10-3ANALOG-MODULATION FORMATS

In Section 10-1 we investigated the simplest type of analog modulation, transmission of a single sinusoidal current variation.

The analysis illustrates *optic baseband transmission* which the signal is carried on a light beam modulated at the baseband frequencies of the information.

For example, a baseband optic communications link carrying a single voice channel would contain modulation frequencies from a few tens of hertz up to 4 kHz.

Because the optic power varies in proportion to the input current, the term *intensity modulation* (IM) applies.

Intensity modulation differs from amplitude modulation (AM), which is commonly used with radio-frequency carriers.

In AM the amplitude of the carrier (rather than its power) varies in proportion to the information waveform.

Fiber systems almost always use some form of intensity modulation.

An exception, frequency modulation of the optic source, will be discussed in Section 10-5.

Analog formats other than baseband IM exist. For comparison purposes, and to simplify the notation, we will first rewrite Eqs. (10-1) and (10-2) as

$$i = I_o + I_s \cos \omega_m t \qquad (10\text{-}18)$$

$$P = P_o + P_s \cos \omega_m t \qquad (10\text{-}19)$$

I_0 is the total dc current and co_m is the modulation frequency. P_0 is the average optic power. These expressions apply for both LEDs and laser diodes, as will all the equations in this section. In all cases, the current I_0 places the operating point at the appropriate place along the linear portion of the source's power-current characteristic.

1. AM/IM Subcarrier Modulation
2. FM/IM Subcarrier Modulation

AM/IM Subcarrier Modulation

Conventional amplitude modulation places the message on a carrier whose frequency is much greater than any of the frequencies contained in the baseband.

The resulting waveform has a spectrum that surrounds the carrier frequency.

In essence, AM shifts the baseband to a new region of the electromagnetic spectrum.

AM radio stations broadcast at different carrier frequencies, so they can be individually received *on,* in by using filters tuned to the assigned carrier.

After reception, the modulated signals are electronically returned (demodulated) to the original baseband frequencies.

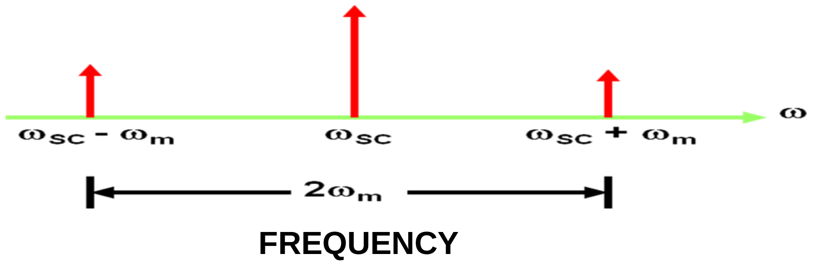


Fig 10.8 Spectrum of an amplitude modulated wave.

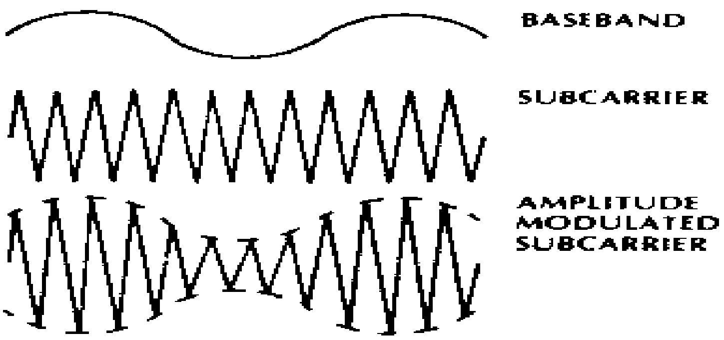
Amplitude modulation of a single sinusoid can be written as

$$i = I_s(1 + m\cos\omega_m t)\cos\omega_{sc} t \qquad (10\text{-}20)$$

where o>$_{sc}$ is the carrier frequency and, to maintain an undistorted signal, /??<!. For 100% modulation, *m* = 1.

The spectrum of this signal appears in Fig. 10-8. We can add a dc current I_0 to the current in Eq. (10-20) and drive an optic source with the result, producing intensity modulation of a light beam by an amplitude-modulated signal. This is AM/IM modulation. Figure 10-9 illustrates the waveforms. AM/IM modulation generates optic power.

$$P = P_o + P_s(1 + m\cos\omega_m t)\cos\omega_{sc} t \qquad (10\text{-}21)$$



Frequency-Division Multiplexing

By using subcarrier modulation, several messages can simultaneously travel along the fiber.

