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.

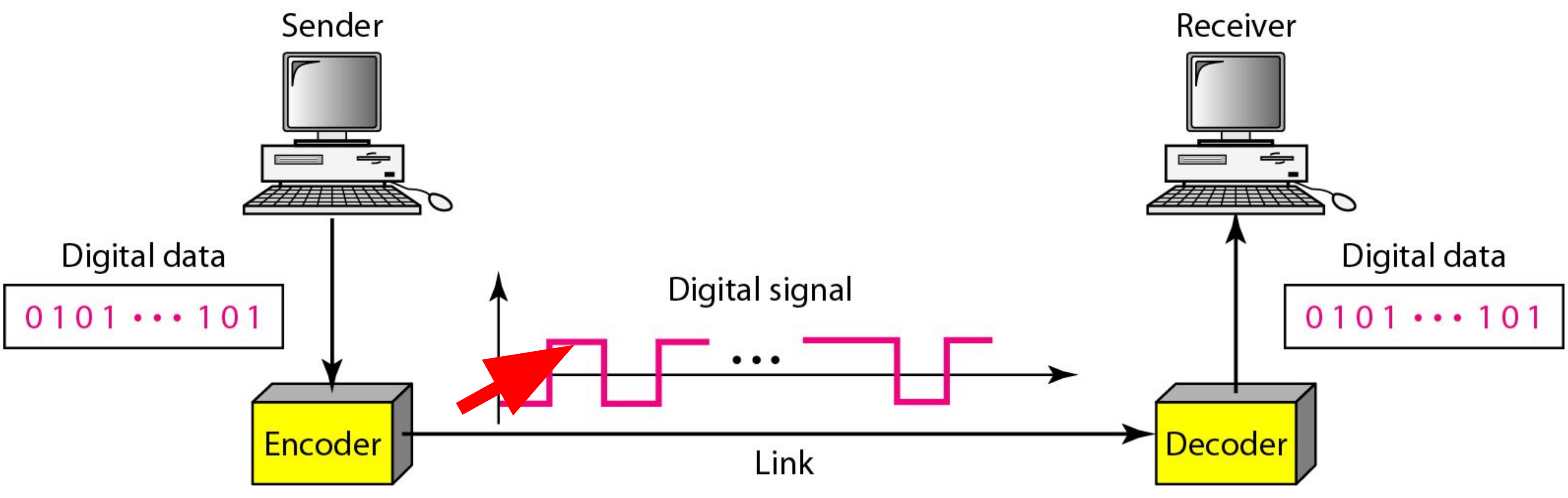
Topics discussed in this section:

- **Line Coding**
- **Line Coding Schemes**
- **Block Coding**
- **Scrambling**

Line Coding

- Converting a string of 1’s and 0’s (digital data) into a sequence of signals that denote the 1’s and 0’s.
- For example a high voltage level (+V) could represent a “1” and a low voltage level (0 or -V) could represent a “0”.

Figure 4.1 *Line coding and decoding*



Mapping Data symbols onto Signal levels

- A data symbol (or element) can consist of a number of data bits:
  - 1 , 0 or
  - 11, 10, 01, ……
- A data symbol can be coded into a single signal element or multiple signal elements
  - 1 -> +V, 0 -> -V
  - 1 -> +V and -V, 0 -> -V and +V
- The ratio ‘r’ is the number of data elements carried by a signal element.

- Two most common/confused words in digital communication – Bit rate and Baud rate.
- Generally, communication is concerned with transmission of data.
- In digital communication, there are two entities that are needed to carry out communication – the data to be transmitted and the signal over which the data is transmitted. Now, we have two entities to be worried about – the data and the signal. The most common misconception is that most people think both travel at the same speed! – NO!

