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Introduction

After a brief description of the components that make up an optical receiver and transmitter, we discuss how digital and analog information is modulated on a lightwave. We explain the difference between continuous-mode and burst-mode transmission and summarize applications and standards for both transmission modes.

1.1 Optical Transceivers

Figure 1.1 shows the block diagram of a conventional optical receiver and transmitter. On the transmitter side, a coder and/or scrambler preprocesses the parallel input data. Optionally, the coder adds redundancy to permit error detection and correction at the receiver end. These coding steps condition the data for the subsequent serial transmission through a band-limited and noisy channel. Next, a *multiplexer* (MUX) serializes the n-bit wide parallel data into a single high-speed bit stream. A *clock multiplication unit* (CMU) synthesizes the necessary bit-rate (or half bit-rate) clock from the n times slower word clock (or another convenient reference clock). After that, a *transmit equalizer* (TXEQ) may be used to shape (predistort) the serial high-speed signal in preparation of the band-limited channel. Finally, a *laser driver* or *modulator driver* drives the corresponding optoelectronic device. The laser driver modulates the current of a *laser diode* (LD), whereas the modulator driver modulates the voltage of a *modulator*, which in turn modulates the light from a *continuous wave* (CW) laser. Some laser/modulator drivers also retime the data to reduce jitter and thus require a clock signal from the CMU (dashed line in Fig. 1.1).

On the receiver side, the same process happens in reverse order. A *photodetector* (PD) receives the optical signal from the fiber and produces a small current in response to the optical signal. A *transimpedance amplifier* (TIA or TZA) amplifies and converts this current into a voltage. A *limiting amplifier* (LA) or an *automatic gain control amplifier* (AGC amplifier) further amplifies

Analysis and Design of Transimpedance Amplifiers for Optical Receivers, First Edition. Eduard Säckinger.

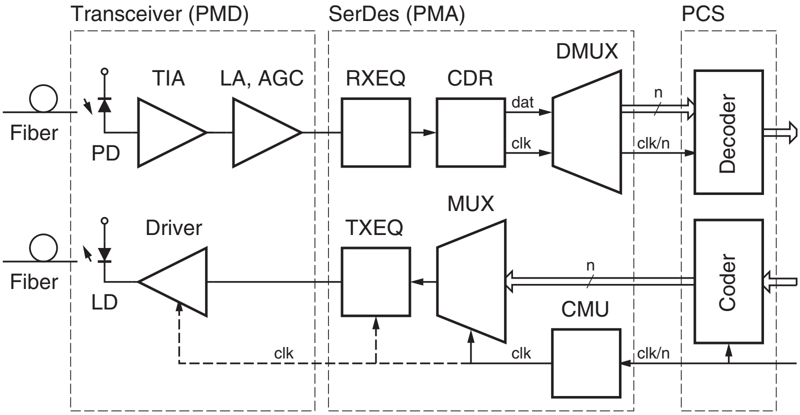


Figure 1.1 Block diagram of a conventional optical receiver (top) and transmitter (bottom).

this voltage signal. The LA and AGC amplifier are collectively known as *main amplifiers* (MAs) or *post amplifiers*. Next, a *receive equalizer* (RXEQ) may be used to undo some of the distortions accrued along the way. After that, a *clock and data recovery circuit* (CDR) extracts the clock signal and retimes the data signal. Finally, a *demultiplexer* (DMUX) converts the fast serial bit stream into *n* parallel lower-speed data streams that are processed by the subsequent decoder and/or descrambler. Optionally, the decoder performs error checks and error corrections. Subsequent digital blocks extract the payload data from the framing information, synchronize the received data to another clock domain, and so forth.

In practice, the blocks may not be as neatly delineated as shown in Fig. 1.1. For example, the MUX in the transmitter may be merged with the driver into one block [1]. On the other hand, if the driver is located far from the MUX (e.g., in a separate package), a CDR may be interposed to clean up the data (reduce the jitter) without the need for a clock signal from the CMU. Furthermore, the RXEQ and the CDR may be merged into a single block, especially when a decision feedback equalizer, which needs feedback from the data output of the CDR, is used. Finally, in parallel sampling architectures, the CDR performs some or all of the DMUX operation [2].

This book covers the optical fiber (Chapter 2), the photodetector (Chapter 3), and the TIA (Chapters 5–9) and provides an introduction to equalization (Appendix E) and forward error correction (Appendix G).

Modules and Subassemblies. A module containing a PD, TIA, MA, laser driver, and LD, that is, all the blocks shown inside the dashed box on the left of Fig. 1.1, is referred to as a *transceiver*. (The term *transceiver* is a contraction of the words "*trans*mitter" and "re*ceiver*.") Figure 1.2 shows a photograph of so-called XFP transceiver modules. The transceiver is often built around a *receiver optical*

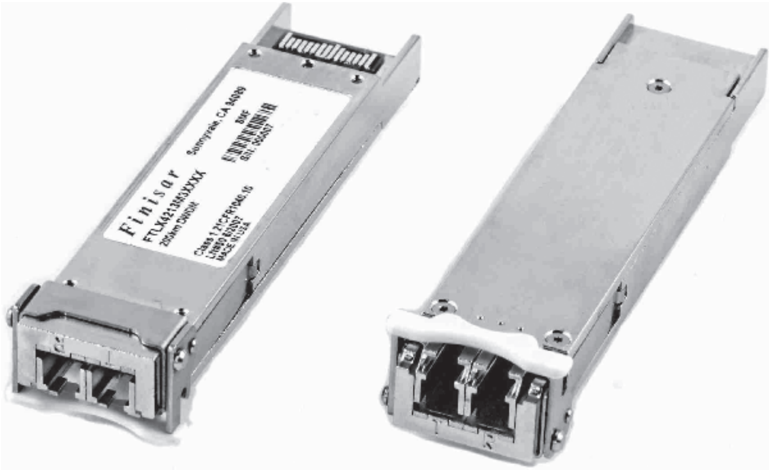


Figure 1.2 Two 10-Gb/s transceivers in small form factor packages following the XFP specification (7.8 cm × 2.2 cm × 1.3 cm). Two fibers are plugged in from the front of the package (LC connectors). *Source*: Reprinted by permission from Finisar Corporation.

