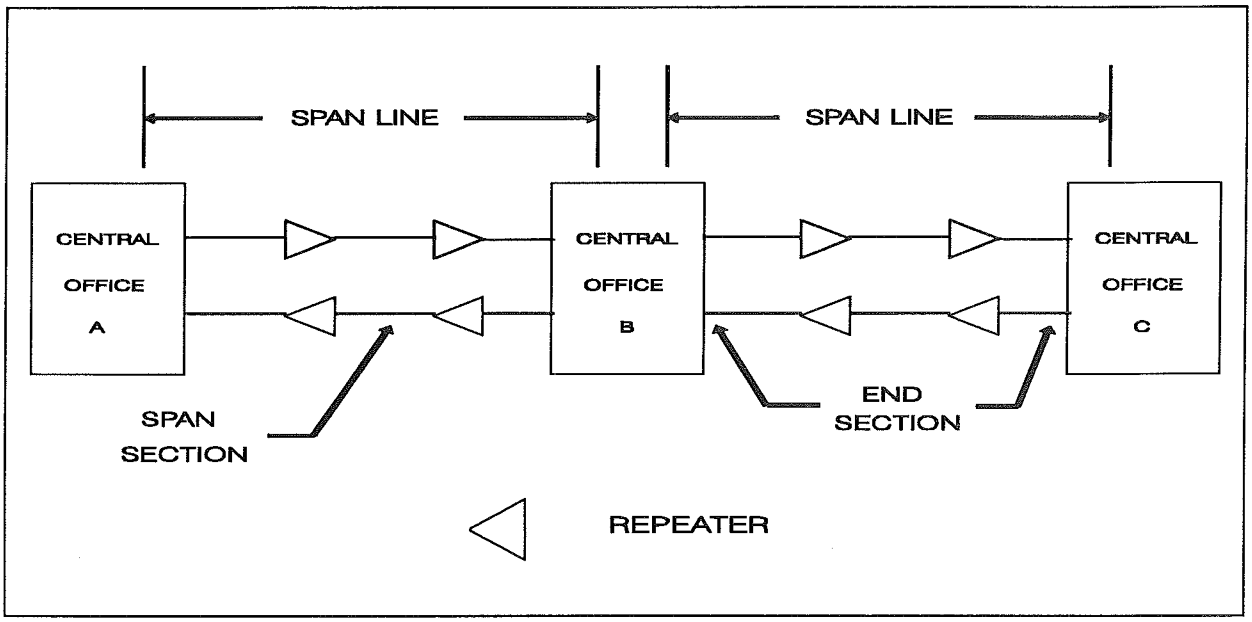
1.1 This chapter discusses T1 span line systems, which are digital transmission systems operating over metallic, paired-wire cable plant. The discussion includes an overview of the basic components of span line systems and their general operation, in addition to the system design and engineering principles. Example problems and figures are included. Appendix A presents the results of an analysis for improved bit error rates on span line systems. This information is advisory.

1.2 This chapter assumes the reader has a general familiarity with basic telephony and digital transmission. For tutorial information on the general topic of digital transmission, the reader is advised to consult REA Bulletin 1751H-403, Fundamentals of Digital Transmission. REA Bulletin 1751H-403 also contains a glossary and a brief history of digital transmission systems.

2. OVERVIEW OF DIGITAL SPAN LINES

2.1 Figure 1 illustrates a T1 span line system consisting of the central office (CO) equipment, associated cable and repeaters. The term span line refers to the facilities connecting two terminating points, such as between two COs. The span line system includes the CO equipment, line repeaters, cable facilities and other terminating equipment. A span section is the facility between two repeaters. The span section nearest to the terminal equipment (located at either a CO, field or subscriber site) is known as an end section.

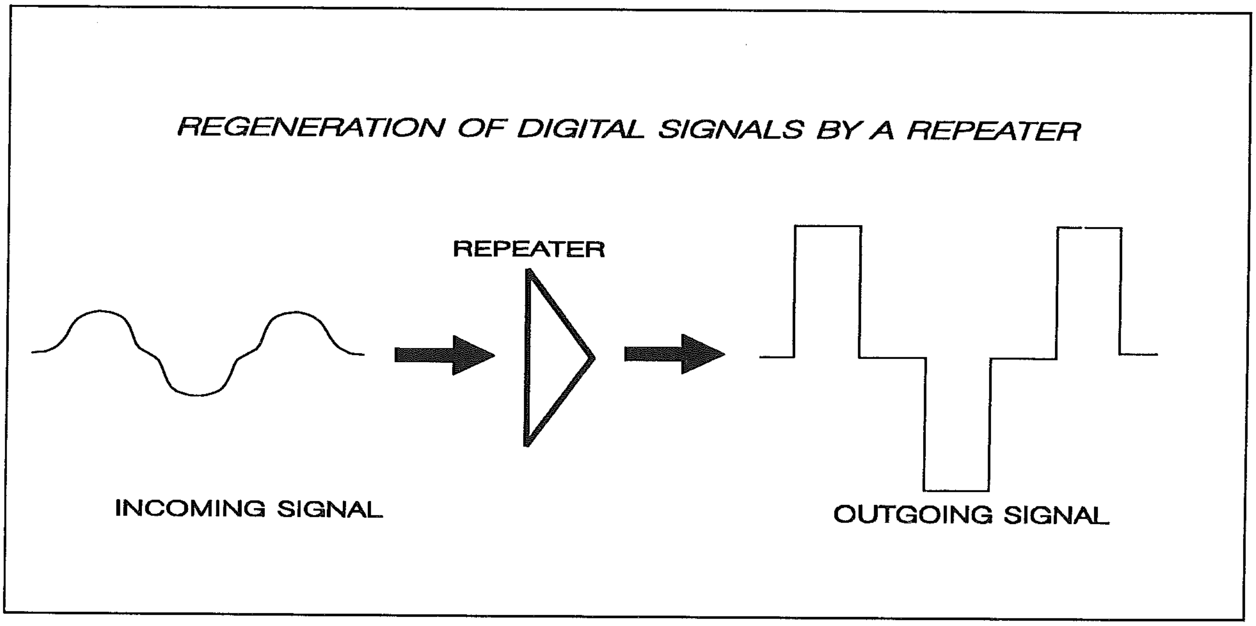
FIGURE 1 - CONFIGURATION OF A T1 SPAN LINE



2.2 A digital connection that allows two-way conversations requires two pairs of wires. Each pair of wire carries a DS1 signal that contains 24 multiplexed voice channels. Additional pairs are used by maintenance personnel for fault location and a talk path, or order wire. Frequently, a spare span line is provided for backup to increase reliability to the network.

2.3 The line repeater is essential to the operation of a span line system. Without repeaters, the digital signal can propagate about 1.6 kilometers before attenuation begins to diminish the clarity of the signal. Analog voice frequency (VF) repeaters amplify the signal along with accumulated noise. However, as Figure 2 shows, a digital repeater actually interprets the deteriorated, yet readable, incoming digital signal and regenerates the original digital signal. It is the regeneration of the original signal as opposed to the amplification of the attenuated signal that minimizes noise in digital signal transmission, making it superior to analog systems. Line repeaters are placed in moisture-resistant housings containing 1 to 24 systems. The housings can be located on poles, stakes or in manholes.

FIGURE 2 - SPAN LINE REPEATER FUNCTION



2.4 At the CO, a T1 span line system may terminate with a switching system in several ways: 1) with a direct DS1 termination on the digital switch; 2) with a channel bank that provides an analog interface to the switch; or 3) with a central office terminal (COT) that terminates a remote digital loop carrier or concentrator system and provides an analog interface to the switch. Among other applications, a span line can connect digital microwave radio multiplexers, subscriber terminal equipment, digital cross-connect systems or other digital terminal equipment.

