FUNDAMENTALS OF CARRIER TRANSMISSION

CONTENTS

1. GENERAL

1.1 This section provides REA borrowers, consulting engineers and other interested parties with technical information on the fundamentals of carrier multiplexing and transmission for trunk and subscriber applications. Carrier fundamentals are presented in a brief descriptive manner to provide a basic understanding of carrier concepts, hardware and application. More detailed information on specific aspects of transmission and carrier are covered in other REA TE&CM Sections in the 400 and 900 series.

1.2 The term "carrier" is often used in a broad sense to describe multiplex systems applied to wire facilities. Multiplexing is the process of combining two or more separate signals or channels on a common transmission path. Two widely used multiplexing techniques are frequency division multiplex (FDM) and time division multiplex (TDM). Channels are separated by frequency assignment in FDM systems, and channels are separated by time assignment in TDM systems. FDM systems for voice communications are generally carrier modulated on a continuously changing basis (noninterrupted), and referred to as analog carrier.

1.3 This section will focus almost entirely on frequency division analog carrier systems. For completeness, time division and digital transmission systems are briefly mentioned. Digital multiplexing and transmission fundamentals are covered in TE&CM Section 950, Digital Transmission Systems.

1.4 The basic concept of carrier multiplexing is older than telephony. To better appreciate the genius of those early scientists and engineers, the origin of carrier and certain evolutionary developments are illustrated. Carrier systems have been used primarily in telephony applications. Carrier is a specialized area of communications engineering. The basic engineering principles of modulation and transmission are thoroughly discussed in communications and electrical engineering textbooks. The adaptation of these concepts to wire line facilities (carrier) has been more thoroughly covered in engineering periodicals and trade publications for over 60 years than in engineering textbooks. One purpose of this section is to assemble and highlight a few of these basic concepts and historical events that have led to the modern carrier systems of today.

1.5 The appeal of carrier as a concept, the development of practical carrier systems, and the continued growth in the use of carrier equipment can be primarily credited to the economic and transmission advantages of carrier. Media efficiency or multiple circuits on a common transmission path provided the economic incentive for carrier development and continued growth. This economic incentive was reinforced by the transmission advantages of carrier, especially for trunk service. These transmission advantages include low and uniform losses, propagation speeds substantially higher than voice frequency, and improved return losses resulting from design controlled impedances. Advances in carrier can be directly linked with advancements in electronic technology. Carrier system needs led to technology improvements, and technology advancements led to carrier design improvements.

2. CARRIER ORIGIN AND EVOLUTION

2.1 Simplified Description: In layman's terms, carrier is "Radio on Wire." Radio requires a transmitter and a receiver (Figure 1A). A radio receiver can tune in one station, and tune out all other stations (unidirectional). Two way communications (bidirectional) require a transmitter and receiver at both ends (Figure 1B). CB radio serves as an example of two-way radio.

2.1.1 Carrier is just like radio except that signals are transmitted over wires rather than through the air (Figure 1C). Voice signals are converted from sound waves to electrical waves by a microphone. These electrical waves are amplified and fed into a radio generator or transmitter. The transmitter output is a radio frequency signal that contains characteristics of the voice input signal. The radio signals are transmitted over wires to a distant location to a receiver. At the receiver, the desired signal (station, channel, etc.) is filtered or tuned in. All unwanted signals or channels are filtered out and discarded. The radio signal is then demodulated, or converted back into a voice signal. The voice signal is then amplified and fed into a speaker and converted from electrical waves back into sound waves. The only basic difference between radio and what is called "carrier" is how the signal is transmitted from one point to another -- over wires rather than through the air.

2.1.2 The term "carrier" is an abbreviated form of the original term "carrier current." Modulation is a "voice on radio", or "voice on carrier" signal (Figure 2A). When a radio or carrier frequency and a voice frequency are fed into a mixer or modulator, the resultant output contains the original voice and carrier signals; but more important, it contains combined voice and carrier signals including a modulated carrier signal. The voice frequency and other unwanted signals are discarded at the modulator output. The modulated carrier signal is a radio frequency signal and cannot be heard by the ear. But the radio signal is "carrying" voice information that can be retrieved.

2.1.3 "Carrier" is often used to described a concept, hardware and/or systems. The following are descriptive examples of the term "carrier".

Carrier: A concept of multiplexing two or more signals onto a common path.

Carrier Transmission: This usually describes electrical waves applied to a transmission media, and the effects of the media on the electrical waves.

Carrier Transmission Media: A metalic path for the transmission of electrical waves.

Carrier Equipment: Electronic hardware for multiplexing and transmission of signals.

Carrier Terminal Equipment: Electronic hardware for multiplexing two or more signals onto a common path.

Carrier Line Equipment: Electronic hardware used along the transmission media to offset the degrading effects of the media by amplifying and/or reshaping the signal.

Carrier System: The organized assembly of carrier equipment and transmission media.

2.1.4 Radio can be transmitted between locations without the need for wire facilities. Since radio and carrier are essentially the same technique using different transmission media, the basic need for carrier may be questioned. The justification for carrier, and continued accelerated use of carrier lie in two basic areas - economics and limited frequency spectrum. The design of carrier systems can be made less complex than radio because of the controlled transmission media (wire, rather than air). Carrier systems require less power, less sensitivity, and less selectivity or discrimination from undesired signals. These factors will generally result in lower cost telephone service through the use of carrier rather than radio - including the cost of wire facilities for the carrier. In many cases, the necessary wire plant will already be in place for carrier application. The other major factor is the availability of radio frequency spectrum. There is a limited radio spectrum available for these services. Thus, it is not practical to serve every subscriber by radio. Carrier frequencies can be reused on each pair or wires within a cable (within defined limits). Carrier and radio are competitive techniques in telephone service. The use of radio is primarily limited to point-to-point high density service in the trunk network. In rural areas, carrier is generally more economical than radio for both trunk and subscriber service.

2.2 Early History: It was from experiments in the 1870's with telegraph multiplex (or "harmonic" telegraph) that Alexander Graham Bell recognized the possibility of transmitting voice. Thus, the basic concept of carrier multiplexing is older than telephony. Telephone carrier principles for voice communications were developed by the French and Americans in the 1890's. A laboratory model of a carrier system was tested by the American Bell Telephone Company in 1894. It was in 1918 (24 years later), that the first commercial carrier system was placed into service between Baltimore and Pittsburgh. The development of economical and practical hardware was required to implement these concepts and laboratory models. The separate efforts of several scientists and engineers were combined to begin a technological revolution in telephony hardware that included radio, carrier and voice frequency electronics. Electronic gain was the key to this technological revolution, and was the result of three development steps. Thomas Edison discovered the Edison effect (electron emission and flow) in 1883; John Ambrose Fleming converted the Edison effect into the thermionic valve (vacuum diode) in 1904; and Lee de Forest developed the audion (triode vacuum tube) by adding a third element in 1906. Two other key factors in the development of carrier were the discovery of positive feedback (oscillator) by Edwin Armstrong in 1912 and the wave filter invented by George Campbell in 1915. A wide range of developments in this technological revolution were assembled and illustrated in 1921 AIEE Transactions paper "Carrier Current Telephony and Telegraphy" by E. H. Colpitts and O. B. Blackwell.

2.3 Equipment Evolution: The early evolutionary directions in carrier equipment development were shaped by the Bell System. The carrier systems were identified alphabeticaly, Types A, B, C, etc. These early systems were generally ampitude modulated, single sideband, suppressed carrier systems designed for open wire application (except Type E for power line application). Type A carrier was a 4 channel system that began service in 1918. Some of the A carrier equipment remained in service until the 1940's. The 3 channel Type C carrier was the most versatile and most widely used of the early carrier systems. The C carrier had a wider voice frequency response, a top frequency below 30 kHz, and a range of 1000 to 2000 miles with repeaters at 125 mile intervals.

2.3.1 The J and K carrier systems developed in the 1930's were the foundation of modern analog carrier systems. The two systems were similar; J carrier was applied to open wire and K carrier was developed for cable application. Carrier frequencies were at multiples of 4 kHz, and generated in 12 channel single sideband basic groups of 60 to 108 kHz before being converted into other frequency allocations. The K carrier was the first system where the transmission medium (cable) was not shared with a voice frequency channel or another carrier system. The same carrier frequencies were used in both directions of transmission. Due to near end crosstalk, separate cables were generally used for the two directions fo transmission.

2.3.2 Even though the initial patent for a coaxial cable transmission system was granted in 1929, it was 1941 when the first (L1) coaxial cable system was placed in service. A coaxial cable or coaxial line is a transmission line where one conductor completely surrounds the other conductor, both sharing a common axis. A coaxial cable has no external field and is not subject to external fields (interference) from other sources. The L1 system began with 480 channels over a pair of coaxial cable tubes. The L5 system is now up to 13,200 channels over a pair of coaxial cable tubes (22 mastergroups of 600 channels each).

2.3.3 Service by N carrier began in 1950. The N carrier development beginning in the late 1940's represents one of the final stages of analog trunk carrier development for paired telephone cables. The N carrier was designed to fill the need for an economical short haul system (up to 200 miles). Design engineers utilized existing technologies and explored new techniques to improve transmission performance and reduce transmission costs. In a return to design simplicity, the N1 carrier was a 12 channel double sideband system with transmitted carrier for easy modulation and demodulation. System performance was improved through the use of syllabic compandors (operating on speech syllables). Compandors provide a signal-to-noise advantage, a system crosstalk advantage, and an idle channel noise advantage. This eased the equipment design requirements in areas such as filtering. Compandors also eased the cable crosstalk requirements eliminating the need for extensive cable balancing to reduce the crosstalk coupling between cable pairs.

2.3.4 The N2 carrier was essentially a redesign of the N1 carrier using transistors instead of vacuum tubes. The N3 carrier was a return to single sideband to achieve 24 channels in the same frequency range as the 12 channel N1 and N2. To keep the N carrier repeatered lines compatible for N1, N2 and N3 terminals, the N3 carrier transmitted 12 pilot tones (one for each pair of channels) corresponding to the 12 carrier frequencies of N1 and N2 carrier.

2.3.5 While carrier system development was dominated by the Bell System, Independent manufacturers began contributing to this technology. The contributions of Independent manufacturers to carrier development have been vital to rural telephony. However, the contributions are more difficult to trace because they are not as well documented. Some factors are the small size, diversity and ownership changes of Independent manufacturers over the past 40 to 50 years. Independent manufacturers developed a variety of unique carrier systems, as well as systems that were compatible with Western Electric carrier systems. The term "unique" is used to describe individual systems that are not compatible with other systems. Some systems were not end-to-end compatible but were interference compatible (coexist) on the same wire route. An example is the Lenkurt 33 carrier. The 33 is 3 channel open wire system with a carrier frequency range up to 35 kHz and designed to be compatible on the same open wire route with Western Electric C carrier. Lenkurt 33 carrier remained in general service until recent years. (Some may still be in service in isolated areas.) Other trunk carrier pioneers were Lynch, Collins, Kellogg, Stromberg Carlson, Panhandle Electric, North Electric and RF Labs.

2.4 Subscriber carrier was developed to provide rural telephone service where service by other means was not practical or economical. The Bell System M subscriber carrier was placed in service in 1945. This was a 5 channel system applied to power line distribution facilities. Coordinated testing was conducted by the Bell System, rural electric cooperatives and the REA. While power line carrier had been successfully applied to power transmission facilities, the obstacles of applying carrier to power distribution facilities were formidable (especially bridge taps). M carrier use was limited. The Bell System's second attempt at subscriber carrier was the P1 carrier in 1954. The P1 carrier was designed for open wire or cable application and incorporated several advanced technological developments -- the most notable being the first use of transistors in carrier systems. There was limited use of P1 carrier also. While the Bell System has primarily shaped the development of trunk carrier systems, credit for key developments and the general acceptance of subscriber carrier belong to the Independent telephone industry -- to manufacturers, operating telephone companies and organizations such as the Rural Electrification Administration (REA).