Figure 1.3 A 10-Gb/s receiver optical subassembly (ROSA) with a GaAs p–i–n photodetector and a TIA (Ø 0.6 cm × 1.2 cm). *Source*: Reprinted by permission from Finisar Corporation.

subassembly (ROSA) and a *transmitter optical subassembly* (TOSA). The ROSA is a small package that contains the PD, in most cases the TIA, and optical components, such as a lens and means for optical fiber alignment (see Fig. 1.3). The TOSA is a small package that contains the LD, in some cases the driver, and optical components, such as an optical isolator, a lens, and means for optical fiber alignment. The blocks in the dashed box in the middle, namely the RXEQ, CDR, DMUX, CMU, MUX, and TXEQ form the *serializer/deserializer* or SerDes for short. A module that contains the functionality of the transceiver and the SerDes is frequently called a *transponder*.

OSI Layers. The functionality shown in Fig. 1.1 can be identified with the bottom *layer* of the OSI communication system model. This layer is known as the *physical layer* (PHY) and has three sublayers: the *physical medium dependent* (PMD) sublayer, the *physical medium attachment* (PMA) sublayer, and the *physical coding sublayer* (PCS). The PMD sublayer, at the very bottom, corresponds to the transceiver. In our case, the physical medium is the optical fiber. The PMA sublayer, on top of the PMD, corresponds to the SerDes. The PCS sublayer, on top of the PMD, corresponds to the coder and decoder.

DSP-Based Coherent Receiver and Transmitter. Around 2007, *digital signal processors* (DSP) and data converters became sufficiently fast to enable a new architecture for optical receivers and transmitters [3] (see Fig. 1.4). In this architecture only the front-end blocks, TIA, AGC amplifier, and modulator driver, remain in the analog domain. The functionality of the RXEQ, CDR, DMUX, MUX, and TXEQ blocks are implemented with a DSP. This approach permits the use of sophisticated algorithms for equalization, clock recovery, and so on but requires high-speed *analog-to-digital converters* (ADC) and *digital-to-analog converters* (DAC) at the interface between the analog transceiver section and the DSP (cf. Appendix E).

This DSP-based architecture is the preferred approach for 100- Gb/s transceivers with phase- and polarization-diverse coherent detection [4, 5]. In these transceivers, an optical-to-electrical (O/E) converter outputs four electrical signals corresponding to the in-phase and quadrature components and the x-polarized and y-polarized components of the incoming optical signal. (We discuss this type of detector in Section 3.5.) Similarly, an electrical-to-optical (E/O) converter, driven by four electrical signals, controls the phase and amplitude of the transmitted optical signal for both polarizations. As a result, four TIAs, four AGC amplifiers, and four ADCs are needed on the receiver side, and four DACs and four modulator drivers are needed on the transmitter side (see Fig. 1.4). The coherent approach permits the use of advanced modulation formats such as DP-QPSK and enables the effective compensation of large amounts of fiber dispersion in the electrical domain [5, 6].

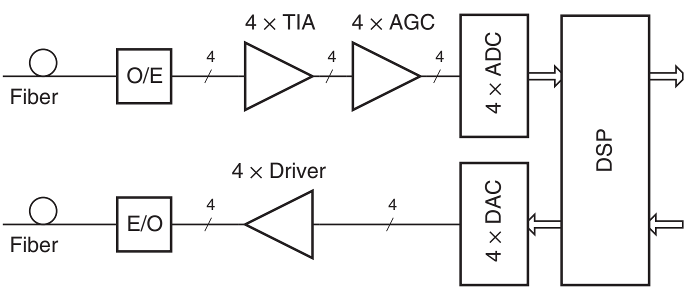


Figure 1.4 Block diagram of a DSP-based optical transceiver with phase- and polarization-diverse coherent detection.

1.2 Modulation Formats

Basic Modulation Formats. The most commonly used modulation format in optical communication is the *non-return-to-zero* (NRZ) format shown in Fig. 1.5(a). Despite the forbidding name, this modulation format is as simple as it gets. The laser light is turned on to transmit a one bit, and it is turned off to transmit a zero bit. When the light is on, it stays on for the entire bit period. The latter feature explains why this format is called *non-return-to-zero*. When transmitting the periodic bit pattern "010101010…" in the NRZ format at 10 Gb/s, a 5-GHz square wave with 50% duty cycle is produced. The NRZ format is used, for example, in SONET/SDH telecommunication systems as well as in Ethernet data communication systems (see Tables 1.1 and 1.2). Some standards, such as Fast Ethernet and FDDI, call for the *non-return-to-zero change-on-ones* (NRZI or NRZ1) format. The waveform for this format is the same as for NRZ, but the bit stream is preprocessed by a differential encoder that changes its (binary) output value when the input bit is a one and leaves the output value unchanged when the input bit is a zero.

The *return-to-zero* (RZ) format, shown in Fig. 1.5(b), shortens the pulses, which represent the one bits, to only a fraction of the bit period. The figure shows 50%-RZ pulses, but other fractions, such as 33% or 67%, are also used. In many situations, the RZ signal can be detected at a lower signal-to-noise ratio than the NRZ signal [7]. This can be understood intuitively by recognizing that, for the same average signal power, the narrower RZ pulses exhibit a larger signal swing, which can better overcome the noise. The RZ format also can tolerate more pulse distortion and spreading without disturbing the adjacent bits. On the downside, faster, more expensive transceiver components (laser/modulator, photodetector, front-end electronics, etc.) are required to handle the shorter pulses. Furthermore, because of its shorter pulses, the RZ signal occupies a wider bandwidth than the NRZ signal (for a given bit rate), making it less tolerant to chromatic fiber dispersion (cf. Section 2.2). The RZ format has been used extensively in undersea (submarine) lightwave systems [8]. In contrast to terrestrial systems, these custom-built lightwave systems tend to be very

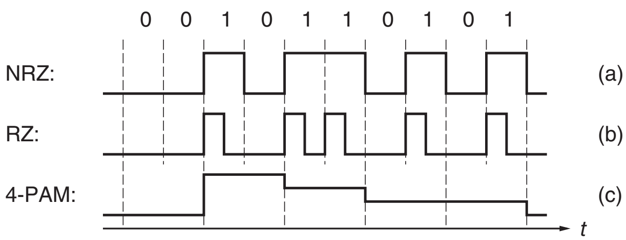


Figure 1.5 Modulation formats: (a) NRZ, (b) RZ, and (c) 4-PAM.

long (e.g., connecting two continents) and benefit from the robustness of the RZ format.