2.5 Figure 3 shows the CO portion of a T1 span line containing additional components integral to the reliable operation of a digital transmission system. This system is suitable for termination on an analog or digital switch. The component on the far left is a channel bank which converts analog signals into digital signals, and vice versa. Most digital switches accept a DS1 level digital signal, eliminating the need for channel banks. Non-switched special service circuits will, in many cases, require the use of channel banks.

2.6 Next in the span line system is a digital signal cross-connect at the DS1 rate, or DSX-1. Digital signals at this interconnection point are standardized[1] according to pulse height, width and slope. The standardization permits the digital interconnection of different

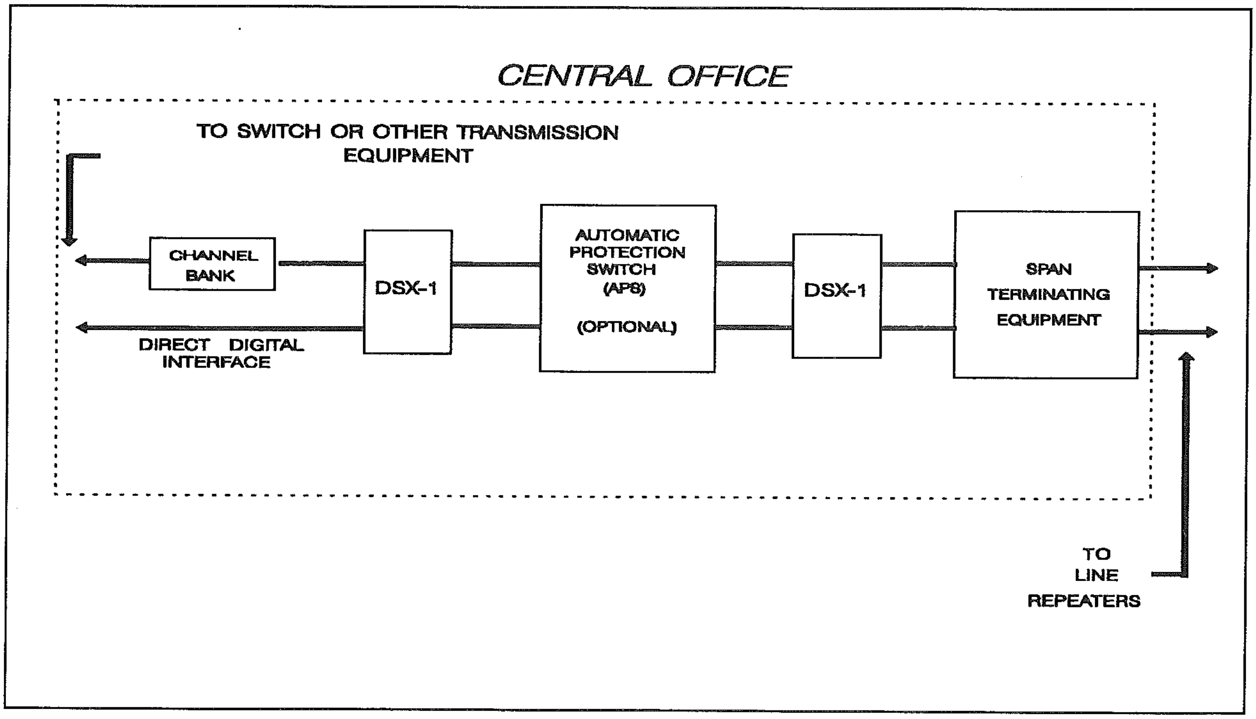
---

[1] ANSI Telecommunications Standard T.102-1987, Digital Hierarchy - Electrical Interfaces.

equipment types operating at the DS1 rate. The DSX-1 interconnection facilitates the testing, access and mixing of certain types of traffic.

2.7 Typically, the DSX-1 is followed by an automatic protection switch, or APS, and a second DSX-1. Though not essential for span line operation, the APS increases the reliability of the system. The APS monitors each span line and switches the traffic to an active spare span line in the event of a failure or excessive errors. An APS system is usually installed on important interoffice toll facilities or for loop facilities serving hospitals, police stations or critical data centers. The span line terminating equipment, at the far right of Figure 3, includes office repeaters and line powering components.

FIGURE 3 - CENTRAL OFFICE SPAN LINE EQUIPMENT



2.8 Because digital span lines regenerate (rather than amplify) attenuated signals, they can operate at zero loss. This means that both input and output levels to the span line equipment are always the same, thereby facilitating terminal equipment interconnection at the DS1 rate.

2.9 Span line systems are also designed to operate within specific parameters for control of bit errors. In all digital systems bits are occasionally lost or misinterpreted due either to noise, interference or equipment malfunction. For span lines the spacing between repeaters is a significant factor affecting the accuracy of the end-to-end signals. The digital pulses can be improperly read by repeaters and terminal equipment, if allowed to become sufficiently attenuated and distorted from the paired-wire transmission without regeneration. Consequently, field repeater spacings are engineered to strike a balance between transmission accuracy and minimizing the number of repeaters used on a given route.

2.10 The design or engineering standard commonly used in the industry today is a maximum end-to-end bit error rate (or BER) of 1×10^{-6}. This means that, at worst, one bit out of 1 million bits transmitted can be in error under normal operating conditions. Although most span lines are engineered to this criterion, many operate at lower error rates because of conservative assumptions used in the formulae for repeater spacings. Appendix A, Considerations for Improved Span Line Bit Error Rates, provides additional information on span line error rates.

3. COMPONENTS OF A SPAN LINE SYSTEM

3.1 Introduction

3.1.1 In this section each element of the span line system is described in detail, including the span terminating equipment and repeaters. Table 1 lists and describes the terminating equipment. Higher capacity systems, crosstalk and cable considerations are also discussed.

TABLE 1 - SPAN LINE TERMINATING EQUIPMENT

Office Repeater	Essentially one-half of a line repeater, performs regeneration of the received signals. Also known as a terminating repeater.
Power Converter	Provides a DC-to-DC power conversion from the CO 48 VDC to supply both $\pm$48 VDC and $\pm$130 VDC which are, in turn, used in various combinations to produce a line-powered supply ranging from 48 VDC to 260 VDC, depending on the power requirements of the span. Sometimes combined with an office or terminating repeater and termed a powering repeater.
Orderwire	Provides a communication circuit for maintenance purposes between the span terminating equipment and field repeater housing.
Interrogation Fault Location	Diagnoses repeater failures or open line sections by transmitting multiple VF tones which are looped-back from line repeaters based on frequency-selective filters.
Automatic Protection Switching	Equipment that automatically switches both ends of a working span line to a spare or protection span line whenever a failure or other fault occurs on the working line.

3.2 Office & Field Repeaters

3.2.1 Both the office and field repeaters examine the incoming digital bitstream at regular intervals for ones and zeroes. A new pulse is generated in the same time position as in the incoming pulse. For sampling the incoming signals, the repeater contains an accurate clock that derives its timing from the incoming "one" pulses of the digital signal. To maintain proper timing, restrictions are placed on the maximum number of continuous zeroes in digital signals.

3.2.2 Repeaters contain DS1 signal regenerators that are contained on a single integrated circuit. They are designed to accept a signal that has undergone attenuation up to 35 dB. When the attenuation is less, additional loss is inserted by an automatic line build-out (ALBO) network that models the loss characteristic of the cables. This, coupled with the repeater's gain and equalization capabilities, permits operation with a cable loss ranging from approximately 7.5 dB to 35 dB. A repeater also contains several types of electrical protective devices. These include multi-stage protection with low and high voltage shunts; and series limiting resistors to protect equipment from AC induction, lightning surges and other electrical transients.