2.4.1 Soon after the REA was authorized by Congress in 1949 to make loans for rural telephone service, REA engineers investigated unique methods to provide this service economically. REA encouraged, supported and worked closely with carrier manufacturers to develop subscriber carrier for rural service. The support included a small development contract for a subscriber carrier with multiparty selective ringing in late 1951. Driven by the necessity to overcome the economic and transmission impairments of serving subscribers in sparcely populated rural areas, Independent telephone companies accepted subscriber carrier and encouraged its continued development. Encouragement of trunk and subscriber carrier development resulted in advantages and disadvantages. Equipment became available from multiple sources. However, each new system often resulted in a new carrier frequency allocation and generally restricted each wire line route to one type of equipment. In April 1954, REA held a Carrier Coordination Meeting, but was unsucessful in establishing a voluntary informal frequency standard for carrier systems. These subscriber carrier systems had several shortcomings, but were partially successful because they provided a needed service.

2.4.2 About 1960, there was a gradual but certain shift toward cable carrier systems utilizing solid state electronics, standby batteries, and other improved features. This shift was accelerated by the use of buried cable facilities. These systems were designed for both trunk and subscriber applications. Examples of this technology were the Panhandle X (trunk) and XU (subscriber) carrier systems and the ITT K24A (trunk) and K24S (subscriber) carrier systems. These cable carrier systems were built on the experience of open wire carrier systems and provided improved service reliability. Each equipment type had its own carrier frequency allocation, and each cable route had to be dedicated to one type of carrier.

2.4.3 During the period from 1963 to 1965, REA again tried to obtain agreement on a voluntary carrier frequency standard. Sponsored by the IEEE Wire Communications Committee, a Carrier Task Force met from January 1963 until October 1964 to establish recommended (voluntary) frequencies and levels for subscriber cable carrier. Even with reasonable outside support and agreement within the task force, the committee recommended further study rather than acceptance of the voluntary standard.

2.4.4 Prompted by the need for a frequency standard and support by some manufacturers. REA continued efforts toward the establishment of informal standards on key items for subscriber cable carrier. These were presented in an IEEE Conference Paper, "Objectives for a One Party Subscriber Carrier System" by A. H. Flores and J. M. Flanigan of REA, June 7-9, 1965. This paper became the informal guidelines for a new type of subscriber carrier. Lester Krasin and Cliff Greene of the PED Company developed a 4 channel subscriber carrier for the Superior Cable Corporation. It was called the Electronic Distribution System (EDS) to denote a new and innovative system for subscriber service. This type of equipment (from all manufacturers) came to be known as "station carrier". The improved characteristics including reliability and coordination of different systems in the same cable led to widespread use of subscriber carrier. Station carrier has been the most successful analog subscriber carrier in the telephone industry. The successful use of station carrier in rural areas paved the way for the development of a wide array of subscriber electronic equipment and services. Without this success, these new systems and services would have been introduced more slowly.

2.5 Digital Systems: The term "digital" refers to information that is represented numerically. Pulse code modulation (PCM) is the only form of digital transmission used extensively for communications in telephony. PCM principles were developed by Alec Reeves of ITT in Europe in 1937. At that time, there was no hardware available to convert these concepts into practical systems. In 1956, Bell Labs began the development of the first commercial PCM system using solid state technology. PCM carrier began commercial service in 1962 -- 25 years after Reeves introduced the principles in PCM.

2.5.1 The invention of the solid state amplifier or transistor in 1947 triggered a large scale electronic revolution. The later development of the integrated circuit enhanced the role of digital technology for computer and communications systems. John Bardeen, Walter Brattain and William Shockley developed the transistor at Bell Laboratories in 1947. Development of the integrated circuit is generally credited to the independent work of Jack Kilby of Texas Instruments and Robert Noyce of Fairchild during the 1958-59 period.

2.5.2 The Bell System's PCM system was designated as the Western Electric T1 carrier system. Bell developed digital system building blocks or modules, and identified the digital transmission system as T1 span lines and the encoding and decoding PCM terminals as D1 channel banks. From this beginning, a digital hierarchy concept was developed for the trunk network. Independent manufacturers began the development of compatible digital trunk carrier equipment in the mid 1960's. REA placed the first digital trunk carrier on the List of Materials in 1968; that same year, 30 percent of the trunk carrier channels purchased by REA borrowers were digital. This new technology showed promise in all areas of telephone communications.

2.5.3 Again prompted by need, the Independent telephone industry pioneered in the development and use of PCM subscriber carrier. Adaptations of the T1-D1 PCM carrier were developed by Independent manufacturers and applied to rural subscriber loop plant before 1970. PCM carier had been developed as an interexchange metropolitan area carrier system. The introduction of this equipment into rural areas brought on problems -- especially when applied to subscriber cables. The additional problems of electronic component reliability and accelerated moisture ingress into air core cables during the early 1970's combined to present a formidable challange to the use of digital carrier in rural areas. Through a series of investigations and actions, digital carrier was made more reliable and more adaptable to rural applications.

2.5.4 Digital transmission techniques have now been extended into switching systems. Early Bell efforts were concentrated on digital toll switches, while the Independent manufacturers have concentrated on integrated Class 5 digital switches, remote switches, digital subscriber carrier and digital subscriber line concentrators. The accelerating development of integrated circuits has further enhanced the role of digital transmission and switching systems in telephony. Major parts of telephone systems can be incorporated into one or several integrated circuits. The circuit elements or information that can be stored on a single integrated circuit continues to expand, providing new markets for these devices. An increase in the use of data transmission by telephone business customers is expected in the future. Digital transmission systems are especially suited for efficient data transmission. The developed technology and hardware have expanded the application of this equipment such that few areas of telephony remain untouched by digital transmission and switching.

3. CARRIER SYSTEM CLASSIFICATION

3.1 Classification: The characteristics of specific carrier equipment and systems are shaped by the design engineer by optimizing the service and application criteria, available component hardware and cost. From this optimization evolved classes of carrier systems with unique characteristics. Some of these classifications, functions and characteristics are briefly summarized.

3.1.1 Trunk and Subscriber Carrier represent classification by service. Trunk carrier is used to provide circuits between central office switches. Subscriber carrier is used to provide circuits between a central office switch and subscribers. The primary difference between trunk and subscriber carrier is in the signaling. Trunk signaling primarily transmits dialing information and supervisory status between central office switches. Subscriber signaling primarily transmits ringing information from the central office to the subscriber end; and, on-hook and off-hook status as well as dialing information from the subscriber to the central office end.

3.1.2 Classification by application includes cable carrier, open wire carrier and power line carrier. Early carrier systems were applied to open wire telephone facilities and later to power line facilities. These facilities are characterized by low transmission losses, except during adverse weather conditions. Cable facilities exhibited higher transmission losses than open wire, but represented a much more controlled, stable and shielded environment for transmission. As gain devices became more practical and reliable, cable became the primary transmission medium for carrier. Cable carrier transmit levels are generally in the order of 0 dBm, or 1 milliwatt. Open wire transmit levels were in the order of +5 dBm to +20 dBm, or 3 to 100 milliwatts. Power line carrier transmit levels are greater than +30 dBm, or in the watts range. Power line carrier systems have been widely used by power utilities applied to transmission lines for voice and telemetry. Because of the high cost of filtering, power line carrier for distribution facility application is generally not practical for voice service, but is used extensively for telemetry (signal-to-noise less critical).

3.1.3 As a variation of classification by service or application, carrier is often classified by certain component hardware, modulation technique or other distinguishing characteristic. As transistors replaced vacuum tubes, the equipment was often called "transistorized" carrier. Modern day carrier systems are designed around the use of solid state components such as transistors and integrated circuits; thus, the term "transistorized" faded as quickly as it was born. Other comparison catagories in this area are analog and digital, amplitude modulated and frequency modulated, compandored and noncompandored, repeatered and nonrepeatered, short haul and long haul, etc.

3.2 System Components: The fundamentals of analog carrier are presented in the following manner. The basic building blocks of an analog cable carrier terminal are illustrated in Figure 3 and line repeaters are illustrated in Figure 4. A 12 channel amplitude modulated, double sideband system with transmitted carrier for each channel is used as a model (AM DSBTC). Variations of the model are also discussed as each block is examined. After the basic building blocks are examined individually, the block diagram is examined as a unit by tracing a signal through a carrier system.

4. CARRIER SYSTEM COMPONENTS

4.1 Filters: Wave filters are among the most important units of analog carrier systems. A wave filter is used for separating electrical signals or waves on the basis of frequency. It introduces a relatively small insertion loss at some frequencies and a relatively large insertion loss at other frequencies. Through the use of wave filters, separately generated electrical signals can be mixed or multiplexed at the transmission end and separated or demultiplexed at the receiving end of a common transmission facility or other medium. Electrical filters using passive electrical components (inductors, capacitors and resistors) are used to illustrate filter characteristics. Active filters are now in wide use in carrier systems, but have not completely replaced passive filters in analog carrier systems. An active filter consists an amplifier, resistors and capacitors where filtering (separation) is accomplished by amplifier feedback and wave phase relationships. Wave filtering is also accomplished by mechanical, piezoelectric, acoustic and other means. Electrical wave filters are generally classified as low-pass, high-pass, band-pass and band-rejection. Figure 5 illustrates some simple examples of these four types of filters.

4.1.1 Low-pass filters pass electrical currents from dc up to a specified frequency (the cut-off frequency) with minimum loss, and attenuate or reject frequencies above this specified frequency.

4.1.2 High-pass filters pass electrical currents above a specified frequency (also called the cut-off frequency) with minimum loss, and attenuate or reject frequencies below this specified frequency.

4.1.3 Band-pass filters pass electrical currents within a specified frequency band, and attenuate or reject frequencies outside the specified band of frequencies. The midpoint of the passband is called the center frequency or resonant frequency. The passband edges are called the cut-off frequencies, or the lower cut-off frequency and the upper cut-off frequency.

4.1.4 Band-rejection filters attenuate or reject a specific frequency or band of frequencies, and generally pass all electrical currents outside the rejection band with minimum loss.

4.1.5 Low-pass and high-pass filterss are used to separate voice frequency and carrier frequency signals, or to separate broad groups of carrier frequencies. An example of the latter case is the use of low-pass and high-pass filters in a carrier repeater to separate the directions of signal transmission. Low-pass and high-pass filters may also be used in combination to form a band-pass filter with a wide passband. Band-pass filters are most frequently used to separate the analog carrier frequency spectrum into channels. Each carrier channel is assigned a transmit frequency and a receive frequency, each of which is separated by a band-pass filter. Band-rejection filters are special purpose devices. One of the most common uses of band-rejection filters is for signaling. A sharp band-pass filter (narrow band-pass frequency range) is used to accept the signaling frequency for demultiplexing along with a sharp band-rejection filter (narrow band-rejection frequency range) to keep the signaling frequency out of the voice frequency circuit.

4.2 <u>Oscillators</u>: Oscillators are electronic devices that generate sustained alternating currents at one frequency. An oscillator may be considered an amplifier with positive feedback; the amplifier circuit parameters and components determine the frequency of oscillation (Figure 6). The oscillator frequency may be determined almost entirely by the resonant frequency of an inductor-capacitor tuned circuit or by a piezoelectric crystal for high frequency stability. Where frequency stability is less critical, oscillation can be sustained by using an amplifier, resistors and capacitors in a circuit similar to that of our active filter using positive feedback and a net gain greater than unity at the frequency of interest.

4.2.1 Oscillators are used to generate carrier frequencies for each carrier channel, pilot frequencies and group modulation frequencies. The major use of oscillators at voice frequencies in a carrier system is for channel signaling. Low density analog carrier systems often use a separate, independent oscillator for each carrier channel transmitter. Higher density wire line carrier and radio multiplex systems require more precise oscillators. Each carrier frequency may be generated from one primary frequency source in multiples of 4 kilohertz using a phase lock loop or other technique for synchronization. Higher density systems generally transmit only one sideband to conserve frequency spectrum, and suppress the carrier to reduce system loading. A pilot tone is transmitted to the distant end for system regulation, and for the precise regeneration of carrier frequencies for demodulation. A small amount of frequency drift may not be critical for low density analog carrier systems, but frequency stability becomes very critical for higher density systems.