The four-level *pulse amplitude modulation* (4-PAM) format, shown in Fig. 1.5(c), extends the on/off concept and controls the brightness of the light source in four discrete steps: off, one-third on, two-thirds on, and fully on. By using a four-level signal, two bits can be transmitted in every signaling period: bit pair "00" selects the first (lowest) level, "01" selects the second level, "11" selects the third level, and "10" selects the fourth (highest) level. The coding is chosen such that an accidental confusion of two adjacent levels results in only a single-bit error (Gray code). Because of its capability to encode more than one bit per symbol, 4-PAM is known as a *higher-order modulation format*. Compared with the NRZ signal, the 4-PAM signal occupies only half the bandwidth for a given bit rate, making it a *bandwidth-efficient modulation* format. The reduced bandwidth helps to mitigate the effects of chromatic fiber dispersion, permitting an increased reach, and relaxes the speed requirements for the laser and the photodetector. However, the 4-PAM format requires a higher signal-to-noise ratio than the NRZ format for reliable detection. In other words, because the receiver has to discriminate between four levels, it is more affected by noise, leading to a substantially lower sensitivity. The 4-PAM format also requires a more complex multilevel transmitter and receiver. The upcoming 400-Gigabit Ethernet standard is expected to use the 4-PAM format (see Table 1.2). Other higher-order and bandwidth-efficient modulation formats have been studied as well [9–11].

An analytical comparison of the NRZ, 50%-RZ, and 4-PAM signals with respect to the required bandwidths and signal-to-noise ratios can be found in Appendix A.

Advanced Modulation Formats. Let us examine the modulation process in more detail. Modulation is the mapping of data bits (zeros and ones) into signal waveforms [12]. As illustrated in Fig. 1.6, modulation in an optical transmitter occurs in two steps. First, the bits are mapped to an electrical current or voltage waveform. Second, the electrical waveform is mapped to an optical field (electromagnetic field) waveform. The optical field oscillates at around 200 THz, which means that there are about 20,000 oscillations in a bit period of a 10-Gb/s signal, but for clarity, only two oscillations are shown in the figure. The NRZ, RZ, and 4-PAM signals, shown in Fig. 1.5, are outputs of the

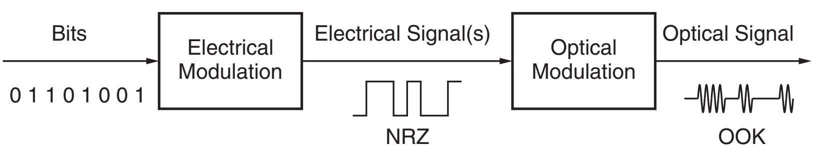


Figure 1.6 Modulation in an optical transmitter.

electrical modulation step. They are so-called *baseband signals* because their spectra extend down to DC. Modulating the intensity of the optical signal with an NRZ or RZ signal is known as *on-off keying* (OOK) and what we called NRZ and RZ formats earlier, more precisely should have been called NRZ-OOK and RZ-OOK formats. Similarly, modulating the intensity of the optical signal with a 4-PAM signal is known as four-level *amplitude-shift keying* (4-ASK). (Note that intensity modulation implies an amplitude modulation of the optical field.) The optical field signals are so-called *passband signals* because their spectra are concentrated around the optical carrier frequency. In practice, the electrical and optical modulation steps often are not clearly distinguished and by saying that an optical system uses NRZ modulation, NRZ-OOK is implied.

Now that we understand optical modulation as a two step process, it becomes clear that the second step does not necessarily have to be intensity or amplitude modulation alone but could include phase and frequency modulation. This possibility is exploited in advanced optical modulation formats. Some examples are illustrated in Fig. 1.7.

- The *optical duobinary* format combines amplitude and phase modulation [13]. The amplitude of the optical carrier is modulated with an NRZ signal, as in the OOK case, but additionally, the optical phase is shifted by 180° for one bits that are separated by an odd number of zero bits (see Fig. 1.7(a)).
- The *chirped return-to-zero* (CRZ) format modulates the amplitude of the optical carrier with an RZ signal, but additionally, some frequency modulation (chirp) is applied [14].
- The *carrier-suppressed return-to-zero* (CS-RZ) format also modulates the amplitude of the optical carrier with an RZ signal, but additionally, the optical phase is shifted by 180° for every bit (no matter if the bit is zero or one) with the result that the carrier becomes suppressed in the optical spectrum [15] (see Fig. 1.7(b)).

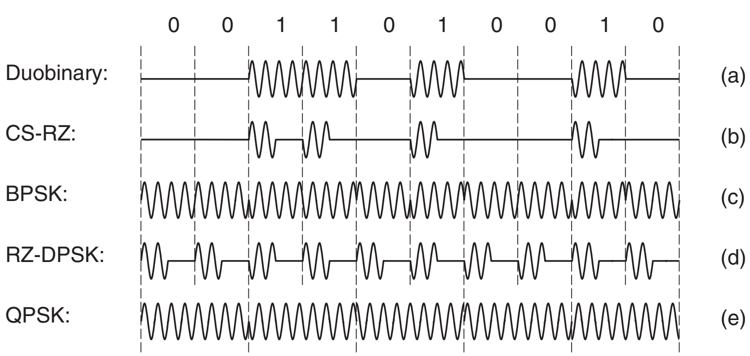


Figure 1.7 Advanced modulation formats (optical field): (a) optical duobinary, (b) CS-RZ, (c) BPSK, (d) RZ-DPSK, and (e) QPSK.