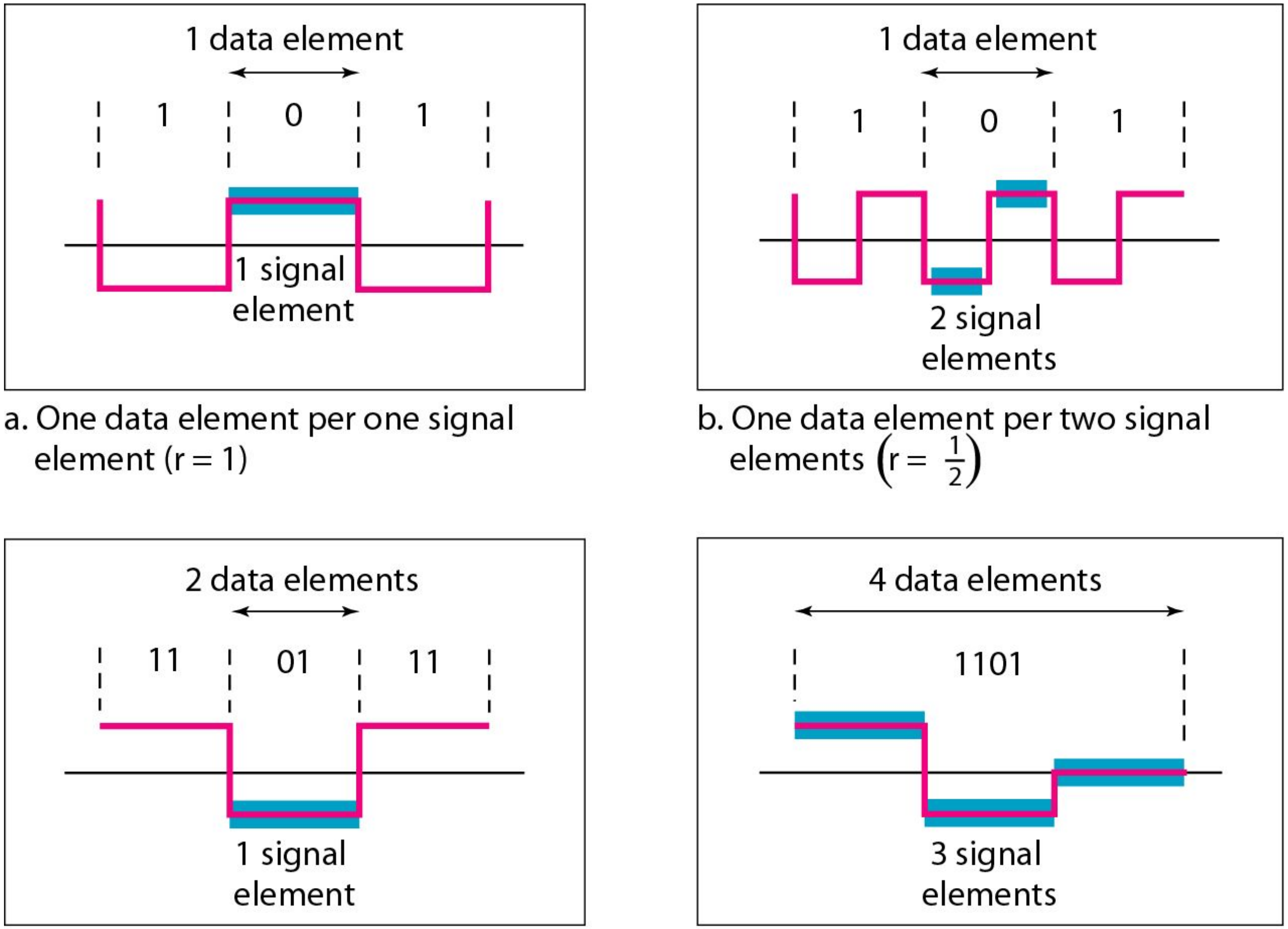
The difference:

- Digital data is very different from digital signal. The process of converting digital data to digital signal is called as **line coding**. Now, to discriminate between data and signal, data is what we need to send. But signal is what we can send. So, signal is the carrier which carries data. Also, keep in mind that the smallest entity of the data, that can represent a piece of information is called data element and shortest meaningful unit of a signal is called signal element. Consider this as in the following scenario – Consider a train. Each carriage is a signal element. Each passenger inside the train is a data element. The train as a whole is a signal and all passengers together represent a data.