3.3 Power Converters

3.3.1 The power converter supplies the line repeaters with a constant current DC voltage applied across two separate cable pairs. Both cable pairs, to transmit and to receive, are connected in parallel. The two pairs are looped together at the far end to form a continuous circuit. With the tips and rings connected in parallel, the resistance in the DC power path is lowered. This is known as simplex powering. Span lines of various lengths and containing a varying number of repeaters can be served since a variety of voltages are available from the power converter.

3.3.2 Span power is regulated through the use of a constant current regulator in the power converter. At the line repeater, the simplex loop current passes through a zener diode; this results in a fixed voltage to power the repeater's electronic circuits. Power test points are available at the power converter so that the actual power loop voltage and any induced voltage from AC sources may be measured by operating personnel.

3.4 Electrical Protection

3.4.1 Electrical protection of span line equipment is essential to maintain reliable operation from exposure to external influences such as electrical transients, lightning, AC power induction and AC power cross (contact with AC power lines). Most field repeaters contain multistage protection consisting of high energy surge protection devices (such as gas tubes), in-line series current limiting resistors and low voltage shunt solid state protective devices.

3.4.2 For additional information on electrical protection of line equipment and surge protection devices refer to REA Bulletin 345-83, REA Specification for Gas Tube Surge Arresters and REA Bulletin 345-78, REA Specification for Carbon Arrestor Assemblies for Use in Station Carrier Protectors.

3.5 Interrogation

3.5.1 The capability to remotely isolate repeater problems or other failures on a span line system from the terminating sites is important from a cost/maintenance and customer service perspective. This testing uses a repeater test set (containing both a pulse generator and a frequency selective receiver) at one end of the span line and fault locating interrogation filters in the line repeaters along the span line. The testing can only be performed with the facility out-of-service.

3.5.2 The test set transmits what resembles a 1.5 Mb/s digital signal. However, these patterns represent 12 different audio tones (denoted A to M). Each repeater passes the digital signal to the next repeater. However, a portion of the signal, after passing through the fault interrogation filter, is returned to the test site on the fault location pair. The filter removes the high frequency 1.5 Mb/s components and extracts one of the twelve audio frequencies (based on its particular filter characteristics) for retransmission back to the test site.

3.5.3 If a repeater is: 1) out-of-service, 2) operating improperly and causing excessive errors, or 3) not receiving input signals because the preceding cable section is faulty, its characteristic tone is not returned, or is returned at significantly lower levels, to the test site. Because each repeater's fault locating filter is tuned to a unique frequency, the frequency returned on the fault location pair can be used to determine the last working repeater on the line from the test site. Hence, through the process of elimination, this process can determine any faulty repeaters or faulty cable sections.

3.5.4 Fault locating filters can be either active or passive. While passive filters offer lower cost, the active versions double the number of repeaters that can be tested on a single fault location pair. One-half of the active filters are served by one polarity of supply voltage; the other half by the opposite polarity. Thus, 12 repeaters can be tested by enabling the active filters with one polarity of the supply voltage; and the other 12 repeaters can be tested by reversing that polarity and enabling a different set of 12 active filters. This allows for testing longer span lines with up to 24 repeaters, or for testing each direction of a 12-repeater two-way span from one end.

3.5.5 Using a repeater test set and fault locating interrogation filters adequately maintained long span lines. However, shorter loops and delivery of data services required a more cost effective and reliable means of detecting and localizing faults on the line. This type of testing detected physical or continuity problems on the span line but was unable to detect electronic problems.

3.5.6 Recently developed span line repeaters with in-band loop-back capability[4] can detect both physical and electronic faults. A more sophisticated means of troubleshooting, this method provides a more timely, economical and reliable means of detecting faults. However, the lack of industry standards will leave the door open to network compatibility concerns.

3.6 Automatic Protection Switching

3.6.1 Automatic Protection Switching (APS) is used to replace an inoperable span line with a spare or protection span line. Although generally considered optional, APS can ensure that repeater failures, minor cable problems, and external noise or interference do not completely interrupt important circuits. APS equipment has to be located at both ends of a span line.

3.6.2 APS units protect on a 1:N basis. This means that one spare span line can be switched to protect N working lines, where N can be a single system or up to 48 systems. In other words, considerable flexibility exists, depending upon the vendor's product characteristics, as to how many lines can be protected with APS. Some systems require 100% redundancy and therefore use 1:1 protection for critical or emergency applications. Frequently, 1:5, 1:7, 1:12 or 1:24 protected APS systems offer adequate protection.

3.6.3 Figure 4 shows a 1:3 protected APS system serving three terminal locations all connected with three working span lines and one spare protection line. The top illustration shows the facilities in a normal working status. The middle illustration depicts a fault (either a repeater or partial cable failure) occurring on one of the span lines. As shown in the lower illustration, this is followed by the spare protection line switched into service and the faulty line taken out of service. The detection of a faulty span line and the switch to the protection span line can take place in approximately 5 milliseconds.

3.6.4 For APS systems with less than 1:1 protection, a priority switching scheme is available. Here, circuits are provided with spares based on their importance to the network, as determined by the network operator. A lower priority line is protected by the spare span only if a higher priority line is not already out of service at that time. If a higher priority line fails while the spare line is switched to a lower priority line, the APS will drop the lower priority line in order to serve the higher priority one.

