Chapter 4

Digital Transmission

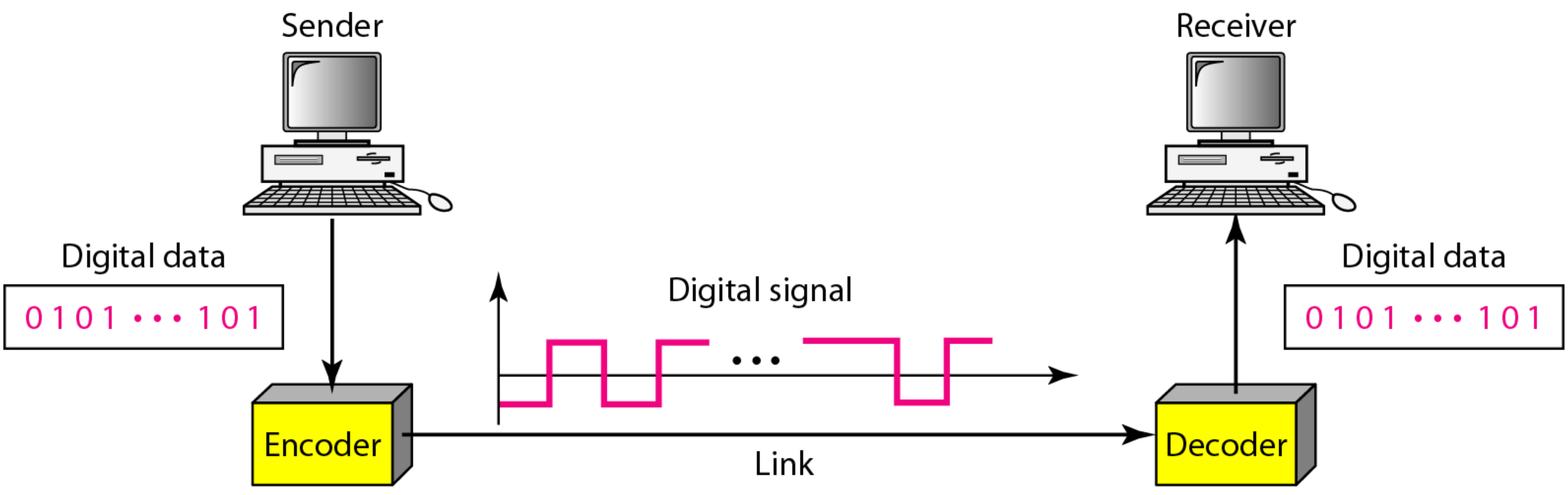
4-1 DIGITAL-TO-DIGITAL CONVERSION

In this section, we see how we can represent digital data by using digital signals. The conversion involves three techniques: line coding, block coding, and scrambling. Line coding is always needed; block coding and scrambling may or may not be needed.

Topics discussed in this section:

Line Coding
Line Coding Schemes
Block Coding
Scrambling

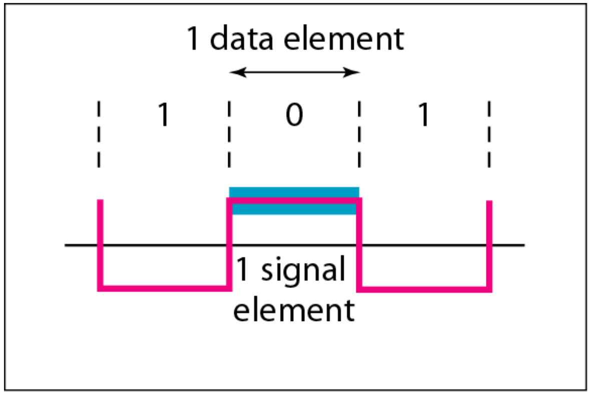
Figure 4.1 *Line coding and decoding*



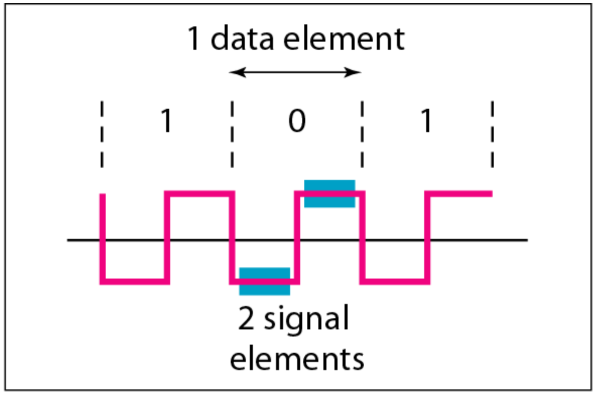
Line coding is the process of converting digital data to digital signals.

At the sender, digital data are encoded into a digital signal; at the receiver, the digital data are recreated by decoding the digital signal.

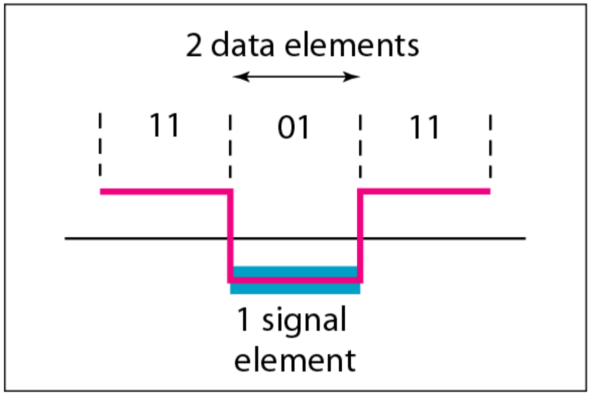
Figure 4.2 *Signal element versus data element*



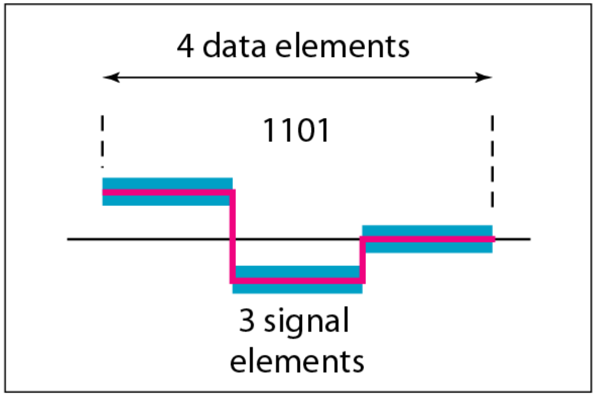
a. One data element per one signal element (r = 1)



b. One data element per two signal elements $\left(r = \frac{1}{2}\right)$



c. Two data elements per one signal element (r = 2)



d. Four data elements per three signal elements $\left(r = \frac{4}{3}\right)$

Cases of Live Example

- Suppose each data element is a person who needs to be carried from one place to another.
- We can think of a signal element as a vehicle that can carry people.
- When $r = 1$, it means each person is driving a vehicle.
- When $r > 1$, it means more than one person is travelling in a vehicle (a carpool, for example).
- We can also have the case where one person is driving a car and a trailer ($r = 1/2$).