- The *binary phase-shift keying* (BPSK) format encodes the data bits in the phase of the optical signal while the amplitude remains constant. A one bit is encoded with a phase that is 180° shifted compared to the phase of a zero bit (see Fig. 1.7(c)).
- The *return-to-zero differential phase-shift keying* (RZ-DPSK) format modulates the amplitude of the optical carrier with an all-one RZ signal and encodes the data bits in the phase *difference* of two adjacent optical pulses [16]. A one bit is encoded with a 180° phase shift; a zero bit is encoded with a 0° phase shift (see Fig. 1.7(d)).

The purpose of these advanced modulation formats is to mitigate the detrimental effects of the optical communication channel (fiber dispersion, fiber nonlinearity, and crosstalk) in an attempt to increase the reach and capacity of the link at the lowest possible system cost [17].

Phase modulation can also be used to encode multiple bits per symbol. For example, the *quadrature phase-shift keying* (QPSK) format encodes pairs of bits with four different phase shifts relative to a reference phase: bit pair "00" selects a 0° phase shift, "01" selects 90°, "11" selects 180°, and "10" selects 270° (see Fig. 1.7(e)) [3]. Like for the 4-PAM format, the coding is chosen such that an accidental confusion of two adjacent phases results in only a single-bit error. The *differential quadrature phase-shift keying* (DQPSK) and the *return-to-zero differential quadrature phase-shift keying* (RZ-DQPSK) formats similarly encode pairs of bits with four different phase shifts, but this time the shift is relative to the phase of the *previous* symbol [18]. The advantage of these higher-order modulation formats is their bandwidth efficiency: a two-bit per symbol format requires only half the bandwidth of the corresponding one-bit per symbol format given the same bit rate. Conversely, twice the bit rate can be transmitted in the same optical bandwidth. The bandwidth efficiency can be further increased by using constellations with more phase/amplitude values (e.g., 16-QAM) or by using both optical polarizations to transmit information (polarization division multiplexing). The dual-polarization QPSK format (DP-QPSK) is used in commercial 100-Gb/s systems (see Table 1.2).

Direct detection receivers are insensitive to phase and frequency modulation. Thus, special phase-sensitive receivers are required to detect formats such as DPSK, DQPSK, BPSK, and QPSK (cf. Section 3.5). However, a direct detection receiver designed for NRZ can also receive an optical duobinary signal and a direct-detection receiver designed for RZ can also receive CRZ and CS-RZ signals.

Multicarrier Modulation Formats. Since the late 1980s, the TV signals in *community-antenna television* (CATV) systems are often transported first *optically* from the distribution center to the neighborhood before they are distributed to the individual homes on conventional coaxial cable. This combination, called *hybrid fiber-coax* (HFC), has the advantage over an

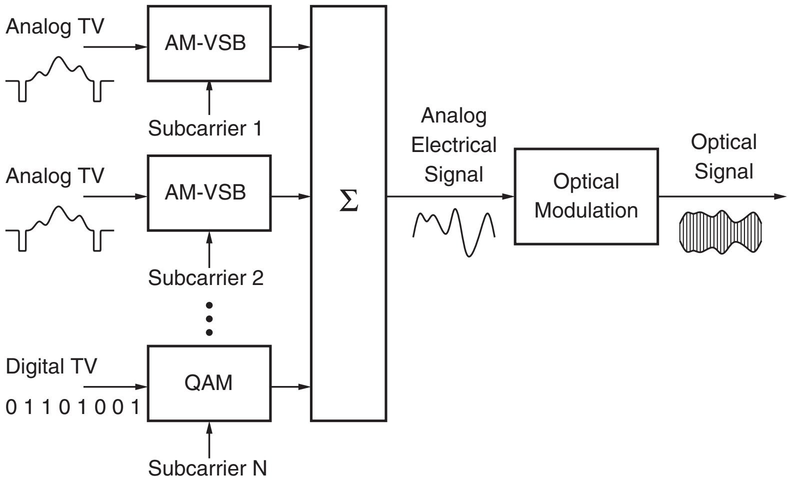


Figure 1.8 Subcarrier multiplexing (SCM) in a CATV/HFC system.

all-coax system of saving many electronic amplifiers (the loss of a fiber is much lower than the loss of a coax cable) and providing better signal quality (lower noise and distortions) [19].

The modulation process used in CATV/HFC systems is illustrated in Fig. 1.8. In North America, analog TV channels use *amplitude modulation with vestigial sideband* (AM-VSB) and digital TV channels use *quadrature amplitude modulation* (QAM). In either case, the TV signal is modulated on a radio frequency (RF) carrier. Many of these modulated carriers, each one at a different frequency, are combined (added) into a single analog broadband signal. To avoid interference between adjacent channels, a small guard band is left between the channels. Then, this analog broadband signal linearly modulates the intensity of a laser to produce the optical signal that is transmitted over the fiber from the distribution center (a.k.a. head end) to the remote node in the neighborhood. At the remote node, the analog broadband signal is recovered from the optical signal and distributed over coaxial cable to the homes. This method of modulation and aggregation is known as *subcarrier multiplexing* (SCM) [20]. The optical carrier can be regarded as the main carrier and the electrical RF carriers of the individual TV channels as the subcarriers. For a discussion of analog and digital TV signals, see Appendix A.

In contrast to NRZ and RZ modulations, which produce two-level digital signals, the AM-VSB and QAM modulation used in CATV applications produce *analog* signals. The latter signals are more easily corrupted by noise and, especially if many TV channels are multiplexed together, are very sensitive to nonlinear distortions (cf. Appendix D). For this reason, special analog optical receivers and transmitters featuring low noise and high linearity are required for CATV/HFC applications.

Although we have introduced SCM in the context of CATV systems, this is not the only application. SCM can also be used to transport digital data. The use of N subcarriers to transmit a total bit rate B, results in a bit rate of only B/N per subcarrier. The corresponding long bit (or symbol) interval makes the SCM signal insensitive to channel impairments (such as fiber dispersion). Moreover, SCM with high-order QAM-modulated subcarriers achieves a high spectral efficiency. Finally, the baseband section of an SCM system runs at only a fraction of the full speed (B/N), possibly simplifying the implementation and reducing the cost. For example, the SCM system in [21] uses 16 subcarriers, each one modulated with a 16-QAM signal running at a symbol rate of 666 Mb/s to transmit a total of 40 Gb/s in a bandwidth of only 14 GHz.