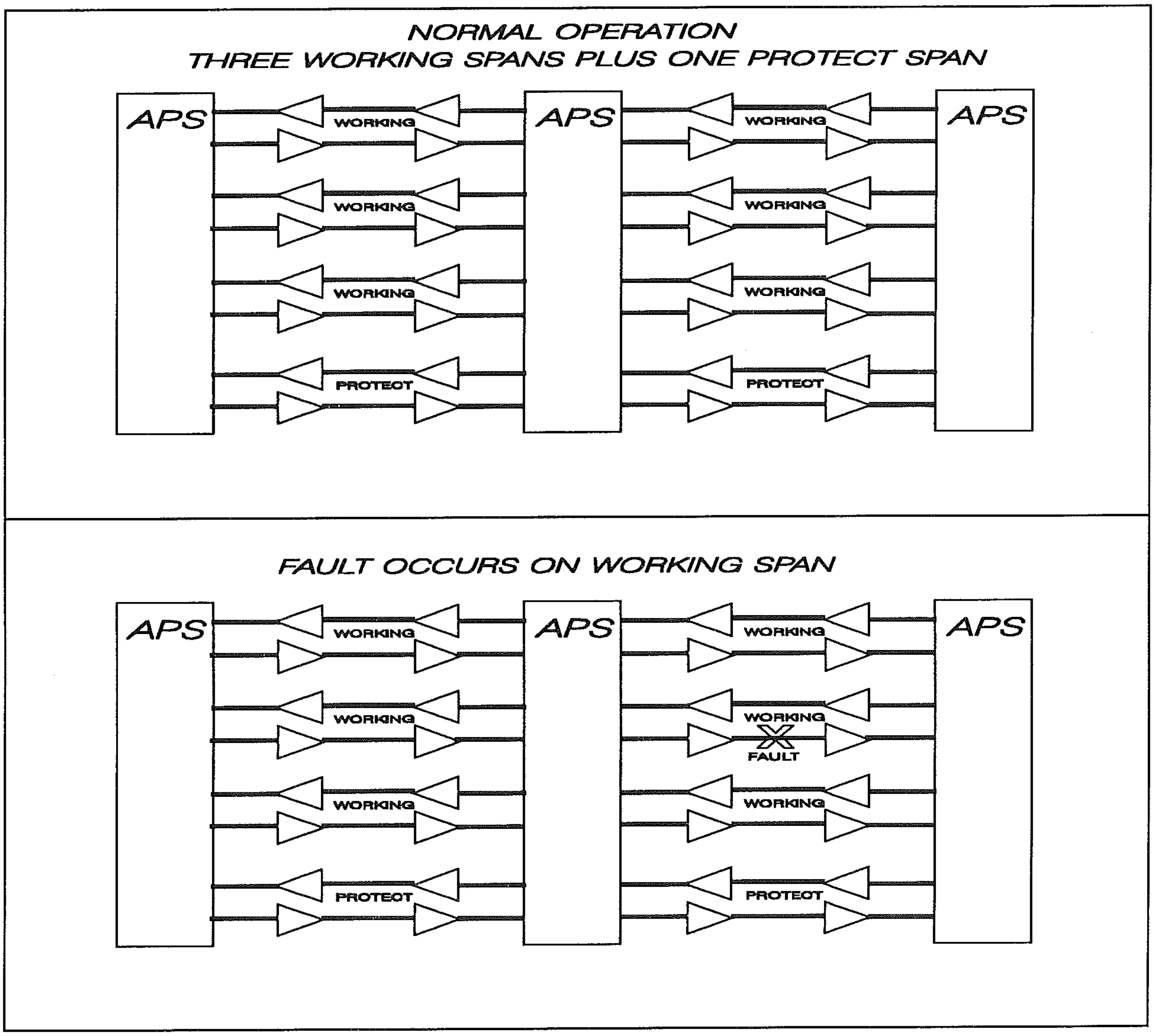
---

[4] United States Telephone Association (USTA) Technical Information Document TID No. 92-005, DS-1 Repeaters With Loop-Back Considerations.

3.6.5 APS equipment continuously monitors the performance of the span lines. If the failed line should return to service with an acceptable level of performance, the APS will reset and return it to active status. Acceptable performance is determined by an APS monitoring DS1 signal characteristics such as number of bipolar violations, pulse density and bit error rate (BER).

3.6.6 Even though an APS can switch to spare span whenever a fault occurs, the reliability of the system is dependent upon the cable facility. A complete cable cut would interrupt the working and the spare spans. As a result, reliability using an APS with spare span lines improves but is not maximized. Only through use of physically separate cable routes (route diversity or ring configuration) for working and protection span lines would the highest level of reliability be possible.

FIGURE 4 - AUTOMATIC PROTECTION SWITCHING OPERATION



3.8.6 Two types of crosstalk can arise in span line systems: near-end crosstalk (NEXT) and far-end crosstalk (FEXT). NEXT is the crosstalk that occurs between two systems operating in opposite directions where the interfering signal is induced at the near end, or at the source. The strong signal output from a line repeater that couples onto a different cable pair carrying an attenuated and weak input signal in the opposite direction is an example of NEXT. To minimize NEXT, it is desirable to maximize the physical distance between high and low level signals within a cable.

3.8.7 The other type of crosstalk coupling, FEXT, occurs between two transmission systems operating in the same direction. The crosstalk couples from one system with a weak signal at the distant end to another system with a weak signal at the distant end. In digital span lines, NEXT is the type of crosstalk of most concern. FEXT can largely be ignored for span line systems. Figure 5 shows both NEXT and FEXT in a span line system and depicts how NEXT, compared to FEXT, is more likely to produce an interfering signal because of the wide disparities in signal strengths.

3.9 Cable Considerations

3.9.1 As discussed previously, cable construction is of significant interest in engineering digital span line systems because of its effect on attenuation (or design loss, L_d) and crosstalk coupling loss (specifically, NEXT). Because cable construction affects both of these electrical parameters, it is important to have a rudimentary understanding of basic cable design.

3.9.2 With the exception of small-sized cables (25-pair and less), paired cables for telecommunications uses are generally grouped with collections of pairs within the cable sheath. These groupings, often referred to as binder groups, serve several functions. Binder groups facilitate the cable's construction, the identification and organization of specific cable pairs, and splicing and terminating activities.

3.9.3 Binder groups also serve to minimize crosstalk coupling. For example, the crosstalk coupling between two pairs within the same binder group is significantly greater than the crosstalk coupling between two pairs that are located within separate binder groups. A cross section of a conventional cable design is shown in Figure 6. Here, the physical positions of the binder groups and the overall cable geometry can be seen. Adjacent, non-adjacent and opposite group locations are shown. Clearly, the physical distances separating the different binder groups vary. The physical spacing affects the NEXT characteristics, with the opposite binder group affording the best crosstalk isolation or greatest NEXT loss. Adjacent groups afford the worst crosstalk isolation or the lowest NEXT loss. Nonadjacent groups offer better crosstalk isolation than adjacent groups but less than opposite groups.

3.9.4 Manufacturers differ in cable design by how pairs are wrapped and twisted together. This characteristic also affects the crosstalk coupling loss. Cable pairs that are in close proximity have different twist lengths to minimize the coupling effect and maximize the crosstalk loss.

3.9.5 When considering NEXT and maximizing repeater spacings, a small number of the cable pairs should be used. Crosstalk can be minimized by maximizing the distance between the transmit and receive pairs. These pairs should not be located within the same binder group. At a minimum, they should be placed in adjacent binder groups. To provide some indication how cable geometry may vary for different cable sizes, four variations are shown in Figure 7.