Data Rate Versus Signal Rate

- The **data rate** defines the number of data elements (bits) sent in 1s. The unit is bits per second (bps).
- The **signal rate** is the number of signal elements sent in 1s. The unit isthe baud.
- There are several common terminologies used in the literature.
- The data rate is sometimes called the **bit rate;** the signal rate is sometimes called the **pulse rate,** the **modulation rate,** or the **baud rate.**
- One goal: To increase the data rate while decreasing the signal rate.
- Increasing the data rate increases the speed of transmission; decreasing the signal rate decreases the bandwidth requirement.

Relationship between data rate (N) and signal rate (S)

$$S = N/r$$

$$S_{\mathbf{average}} = c \times N \times (1/r) \ \mathbf{baud}$$

- Where, a ratio r which is the number of data elements carried by each signal element.
- where N is the data rate (bps);
- c is the case factor, which varies for each case;
- S is the number of signal elements per second

Example 4.1

A signal is carrying data in which one data element is encoded as one signal element (r = 1). If the bit rate is 100 kbps, what is the average value of the baud rate if c is between 0 and 1?

Solution

We assume that the average value of c is 1/2 . The baud rate is then

$$S = c \times N \times \frac{1}{r} = \frac{1}{2} \times 100{,}000 \times \frac{1}{1} = 50{,}000 = 50 \text{ kbaud}$$

Note

Although the actual bandwidth of a digital signal is infinite, the effective bandwidth is finite.

Example 4.2

The maximum data rate of a channel is $N_{max} = 2 \times B \times \log_2 L$ (defined by the Nyquist formula). Does this agree with the previous formula for N_{max}?

Solution

A signal with L levels actually can carry $\log_2 L$ bits per level. If each level corresponds to one signal element and we assume the average case ($c = 1/2$), then we have

$$\boxed{N_{\max} = \frac{1}{c} \times B \times r = 2 \times B \times \log_2 L}$$

Definitions

- In decoding a digital signal, the receiver calculates a running average of the received signal power. This average is called the ***baseline*.**
- A long string of 0s or 1s can cause a drift in the baseline (**baseline wandering**) and make it difficult for the receiver to decode correctly.
- A good line coding scheme needs to prevent baseline wandering.

Definitions

- When the voltage level in a digital signal is constant for a while, the spectrum creates very low frequencies.
- These frequencies are around zero, called DC (direct-current) *components,* present problems for a system that cannot pass low frequencies or a system that uses electrical coupling (via a transformer).
- DC component means 0/1 parity that can cause base-line wondering.
- For example, a telephone line cannot pass frequencies below 200 Hz. Also a long-distance link may use one or more transformers to isolate different parts of the line electrically. For these systems, we need a scheme with no **DC component.**

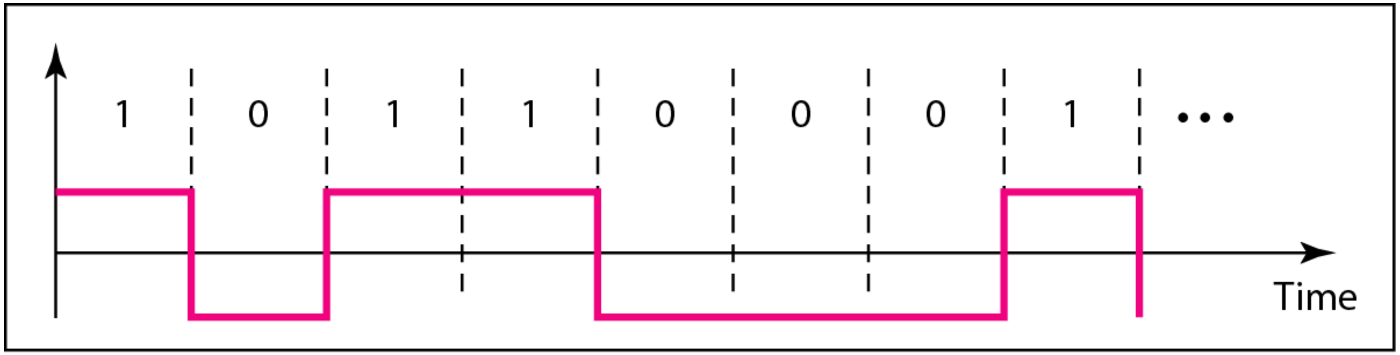
Synchronization

- To correctly interpret the signals received from the sender, the receiver's bit **intervals** must correspond exactly to the sender's bit intervals.
- If the receiver clock is **faster or slower**, the bit intervals are not matched and the receiver might misinterpret the signals.
- Figure 4.3 (next slide) shows a situation in which the receiver has a shorter bit duration.
- The sender sends 10110001, while the receiver receives 110111000011.
- A **self-synchronizing** digital signal includes timing information in the data being transmitted.
- This can be achieved if there are transitions in the signal that alert the receiver to the beginning, middle, or end of the pulse.
- If the receiver's clock is out of synchronization, these points can reset the clock.

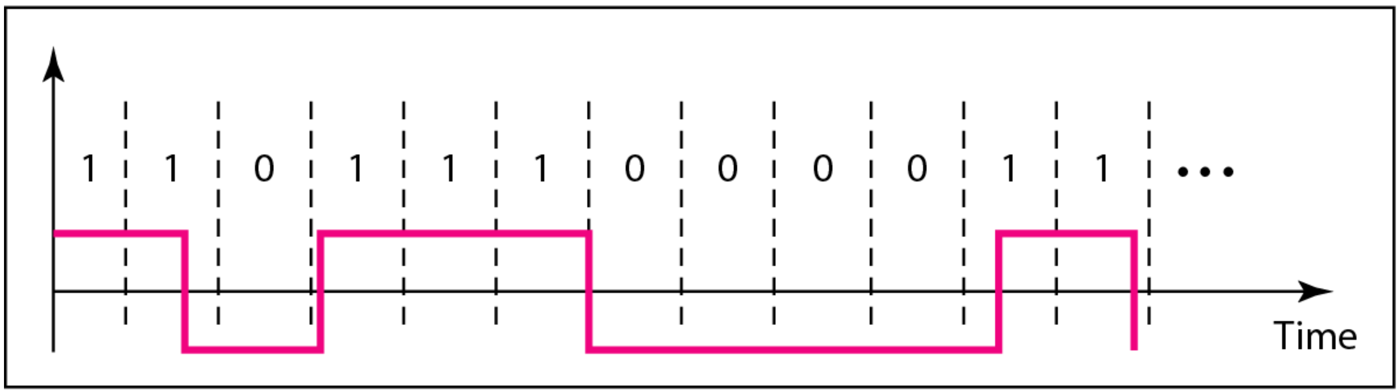
Definitions

- ***Built-in Error Detection***
  It is desirable to have a built-in error-detecting capability in the generated code to detect some or all of the errors that occurred during transmission. Some encoding schemes that we will discuss have this capability to some extent.
- ***Immunity to Noise and Interference***
  Another desirable code characteristic is a code that is immune to noise and other interferences. Some encoding schemes that we will discuss have this capability.
- ***Complexity***
  A complex scheme is more costly to implement than a simple one. For example, a scheme that uses four signal levels is more difficult to interpret than one that uses only two levels.