Each message must modulate a different sub-carrier, and the subcarriers must be so far apart that the spectra of adjacent channels do not overlap. Overlapping spectra produce crosstalk.

Referring to Fig. 10-8, we see that each channel occupies a bandwidth equal to twice the highest modulation frequency; that is, half of the band is above the subcarrier and half is below.

Therefore, subcarriers separated by twice the maximum expected modulation frequency will prevent overlap.

The different channels of information are separated at the receiver (by filters) after photodetection.

There is a limit, of course, to the number of channels added. New subcarriers can be added only if their frequencies are less than the fiber's bandwidth.

Simultaneous transmission of several messages by using different radio-frequency subcarriers is frequency-division *multiplexing* (FDM).

FDM differs from wavelength-division multiplexing, described in Section 9-5, in which different optic carriers were used to distinguish between channels.

Both of these multiplexing strategies increase the number of messages transmitted.

In fact, the two techniques can be combined. The resulting system would contain several sources, each emitting at a different wavelength and each intensity modulated by a frequency-multiplexed modulated current

FM/IM Subcarrier Modulation

In conventional FM systems, operating at radio frequencies, the transmitted information is contained in the *phase* of the carrier wave. The current may be described generally by

/ = I_s cos [$<o_x t$ + 0(/)]   (10-22)

where the message resides in the time variation of the phase angle ft If the modulation is a single sinusoid oscillating at frequency *fm* ~ ^m/2^ the FM current takes the form

/ = I_s cos ($<»_K t$ + *ft* sin $<o_m t$)   (10-23)

where *(3* is the *modulation index.* The spectrum of an FM signal occupies a region that surrounds the carrier $/_{sc}$ = ***w_x/2ir.*** The spectrum has (approximately) a total bandwidth

B_T = 2A/ + *28*   (10-24)

In this expression, *B* is the baseband bandwidth (equal iof_m for the single sinusoid) and A/ is the maximum *frequency deviation.* It is given by

A/=£$/_w$ (10-25)

where f_m is the highest modulation frequency in the message. Normally, the baseband bandwidth equals the highest modulation frequency, so that

B_T= $2f_{tn}$(\ + *ft)*   (10-26)

For small values of the modulation index *((3* <^ 1), the total system bandwidth is just $2f_m$, the same as the bandwidth of an AM system. For larger values of /?, however, the FM spectrum exceeds that of the comparable AM channel. Since the modulation index can be much bigger than one, the FM spectrum can far exceed that required for AM.

Adding a dc current to either Eq. (10-22) or (10-23) and intensity-modulating an optic source with the result produces FM/IM sub-carrier modulation. For the single sine wave, the optic power varies as

$$P = P_0 + P_s \cos (aj_x t + ft \sin a>_m t) \quad (10\text{-}27)$$

FM waveforms are sketched in Fig. 10-10. The detected current has the same form as the optic power. Conventional FM demodulation circuits retrieve the information embedded in the phase of the detected current.

As first discussed in Section 10-1, non-linearities in fiber-optic analog-modulated systems distort the transmitted signal waveforms. The signal degradation severely limits the application of fibers (using analog techniques) if good signal reproducibility is required. Commercial television picture transmission is just such an application. The effects of non-linearities can be minimized by using FM/IM sub-carrier modulation rather than baseband intensity modulation or AM/IM subcarrier modulation. The reason is that the information is extracted from the phase of the FM/IM waveform and not from its amplitude. High-quality television signals can be transmitted over fibers in the FM/IM format if a bandwidth of about 10 MHz is used.

Several FM channels can be simultaneously transmitted by frequency-division multiplexing, just as we described for subcarrier amplitude modulation. However, because the FM bandwidth is larger than the AM bandwidth, fewer FM messages can be fitted within the fiber's limited range of frequencies. The FM subcarriers must be separated by the bandwidth B_T given by Eq. (10-26).