FIGURE 6 - BASIC CABLE GEOMETRY

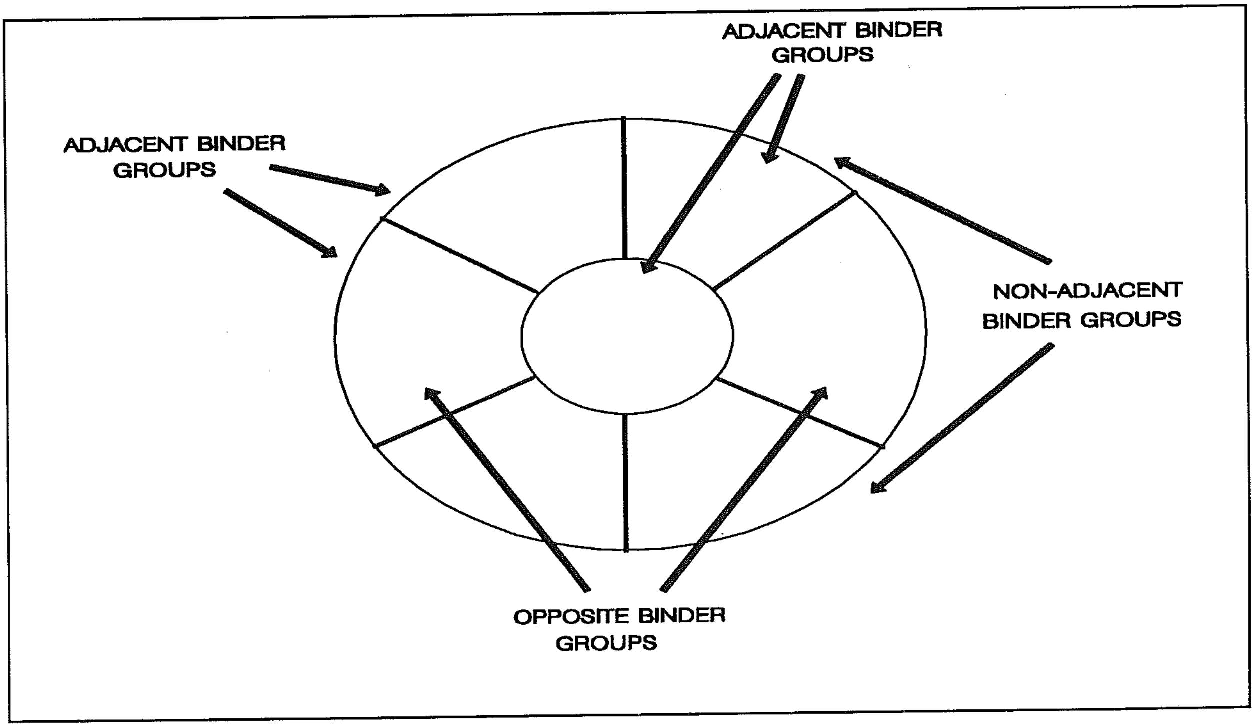
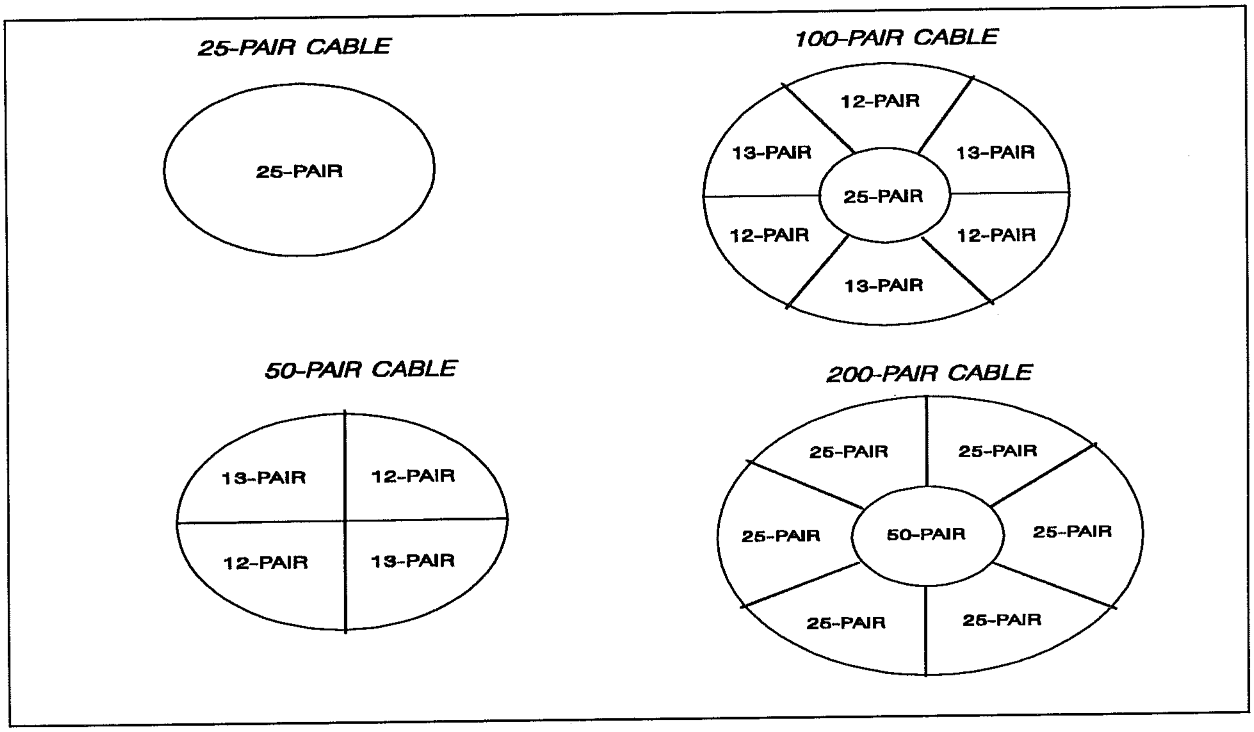


FIGURE 7 - CROSS SECTIONS OF TYPICAL CABLE CONSTRUCTION



3.9.6 Cable manufacturers continued to improve cable designs as digital span lines were increasingly used. One important improvement was to introduce of metallic screens within the cable to separate binder groups. Consequently, the electromagnetic coupling between cable pairs was decreased. With reduced crosstalk coupling, span line systems were able to operate at maximum repeater spacings within a single cable having NEXT isolation comparable to two separate cables. Moreover, screened cables permit 100% cable utilization for span line applications irrespective of pair location, as long as the transmit and receive pairs are on opposite sides of the screen. Figure 8 shows two types of screened cables.

4. SPAN LINE ENGINEERING

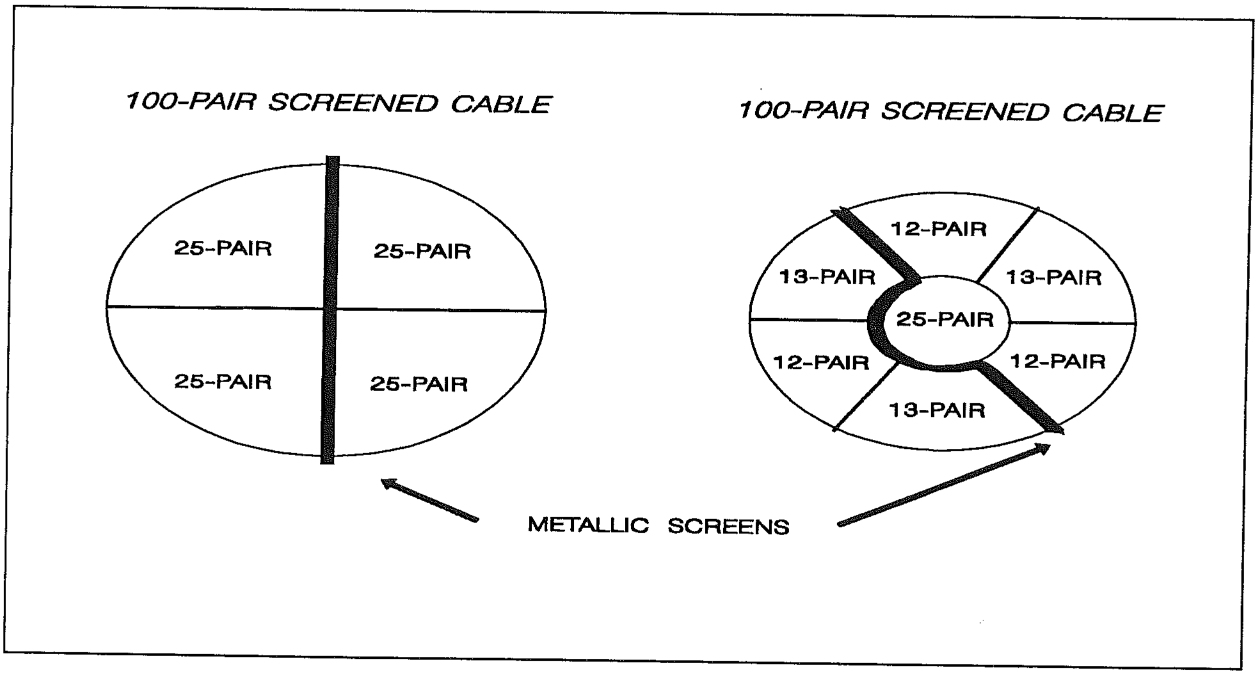
4.1 Introduction

4.1.1 This section will provide information on the principal areas of digital span line design including repeater spacing and line powering. Sample calculations are presented to illustrate the various design techniques. These calculations use values representative of typical equipment. However, the reader is advised to use data, where available, specific to the equipment that is under consideration.