Figure 4.3 *Effect of lack of synchronization*



a. Sent



b. Received

Example 4.3

In a digital transmission, the receiver clock is 0.1 percent faster than the sender clock. How many extra bits per second does the receiver receive if the data rate is 1 kbps? How many if the data rate is 1 Mbps?

Solution

At 1 kbps, the receiver receives 1001 bps instead of 1000 bps.

1000 bits sent	1001 bits received	1 extra bps

At 1 Mbps, the receiver receives 1,001,000 bps instead of 1,000,000 bps.

1,000,000 bits sent	1,001,000 bits received	1000 extra bps

Figure 4.4 *Line coding schemes*

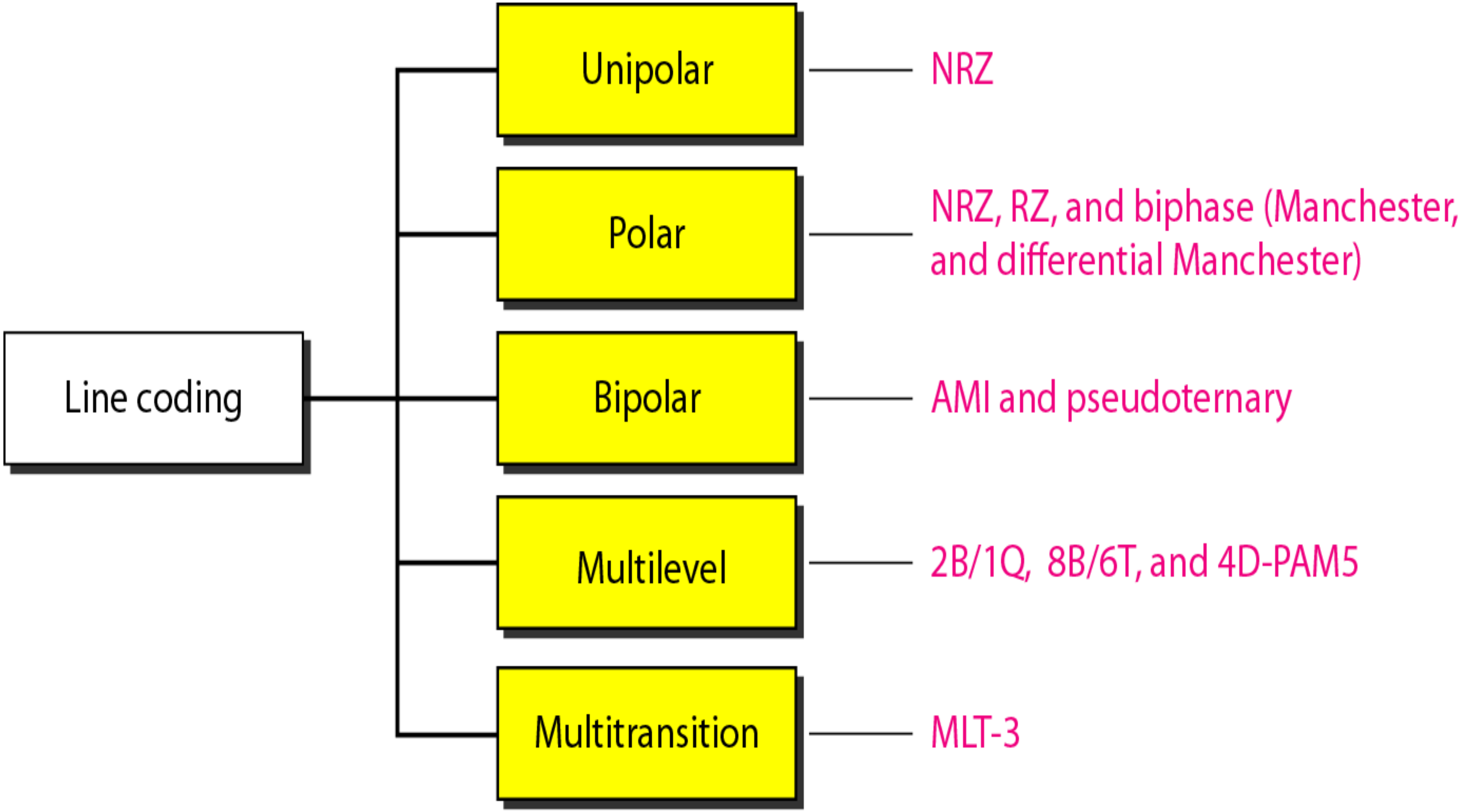
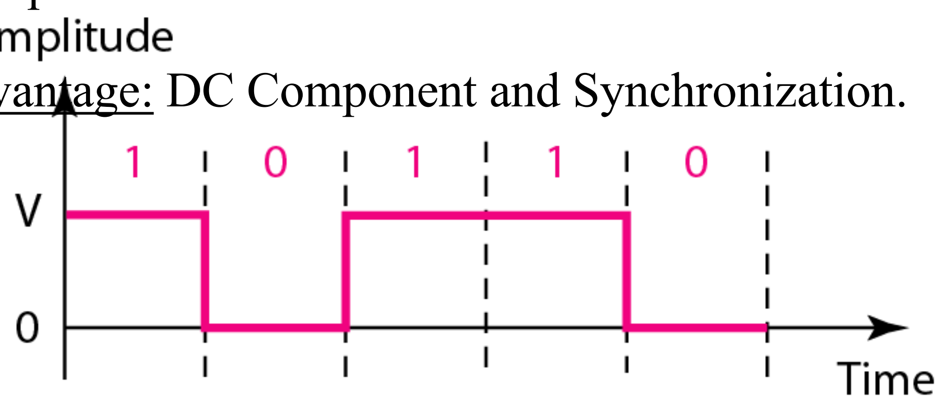


Figure 4.5 ***Unipolar NRZ scheme***

In a unipolar scheme, all the signal levels are on one side of the time axis, either above or below. In ***Non-Return-to-Zero,*** the signal does not return to zero at the middle of the bit, *where* positive voltage defines bit 1 and the zero voltage defines bit 0. Costly. the normalized power (the power needed to send 1 bit per unit line resistance) is double that for polar NRZ.