Even higher spectral efficiencies can be obtained with *orthogonal frequency division multiplexing* (OFDM). The guard bands in between the channels of an SCM signal are eliminated by making the carriers orthogonal. The orthogonality condition is satisfied when the carrier spacing is a multiple of the QAM symbol rate [22, 23]. The generation and demodulation of OFDM signals rely on DSPs and data converters.

To overcome the speed limitations of the DSP and the data converters, OFDM can be combined with SCM, resulting in *multiband OFDM*. For example, the system in [24] uses 8 bands, each one containing an OFDM signal consisting of 520 subcarriers, each one modulated with an 8-QAM signal at a symbol rate of 9.6 Mb/s to transmit a total of 100 Gb/s in a bandwidth of only 23 GHz.

Preprocessing. As we know from Fig. 1.1, the raw input data is first scrambled or coded (or both) before it is transmitted. Figure 1.9 shows conceptually how the *information bits* are transformed into *channel bits* before they are passed on to the modulator. The purpose of this preprocessing step is to shape the spectrum of the modulated electrical signal and give it the following desirable properties: DC balance, short run lengths, and a high transition density.

A *DC-balanced signal* has an average value (DC component) that is centered halfway between its minimum and maximum values. This property often permits the use of coupling capacitors (AC coupling) between circuit blocks. To obtain a DC-balanced NRZ signal, the transmitted bit sequence must contain on average the same number of zeros and ones. Equivalently, the average

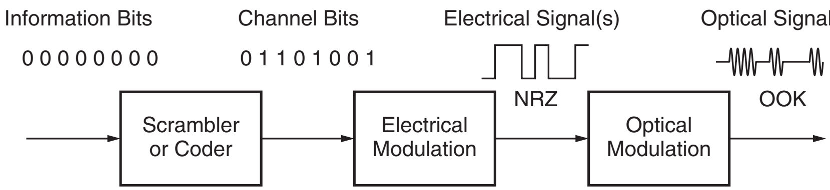


Figure 1.9 Scrambling, coding, and modulation.

mark density, defined as the number of one bits divided by the total number of bits, must be 50%.

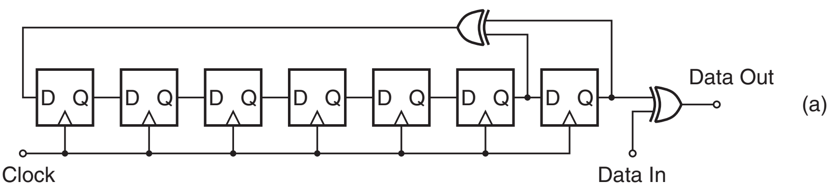
The *run length* is the number of successive zeros or ones in a bit sequence. Keeping the run length short reduces the low-frequency content of the modulated NRZ signal (cf. Fig. A.2 on p. 399) and limits the associated *baseline wander* (a.k.a. *DC wander*) when AC coupling is used. Short runs also imply a high *transition density*, which aids the clock recovery process.

Scrambler. Figure 1.10 shows an example of a *scrambler*. It consists of a *pseudorandom bit sequence* (PRBS) generator, implemented with a feedback shift register, and an XOR gate that combines the PRBS with the information bit stream to form the scrambled channel bit stream.

Because two inversions restore the original bit value, the channel bits can be descrambled with the same arrangement, provided the descrambling PRBS generator is synchronized with the scrambling PRBS generator. Scrambling provides DC balance without adding overhead bits to the bit stream, thus keeping the bit rate unchanged. However, the maximum run length is not strictly limited, that is, there is a small chance for very long runs of zeros or ones, which can be hazardous. Equipment designed to process scrambled bit streams is usually tested with runs up to 72 bits [25]. The scrambling method is used, for example, in SONET and SDH telecommunication systems.

Modulation Codes. A *modulation code* replaces a contiguous group of information bits (a block) by another slightly larger group of channel bits such that the average mark density becomes 50% and DC balance is established. Modulation codes (a.k.a. *line codes*) are named after the block length before and after the encoding. Typical examples are the 4B/5B, 8B/10B, and 64B/66B codes:

- 4B/5B code. This code, as the name suggests, replaces 4-bit blocks with 5-bit patterns based on a look-up table. The 4B/5B code is simple to implement



Data In:	... 00000000 00000011 00000101 00000001 ...	
PRBS:	... 01101001 01110111 00110010 10101111 ...	(b)
Data Out:	... 01101001 01110100 00110111 10101110 ...	

Figure 1.10 SONET scrambler: (a) implementation and (b) example bit patterns.

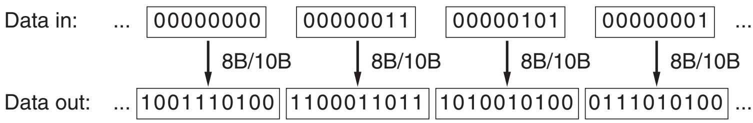


Figure 1.11 Example of 8B/10B encoding.

but increases the bit rate by 25% and does not achieve perfect DC balance; the worst-case unbalance is ±10% [26]. It is used, for example, in the Fast Ethernet and FDDI data communication systems.

- 8B/10B code. This code replaces 8-bit blocks with 10-bit patterns, as illustrated in Fig. 1.11 [27]. Again, the mapping is defined by look-up tables. Besides the 256 data codes, the 8B/10B code maps 12 control codes into the 10-bit code space. The 8B/10B code also increases the bit rate by 25%, but unlike the 4B/5B code, it does achieves exact DC balance. The maximum run length is strictly limited to five zeros or ones. The 8B/10B code is used, for example, in the Gigabit Ethernet (GbE) and Fibre Channel data communication systems.
- 64B/66B code. This modulation code is somewhat different from the 4B/5B and 8B/10B codes in that it partly relies on scrambling rather than a look-up table. The 64B/66B code takes a block of 64 information bits and appends the bit pattern "01" to the beginning. The resulting 66-bit block is scrambled (excluding the two-bit preamble) with a PRBS generated with a 58-bit feedback shift register, producing 66 DC-balanced channel bits. The 64B/66B code also permits the transmission of control information by appending the preamble "10" to a block of 64 control and data bits. The remaining two preambles, "00" and "11," are not used. The 64B/66B code strictly limits the run length to 66 bits by virtue of its two-bit preamble and increases the bit rate by only about 3%. This code is used in many high-speed (10 Gb/s and above) communication systems.