4.2 Repeater Spacing for Conventional One & Two Screened Cable Systems

4.2.1 Techniques for calculating maximum repeater spacings for two-cable systems are presented first in this discussion because of their inherent simplicity when compared to one-cable systems. A two-cable system uses a screened cable for the bi-directional transmission placing them on opposite sides of a metallic shield. NEXT considerations can be largely ignored when span lines for each direction of transmission are placed in either separate cables or separated by a metallic shield within the same cable. NEXT is the limiting factor in one-cable designs. One-cable designs are covered in detail in Section 4.3.

FIGURE 8 - CROSS SECTIONS OF SCREENED CABLES



4.2.2 NEXT is generally not a factor for two-cable systems. However, the DS1 signal attenuation, or the 772 kHz loss, between repeaters is a limiting factor . This loss affects the repeater spacing for each span line *section*. When considering the 772 kHz loss, maintain a minimum S/N ratio. Excessive attenuation of the DS1 signal before it reaches a repeater location will lead to an erroneous interpretation of incoming signals, causing bit errors.

4.2.3 In the late 1950s and early 1960s, researchers at the Bell Telephone Laboratories developed recommendations for engineering T1 span lines.[7] These recommendations are still used. Part of their work resulted in a maximum design loss (L_d) for span line cable sections. L_d has a nominal value of 32 dB at a temperature of 13 degrees Celsius and is based on the average of all the pairs within a cable. This value of L_d was determined from a variety of factors including the probabilities of noise distribution along the cable path, adequate margins for variations in both cable attenuation and repeater gain, and the minimum bit error rates (BERs) needed for acceptable voice transmission. Table 2 summarizes the three most common values of L_d and defines their values.

4.2.5 Cables frequently experience ambient temperatures greater than 13 degrees Celsius. Therefore, L_d should be adjusted according to the appropriate maximum expected temperature. In the United States, 38 degrees Celsius typically is used as a maximum ambient temperature for buried cable while 60 degrees Celsius is used for aerial cable. Minimum temperature conditions are not considered because cable attenuation decreases with lower temperatures.

TABLE 2 - MAXIMUM SECTION LOSS VALUES (L_d)

L_d Value	Description
35 dB	Maximum allowable section loss of any single cable pair based upon the highest expected operating temperature.
33.5 dB	Maximum allowable section loss based on the average of all cable pairs at the highest expected operating temperature. Allows for a 1.5 dB margin for the worst cable pairs.
32 dB	Maximum allowable section loss based on the average of all buried cable pairs in a cable section at a nominal operating temperature of 13 degrees Celsius . The aerial equivalent is approximately 31 dB.

4.2.6 Design loss at temperatures other than 13 degrees Celsius is calculated using Equation 1. A temperature adjustment factor, f_T, is used in Equation 1 to calculate a temperature-specific design or maximum section loss at these temperatures. The f_T factor varies with the specific cable gauge and type. Table 3 lists f_T factors for commonly used aerial and buried cables.

---

[7] H. Cravis and T. V. Crater, "Engineering of T1 Carrier Repeatered Lines," Bell System Technical Journal, March 1963.

$$L_d@T \text{ degrees Celsius} = \frac{L_d@13 \text{ degrees Celsius}}{f_T} \qquad (1)$$

4.2.7 To determine the maximum spacing between repeaters, one begins with a nominal maximum L_d of 32 dB, at 13 degrees Celsius. An adjustment is made using Equation 1 and the temperature adjustment factors (f_T) in Table 3 to calculate L_d at the desired temperature. Then the adjusted L_d is divided by the cable engineering loss (in dB/km from manufacturer's data), as in Equation 2, to determine the maximum section length, L, between repeaters.

$$L = \frac{L_d}{\text{Engineering Loss}} \qquad (2)$$

4.2.8 As an example, for a filled, solid insulation 24-gauge buried cable, the f_T factor from Table 3 is 1.043. L_d at 60 degrees Celsius then equals:

$$L_d \text{ @ 60 degrees Celsius} = 32 \text{ dB} / 1.043 = 30.68 \text{ dB}.$$

The engineering loss per km for this cable from manufacturer's data is 16.4 dB/km. The maximum section length, L, is then:

$$L = 30.68 \text{ dB} / (16.4 \text{ dB/km}) = 1.87 \text{ km}$$

TABLE 3 - CABLE LOSS TEMPERATURE ADJUSTMENT FACTORS (f_T)

@ 38 degrees Celsius/100 degrees Fahrenheit (BURIED)				
Cable Type	19 Gauge	22 Gauge	24 Gauge	26 Gauge
Filled, Solid Insulation	1.031	1.044	1.043	1.046
Filled, Expanded Insulation	1.038	1.041	1.043	1.044
Aircore	1.046	1.044	1.043	1.042
@ 60 degrees Celsius/140 degrees Fahrenheit (AERIAL)				
Cable Type	19 Gauge	22 Gauge	24 Gauge	26 Gauge
Filled, Solid Insulation	1.059	1.072	1.082	1.088
Filled, Expanded Insulation	1.083	1.077	1.080	1.088
Aircore	1.088	1.083	1.080	1.083

4.2.9 This distance is the maximum spacing for all repeaters *except* those used on the end sections of a two-cable or a one-cable screened span line. End sections, or the cable sections adjacent to the central office end of the span line, are treated differently. See Section 4.4.

4.2.10 If mixed cable types are used, this calculation has to be performed for each type to determine the resulting maximum section length. Additional loss results from a section containing a splice from two different cable types. For each junction in a mixed cable section, *subtract* 0.25 dB from L_d to account for this loss.

4.3 Repeater Spacing for One-Cable Systems

4.3.1 With the exception of screened cables, NEXT causes one-cable and two-cable systems to be treated differently. When considering cable size, binder group position, the number of operating span line systems and cable-specific NEXT characteristics, more complex calculations are necessary. This section will cover this process.

4.3.2 In addition to the research performed by the Bell Laboratories discussed earlier for two-cable systems, Bell also devised techniques for engineering one-cable systems. These methods are still used. They are discussed in further detail in the Bell Laboratories technical reference given earlier.

4.3.3 The maximum section loss is a key factor when considering the section spacing for one-cable and two-cable systems. Two-cable systems consider the cable's attenuation, L_d, while one-cable systems must calculate several plant-specific characteristics. The maximum section loss for a one-cable system is referred to as L_{d2}. L_{d2} is calculated from Equation 3.

$$L_{d2} = (\text{m - sigma}) - L_d - (10 \text{ LOG N}) \qquad (3)$$

Where ...
m = mean or average cable-specific NEXT loss
sigma = standard deviation of m, the cable NEXT loss
n = ultimate number of T1 systems that will occupy the cable

4.3.4 Both NEXT factors, m and sigma, are dependent on four cable-specific characteristics:

1) The type of cable insulation, i.e. (PIC).
2) The cable gauge.
3) The cable size in terms of pair count.
4) The relative location of the transmit and receive pairs, such as same binder group, adjacent binder group, etc.

4.3.5 The expression (10 LOG N) in Equation 3 accounts for the accumulative effects of crosstalk coupling from multiple T1 span line systems that would operate in the cable. Values for the quantity of 10 LOG N are shown in Table 4.