4.3 <u>Modulators</u>: Modulators are used to combine voice frequencies with a carrier frequency to form a modulated carrier frequency. A modulator is often called "mixer". Modulation is a process of imposing the information contained in a lower frequency signal on a higher frequency signal. The higher frequency signal is called the carrier and the lower frequency (voice) is the modulating signal. The voice frequency information or intelligence is contained in the sidebands of the carrier, and not in the carrier itself. Analog carrier systems generally use amplitude modulation (AM), frequency modulation (FM) or phase modulation (PM) techniques. FM and PM are similar, and are often simply called FM.

4.3.1 The intelligence of AM is contained in the amplitude and frequency of the sidebands. The amplitude of the modulating signal determines the relative amplitude of the sidebands; and the frequency of the modulating signal determines the frequency of the sidebands. The intelligence of FM is contained in the frequency components of the sideband. The amplitude of the modulating signal determines the sideband frequency deviation or swing from the carrier; and the frequency of the modulating signal determines the rate (frequency) at which the sideband deviates or swings from the carrier. The amplitude of the FM signal remains constant.

4.3.2 This discussion will focus on amplitude modulation only. Carrier systems use double sideband (DSB), single sideband (SSB) and sometimes vestigial sideband (VSB) AM. SSB AM and VSB AM are similar. SSB eliminates one sideband by using a sharp cutoff bandpass filter. VSB suppresses one sideband by having a gradual cutoff near the carrier frequency. Most DSB AM systems transmit a carrier signal for each channel, and most SSB AM systems suppress the channel carrier and transmit one or more pilot signals for the regulation of channel groups or systems. To conserve frequency spectrum and minimize system loading, higher density radio and coaxial cable systems use AM SSB transmision. Low density carrier systems (up to about 12 channels) for exchange cable application generally use AM DSB with a carrier transmitted for each channel. To achieve more channels on exchange cables (up to 24), some systems use AM SSB with a carrier or pilot signal transmitted for each channel or each pair of channels.

4.3.3 The modulator used for illustrative purposes is AM DSB with transmitted carrier. Figure 7 illustrates a simple modulator that is composed of the oscillator in Figure 6 plus two resistors and a capacitor. Figure 2 is referenced for the following discussion. When a carrier frequency (F1) and a voice frequency (F2) are fed into a modulator, the resultant output includes the input signals (F1 and F2) and the sum and difference frequencies of the input signals (F1 + F2 and F1 - F2). For a carier frequency (F1) of 100 kHz and voice frequency (F2) of 1 kHz, the output consists of 1 kHz (F2), 99 kHz (F1-F2), 100 kHz (F1) and 101 kHz (F1 + F2). The voice frequency is discarded and the carrier and sidebands are retained by filtering. At full 100 percent modulation, each of the two sideband signals would measure 6 dB below the carrier. (The combined two sidebands would be 3 dB below the carrier.) To provide for overload margin, a zero dBm modulatng voice frequency results in modulating typical sideband signals that are 9 to 12 dB below the carrier as illustrated in Figure 2B. The frequencies and levels of carrier and sideband signals can be readily measured individually using a frequency selective voltmeter (FSVM) with a narrow passband selectivity.

4.4 <u>Demodulators</u>: Demodulators are used to recover the voice signal from modulated carrier signal. This is accomplished by separating the voice and carrier frequency signals from the modulated carrier signal, and then eliminating the carrier signal. A simple demodulator for AM DSB consists of a series diode for rectification, a shunt capacitor for elimination of the carrier, and a resistor to complete the electrical circuit (Figure 8). Only one sideband is necessary for demodulation; but the demodulation of suppressed carrier AM requires that the carrier be reconstructed before demodulation can take place.

4.5 Amplifiers: An amplifier is a device that produces at its output an enlarged reproduction (higher level) of the input signal, usually without altering other input signal characteristics. Amplifiers are electronic gain devices to boost the strength of weak signals to a usable level. Amplifiers in carrier systems are used at dc, voice frequency and carrier frequency. Figure 9A illustrates a simple transistor amplifier. The integrated circuit operational amplifier (op amp) as illustrated in Figure 9B is more frequently encountered in modern electronic systems. (Note: The op amp is a versatile device used for a variety of purposes including amplification, signal comparison, etc.)

4.6 Hybrid Circuits: In telephony, a hybrid circuit is a 4-wire to 2-wire termination set or signal combiner. The term hybrid generally refers to combining or mixing in some form. In electronics, hybrid refers to the combining of technologies such as vacuum tubes and transistors, thin film and discrete integrated circuits, etc. In this text, hybrids and hybrid circuits refer to signaling combining. Most often, it refers to one-coil and two-coil hybrid transformer circuits.

4.6.1 A wheatstone bridge circuit (Figure 10A) is used to illustrate the function and characteristics of a hybrid circuit. If all resistors are equal, the wheatstone bridge is "balanced" and no oscillator signal (or minimum signal) reaches the voltmeter or detector. The same is true when the ratio of R1/R3 is equal to R2/R4. This is a simple hybrid circuit where R1 and R2 are the hybrid, R3 is the balancing network and R4 is the 2-wire line circuit. The oscillator represents the carrier demodulator and the voltmeter represents the carrier modulator. R1 and R2 (hybrid) are generally equal, and R3 (balancing network) is adjusted to match R4 (2-wire line) for minimum signal into the voltmeter. R3 and R4 are actually complex impedances rather than resistors.

4.6.2 The similarity or difference between two impedances may be expressed in several ways. Impedance ratio is an expression that recognizes the impedance magnitude relationship, but excludes the impedance phase relationship. Return loss (RL) is the method chosen in telephony to compare both the magnitude and phase relationships of two impedances. Return loss is expressed in decibels (dB), and can be readily calculated and measured. Return loss is calculated:

$$RL\ (dB) = 20 \log \left| \frac{Z1 + Z2}{Z1 - Z2} \right|$$

A comparison of 600 and 900 ohms (Z1 = 600 ohms and Z2 = 900 ohms) yields 14 dB return loss. This can be readily measured by using a test hybrid as illustrated in Figure 10B. The degree of match or balance between Z1 and Z2 determines the voltmeter reading, or return loss. A perfect match of Z1 and Z2 yields infinite return loss (no voltmeter reading). Z1 of Figure 10B (balancing network) is the same as R3 of Figure 10A. Z2 of Figure 10B (line) is the same as R4 of Figure 10A.

4.6.3 A two-coil hybrid is used to more specifically illustrate the function of the hybrid in a carrier circuit (Figure 10C). The object is to choose a balancing network to match the 2-wire line impedance and minimize the signal from the demodulator that "spills" across the hybrid to the modulator to be transmitted back to the distant end. Signals that spill across the hybrid result in echo or other degrading characteristics at the originating distant end. A balancing network is chosen to approximate the 2-wire line impedance. One standard balancing network is 900 ohms in series with 2.16 microfarads, and is called a compromise network. Maximum signal will cross the hybrid from the demodulator to the modulator if the line is open or short circuited. This maximum signal at the modulator is considered a "reference". A typical reference is 7.0 dB loss across the hybrid, or 3.5 dB for each transformer. Any improvement or loss of signal below this reference reflects the balance or match between the network and line, and is expressed as trans-hybrid balance which is similar to return loss. (Return loss is actually an input impedance measurement that considers both near end and far end effects.) If the network and line are matched, the current from the demodulator into the network and line are equal. This results in equal currents in L2. Note that the phase of coil windings in L2 are opposite. Since L2a and L2b are equal and opposite, the currents cancel and no signal is induced across L2 into the modulator. The degree of match between the network and line determine the transhybrid balance. The network and line are complex impedances and both magnitude and phase angle of these impedances determine the transhybrid balance.

4.6.4 The input or terminal impedance of a carrier hybrid (measured and expressed as return loss) is determined by the modulator and demodulator impedance and the hybrid coil turns ratio. The modulator and demodulator act in parallel to terminate a signal entering the hybrid from the 2-wire line. The near end balancing network has an insignificant effect on the input impedance of the hybrid unless the modulator and demodulator impedances are severely mismatched. (The match between the network and line at the far end affect the near end input impedance and return loss.)

4.6.5 Proper carrier system hybrid design is important to minimize echo, singing and other degrading characteristics in the telephone network. Echo is a problem only on long distance circuits. However, a local trunk or subscriber carrier with poor terminal impedance characteristics may cause echo problems when it is connected to long distance circuits. Therefore, each part of the telephone system must be designed to certain standards to provide good service in the telephone network.

4.6.6 Figure 10D illustrates two subscribers connected by a carrier system (assume a long distance between subscribers). The degree of match (transhybrid balance) between the network and line at the West terminal determines the talker echo for the East subscriber. (Talker echo occurs when the talker hears an echo of his own voice.) Likewise, the network and line match at the East terminal determines the talker echo for the West subscriber. Listener echo can occur only if the transhybrid balance is poor at both ends. (Listener echo occurs when the listener hears the talker plus an echo from the talker.)

4.6.7 The input or terminal impedance of the hybrid is important because the local carrier system becomes the terminating impedance of other links such as a long distance carrier system. If the path between the East and West terminal is open or broken, the input impedance is entirely a function of the modulator and demodulator impedance and the turns ratio of the hybrid coils. With the completed path between the terminals, this basic hybrid input impedance is modified by the signal returning form the distant end. Thus, the final input impedance of East terminal is a function of the (a) loss from East to West, (b) transhybrid balance at the West terminal, and (c) the loss from West to East. The return signal acts to partially add to or cancel the original signal, modifying the basic input impedance. These effects can readily be verified by return loss measurements.

4.7 Compandors: A compandor is an abbreviated term for a compressor and expandor. A compandored carrier system utilizes a compressor on the transmitting end and expandor on the receiving end of each channel. Compandors are used in analog carrier systems to improve the channel noise and crosstalk performance. Analog compandors operate at a syllabic rate, on syllables of speech. Syllabic compandors used in analog systems should not be confused with instantaneous compandors used in digital transmission systems. (The instananeous compandor in digital systems is used to achieve nonlinear encoding.)

4.7.1 Compandors improve the channel noise during quiet periods and improve the signal-to-noise (S/N) ratio during speech periods. The expandor portion of the compandor acts to reduce noise and crosstalk. During quiet periods when both parties are listening, the noise and crosstalk must be kept at very low levels to avoid customer complaints. The worst type of crosstalk is intelligible crosstalk where speech from other channels or systems can be heard and understood. The compressor acts to improve the speech S/N ratio by compressing a wide range of speech levels into a narrower range of levels. In effect, the weak speech levels are boosted before modulation takes place. While talking on a channel, the noise can increase considerably before it becomes disturbing. The controlling factor becomes S/N, and not noise alone. A S/N ratio of 25 to 30 dB is generally sufficient for high quality speech transmission.

4.7.2 Figure 11 illustrates how a compandor reduces noise. In this illustration, a 60 dB range of speech is compressed into a 30 dB range (2 to 1 compression). With 0 dB (not necessarily 0 dBm) as a high level reference, 0 dB signal levels remain unchanged by the compressor. All lower level signals are compressed on a 2 to 1 basis. A -20 dB signal becomes -10 dB, -40 dB becomes -20 dB, etc. At the distant end, the expandor returns the signals to their original level. The compandor must "track" or compress and expand equally over this range of speech levels to restore the original signal. Noise and crosstalk interference are of greater concern after modulation (thus, after compression) than before modulation. A high level noise of 40 dB below full modulation (i.e., 0 dB) is used to illustrate compandor advantage.

4.7.3 A speech signal at -20 dB is compressed to -10 dB. This results in 30 dB S/N ratio over the -40 dB noise level. Without compression, the S/N would only be 20 dB. Thus, the compressor has provided a 10 dB S/N improvement. At the receiver, the expandor restores the speech level to -20 dB. The compandor operates at a syllabic rate. That is, the compression and expansion change as a function of the composite power in each syllable of speech. During speech, the expandor's role is to restore the speech to its original level. The expandor serves no other function during speech.

4.7.4. During the quiet period (both parties listening), the compandor provides maximum compression and expansion. The -40 dB noise is expanded by 30 dB to -70 dB. This would be measured as 20 dBrnc0 noise (C-message weighted noise referenced to zero level). Without the expandor, the noise would measured -40 dB, or 50 dBrnc0. The compressor serves little purpose during this quiet condition. It is the expandor that provides the channel noise improvement during the quiet period. The 30 dB improvement illustrated in this example is typical.