Relationship between data rate and signal rate

- The data rate defines the number of bits sent per sec - bps. It is often referred to the bit rate.
- The signal rate is the number of signal elements sent in a second and is measured in bauds. It is also referred to as the modulation rate.
- Goal is to increase the data rate whilst reducing the baud rate/signal rate/modulation rate.

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 $\left(r = \frac{4}{3}\right)$

Data rate and Baud rate(signal rate)

- The baud or signal rate can be expressed as:

$$S = c \times N \times 1/r \text{ bauds}$$

where N is data rate

c is the case factor (worst, best & avg.)

r is the ratio between data element & signal element

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.

Bandwidth is measured as the amount of data that can be transferred from one point to another within a network in a specific amount of time. Typically, **bandwidth** is expressed as a bitrate and measured in bits per second (bps).

Bandwidth:ডাটা স্থানান্তরের হার, র্পতি সেকেন্ডে যে পরিমাণ ডাটা স্থানান্তর হয়

BANDWIDTH OF DIGITAL SIGNAL

The minimum bandwidth can be given as

$$B_{min} = c \times N \times \frac{1}{r}$$

We can solve for the maximum data rate if the bandwidth of the channel is given.

$$N_{max} = \frac{1}{c} \times B \times r$$

Example 4.2

The maximum data rate of a channel (see Chapter 3) 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

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

Considerations for choosing a good signal element referred to as line encoding

- Baseline wandering - a receiver will evaluate the average power of the received signal (called the baseline) and use that to determine the value of the incoming data elements. If the incoming signal does not vary over a long period of time, the baseline will drift and thus cause errors in detection of incoming data elements.
- A good line encoding scheme will prevent long runs of fixed amplitude.

Line encoding C/Cs

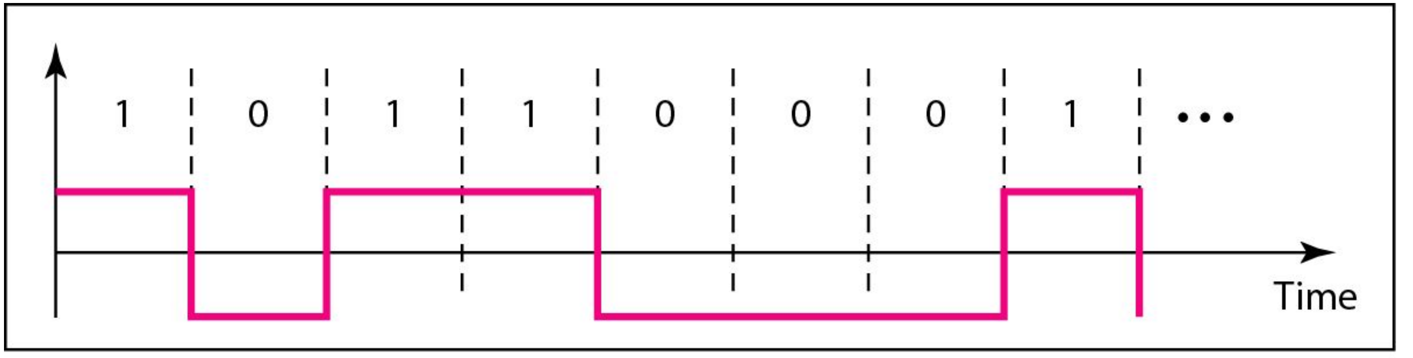
- DC components - when the voltage level remains constant for long periods of time, there is an increase in the low frequencies of the signal. Most channels are bandpass and may not support the low frequencies.
- This will require the removal of the dc component of a transmitted signal.

- DC components: After line coding, the signal may have zero frequency component in the spectrum of the signal, which is known as the direct-current (DC) component. DC component in a signal is not desirable because the DC component does not pass through some components of a communication system such as a transformer.