4.3.6 As an example of calculating L_{d2}, consider a 22-gauge, PIC-filled, (solid insulation) buried 50-pair cable. From Table 2, L_d at 13 degrees Celsius is 32 dB. The number of span line systems is fifteen. Transmit and receive pairs will be placed in *adjacent* binder groups in the cable. Therefore, referring to the manufacturer's cable data and Table 4 for the logarithmic values:

m = 81 dB　　　　n = 15
sigma = 10 dB　　　　10 LOG N = 11.8

Plugging the above values into Equation 3 for L_{d2} gives:

$$L_{d2} = (\text{m - sigma}) - L_d - (10 \text{ LOG } 15)$$
$$L_{d2} = (81 - 10) - 32 - 11.8$$
$$L_{d2} = 27.2 \text{ dB @ 13 degrees Celsius}$$

TABLE 4 - VALUES OF 10 LOG N FOR SPAN LINE CALCULATIONS

n	10 LOG n	n	10 LOG n	n	10 LOG n	n	log n	n	log n
1	0	11	10.4	21	13.2	31	14.9	41	16.1
2	3.0	12	10.8	22	13.4	32	15.1	42	16.2
3	4.8	13	11.1	23	13.6	33	15.2	43	16.3
4	6.0	14	11.5	24	13.8	34	15.3	44	16.4
5	7.0	15	11.8	25	14.0	35	15.4	45	16.5
6	7.8	16	12.0	26	14.2	36	15.6	46	16.6
7	8.5	17	12.3	27	14.3	37	15.7	47	16.7
8	9.0	18	12.6	28	14.5	38	15.8	48	16.8
9	9.5	19	12.8	29	14.6	39	15.9	49	16.9
10	10.0	20	13.0	30	14.8	40	16.0	50	17.0

4.3.7 Thus, the maximum section loss for this 50-pair cable with fifteen span line systems is 27.2 dB. It is 5 dB less than for a two-cable system (where L_d equals 32 dB) because of the NEXT considerations. To convert this loss to a maximum span length, one uses the same engineering cable loss data for computing span lengths as with L_d. However, the value for L_{d2} should first be temperature-corrected. With the temperature correction factors in Table 3, a factor of 1.041 is listed for a 22-gauge, solid filled cable. L_{d2} at 38 degrees Celsius is then calculated using Equation 1.

$$L_{d2} \text{ @ 38 degrees Celsius} = L_{d2} \text{ @ 13 degrees Celsius} / 1.044$$
$$L_{d2} \text{ @ 38 degrees Celsius} = 27.2 / 1.044$$
$$L_{d2} \text{ @ 38 degrees Celsius} = 26.1 \text{ dB}$$

4.3.8 The maximum section length, L, is calculated using Equation 2 in a manner identical to L_d, once the temperature corrected value of L_{d2} is determined. For example, if the engineering loss for the 50-pair cable is 16.4 dB/km, the maximum span length would be 26.1 dB divided by 16.4 dB/km, giving 1.59 km.

4.4 Treatment of Cable End Sections

4.4.1 Cable end sections are span line sections adjacent to the terminating office. Here, impulse noise from a variety of sources, such as switching equipment and other electrical devices, can be a problem. The increased impulse noise at these locations can reduce the S/N ratio of incoming and outgoing signals. To prevent such problems, it is recommended that the maximum design loss (L_d or L_{d2}) be reduced by 33% in order to maintain a higher S/N ratio in other sections of the span line. For most situations, simply limiting the L_d and L_{d2} design losses to approximately 22 dB will be sufficient. The exception would be when the calculated L_{d2} is less than 22 dB; then L_{d2} is the limiting factor. Maximum section length is calculated by dividing 22 dB by the cable's per unit engineering loss.

4.5 Span Line Powering

4.5.1 Span line power using simplex power loops is described in paragraph 3.3. The power converter at the CO supplies two DC voltages at both negative and positive polarities.

Power converters can provide a range of voltages to accommodate span lines of various lengths. The basic power converter voltages are ±48 VDC and ±130 VDC; in combination they can supply a range of voltages, as shown in Table 5.

TABLE 5 - CO POWER CONVERTER VOLTAGE RANGES (VDC)

Output Voltage	Combination
48	48
130	130
178	130 + 48
260	130 + 130

4.5.2 To engineer span line power systems, one should consider the repeater current requirements and the cable voltage drops. These are:

1) V_{loop} - the voltage drop associated with the cable plant based on the repeater current requirements.
2) V_{term} - the CO terminating equipment voltage drops.
3) V_{rptr} - the voltage drops of the field repeaters.

4.5.3 All of the voltage drops in the looped DC power feed circuit (V_{span}) are added to determine the minimum required source voltage at the CO. The loop power converter is then configured to supply a voltage equal to or greater than V_{span}. In many cases, this power can be supplied from a single power converter located at one end of the span line. If the sum of all voltage drops, V_{span}, exceeds 260 VDC, then both ends of the span line will require power sources. This voltage relationship for powering is shown in Equation 4.

$$V_{span} = V_{loop} + V_{rptr} + V_{term} \qquad (4)$$

4.5.4 Today, most miniature integrated circuit repeaters use 60 mA. Older, discrete component repeaters required currents of either 100 mA or 140 mA. Typically for the 60 mA repeaters, a drop of 7 VDC is representative. However, a repeater's voltage drop may vary based on a vendor's model and characteristics. Higher current repeaters drop 10 VDC to 12 VDC. In addition, the current requirements and voltage drops associated with the office repeater and the power converter itself should be considered when calculating loop power requirements. Consult the manufacturer's product specifications to determine the exact characteristics of both field and office equipment.

4.5.5 To arrive at a voltage requirement for the cable plant voltage drop, V_{loop}, one first starts with the cable resistance. The total cable resistance multiplied by the repeater current requirement equals V_{loop}. The cable resistance is not the same as the engineering loss discussed in paragraphs 4.2 and 4.3. Engineering loss refers to the cable impedance at 772 kHz whereas the cable resistance refers to the DC resistance only.

4.5.6 To determine the loop cable line resistance (R_{loop}), one multiplies the unit cable resistance by the total cable length. Separate calculations are necessary for mixed cable

A.2.5 Customer-owned data equipment has the capability to perform some error correction. The two basic methods of error correction are automatic request for repeat (ARQ) and forward error correction (FEC). Both automatically detect errors. ARQ requires retransmission whereas FEC does not.

A.2.6 ARQ issues instructions to the transmit end for retransmission when an error is detected. However, FEC performs its own correction at the receive end when an errors occurs. Both methods can significantly improve the BER of the transmitted signal. An error rate improvement of two orders of magnitude is possible (e.g., improving a 10^{-6} BER to 10^{-8}). The resulting error rate after being acted upon by a form of error correction is known as the residual error rate (RER).

A.2.7 Another consideration is that of test equipment capability to detect bit errors. There may be little point in considering improved BERs if the ability to properly measure performance at that level does not exist. Based upon the characteristics of currently available BER test sets, the most sensitive threshold for BER detection is in the range of 10^{-9} to 10^{-12}.

A.2.8 Currently available lightwave terminal equipment, including both the optical/electrical interface and the multiplexer, have rated BER specifications in the range of 10^{-9} to 10^{-12}.

A.2.9 The CCITT (International Consultative Committee on Telegraph and Telephone) has established a BER standard. CCITT Recommendation G.821 specifies an end-to-end BER of no worse than 10^{-6} for 90% of all one-minute intervals.[2] This is for an end-to-end international ISDN call over what is termed a "Hypothetical Reference Connection" (HRX) of 27,500 km for a 64 kb/s circuit-switched connection. However, the BER component is constant and does not vary over distance. The Recommendation further specifies an EFS criterion of 92%.

A.2.10 In addition, the American National Standards Institute (ANSI) Telecommunications Standard, T1.601-1988, specifies a BER for the Basic Rate ISDN "U" Interface.[3] This interface is between the digital subscriber line and the customer. T.601 specifies a BER of "$< 10^{-7}$."