Disadvantage: DC Component and Synchronization.

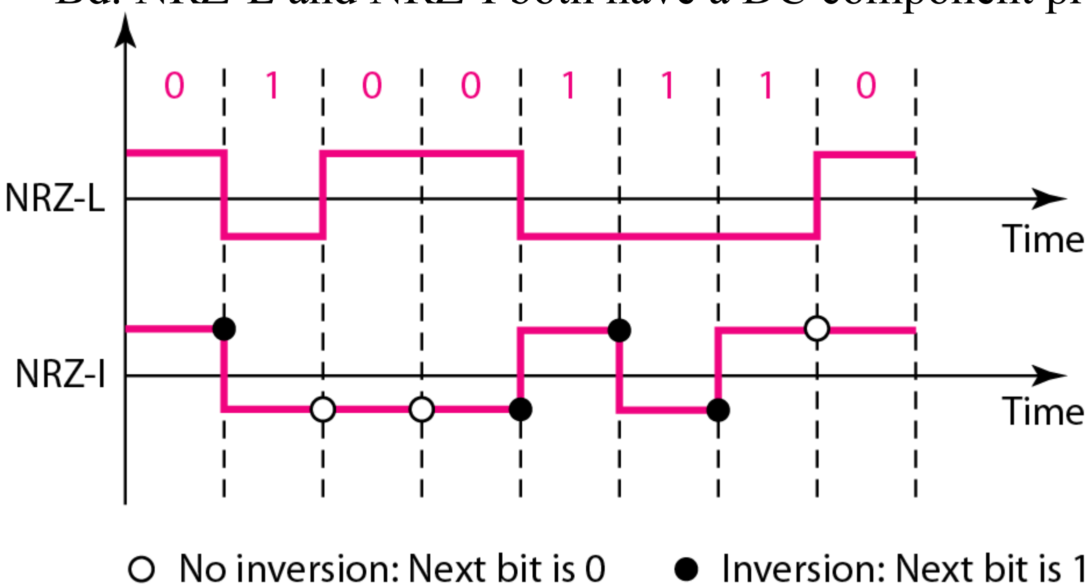


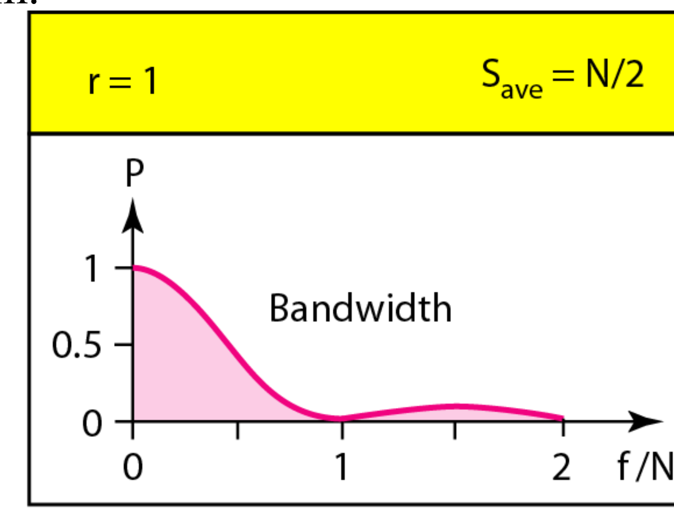
$$\frac{1}{2}V^2 + \frac{1}{2}(0)^2 = \frac{1}{2}V^2$$

Normalized power

Figure 4.6 *Polar NRZ-L and NRZ-I schemes*

Non-Return-to-Zero (NRZ) with L (Level) and I (Invert). In NRZ-L the level of the voltage determines the value of the bit. In NRZ-I the inversion or the lack of inversion determines the value of the bit. If there is a long sequence of 0s or 1s in NRZ-L, the average signal power becomes skewed. In NRZ-I this problem occurs only for a long sequence of 0s. The synchronization problem. Another problem with NRZ-L occurs when there is a sudden change of polarity in the system. NRZ-L and NRZ-I both have an average signal rate of N/2 Bd. NRZ-L and NRZ-I both have a DC component problem.





Example 4.4

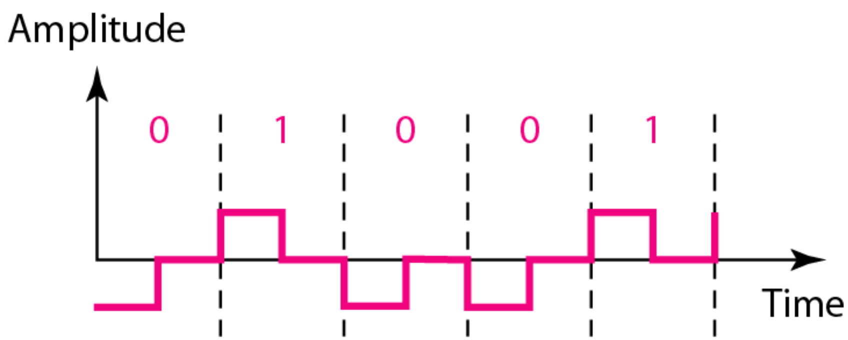
A system is using NRZ-I to transfer 1Mbps data. What are the average signal rate and minimum bandwidth?

Solution

The average signal rate is $S = N/2 = 500$ kbaud. The minimum bandwidth for this average baud rate is $B_{min} = S = 500$ kHz.

Figure 4.7 *Polar RZ scheme*

- ***Return-to-Zero (RZ)*** uses three values: positive, negative, and zero.
- Signal changes not between bits but during the bit.
- Occupy greater bandwidth as needs change during the bits.
- No DC component problem.
- Another problem is the complexity due to 3 signals.
- Not in use.