4.8 Level Regulation: Regulation is required in carrier systems to maintain carrier frequency, voice frequency and signaling levels within certain operating ranges. Regulation is often accomplished by dc feedback rectified from a demodulator or amplifier output. It is often called inverse automatic gain control (IAGC) because it is a negative or inverse feedback component used to control the gain of an amplifier. Through the use of IAGC in modern semiconductor components, installation and maintenance adjustments have been minimized or eliminated.

4.8.1 Two major areas where gain adjustments have not been completely eliminated are the setting of voice frequency net loss and analog repeater gain and slope. Voice frequency net loss adjustments remain in trunk carrier systems to allow for flexibility; loss adjustments have been minimized or eliminated in most types of subscriber carrier equipment. While gain adjustments have been minimized in carrier repeaters, some form of gain and slope adjustment is still required on long haul analog carrier systems to compensate for the cumulative effects of level variation.

4.8.2 Perhaps the major use of IAGC is to maintain a constant voice frequency level or net loss. Figure 12 illustrates how this might be accomplished by combining the simple AM demodulator and amplifier discussed earlier. The demodulated carrier signal contains rectified dc as well as voice frequencies. The dc is fed back to change the bias of one or more transistor amplifier circuits, which changes the amplifier gain. A strong incoming carrier signal provides a large rectified dc to reduce the amplifier gain. A weak incoming carrier signal provides a smaller dc which allows the amplifier gain to increase. This provides an automatic gain control through the use of feedback.

4.9 Signaling: Since a carrier system transmits information in the form of modulation, functions such as off hook, on hook, dial pulses and ringing must be converted into signals to modulate the carrier before transmission. Signaling transmission requires only status recognition, and does not need the wide dynamic range and low noise required for voice frequence transmission. Thus, signaling and voice modulation are handled separately over a common transmission medium. Central office signaling and supervision functions are recognized by the carrier channel, converted into an efficient modulation form, transmitted to the distant carrier terminal, detected and regenerated. The key point is that the function is regenerated. A carrier system can regenerate a signal or function only if it falls within the design capability of the carrier system to identify and transmit the signal. Certain interface criteria must be established for proper recognition, transmission and regeneration of signaling functions. The following is a brief description of several signaling functions and common methods of transmitting those functions over analog trunk and subscriber carrier systems.

4.9.1 Modulation: The most common methods of carrier modulation for analog transmission of signaling functions are direct modulation, inband tones, out-of-band tones, carrier interruption, and separate paths. These techniques may be used individually or in combination.

4.9.1.1 Direct Modulation: Ringing is sometimes reduced in level and modulation directly on the carrier without translation. Direct modulation of ringing is a simple method of providing ring frequency identification for multiparty frequency ringing. Direct modulation is often used in combination with another technique to minimize false ringing.

4.9.1.2 Inband Tones: Inband tones are keyed or turned on and off and applied directly to the voice frequency terminals of the carrier. The inband tones must be within the voice frequency passband of the carrier, generally between 500 and 3000 hertz. The most common frequency is 2600 hertz applied on a 4-wire basis only (also called SF signaling). Two (or more) frequencies must be used for signaling in both directions over 2-wire circuits; 2400 and 2600 hertz are the most common frequencies. Inband signaling may be an integral part of the carrier system, or may be applied externally to the modulator and demodulator (4-wire). Inband signaling units are complex devices designed to guard against false signaling and talk-off from the subscriber's voice conversation. During the dynamic conditions of speech transmission, the inband signaling receiver will not respond to a signaling frequency tone (i.e., 2600 hertz) unless the level of that tone is greater than the composite speech power level. The voice circuit generally cannot be properly measured with a single frequency tone slowly swept across the passband. A notch in the bandpass response will generally be measured near the signaling frequency unless another guard tone is also transmitted. This notch is to keep the inband signaling tone from being transmitted beyond the signaling receiver. Inband signaling is generally used to transmit off-hook and on-hook status, but is sometimes used to transmit ringing and other information.

4.9.1.3 Out-of-Band-Tones: When out-of-band signaling is used, it is usually an integral part of the carrier system design. Out-of-band signaling units utilize frequencies above 3200 hertz, usually between 3700 and 3900 hertz. The signaling frequencies are modulated on the carrier, but are kept separate from the voice passband by filters. Out-of-band signaling units are less complex and less costly than inband signaling.

4.9.1.4 Carrier Interruption: Carrier interruption provides a simple and inexpensive method of transmitting signaling information for subscriber carrier. It is generally limited to the transmission of on-hook and off-hook status (including dial pulsing) from the subscriber terminal where carrier is transmitted only in the off-hook condition. A received carrier at the central office terminal is converted into a loop closure to seize the central office equipment. Interruption of carrier is avoided if carrier is used for repeater regulation. (In subscriber carrier, repeaters may be regulated in both directions by using carrier from the central office direction only. This allows for carrier interruption from the subscriber direction.)

4.9.1.5 Separate Paths: The trend is toward separate transmission paths for trunk carrier signaling. The signaling for a large number of channels is multiplexed on a common channel. This is called common channel interoffice signaling.

4.9.1.6 Miscellaneous: The use of multiple tones, frequency shift keying, or phase shift keying may also be used to transmit signaling and/or data information. Inband tones, out-of-band tones and carriers are used in this manner. In frequency shift keying, only one of two tones or carriers are present (keyed) at one time. Multiple tones may be used independently for signaling or data transmission. Phase shift keying is where a single frequency is used and the phase is abruptly changed (i.e., 90° or 180°) to transmit information.

4.9.2 Detection and Regeneration: The detection and regeneration of dc signaling and ringing functions are primarily discussed. Similar principles apply regardless of the modulation and transmission techniques used. Trunk carrier primarily requires the detection and transmission of dc functions in both directions. Subscriber carrier requires the detection and transmission of dc functions in the subscriber to office direction, and ringing in the other direction. Except for brief mention, other signaling functions are omitted in this discussion.

4.9.2.1 DC Signaling: On-hook and off-hook status are easily detected and transmitted at one end, and again detected and regenerated at the distant end. The receiver simply detects the presence or absence of tones, carrier, or other signal and causes the loop to open or close in response to the received signal. E&M signaling in trunk carrier operates in a similar manner. (E&M signaling is discussed in more specific detail in TE&CM Section 905.) Battery reversal is often not transmitted and regenerated in subscriber carrier equipment. For economic reasons, the detection and regeneration of all number identification (ANI) for party lines over subscriber carrier is limited to two-party identification, or omitted entirely.

4.9.2.2 Ringing: Two approaches prevail in the detection and regeneration of ringing in analog subscriber carrier. Where a single ringing frequency (i.e., 20 hertz) is used, the ringing signal is detected and a new ringing voltage is generated by the subscriber terminal. A single ringing frequency can be used for one-party service, and for two-party service by applying the ringing to either the tip side or ring side of the line. Where multifrequency ringing is used, the ringing signal is "amplified" or used to trigger regeneration of the same ringing frequency. The major difference in the regenerated ringing is that single frequency ringing can be regenerated on a common basis and until very recently multifrequency ringing was usually regenerated on a channel basis because of economic and technology limitations. Sine waves could be generated for single frequency ringing but multifrequency ringing was limited to the generation of square waves or variations of square waves. The generation of ringing requires a large quantity of power. The limitations imposed in supplying power to carrier subscriber channels over cable pairs are largely imposed because of ringing power requirements.

4.10 Power Supplies: Several techniques are used to provide dc power to various parts of carrier systems. The techniques primarily used are transformers and rectifiers for ac power, dc-to-dc converters to raise or lower the dc voltage, and dc voltage divider circuits. Because commercial ac power may be interrupted, ac power is generally used in noncritical areas of the telephone system, and to charge batteries. Thus, batteries are generally the primary source of power for carrier systems. The central office battery is used to the maximum practical extent, including power for carrier repeaters and subscriber terminals. Where ac power is used along a cable route for repeaters and subscriber terminals, battery backup is recommended for service reliability.

4.10.1 AC Power Supplies: Through the use of transformers and rectifiers, a wide range of dc voltages can be obtained from a 110 volts ac primary power source. Figure 13A shows a simple ac power supply. Simple or elaborate voltage and/or current control circuits may be added for specific applications. The importance of power transfer efficiency increases in direct proportion with power consumption. Large ac power supplies are generally designed to be more efficient than small ac power supplies (each operated at or near its rated output).

4.10.2 The major use of ac power supplies in carrier systems is to charge batteries. This may range from charging 48 volt high current batteries at carrier subscriber terminals to lower voltages and lower current capacities at subscriber terminals and repeaters. Small energy limiting transformers are sometimes used at subscriber locations to charge small batteries in one channel subscriber terminals.

4.10.3 <u>DC-to-DC Converters</u>: DC-to-dc converters are widely used in carrier systems to raise or lower the primary source dc voltage. Power efficiency is the major reason for this widespread use in carrier systems. Figure 13B illustrates a simple dc-to-dc converter. Modern dc-to-dc converters usually contain elaborate semiconductor circuits to control output voltage and current. These same modern semiconductors have increased the power efficiency and reliability of dc-to-dc converters, and have significantly reduced manufacturing costs.

4.10.4 DC-to-dc converters are used in a variety of carrier system component parts. They are used to provide terminal equipment semiconductors with operating voltages of 5 to 20 volts from primary 48 volt battery supplies. Power for line repeaters (generally +130 volts and -130 volts) is also provided by dc-to-dc converters from 48 volt battery supplies. Earlier carrier systems used larger dc-to-dc converters that were common to many repeatered lines. The trend is toward small individual converters designed as an integral part of the terminal equipment. Analog subscriber carrier terminals and repeaters convert the higher line voltage (+130 and -130 volts) down to semiconductor operating levels (12 to 20 volts), and to charge small batteries through the use of small, highly efficient converters. DC-to-dc converters may also be used in the generation of ringing voltage at carrier subscriber terminals. One unique and recent use of small converters is to boost the battery feed voltage to telephone sets from the voltage normally used within subscriber channels.

4.10.5 <u>Voltage Dividers</u>: Figures 13C and 13D illustrate two simple voltage divider networks used as secondary dc power supplies. Where the equipment load is constant (Figure 13C), a simple dropping resistor (R1) or divider (R1 and R2) are used to reduce the dc supply voltage to the semiconductor operating level. Figure 13D is a variation of the resistive voltage divider; the zener diode keeps the semiconductor operating voltage at a fixed level, even with varying loads. A more modern version would use a semiconductor regulator circuit (consisting of transistors, zener diode, etc.) instead of the zener diode.

4.10.6 The use of voltage dividers as secondary dc power supplies for terminal equipment has been drastically reduced to conserve power. The power dissipated in the dropping resistor is wasted as heat; and more power is generally used to remove the heat (fans and air conditioning). Voltage divider techniques continue to be used where resistance is a natural element in the overall circuit. Specifically, this technique is used to provide power for repeaters in many cable carrier systems. Power to the repeaters is fed over the cable pairs. The cable wire pair resistance and zener diodes within the repeater form a voltage divider power supply. A current control within the repeater power supply maintains a constant current to the line repeaters.

4.11 <u>Repeaters</u>: Carrier repeaters are used to amplify or boost weak signals at intermediate locations between carrier terminals. Carrier signals are attenuated as they travel along a transmission facility. Repeaters are used at periodic intervals along the facility to maintain an adequate carrier signal level. Applied in this manner, repeaters improve the signal-to-noise ratio and reduce the overall system noise and crosstalk (Figure 4A). Repeaters were seldom used with open wire carrier systems, but are used extensively with cable carrier systems. The early significant use of repeaters was in long haul coaxial cable trunk carrier systems. AC power was required at each repeater location. The development of solid state amplifiers using transistors and the trend from open wire to cable in exchange facilities about 1960 led to extensive use of repeaters for both trunk and subscriber carrier systems.

4.11.1 This discussion is limited to repeaters designed for exchange cable application; the principles are the same or similar for other applications (i.e., coaxial or other special cables). The less complicated four-wire (one-way) repeaters are discussed first. This is followed by a discussion of two-wire (two-way) repeaters. Note: One-way and two-way refer to one-way or two-way transmission over a single cable pair.) A two-wire repeater is essentially a four-wire repeater with additional input and output bandpass filters.