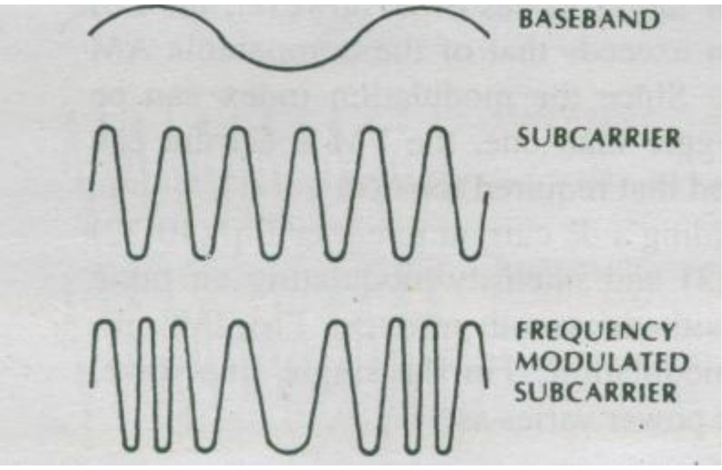


Figure 10-10 Subcarrier-FM waveforms. The optic power and the detected current have the same waveshape as the modulated subcarrier.

10-4 DIGITAL MODULATION FORMATS

In Section 1-2 we noted how analog messages can be coded for digital transmission.

In an example, we showed that sampling and coding of a 4-kHz voice message produced a 64-kbps pulse stream.

A fiber system needs only a 4-kHz bandwidth for analog baseband voice transmission.

According to the equation preceding Eq. (3-20), an RZ pulse train requires an electrical bandwidth equal to the data rate.

Thus the digital 64-kbps signal needs a system with a 64-kHz bandwidth.

For video transmission, representative bandwidths are 6 MHz for baseband analog transmission and 81 MHz for digital RZ signaling at an 81-Mbps data rate.

Clearly, digital systems require much more bandwidth than analog systems.

Why, then, choose optic digital links over analog ones? A few of the reasons follow:

1. LEDs and laser diodes can be switched rapidly, giving them large bandwidths. Fibers and photo detectors also have large bandwidths. Thus, fiber optic systems can operate at data rates comparable to those needed for video and other broadband applications.
2. Analog fiber signals are degraded by nonlinearities in the LD or LED power-current characteristic. Digital signals are less affected by these nonlinearities because only two (or maybe three) power levels are normally used, and one of these levels is zero. Unlike analog transmission, the waveshape need not be accurately preserved. The receiver determines only the existence of pulses in each bit interval, not the pulse shape.
3. Digital systems can use error-checking codes and redundant information transmission to minimize errors.
4. Digital optic links are compatible with non-optic digital systems. For example, a network connecting microprocessors contains only digitized signals. The network could be tied together with a combination of wire and fiber links. In this example, only digital transmission makes sense. In any application that generates data in digital form, a digital link is preferable to an analog one.
5. Digital pulses can be easily regenerated at repeaters. Digital repeaters reshape incoming pulses and amplify them, overcoming both attenuation and distortion. Very long fiber links (several thousands of kilometers long) can be constructed by using repeaters. Analog signals can be amplified by repeaters, but their wave forms cannot be easily restored. For long systems requiring repeaters, digital transmission is highly favored.
6. The required digital bandwidths can be reduced using compression techniques as described in Section 1-2.
7. Generally, digital systems produce better quality signals than analog ones. If desired, signal quality can be traded for increased path length. Improved quality and longer transmission paths are the major rewards for providing a large-bandwidth digital link.

In the remainder of this section we describe a few digital coding schemes compatible with fiber optic transmission.

Pulse-Code Modulation

In Chapter 3 we discussed both non-return-to-zero (NRZ) and return-to-zero (RZ) codes. Both of these two-level unipolar formats (illustrated together in Fig. 10-11) are examples of *pulse-code modulation* (PCM). When viewing these pictures, remember that the waveshapes shown represent the average power in the extremely fast oscillations of an optic carrier.

Because optic PCM involves turning the carrier on and off, it goes by the name *on-off keying (OOK).*

The spectrum of an NRZ pulse train contains a large and important dc component. Its value in any short time period depends on the data. A series of Is produces a larger value than a series of alternating Os and Is or a succession of Os. In the receiver, the dc signal current partially determines the operating point of the amplifiers. A changing dc level changes the operating point, resulting in an undesirable variation (drift) in the receiver's characteristics. A disadvantage of the NRZ code is the need for dc coupling.