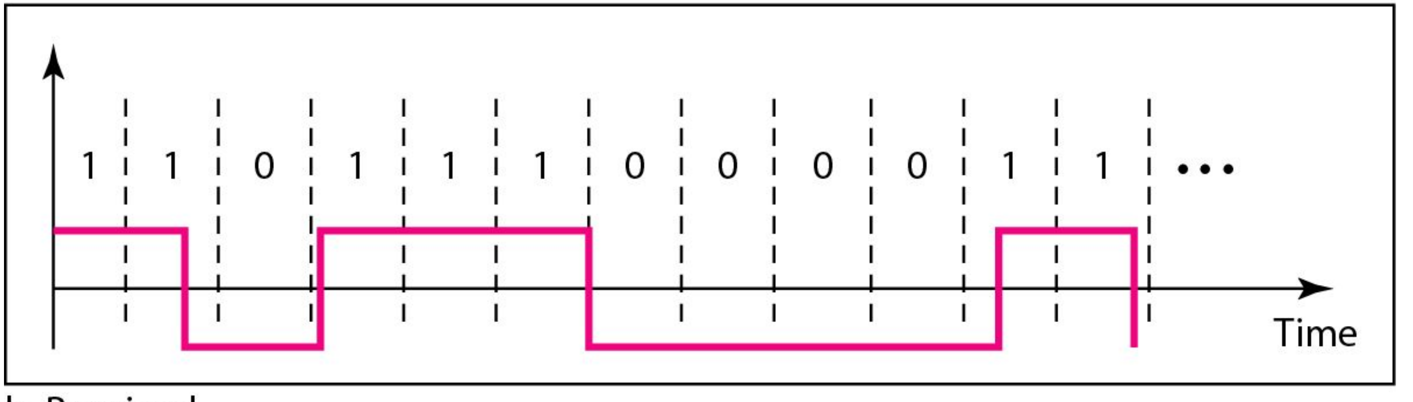
Line encoding C/Cs

- Self synchronization - the clocks at the sender and the receiver must have the same bit interval.
- If the receiver clock is faster or slower it will misinterpret the incoming bit stream.

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

Line encoding C/Cs

- Error detection - errors occur during transmission due to line impairments.
- Some codes are constructed such that when an error occurs it can be detected. For example: a particular signal transition is not part of the code. When it occurs, the receiver will know that a symbol error has occurred.