1.3 Transmission Modes

In the following, we explain the difference between continuous-mode and burst-mode transmission and discuss how these two transmission modes are used in optical point-to-point and point-to-multipoint networks.

Continuous Mode versus Burst Mode. Figure 1.12 schematically shows the difference between a *continuous-mode* signal and a *burst-mode* signal.

In continuous-mode transmission, a continuous, uninterrupted stream of bits is transmitted, as shown in Fig. 1.12(a). The transmitted signal usually is DC balanced by means of scrambling or coding.

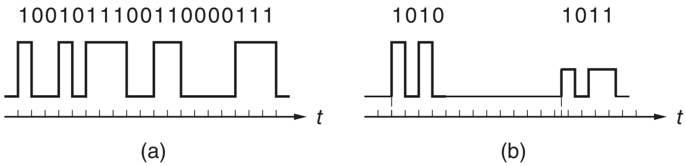


Figure 1.12 (a) Continuous-mode versus (b) burst-mode signals (schematically).

In burst-mode transmission, bits are transmitted in *bursts*, with the transmitter remaining idle (laser off) in between bursts, as shown in Fig. 1.12(b). Bursts typically are longer than 400 bits, but for clarity only 4 bits are shown in the figure. The average value (DC component) of a burst-mode signal varies with time, depending on the burst activity. If the activity is high, it may be close to the halfway point between the zero and one levels, as in a continuous-mode system; if the activity is low, the average drifts arbitrarily close to the zero level. This means that the (overall) burst-mode signal is *not* DC balanced and AC coupling generally cannot be used. (The signal within each burst, however, may be DC balanced.)

Bursts can have a fixed or variable length. For example, bursts that transport (asynchronous transfer mode) cells have a *fixed length*, whereas bursts that transport Ethernet frames have a *variable length*. In either case, the bursts consist of an overhead section followed by a framing structure, such as an ATM cell or an Ethernet frame. Figure 1.13 compares a fixed-length ATM burst with a variable-length Ethernet burst. The burst-mode receiver uses the preamble, which is part of the overhead section, to establish the appropriate gain and decision threshold and to synchronize the sampling clock with the incoming data. In passive optical networks, which we discuss shortly, bursts arrive *asynchronously* and with widely *varying power levels*. Therefore, the gain, the decision threshold, and the clock phase must be acquired for each individual burst.

The lack of DC balance and the fact that bursts may arrive with varying amplitudes necessitate specialized amplifier circuits for burst-mode applications.

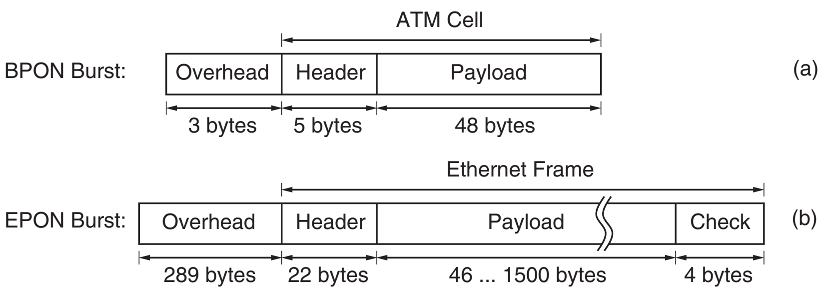


Figure 1.13 (a) Fixed length versus (b) variable length bursts.

Furthermore, the asynchronous arrival of the bursts requires fast-locking CDRs. The design of burst-mode circuits is particularly challenging for bursts with short preambles.

Optical Point-to-Point Connection. An optical *point-to-point connection* between two *central offices* (CO) is illustrated schematically in Fig. 1.14(a). The length of such a connection can range from a few kilometers to more than 10,000 km for the longest undersea lightwave systems. The operating speed per wavelength typically is in the range of 10 Gb/s to 100 Gb/s. In the United States, many point-to-point telecommunication links are based on the SONET (synchronous optical network) standard [28–30]. In Europe, Japan, and other countries the almost identical SDH (synchronous digital hierarchy) standard [25, 31, 32] is used. For example, a SONET OC-192 long reach link has a length of about 80 km and operates at 10 Gb/s (9.953 28 Gb/s to be precise), a bit rate that can carry about 130,000 voice calls. Newer telecommunication standards, such as OTN (optical transport network) [33], respond to the shift from voice traffic to predominantly data traffic as a result of the growing Internet. Besides a framing procedure for voice and data, OTN also supports forward error correction (FEC). See Table 1.1 for more information about the SONET, SDH, and OTN standards.

Point-to-point links are also used in data communication links, that is, in connections between computers. The best-known standard for electrical

Table 1.1 Point-to-point optical telecommunication standards.

Standard	Line speed (Mb/s)	Modulation code	Modulation format
SONET OC-1	51.84	Scrambling	NRZ
SONET OC-3 or SDH STM-1	155.52	Scrambling	NRZ
SONET OC-12 or SDH STM-4	622.08	Scrambling	NRZ
SONET OC-48 or SDH STM-16	2,488.32	Scrambling	NRZ
SONET OC-192 or SDH STM-64	9,953.28	Scrambling	NRZ
SONET OC-192 or SDH STM-64 + FEC (G.975/G.709)	10,664.23	Scrambling	NRZ
SONET OC-768 or SDH STM-256	39,813.12	Scrambling	NRZ
SONET OC-768 or SDH STM-256 + FEC (G.975/G.709)	42,656.91	Scrambling	NRZ
OTN OTU-1 (SONET OC-48 + FEC)	2,666.06	Scrambling	NRZ
OTN OTU-2 (SONET OC-192 + FEC)	10,709.23	Scrambling	NRZ
OTN OTU-3 (SONET OC-768 + FEC)	43,018.41	Scrambling	NRZ
OTN OTU-4 (100GBase + FEC)	111,809.97	64B/66B	NRZ