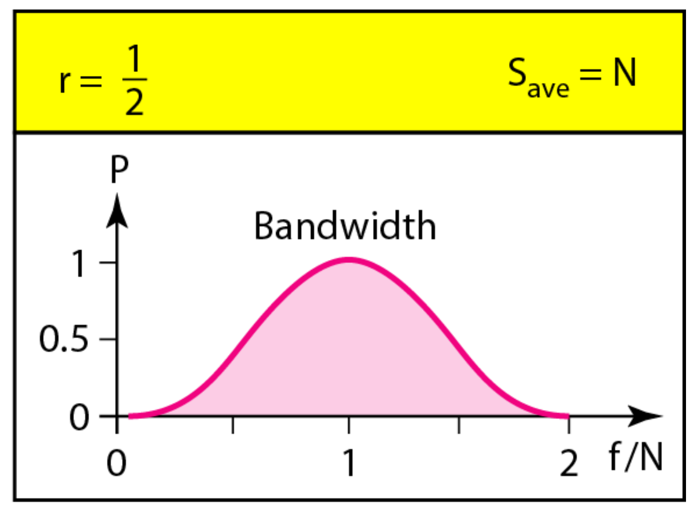
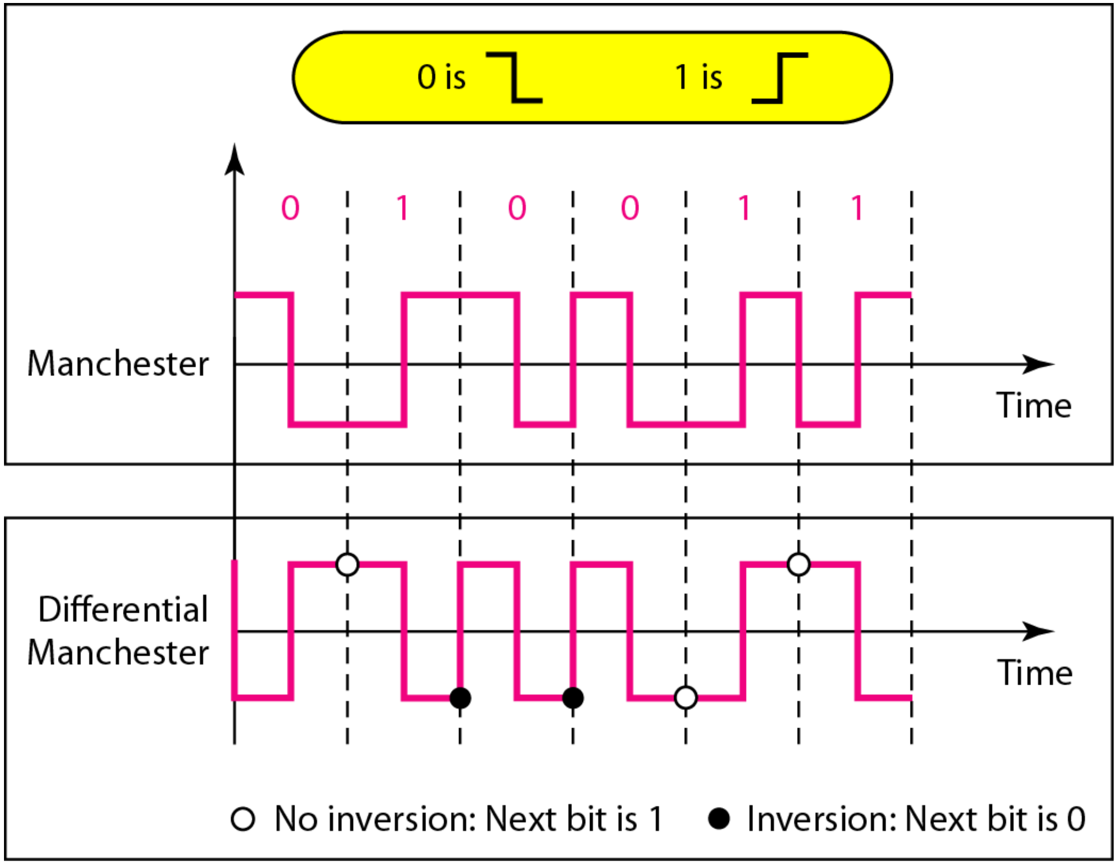
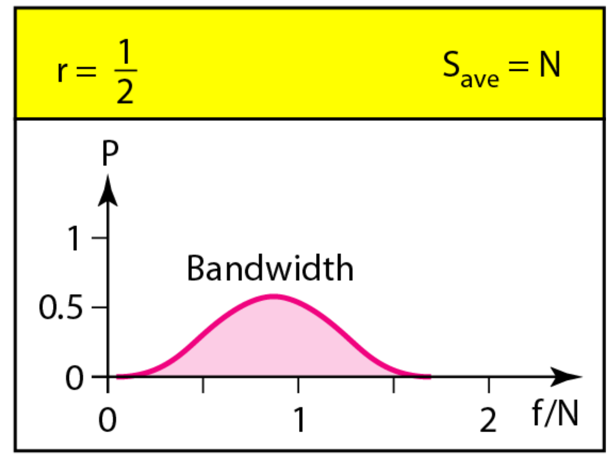


Figure 4.8 *Polar biphase: Manchester and differential Manchester schemes*





Note

In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.

Note

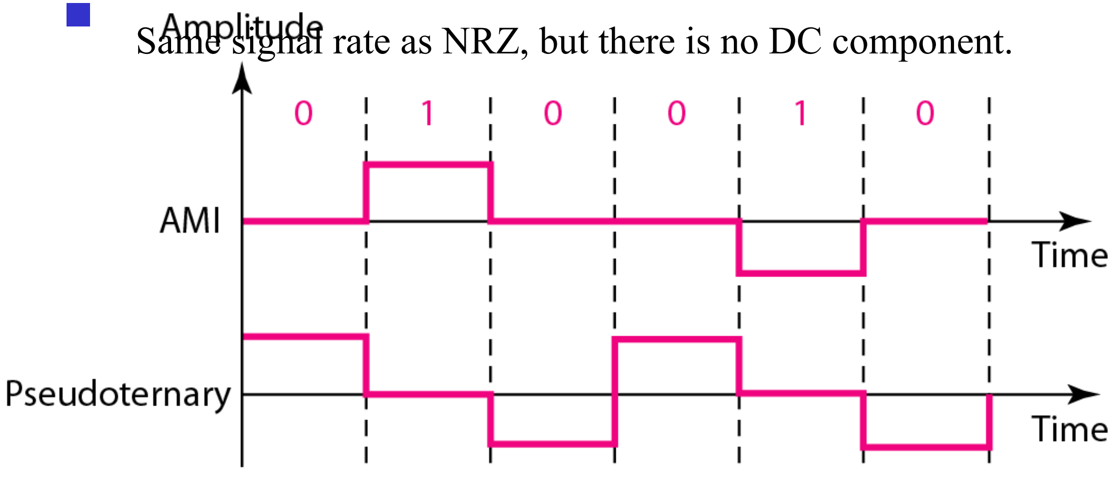
The minimum bandwidth of Manchester and differential Manchester is 2 times that of NRZ.

Note

In bipolar encoding, we use three levels: positive, zero, and negative.