A.3 Analysis For Improved Span Line Bit Error Rates

A.3.1 To determine the effect of improved BERs on repeater spacings, the original published research performed by Bell Telephone Laboratories was consulted by REA. This is outlined in a technical paper authored by H. Cravis and T. V. Crater entitled, "Engineering of T1 Carrier Repeatered Lines," *Bell System Technical Journal*, March 1963.

A.3.2 The Bell researchers started with the assumption that an end-to-end BER of 10^{-6} would be sufficient. In fact, they indicate that the 10^{-6} requirement was conservative in that a BER of 10^{-5} would not seriously impair speech quality. Then they determined that 3×10^{-7} was an acceptable maximum error rate for a single T1 span. A typical end-to-end call routed through three separate T1 spans, each having BERs as high as 3×10^{-7}, resulted in an end-to-end, net BER of $3 \times (3 \times 10^{-7})$, or roughly 10^{-6}. A similar process was followed for the REA analysis to determine the span and section error rates for the improved BERs of 10^{-9} and 10^{-12}. The results are shown in Table A1.

---

[2] CCITT Red Book, Vol. III, Fascicle III.3, Recommendation G.821, International Telecommunications Union, Geneva, 1985.

[3] ANSI Standard No. T1.601-1988, ISDN Basic Access Interface for Use on Metallic Loops for Application to the Network Side of the NT.

A.3.3 The results in Table A1 were input into equations for the NEXT voltage distribution and for the resulting noise power, both of which are quantities used for computing maximum section loss in the Bell paper. This information was, in turn, used to develop the three basic maximum section loss (L_d) equations for the two new BERs. These are Equations A2 and A3, shown below. The original Bell maximum section loss equation for a BER of 10^{-6}, Equation A1, is included for comparison. It is worth noting that the original work included an 8 dB margin (or safety factor) to account for expected variations in a number of parameters, such as peak signal value of the digital bitstream, amplifier gain, signal-to-noise ratio and overall noise power. Equations A1 through A3 also include a second margin of 6 dB that was used in the original Bell research to compensate for uncertainties in near end crosstalk (NEXT) factors among cable varieties, splicing losses and reduction of far end crosstalk (FEXT). Thus, a total of 14 dB of margin has been included to account for uncertainty. Equations A2 and A3 are equivalent to those discussed in paragraph 4.3.6 of Chapter II.

Table A1 - Span Line BER Components

Section BER	Span BER	End-to-End BER
1×10^{-7}	3×10^{-7}	10^{-6}
1×10^{-10}	3×10^{-10}	10^{-9}
1×10^{-13}	3×10^{-13}	10^{-12}

A.3.4 Equations A1, A2 and A3 are shown below, where:

L = maximum section loss in dB
m = mean cable NEXT loss in dB
sigma = standard deviation cable NEXT loss in dB
n = number of T-carrier systems within the cable

For BER = 10^{-6} L_1 = m - sigma - 32 - 10 LOG N (A1)

For BER = 10^{-9} L_2 = m - sigma - 34.5 - 10 LOG N (A2)

For BER = 10^{-12} L_3 = m - sigma - 35.5 - 10 LOG N (A3)

A.3.5 The third term in all three equations is the only variable that is affected by the varying error rates. In decreasing the error rate from 10^{-6} to 10^{-9}, this factor increases by 2.5 dB. A decrease to a 10^{-12} BER results in a total increase of 3.5 dB, or an incremental increase of 1.5 dB. The actual reduction in physical distance that would result is dependent upon the specific cable under consideration and its associated NEXT values.

A.4 Effects On Span Line Spacing

A.4.1 As an example of what the above reductions in T1 section loss can translate to in terms of distance for a given set of conditions, consider the following:

1) A 50-pair, 24-gauge, PIC, filled buried cable
2) Ten operating T1 systems within adjacent 25-pair cable units.

3) NEXT losses of: m = 83 dB and sigma = 13 dB
4) Engineering loss of 5.2 dB/km @ 13 degrees Celsius

A.4.2 Using equations A1, A2 and A3:

For BER = 10^{-6}

L_1 = 83 - 13 - 32 - (10 LOG 10)
L_1 = 28 dB

=> Section Length 1 = 28 dB/(5.2 dB/km) = 5.4 km

For BER = 10^{-9}

L_2 = 83 - 13 - 34.5 - (10 LOG 10)
L_2 = 25.5 dB

=> Section Length 2 = 25.5 dB/(5.2 dB/km) = 4.9 km

For BER = 10^{-12}

L_3 = 83 - 13 - 35.5 - (10 LOG 10)
L_3 = 24.5 dB

=> Section Length 3 = 24.5 dB/(5.2 dB/km) = 4.7 km

A.4.3 As shown from the above calculations, the effect of varying the BER from 10^{-6} to 10^{-9} to 10^{-12} for the given cable and T1 conditions results in a decrease in the section spacing ranging from 9% to 13%.

<u>A.5 Summary & Recommendations</u>

A.5.1 Improving the standard 10^{-6} end-to-end BER has an effect on the maximum section loss and repeater spacings for T1 span line systems. However, these effects are relatively small. The improved BERs of 10^{-9} and 10^{-12} result in calculated reductions in maximum section loss of 2.5 dB and 3.5 dB, respectively. For a typical 50-pair cable, these loss reductions translate into a 9% to 13% reduction in the calculated maximum span lengths. With strict use of the calculated maximum values over a 10-kilometer span, for example, this could cause the placement of one or two additional repeaters to make up for the additional, calculated loss.

A.5.2 In practice, however, operating telephone companies have generally been conservative in their placement of span line repeaters, whether for reasons of physical convenience and security, or to allow margins for possible future cable splices due to road improvements or other damage. Thus, it is likely in many circumstances that sufficient margins already exist (beyond the 14 dB already assumed in the repeater spacing calculations) on the order of several dB, which would provide for improved error performance. A margin of only several dB has been shown to improve the calculated end-to-end BER from 10^{-6} to 10^{-12}.

A.5.3 Moreover, many customers who use digital data circuits terminate or operate them in conjunction with data processing equipment having some form of error correction capability. Thus, a transmission circuit performing at an end-to-end BER of 10^{-6} could deliver data after correction at a residual error rate (RER) of 10^{-8}.

A.5.4 As Table A1 shows, the initial span line designs used an end-to-end BER of 10^{-6}, assuming three separate span lines as the worse case. Each separate span line was assumed to have a BER on the order of 3×10^{-7}. Therefore, for end-to-end connections involving *less* than three separate spans, the end-to-end BER will be better than 10^{-6}. And with T-carrier being replaced in many toll routes with fiber-based networks, it can be assumed that many switched and special service circuits are often routed over less than a total of three span lines and do indeed perform from end-to-end at error rates better than 10^{-6}.

A.5.5 Because comprehensive standards for BER requirements have yet to be developed, those standards that do currently exist suggest a range of acceptable BERs, from 10^{-6} to 10^{-8}. Given that many future digital services and means of transport are just beginning to be offered, it is difficult to indicate with any precision if any level of BER beyond the 10^{-6} to 10^{-8} range may be ultimately required. However, because actual end-to-end span line performance levels can be expected to already be in this range for the above reasons, and that error correction capability in end user equipment will improve this by two orders of magnitude, it is reasonable to conclude that existing span line systems will perform adequately with the advent of new digital services.

A.5.6 Any recommendations to modify repeater spacings, whether for new or existing installations, at this time cannot be justified. As lightwave facilities continue to both replace T-carrier and become more prevalent in both the interexchange and loop plant, questions as to what constitute an adequate BER for span lines will become largely of an academic nature.