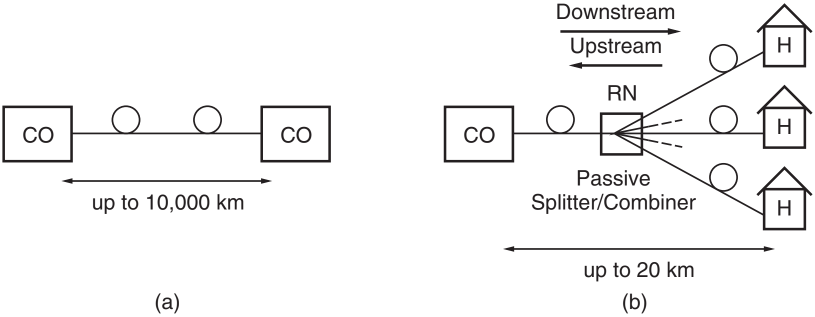


Figure 1.14 Example of (a) a point-to-point link and (b) a point-to-multipoint network.

and optical data communication is *Ethernet* [34]. Ethernet comes at different speed grades, currently ranging from 10 Mb/s to 100 Gb/s and soon 400 Gb/s, and typically resides within the extent of a campus or a building, making it a so-called *local area network* (LAN). For example, Gigabit Ethernet (GbE) operates at a line rate of 1.25 Gb/s providing a usable bit rate of 1.00 Gb/s after 8B/10B decoding. It comes in three main flavors: 1000Base-T, an electrical version operating over a cable with four twisted-pair wires, 1000Base-SX, an optical version using a short-wavelength laser (850 nm), and 1000Base-LX, an optical version using a long-wavelength laser (1, 310 nm). Although the original electrical Ethernet was *not* a point-to-point network (but a bus network), all the optical Ethernet flavors are based on point-to-point connections. Other standards for data communication over optical fiber are the *Fiber Distributed Data Interface* (FDDI) [26, 35–37] and the *Fibre Channel* [38, 39]. See Table 1.2 for more information about data communication standards.

Point-to-point connections can be assembled into more complex structures such as *ring networks* and *active star networks* (see Fig. 1.15). Examples for ring networks are provided by SONET/SDH rings and FDDI token rings. An active star is formed, for example, by Gigabit Ethernet links converging into a hub. Each individual optical connection of the active star has a transceiver on both ends and therefore forms an optical point-to-point link. This contrasts with a *passive star network* or an optical point-to-multipoint network, where multiple optical fibers are coupled with a passive optical device (cf. Fig. 1.14(b)). We discuss the latter network type shortly.

Continuous-mode transmission is used on almost all point-to-point connections. One exception occurs in half-duplex systems, in which bidirectional communication is implemented by periodically reversing the direction of traffic following a ping-pong pattern. This method is known as *time compression multiplexing* (TCM; a.k.a. *time division duplexing*) and requires burst-mode transmitters and receivers. However, for bandwidth efficiency reasons, TCM systems are limited to relatively short links such as home networking applications. In all other cases of bidirectional transmission (i.e., with

Table 1.2 Point-to-point optical data communication standards.

Standard	Line speed (Mb/s)	Modulation code	Modulation format
Ethernet (10Base-F)	12.50	4B/5B	NRZI
Fast Ethernet (100Base-FX)	125.00	4B/5B	NRZI
Gigabit Ethernet (1000Base-SX/LX)	1,250.00	8B/10B	NRZ
10-Gigabit Ethernet (10GBase-LX4)	4 × 3,125.00	8B/10B	NRZ
10-Gigabit Ethernet (10GBase-SR/LR/ER/LRM)	10,312.50	64B/66B	NRZ
40-Gigabit Ethernet (40GBase-SR4/LR4)	4 × 10,312.50	64B/66B	NRZ
40-Gigabit Ethernet (40GBase-FR)	41,250.00	64B/66B	NRZ
100-Gigabit Ethernet (100GBase-SR10)	10 × 10,312.50	64B/66B	NRZ
100-Gigabit Ethernet (100GBase-LR4/ER4)	4 × 25,781.25	64B/66B	NRZ
100-Gigabit Ethernet (100GBase-ZR, non-IEEE)	120,579.00	64B/66B	DP-QPSK
400-Gigabit Ethernet (400GBase-FR8/LR8, proposal)	8 × 53,125.00	64B/66B	4-PAM
400-Gigabit Ethernet (400GBase-DR4, proposal)	4 × 106,250.00	64B/66B	4-PAM
Fiber Distributed Data Interface	100.00	4B/5B	NRZI
Fibre Channel (1GFC)	1,062.50	8B/10B	NRZ
Fibre Channel (2GFC)	2,125.00	8B/10B	NRZ
Fibre Channel (4GFC)	4,250.00	8B/10B	NRZ
Fibre Channel (8GFC)	8,500.00	8B/10B	NRZ
Fibre Channel (16GFC)	14,025.00	64B/66B	NRZ

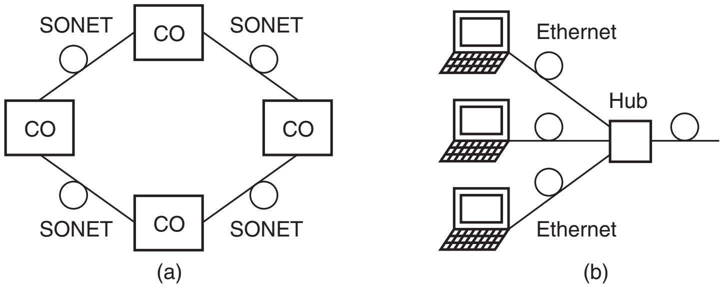


Figure 1.15 (a) SONET ring and (b) Ethernet active star.

two fibers, so-called *space division multiplexing* [SDM], or two wavelengths, so-called *wavelength division multiplexing* [WDM]), continuous-mode transmission is used.