Figure 4.9 *Bipolar schemes: AMI and pseudoternary*

- **Alternate Mark Inversion (AMI)** and **Pseudoternary.**
- Mark means 1. So AMI means alternate 1 inversion.
- A neutral zero voltage represents binary 0. Binary 1s are represented by alternating positive and negative voltages.
- A variation of AMI encoding is called pseudoternary in which the 1 bit is encoded as a zero voltage and the 0 bit is encoded as alternating positive and negative voltages.
- Same signal rate as NRZ, but there is no DC component.



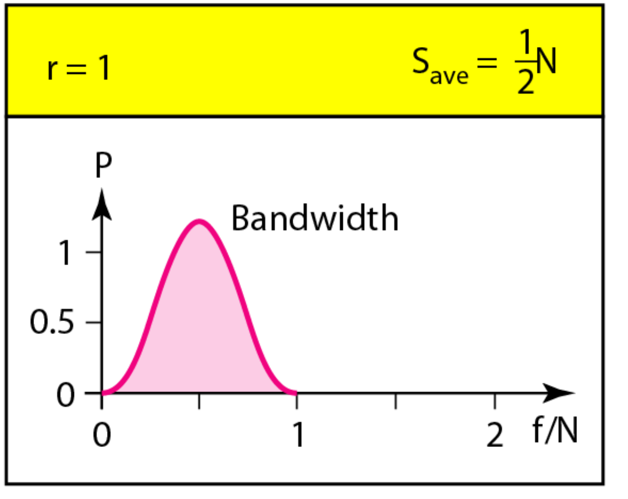
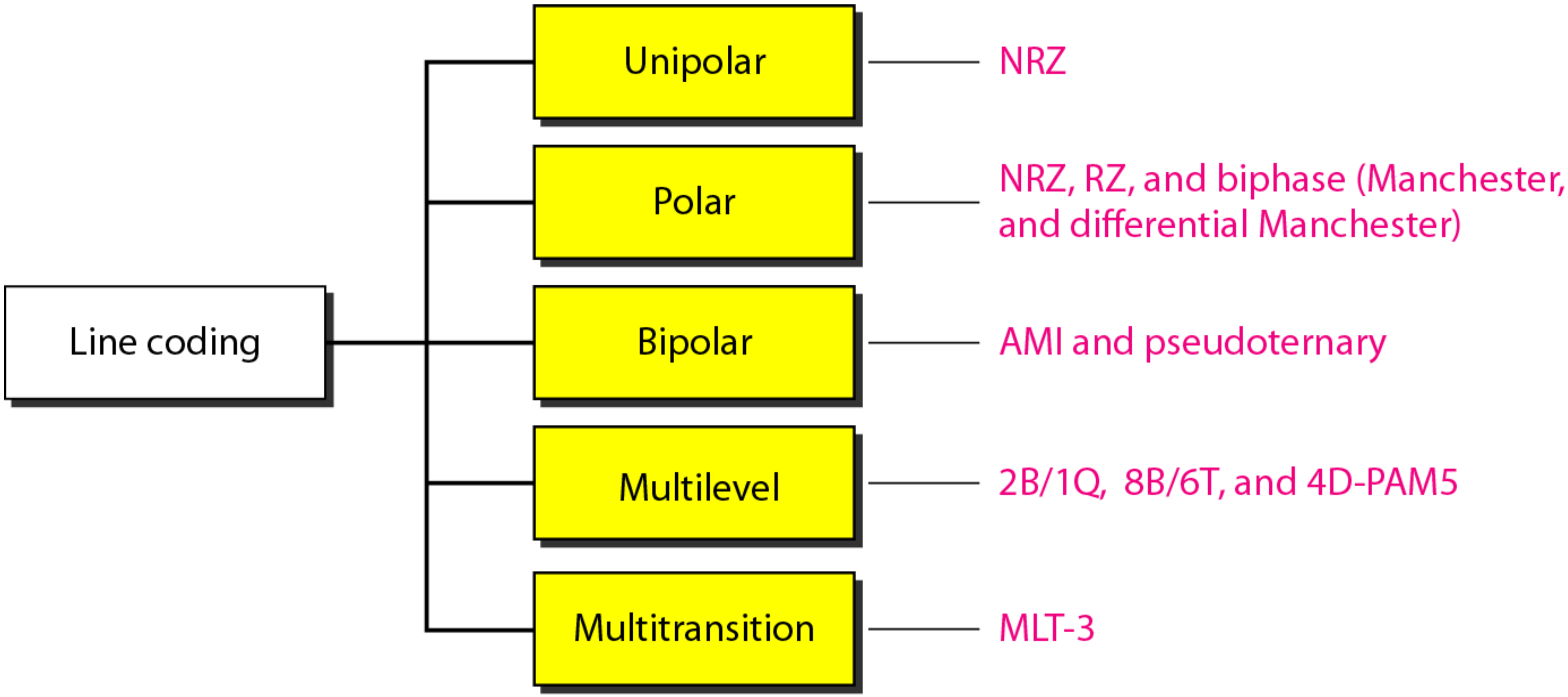


Figure 4.4 *Line coding schemes*



Note

In *m*B*n*L schemes, a pattern of *m* data elements is encoded as a pattern of *n* signal elements in which $2^m \leq L^n$.

Figure 4.10 *Multilevel: 2B1Q scheme*

- The first *mBnL* scheme we discuss, **two binary, one quaternary (2B1Q),** uses data patterns of size 2 and encodes the 2-bit patterns as one signal element belonging to a four-level signal.
- In this type of encoding $m = 2$, $n = 1$, and $L = 4$ (quaternary).
- 2 times faster than by using NRZ-L
- There are no redundant signal patterns in this scheme because $2^2 = 4^1$.
- Used in DSL (Digital Subscriber Line) technology to provide a high-speed connection to the Internet by using subscriber telephone lines