4.11.2 A basic four-wire line repeater is illustrated in Figure 4B. It consists of an equalizer network and broadband amplifier in each direction of transmission plus a power supply common to both directions. Cable carrier repeaters of this type were usually designed for about 20 to 25 dB line spacing at the highest carrier frequency. Utilizing a specialized test set, the equalizer was adjusted to compensate for the cable loss versus frequency (slope) characteristics of the cable section facing the repeater input. The cable section line loss plus the equalizer loss resulted in a total loss that was essentially flat with frequency. The overall repeater gain was set either in the equalizer networks (with a fixed gain amplifier), or in the amplifier. Some repeaters were nonregulated, but most contained automatic gain control feedback for regulation. The repeater may be regulated by a single pilot tone, or by the composite signal power of all carriers in the group. Power for the repeater electronics is obtained using the voltage divider principle (Figure 4B and 4C). Constant current power is applied on a simplex basis; the tip and ring conductors of a cable pair are dc short circuited by transformers. Power is fed out on the transmit side, looped at a convenient point, and returned on the receive side. As the current passes through the repeater, a zener diode provides a fixed voltage to operate the repeater electronic components.

4.11.3 For longer range paired cable carrier systems, a more complex four-wire repeater is used. This repeater is often called a "frequency frogging repeater". The N type carrier repeater (Western Electric or Independent manufacturer equivalent) is representative of a frequency frogging repeater and will be used to illustrate the process. Figure 4D illustrates one-half of an N-type repeater and Figure 4E shows the N3-type carrier frequency allocation. In addition to the equalizer, amplifier and power functions, this repeater also converts the input frequency band into a different output frequency (frequency frogging). The repeater is called a low-high repeater or a high-low repeater in reference to an up-conversion of frequencies or down-conversion of frequencies. A hetrodyne (beat frequency) process is used to translate the 36 to 140 kHz low band into the 164 to 268 kHz high band, or in the reverse direction. The lowest frequency (36 kHz) becomes the highest frequency (268 kHz), etc., as each frequency is converted into a mirror image about a center frequency of 152 kHz. This frogging or translation of frequencies is used to minimize crosstalk and to provide partial cable loss equalization. Crosstalk is reduced by maintaining a frequency separation between the low level incoming signals and the high level outgoing signals. This eliminates crosstalk through tertiary paths at repeater locations. Frequency translation also provides equalization to partially offset the frequency-dependent loss characterics of the cable. The "average" loss of two cable sections is essentially the 152 kHz loss because the "average" frequency of the high and low frequency of any channel is 152 kHz. Cumulative varitions in loss versus frequency do occur, and are corrected by equalizers in each repeater. Bandpass filters are required at each input and output to remove all but the desired band of frequencies after the hetrodyne process.

4.11.4 For practical reasons, two-wire repeaters are generally limited to analog subscriber carrier (i.e., station carrier). Figure 4F illustrates a two-wire analog subscriber carrier repeater. The two-wire repeater is similar to the basic four-wire repeater, but more complex. Input filters are essential to separate frequency bands for proper direction of transmission. Carrier frequency hybrids are generally used at repeater inputs and outputs to aid in the separation of transmission direction; the use of hybrids can reduce filter rejection requirements by 12 to 15 dB. Powering for repeater electronics is likely to be accomplished by dc-to-dc converters bridged across the two-wire transmission path (since four wires are not available for simplex power loop). To conserve power, analog subscriber carrier systems generally do not transmit carrier signals from the subscriber channels while idle. Thus, repeater regulation (IAGC) for both directions of transmission is generally determined by the carrier signals transmitted by the central office channels.

4.12 Protection: Carrier equipment protection is an extension of a philosophy and practice of telephone system protection. Carrier protection must first include considerations for the safety of the general public and telco personel, and also provide for the protection of electronic equipment from damage. Electrical protection of carrier equipment is covered in some detail in TE&CM 822. Only brief highlights of equipment protection are discussed here to illustrate the principles involved. To the maximum practical extent, electrical surges should be diverted away from sensitive electronic equipment. This is accomplished by cable shield continuity, common bonding, grounding, partial isolation, dielectric strength, high voltage arresters, current limiting devices, and low voltage protection.

4.12.1 The multilevel protection incorporated into a carrier repeater serves as an example of the electrical protection used with a wide variety of electronic equipment. This is illustrated in Figure 4B. High voltage gap devices (A) are used to limit the voltage across the line terminals. These are usually 350 volt 2 element or 3 element gas tubes. Series resistors (B) provide current limiting for lightning and electric system fault currents flowing through the repeaters. These resistors are usually 5.6 ohms each. Low voltage limiting devices (C) are placed across the input and output of sensitive electronic circuits. These are usually zener diodes or varistors. The high voltage gaps and series resistors are coordinated; as the surge current through the repeater increases, the series resistors provide enough voltage drop across the repeater to activate the high voltage protector gaps which bypass large surge currents around the repeater or to ground. Voltage differences at repeater inputs and outputs (due to current differences in tip and ring conductors) are low voltage limited or clamped to minimize damage to sensitive electronic circuits within the repeater.

4.12.2 Central office buildings are "cluster" locations for carrier and other electronic equipment. Protection is applied on a coordinated basis for the various types of equipment at that location. Increased emphasis is placed on low earth ground resistance and connections to the power system multigrounded neutral (MGN). High voltage gap protection for the carrier equipment may be part of the main distribution frame (MDF) protection, or may be separate intermediate distribution frame (IDF) protection or carrier protection panels. All high voltage gap protection should be located at the cable entry point to keep electrical surges away from sensitive electronic equipment (i.e., microprocessors, electronic switching equipment, etc.). TE&CM Section 810 covers electrical protection and grounding at central office locations in some detail.

4.12.3 Carrier subscriber terminals range from individual channels to large cluster locations, perhaps installed in buildings. Thus, carrier subscriber terminal protection may range from techniques similar to repeater protection to more elaborate techniques similar to central office protection.

5. CARRIER SYSTEM MODEL

5.1 The individual carrier components are now combined to form a carrier system. A 12 channel trunk carrier system using amplitude modulation, double sideband with transmitted carrier (AM DSBTC) for each channel is used as a model (Figure 3). This 12-channel model is simplified, and does not closely represent any existing carrier system. The illustration shows the components for a single channel, including the common equipment. The 12 channels are combined with the common equipment to form a system. Channel frequencies for both directions of transmission are illustrated. Figure 4B illustrates the four-wire line repeater. Perhaps the best way to illustrate how the carrier building blocks are combined is to trace a signal through the system.

5.2 Refer to Figure 3. Voice frequency signals from the central office equipment trunk circuit enter the carrier system voice frequency hybrid. A hybrid is a signal splitter and combiner, a two-wire to four-wire converter. The voice signals then enter the compressor. (The compressor and expandor form a compandor which aids in noise reduction.) The wide range of voice (speech) signal levels are compressed into a narrower range by the compressor. In effect, the compressor boosts the weak signals. The compressed voice frequency signals enter the modulator along the signaling information (tones). Beyond the modulator, all signals are carrier signals. The system applies a 3700 hertz out-of-band tone to the modulator when the channel is idle, and removes the tone when the channel is in use (seized). This is called tone-on-when-Idle. Central office battery applied to the carrier "M" lead causes the tone to be removed. Hookswitch and dialing information is transmitted by the 3700 hertz tone. (Central office signaling interfaces are discussed in more detail in TE&CM Section 905.)

5.3 A carrier frequency oscillator (i.e., 20 kHz for this channel) is fed into the modulator and mixed with the voice frequency signals (approximately 250 to 3400 hertz) and the signaling oscillator (3700 hertz). The output of the modulator is 20 kHz $\pm$ 3.7 kHz, or a range of 16.3 to 23.7 kHz. This carrier signal is amplified and passed through a bandpass filter to remove all signals outside the range of 16.3 to 23.7 kHz.

5.4 All 12 channels are joined at a common point beyond the bandpass filters. This stage usually contains a broadband amplifier for all channels to be transmitted. It may also contain a bandpass filter and selectible attenuator pads and loss-slope shaping networks at the output for matching the cable characteristics. The output signals are applied to the cable facility through a carrier frequency repeating coil, or transformer. The major purposes for this transformer is to apply simplex dc power for repeaters, and to isolate the carrier electronics from surges and 60 hertz induction.

5.5 The carrier signals are divided into two groups. The low group frequencies range from 20 to 108 kHz carriers with upper and lower sidebands for each carrier. The high group frequencies are 124 to 212 kHz plus sidebands. The low group is assigned to transmit in one direction (i.e., East to West, or E-W) and the low group in the other direction (W-E).

5.6 The low group signals travel from the East terminal over cable to the first repeater location (Figures 4A and 4B). The weak signals enter the repeater East input, pass through a transformer to an equalizer network. The equalizer is a loss-slope network to compensate for the nonlinear attenuation versus frequency characteristics in the cable. The lower carrier frequencies are attenuated less than the higher frequencies in the cable. The network is adjusted so that the loss in the preceeding cable section <u>plus</u> the network loss equals a fixed loss value that is uniform (flat) at all frequencies. The signals are then fed into a broadband amplifier where all signals are amplified to a predetermined output level. The output levels of the terminal equipment and repeaters may be uniform or flat with frequency, or the levels may be "tilted" to compensate for the cable attenuation slope. Since the cable loss is higher for high carrier frequencies, the high frequencies may transmitted at a higher level to maintain a more uniform signal-to-noise ratio for all frequencies. The repeater output signals are then fed through a transformer into the cable (West output). The signals travel down the cable to the next repeater and the amplification process is repeated until the signals are separated and demodulated by the distant (West) terminal.

5.7 High group carrier signals are transmitted from the West terminal through the cable and repeaters to the input of the East terminal (Figure 3). The signals are passed through the input transformer into a unit (perhaps an amplifier) where the signals are fed into 12 channel bandpass filters. The channel 1 filter allows the 124 kHz carrier plus sidebands to pass (120.3 to 127.7 kHz). The signal is amplified and fed into the demodulator. The output of the demodulator is generally separated into three parts. A low-pass filter (cutoff at about 3400 hertz) separates the voice (speech) information. A 3700 hertz bandpass filter (narrow passband) separates the signaling tone. The demodulator also provides a rectified dc feedback signal to the previous amplification stage to provide automatic gain control for the channel. After the demodulated signal is fed through a low-pass filter, it is then passed through an expandor to compensate for the compression on the other end and restore the original speech dynamic range. The voice signal is then passed through a voice frequency hybrid to the central office equipment trunk circuit. After the signaling tone is passed through a narrow 3700 hertz bandpass filter, it is demodulated and amplified to drive a relay. The relay provides (usually) a ground or open condition through the "E" lead connectin to the COE trunk circuit for signaling and supervisory status of the distant COE and carrier terminal.

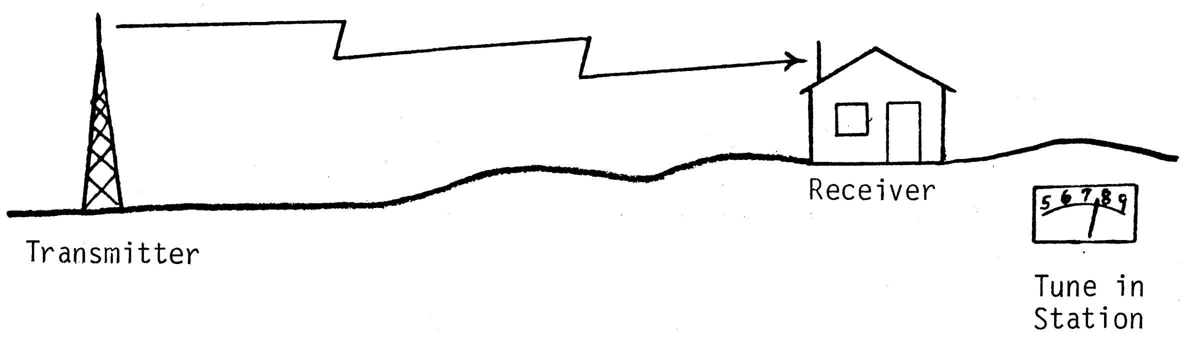
5.8 The carrier terminal contains two power supplies. The local power supply is generaly a dc-to-dc converter to provide a regulated low voltage (i.e., 12 to 14 volts dc) for local channel and common equipment electronic circuits. The repeater power supply is generally a dc-to-dc converter to provide a regulated high voltage (i.e., +130 and -130 volts dc) for line repeaters. The repeater line power is set at a constant current (predetermined by equipment design), and is fed to the repeaters on a simplex loop basis. This is illustrated in Figure 4C. The power is fed out the carrier transmit cable pair, through repeaters, looped at some point along the cable route, and returned on the carrier receive cable pair. As the current passes through the line repeater, a zener diode establishes a constant voltage drop to power the repeater electronic circuits (Figure 4B).