For the RZ code, ac capacitive coupling in the receiver blocks the dc spectral component, minimizing drift. Transitions between levels reveal the presence of Is or Os. Compatibility with ac coupling is ai> advantage of RZ over NRZ formats. Of course, as noted by comparing Eqs. (3-20) and (3-21), a fiber link with a fixed pulse spread (and thus a fixed bandwidth) can transmit NRZ signals at twice the rate of RZ signals. Put another way, for a

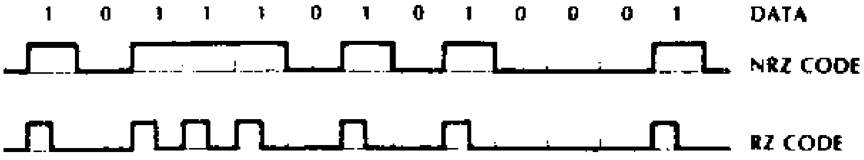


Fig 1011 Non return to zero and return to zero coding formats.

The various types of **multiplexing schemes** presented in this book are summarized as follows:

1. ***Time-division multiplexing (TDM).*** Data bits corresponding to different messages are interleaved to timeshare the fiber channel. A single optic source and a single photodetector are required if the message interleaving and separation are done when the signals are in electrical (rather than optic) form. TDM is appropriate for digital communications. It does not change the information capacity of the fiber: it merely distributes the allowed bits among several messages.
2. ***Wavelength-division multiplexing (WDM)***. Several messages simultaneously travel along the fiber, each message carried at a different optic wavelength. Multiple sources, oscillating at different frequencies, are required. Message separation is performed in the optic domain, before detection. A separate photo-detector is needed for each message. WDM accommodates both analog and digital signals. The information capacity of a fiber is increased (approximately) by a factor equal to the number of multiplexed messages for WDM. Essentially, each source and detector combination constitutes an independent channel.
3. ***Subcarrier frequency-division multiplexing (SFDM).*** Messages are modulated onto different subcarriers and combined electrically. The combined signal modulates a single optic source. A single photodetector returns the signal to electrical form. At this point, electronic filters separate the messages. Subcarrier FDM can be used for both analog and digital signals. As with TDM, subcarrier FDM does not increase fiber capacity. The maximum subcarrier frequency cannot exceed the fiber's bandwidth. This scheme merely divides the available bandwidth among several messages.
4. ***Optic frequency-division multiplexing (OFDM).*** Messages are modulated onto sources having slightly different wavelengths. Heterodyne detection, using a single photodetector, produces a signal current containing all the messages. Each message's spectrum surrounds a different intermediate frequency. Electrical filters then separate the messages. Optic FDM does increase the fiber’s capacity. In practice, however, the speed of the photodetector will limit the maximum intermediate frequency, and this limits the number of messages that can be communicated.

It is sometimes said that digital modulation is more compatible with optic communications than analog modulation.

The arguments include the general advantages of digital systems (improved signal quality, longer transmission paths, simpler repeaters), the relative ease of digital modulation (simply turn the source on and off), and the nonlinearity of optic sources (which degrades analog signals).

Nonetheless, digital transmission of messages that originate in analog form (voice and video, for example) has its problems.

TABLE 10-1. Analog Modulation Formats

Name	**Description**	**Comments**
Baseband modulation		
Intensity modulation	Optic power varies in proportion to the baseband message	Simplest analog scheme
Optic frequency modulation	Direct frequency modulation of an optic carrier	Requires heterodyne detection
Subcarrier modulation		
AM/IM	Intensity modulation of an optic source by a lower-frequency amplitude-modulated signal	Permits subcarrier frequency- division multiplexing
FM/IM	Intensity modulation of an optic source by a frequency-modulated signal	Permits subcarrier frequency division multiplexing

TABLE 10-2. Digital Modulation Formats

Name	**Comments**
Pulse-code modulation	
Non-return-to-zero (NRZ)	Requires the least bandwidth for digital transmission
Return-to-zero (RZ)	Requires twice the bandwidth of NRZ systems
Manchester	Clock recovery is possible
Bipolar	The dc level remains constant
Pulse-position modulation	
Pulse-duration modulation	
Subcarrier modulation	
On-off keying (OOK)	Permits subcarrier FDM
Frequency-shift keying (FSK)	Permits subcarrier FDM
Phase-shift keying (PS κ)	Permits subcarrier FDM