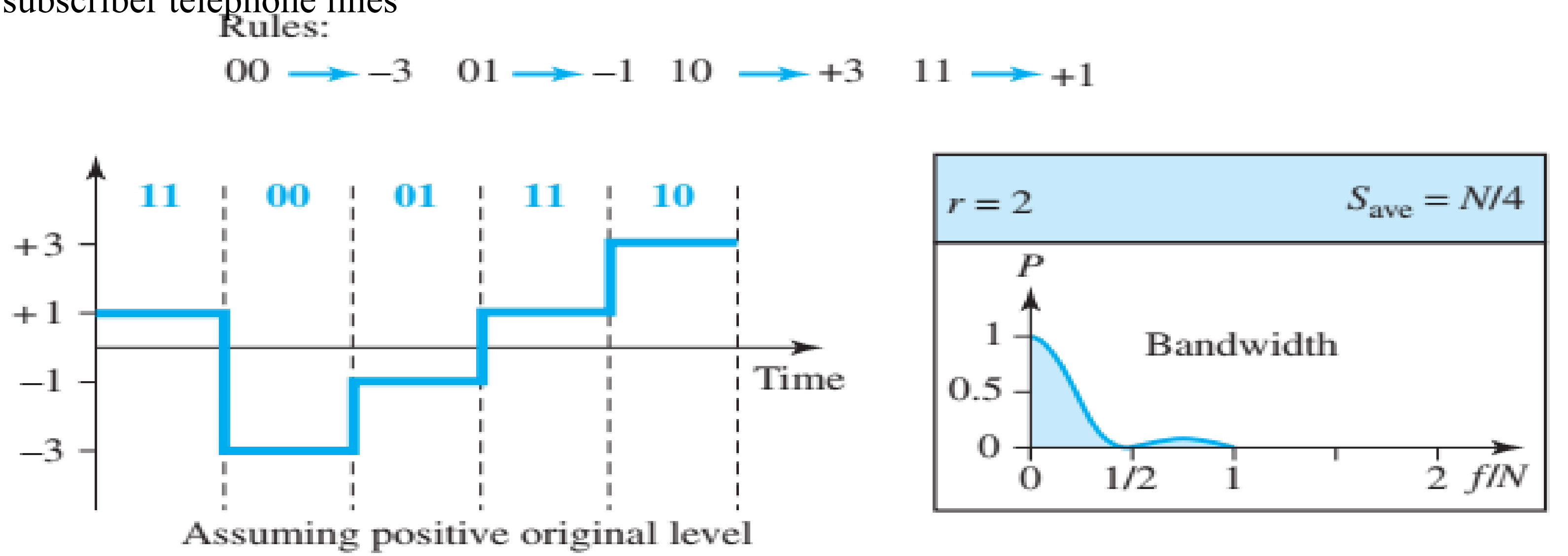
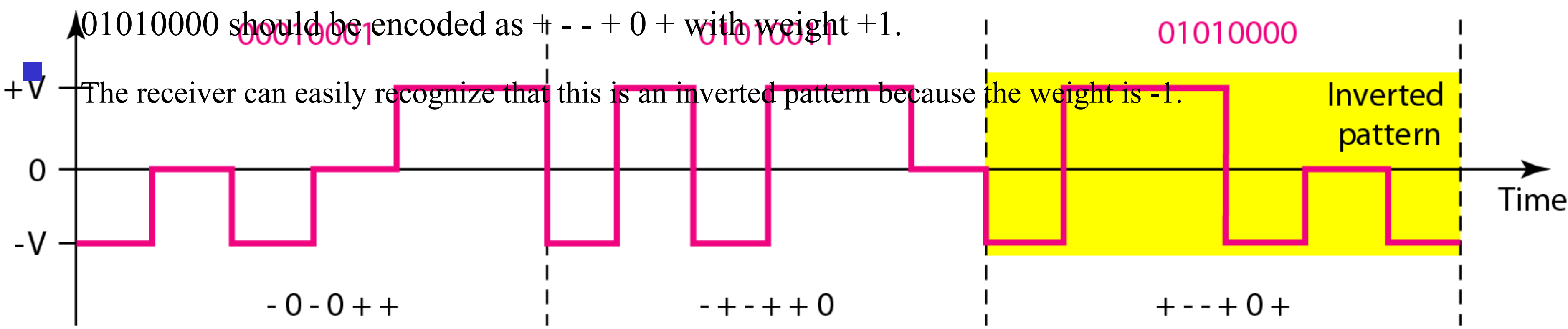


Figure 4.11 ***Multilevel: 8B6T scheme***

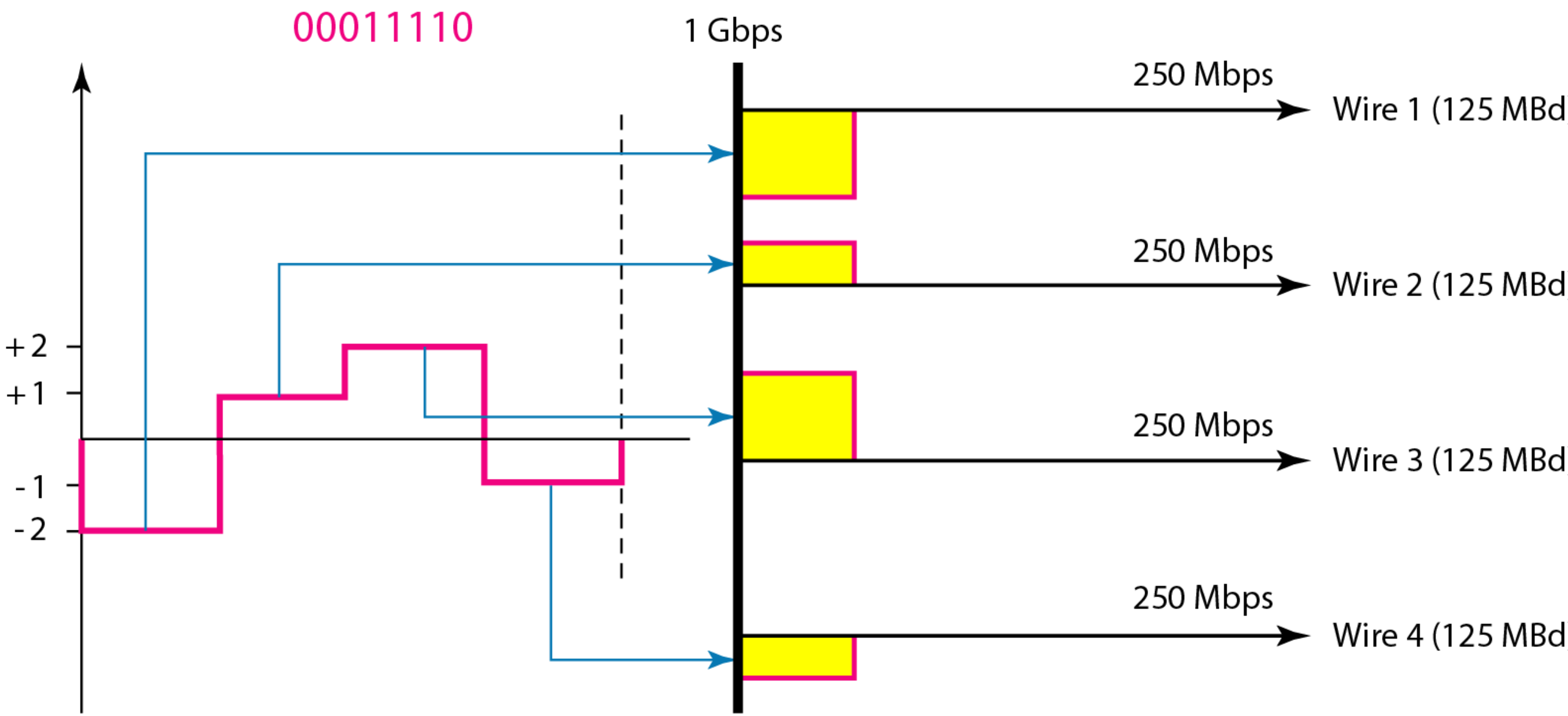
- The **eight binary, six ternary (8B6T)** is used with 100BASE-4T cable.
- Signal has three levels (ternary) $2^8 = 256$ different data patterns and $3^6 = 729$ different signal patterns.
- There are 729 - 256 = 473 redundant signal elements that provide synchronization, error detection and provide DC balance.
- The first 8-bit pattern 00010001 is encoded as the signal pattern - 0 - 0 + + with weight 0; the second 8-bit pattern 01010011 is encoded as - + - + + 0 with weight +1. The third 8-bit pattern 01010000 should be encoded as + - - + 0 + with weight +1.
- The receiver can easily recognize that this is an inverted pattern because the weight is -1.