5.9 There are numerous variations in the design of analog carrier systems that have been in service over the past 65 years. These range from simple low density carrier systems applied to exchange cable facilities to complex high density carrier systems applied to radio or coaxial cable. A basic understanding of carrier fundamentals is the key to separating complex systems into simple functional parts.

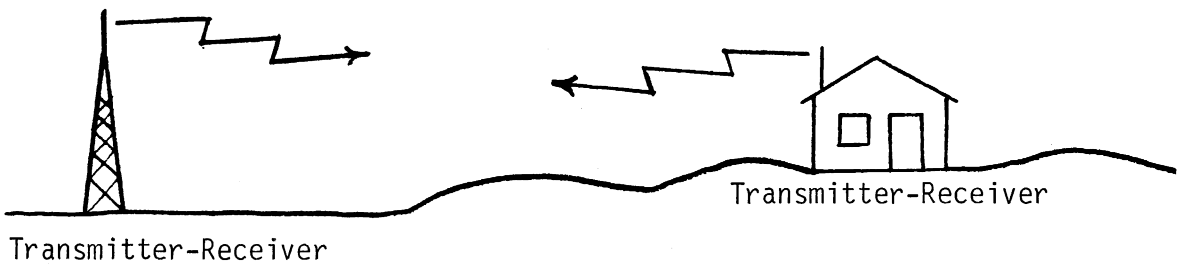
FIGURE 1

CARRIER: RADIO ON WIRE

A. Radio Transmitter and Receiver

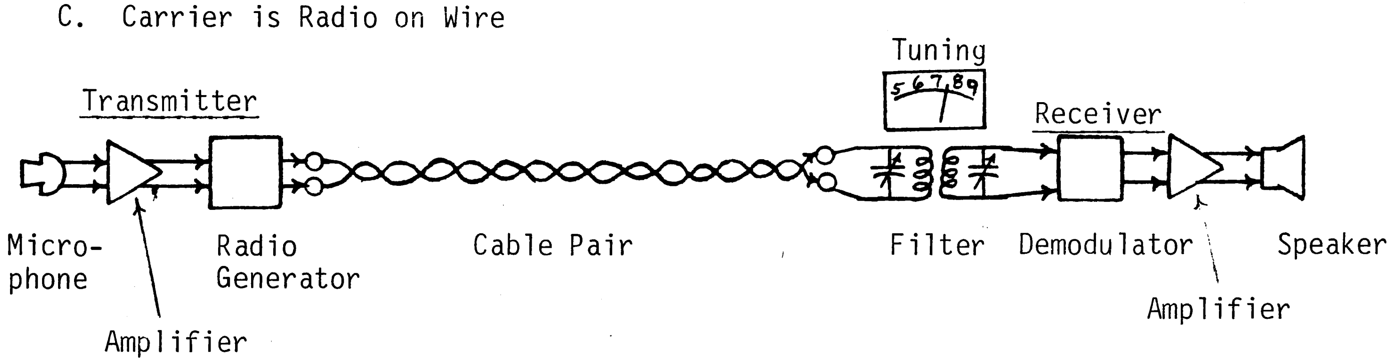


B. Two Way Communications



Two way communications require a transmitter and receiver at both ends.

C. Carrier is Radio on Wire

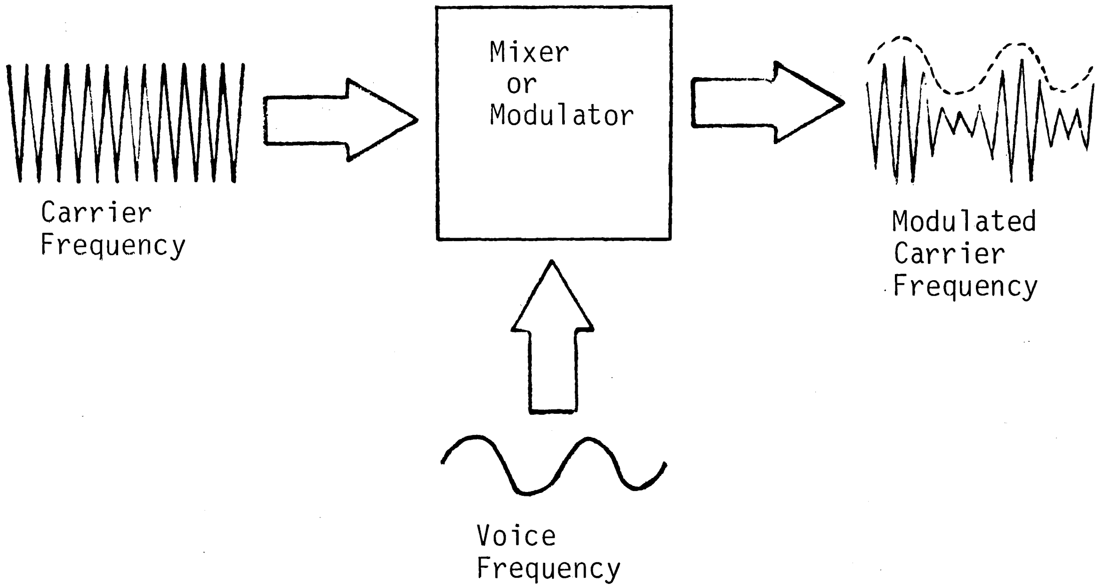


Carrier consists of transmitters and receivers where signals are transmitted over wires rather than air.

FIGURE 2

AMPLITUDE MODULATION

A. Modulation is Voice on Radio or Voice on Carrier



B. 100 kHz Modulated with 1 kHz

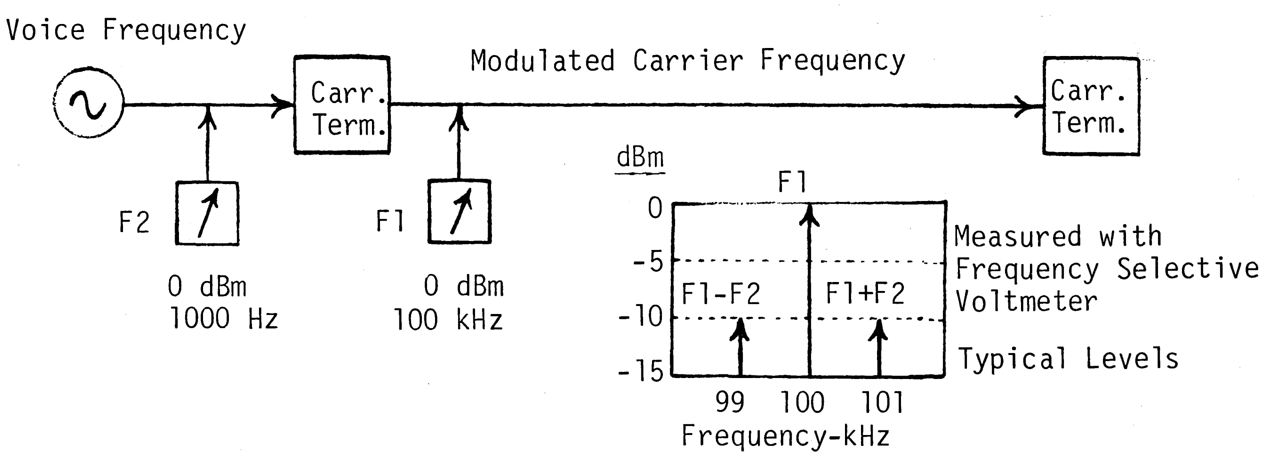
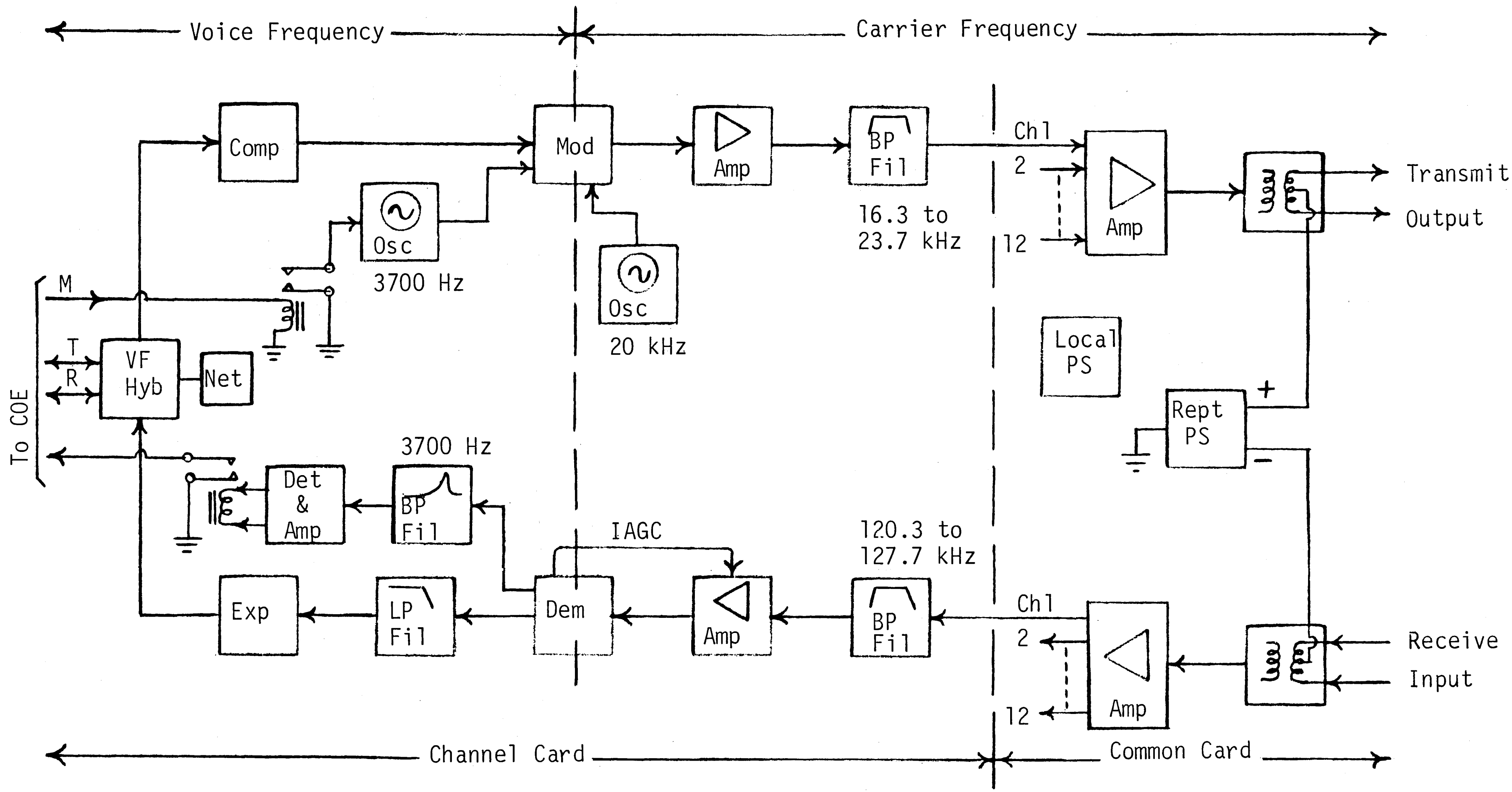