Optical Point-to-Multipoint Network (Passive Optical Network). A *passive optical network* (PON) is illustrated schematically in Fig. 1.14(b). A feeder fiber from the central office (CO) runs to a *remote node* (RN), which houses a passive optical power splitter/combiner. From there, around 32 fibers branch out to the subscribers. If these fibers extend all the way to the *homes* (H), as shown in Fig. 1.14(b), this system is known as a *fiber-to-the-home* (FTTH) system. Alternatively, if the fibers terminate at the curb, the system is known as a *fiber-to-the-curb* (FTTC) system. The final distribution from the curb to the homes is accomplished, for example, by twisted-pair copper wires or radio. All systems that bring the fiber relatively close to the subscriber are collectively known as FTTx systems.

In a traditional telephony access network, the electrical or optical connection from the CO to the remote node is digital. The final distribution from the remote node to the subscribers, however, is accomplished with analog signals over twisted-pair copper wires. Thus, the remote node must be *active*; that is, it needs to be powered to perform the conversion from the high-speed digital signals to the analog signals. In contrast, a PON system is all optical and *passive*. Because a PON does not require outside power supplies, it is low in cost, reliable, and easy to maintain.

A PON is a point-to-multipoint network because the transmission medium is *shared* among the subscribers. Information transmitted downstream, from the CO to the subscriber, is received by all subscribers, and information transmitted upstream, from the subscribers to the CO, is superimposed at the passive combiner before it is received at the CO (see Fig. 1.16). To avoid data collisions in the *upstream direction*, the subscriber must buffer its data and transmit it in short bursts. The CO coordinates which subscriber sends a burst at which point in time. This method is known as *time division multiple access* (TDMA) and requires *burst-mode transmission*. The *downstream direction* is

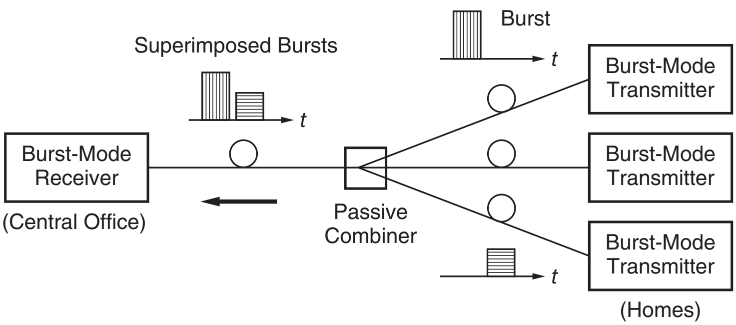


Figure 1.16 Burst-mode transmission in a PON (upstream direction).

more straightforward: the CO tags the data with addresses and broadcasts it to all subscribers in sequential order. Each subscriber simply selects the information with the appropriate address tag. This method is known as *time division multiplexing* (TDM), and conventional continuous-mode transmission can be used. Upstream and downstream transmissions usually are separated by means of two different wavelengths (WDM bidirectional transmission).

One of the first standardized PON systems with significant deployment was BPON (broadband passive optical network) [40, 41]. This system uses ATM cells to transport the data and hence is also known as ATM-PON or APON (cf. Fig. 1.13(a)). In a typical BPON FTTH scenario, 16 to 32 homes located within 20 km from the CO share a downstream bit rate of 622 Mb/s and an upstream bit rate of 155 Mb/s, giving each subscriber an average downstream speed of 20 to 40 Mb/s. This is sufficient for fast Internet access, telephone service, and video on demand. Sometimes, an all-optical CATV service is provided over the PON infrastructure by means of a third wavelength. A typical wavelength plan allocates 1,310 nm for PON upstream, 1,490 nm for PON downstream, and 1,550 nm for the CATV overlay service.

Higher speed PON systems have been standardized since then. EPON (Ethernet passive optical network) transports the data in Ethernet frames, as the name implies (cf. Fig. 1.13(b)), and operates at a line rate of 1.25 Gb/s or 10.3125 Gb/s [42, 43]. GPON (Gigabit-capable passive optical network) operates at bit rates up to 2.5 Gb/s and transports ATM or Ethernet traffic with a high bandwidth utilization [44]. See Table 1.3 for more information about PON standards.

Besides the TDM/TDMA approach outlined earlier, there are several other types of PON systems [45–47]. For example, WDM-PON systems, which use multiple wavelengths, have been studied extensively. In these systems, data collisions are avoided by assigning different wavelengths to different subscribers, thus making burst-mode transmission unnecessary. However, the optical WDM components required for such a system are expensive. Finally, hybrid PON systems combining the TDM and the WDM approach are also being studied.

Note About Numerical Examples. In the following chapters, we make extensive use of numerical examples. When we introduce a new quantity or relationship, we frequently illustrate it with *typical values*. In my own learning experience, this approach is most helpful: it makes the subject more concrete and promotes a feeling for the numerical values. However, specialists tend to be quite critical about such examples because the values are never quite right. Typical values may change over time as the field advances or they may depend on several conditions that may or may not be met in a particular case. It is therefore important to take the subsequent numerical examples only as an illustration and not as the basis for your next design project!

Table 1.3 Point-to-multipoint optical communication standards.

Standard	Downstream speed (Mb/s)	Upstream speed (Mb/s)	Layer 2 protocol	Modulation code	Modulation format
ATM-PON/BPON (option 1)	155.52	155.52	ATM	Scrambling	NRZ
ATM-PON/BPON (option 2)	622.08	155.52	ATM	Scrambling	NRZ
GPON	1,244.16	155.52	ATM, Ethernet, etc.	Scrambling	NRZ
GPON	1,244.16	622.08	ATM, Ethernet, etc.	Scrambling	NRZ
GPON	1,244.16	1,244.16	ATM, Ethernet, etc.	Scrambling	NRZ
GPON	2,488.32	155.52	ATM, Ethernet, etc.	Scrambling	NRZ
GPON	2,488.32	622.08	ATM, Ethernet, etc.	Scrambling	NRZ
GPON	2,488.32	1,244.16	ATM, Ethernet, etc.	Scrambling	NRZ
GPON	2,488.32	2,488.32	ATM, Ethernet, etc.	Scrambling	NRZ
EPON (1000Base-PX)	1,250.00	1,250.00	Ethernet	8B/10B	NRZ
10/10G-EPON	10,312.50	10,312.50	Ethernet	64B/66B	NRZ
10/1G-EPON	10,312.50	1,250.00	Ethernet	64B/66B, 8B/10B	NRZ

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