4D-PAM5

- Four-dimensional five level pulse amplitude modulation (4D-PAM5)
- The 4D means that data is sent over four wires at the same time. It uses five voltage levels, such as -2, -1, 0, 1, and 2.
- However, one level, level 0, is used only for forward error detection.
- Gigabit LANs use this technique to send 1-Gbps data over four copper cables that can handle 125 Mbaud.
- The extra signal patterns can be used for other purposes such as error detection.

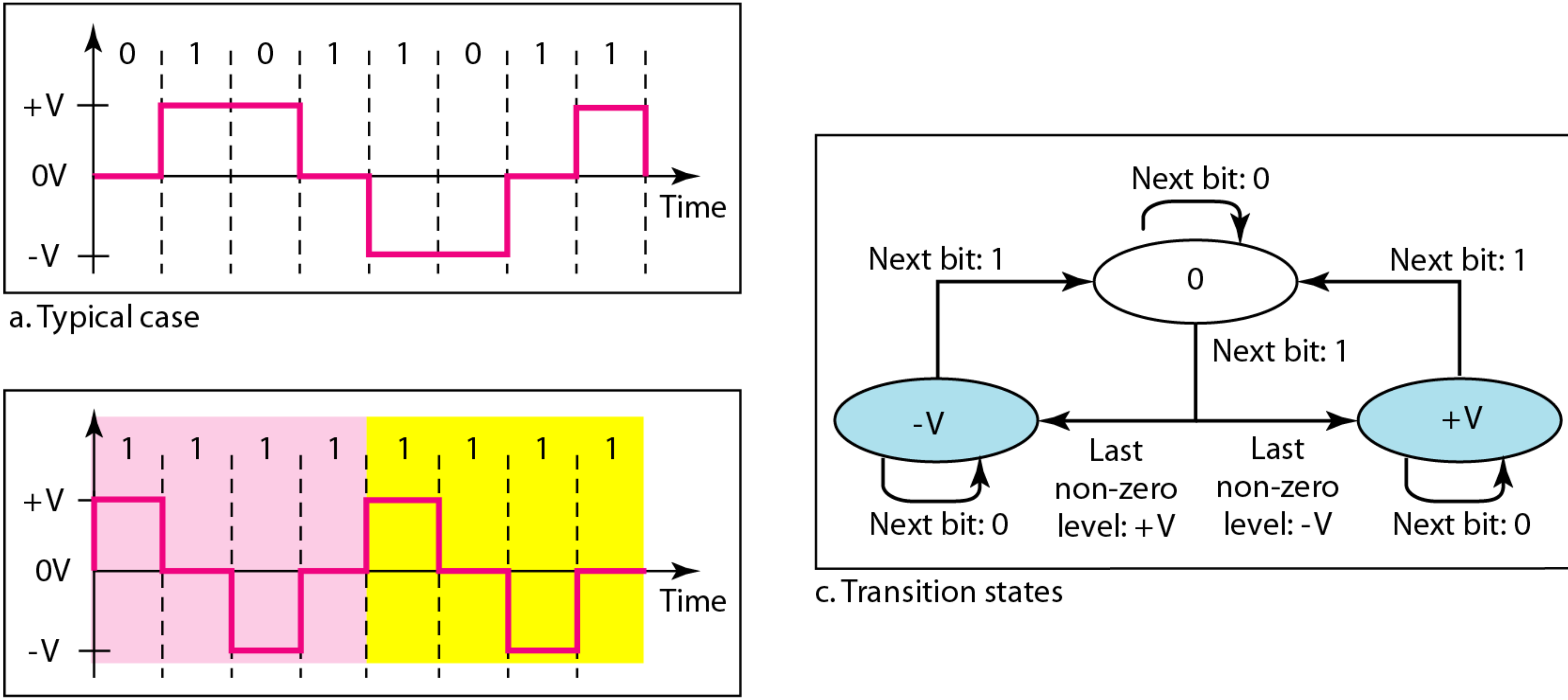
Figure 4.12 *Multilevel: 4D-PAM5 scheme*



Multitransition: MLT-3

- The **multiline transmission, three-level (MLT-3) scheme uses** three levels (+*V*, 0, and -*V*) and three transition rules to move between the levels.
  1. If the next bit is 0, there is no transition.
  2. If the next bit is 1 and the current level is not 0, the next level is 0.
  3. If the next bit is 1 and the current level is 0, the next level is the opposite of the last nonzero level.
- The three voltage levels (-*V*, 0, and +*V*) are shown by three states (ovals).
- It turns out that the shape of the signal in this scheme helps to reduce the required bandwidth.
- MLT-3 a suitable choice when we need to send 100 Mbps on a copper wire that cannot support more than 32 MHz.
- 1 = level change. 0 = no change.

Figure 4.13 *Multitransition: MLT-3 scheme*



a. Typical case

b. Worse case

c. Transition states

Table 4.1 *Summary of line coding schemes*

Category	*Scheme*	*Bandwidth (average)*	*Characteristics*
Unipolar	NRZ	$B = N/2$	Costly, no self-synchronization if long 0s or 1s, DC
Unipolar	NRZ-L	$B = N/2$	No self-synchronization if long 0s or 1s, DC
	NRZ-I	$B = N/2$	No self-synchronization for long 0s, DC
	Biphase	$B = N$	Self-synchronization, no DC, high bandwidth
Bipolar	AMI	$B = N/2$	No self-synchronization for long 0s, DC
Multilevel	2B1Q	$B = N/4$	No self-synchronization for long same double bits
	8B6T	$B = 3N/4$	Self-synchronization, no DC
	4D-PAM5	$B = N/8$	Self-synchronization, no DC
Multiline	MLT-3	$B = N/3$	No self-synchronization for long 0s