FIGURE 3

ANALOG CABLE CARRIER TERMINAL



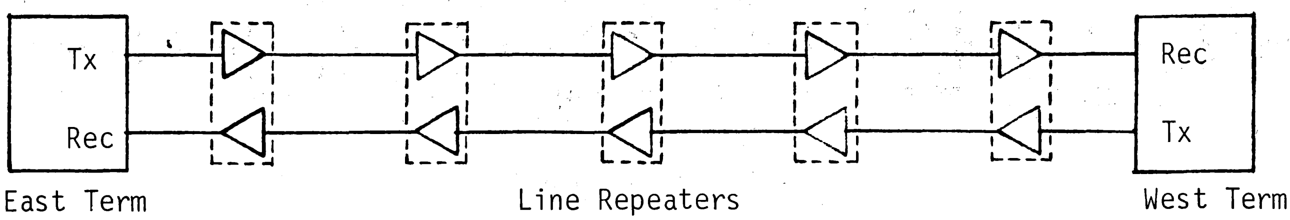
Frequency Allocation

Channel	Transmit	Receive	Channel	Transmit	Receive
1	20 kHz	124 kHz	7	68 kHz	172 kHz
2	28 kHz	132 kHz	8	76 kHz	180 kHz
3	36 kHz	140 kHz	9	84 kHz	188 kHz
4	44 kHz	148 kHz	10	92 kHz	196 kHz
5	52 kHz	156 kHz	11	100 kHz	204 kHz
6	60 kHz	164 kHz	12	108 kHz	212 kHz

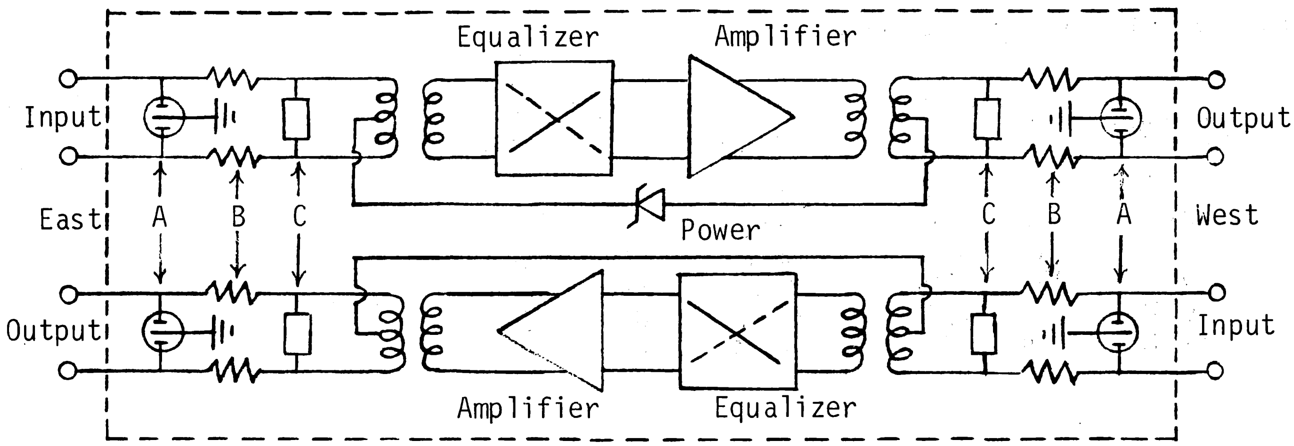
FIGURE 4

CABLE CARRIER REPEATERS

A. Repeatered Line (Four Wire)

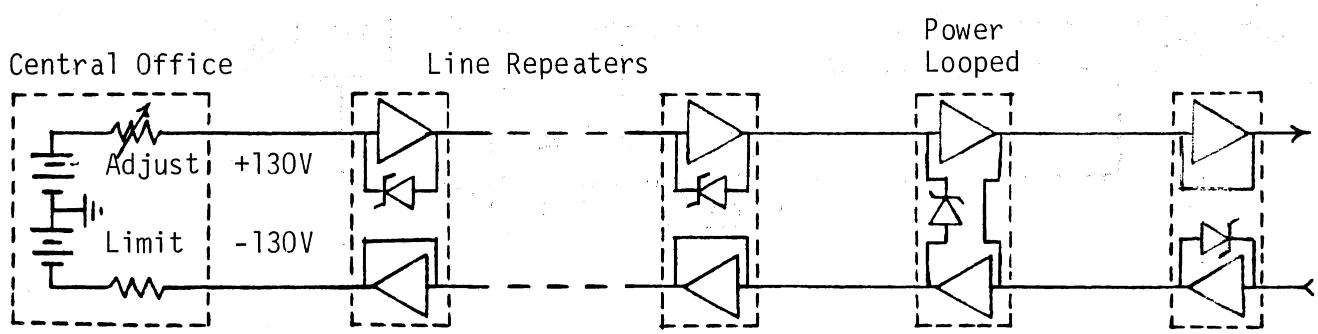


B. Four Wire Line Repeater



Notes: 1. A typical four wire analog repeater consists of two equalizers, two regulated wideband amplifiers, power and protection.
2. The internal power supply consists of a zener diode and a filter capacitor.
3. Protection consists of (A) high voltage gaps, (B) current limiting and (C) low voltage protection.

C. Repeater Power (Four Wire)

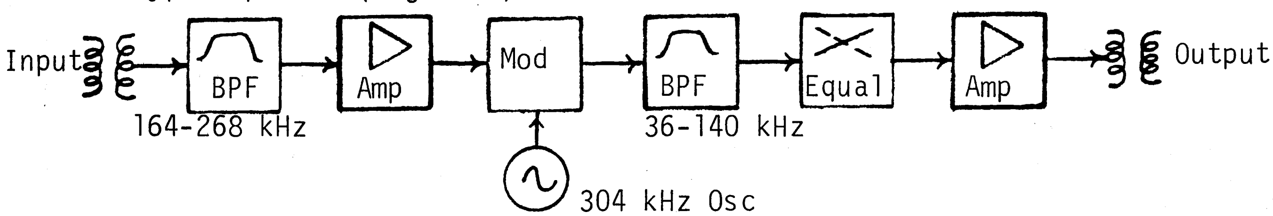


Notes: Line repeaters are generally powered by a +130 and -130 volt power supply that is adjusted to a specified constant current. The line power is fed from each end of the system on a simplex basis to a power loop point and return.

FIGURE 4 - Continued

CABLE CARRIER REPEATERS

D. N-Type Repeater (High-Low)



Notes: One-half of a high-low N-type repeater is illustrated; both sides are the same. A low-high repeater is similar with the band-pass filter frequencies reversed. Power and protection are omitted.

E. N3-Type Carrier Frequency Allocation

Channel	Freq (kHz) Low	Freq (kHz) High	Channel	Freq (kHz) Low	Freq (kHz) High
1-2	128	176	13-14	80	224
3-4	120	184	15-16	72	232
5-6	112	192	17-18	64	240
7-8	104	200	19-20	56	248
9-10	96	208	21-22	48	256
11-12	88	216	23-24	40	264

F. Two Wire Repeater (Subscriber Carrier)

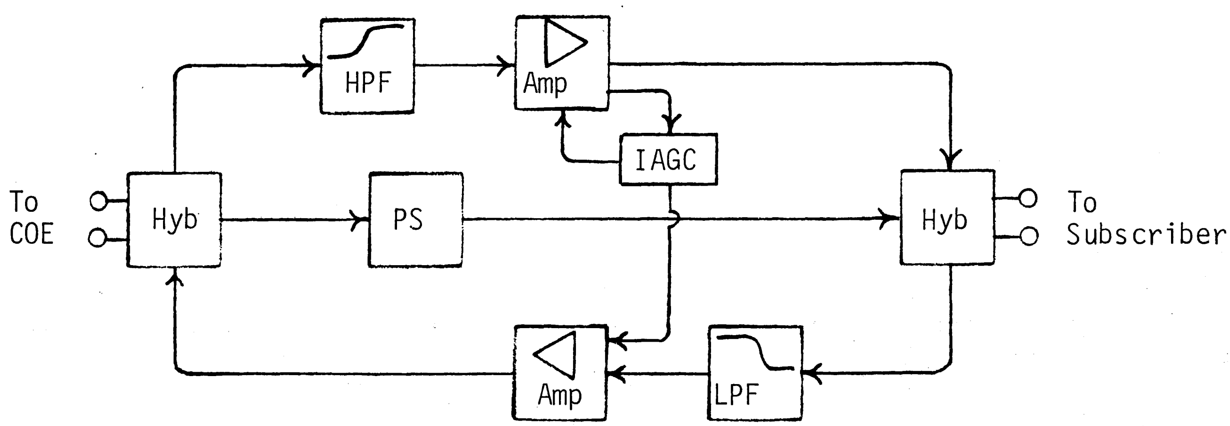
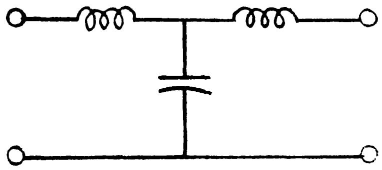


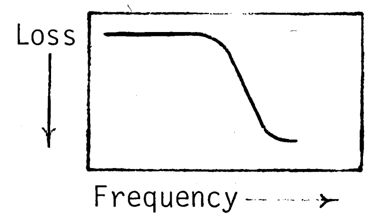
FIGURE 5

FILTERS

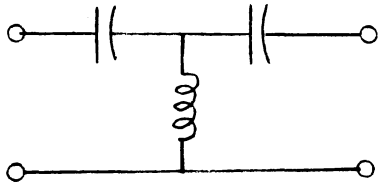
A. Low-pass Filter

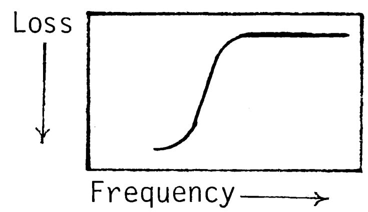


Filter Response (Passband)

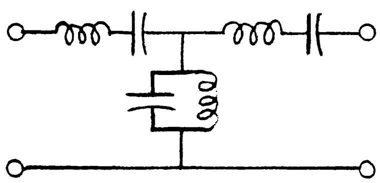


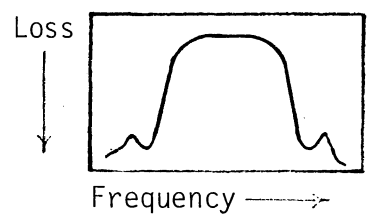
B. High-pass Filter



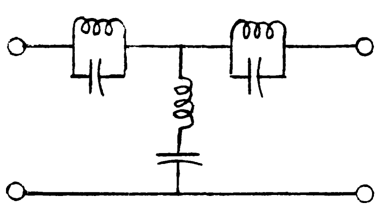


C. Band-pass Filter





D. Band-reject Filter



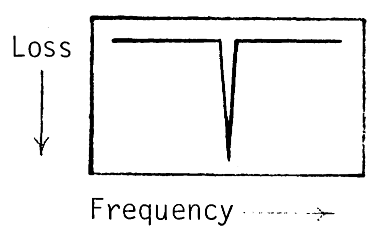


FIGURE 6

OSCILLATOR

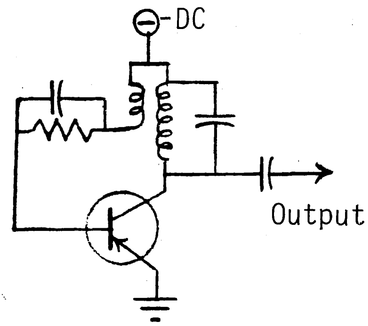


FIGURE 7

MODULATOR

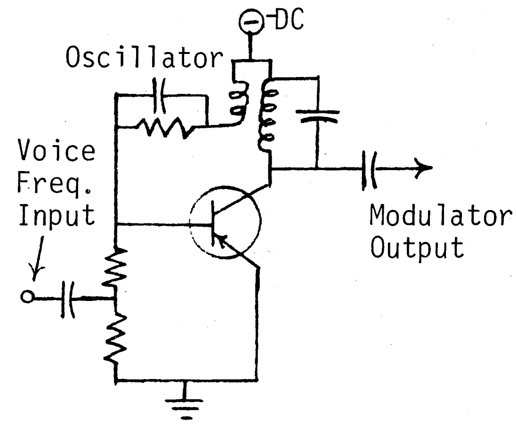


FIGURE 8

DEMODULATOR

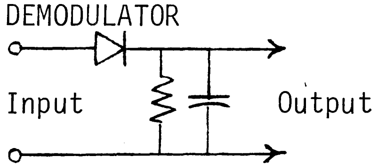
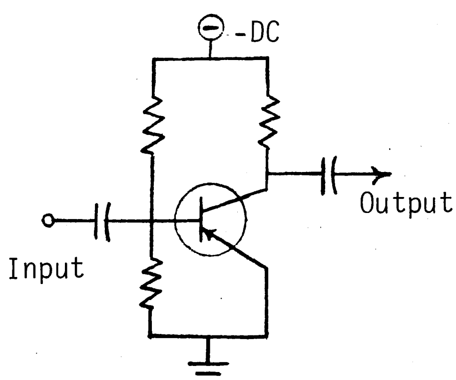


FIGURE 9

AMPLIFIERS

A. Transistor Amplifier



B. Op Amp Amplifier

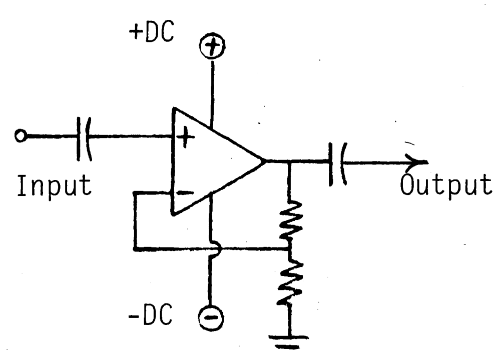
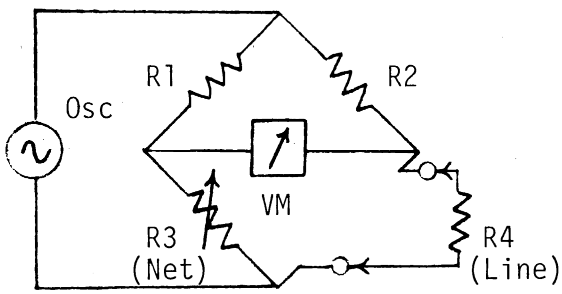


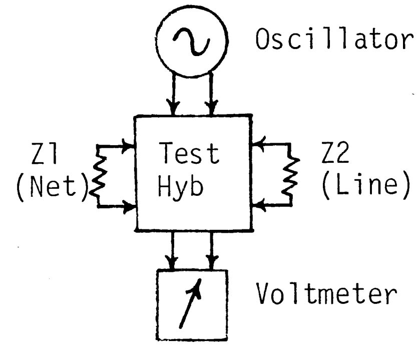
FIGURE 10

HYBRIDS

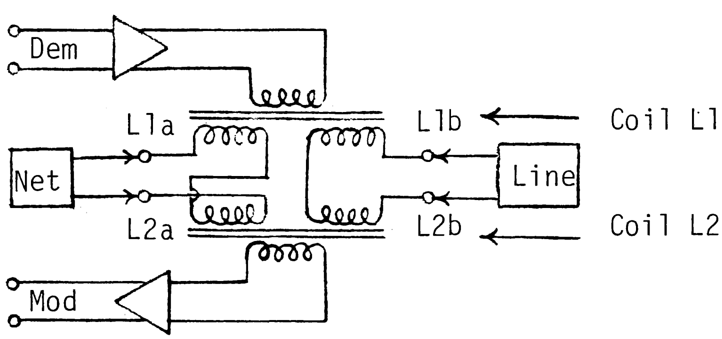
A. Wheatstone Bridge



B. Return Loss Measurement



C. Two Coil Hybrid



D. Echo Paths

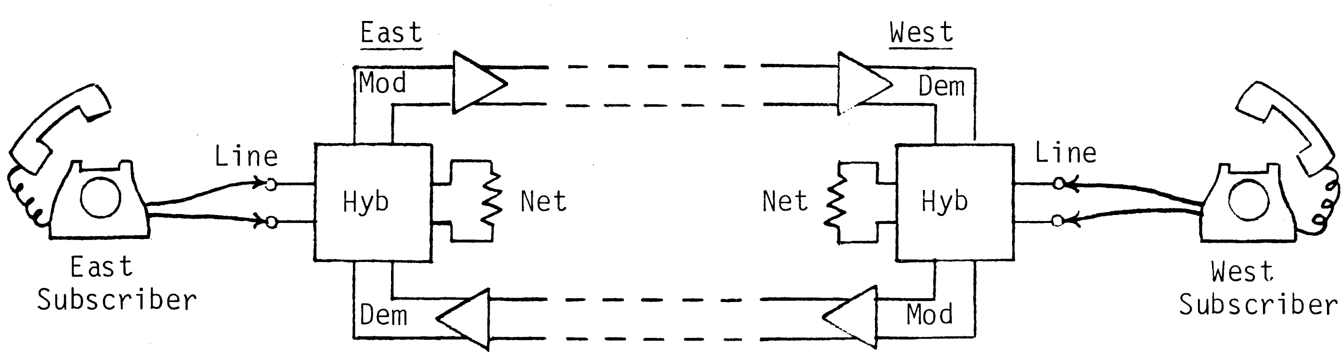
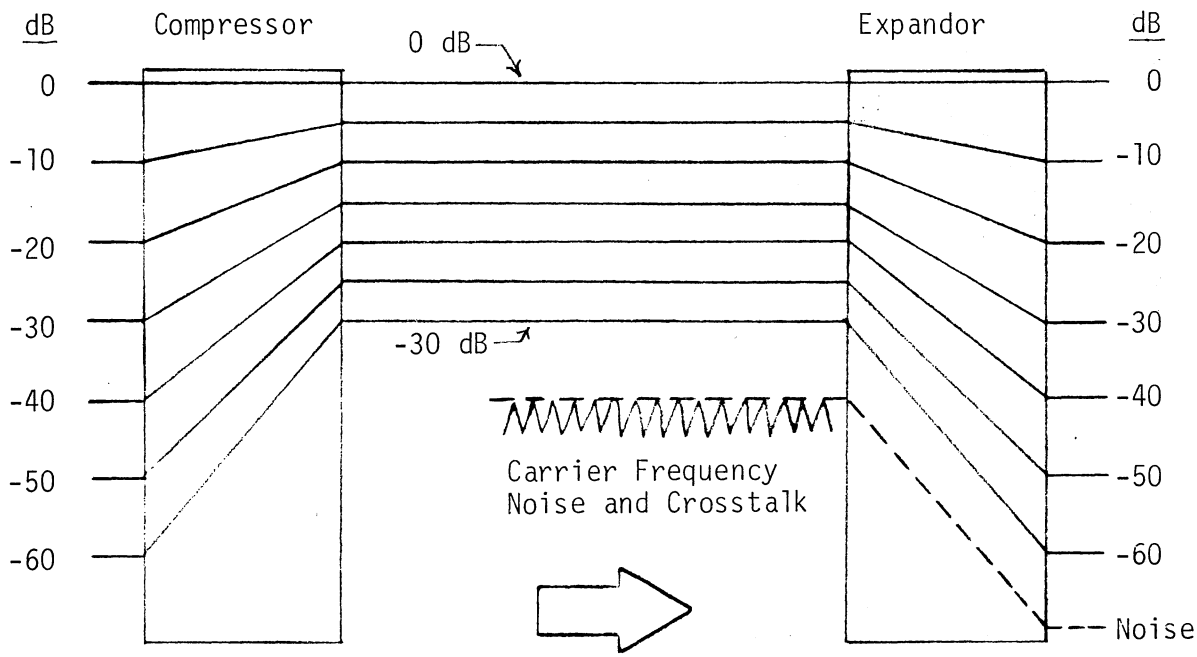


FIGURE 11

COMPANDOR CHARACTERISTICS



A compandor is composed of a compressor on the sending end and an expandor on the receiving end. This compression of speech signals and expansion of speech and interfering noise and crosstalk gives an effective noise and crosstalk advantage.

Compandors in analog carrier systems operate at a syllabic rate and change level as a function of the composite power contained in each speech syllable. Syllabic compandors do not operate on extremely short (instantaneous) peaks of interference.

FIGURE 12

INVERSE AUTOMATIC GAIN CONTROL

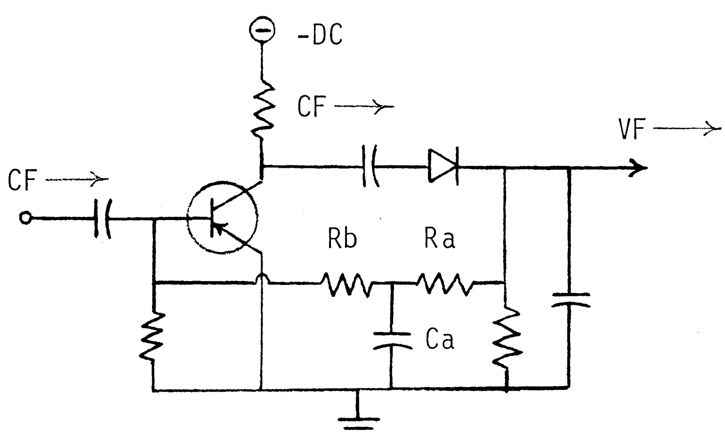
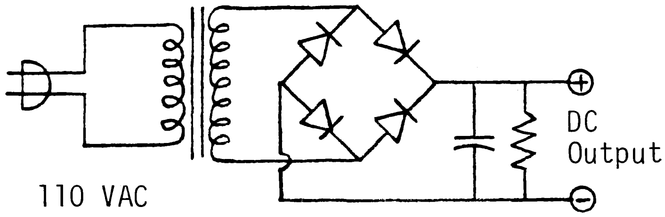


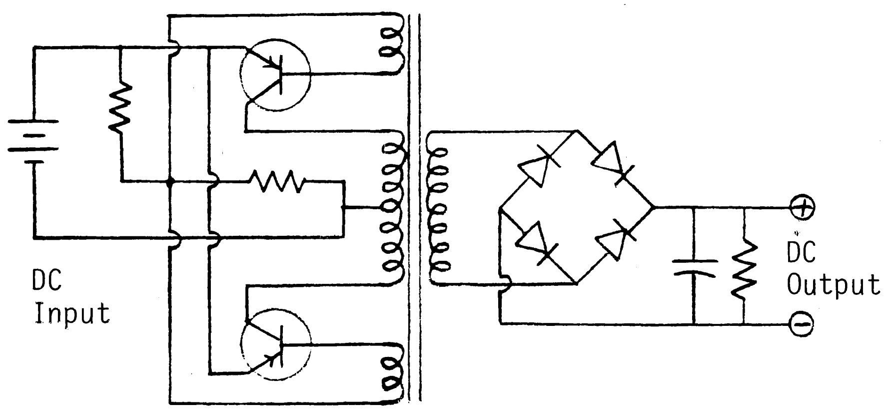
FIGURE 13

POWER SUPPLIES

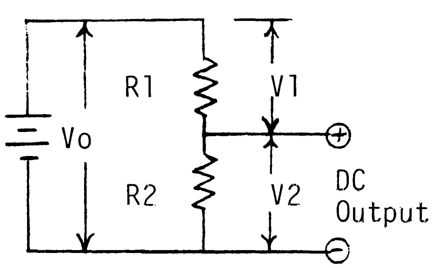
A. AC Power Supply



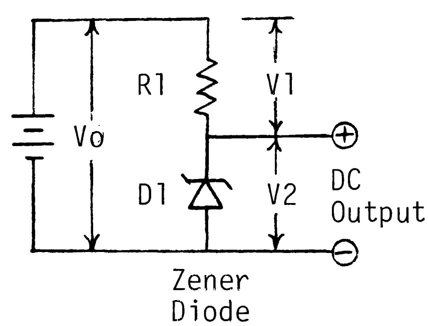
B. DC-to-DC Converters



C. Voltage Divider



D. Regulated Voltage Divider



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