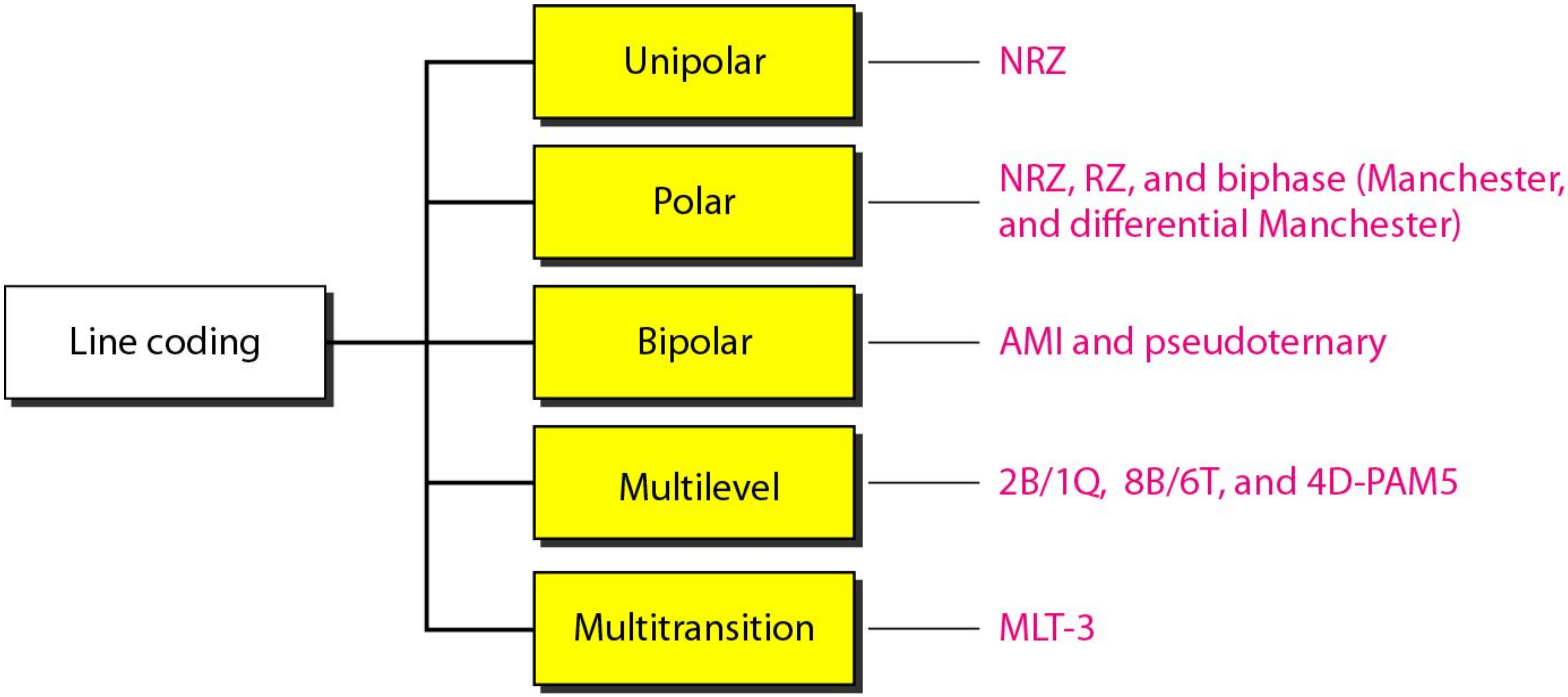
Line encoding C/Cs

- Noise and interference - there are line encoding techniques that make the transmitted signal “immune” to noise and interference.
- This means that the signal cannot be corrupted, it is stronger than error detection.

Line encoding C/Cs

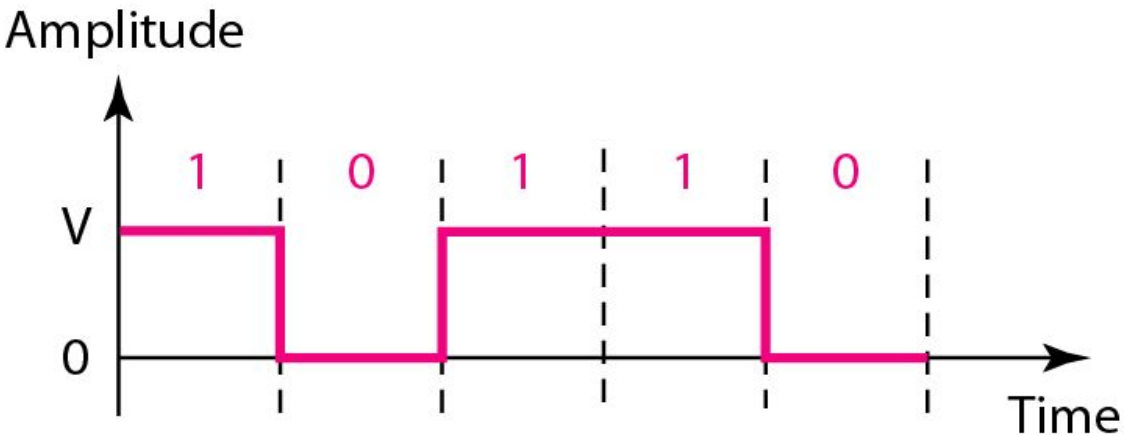
- Complexity - the more robust and resilient the code, the more complex it is to implement and the price is often paid in baud rate or required bandwidth.

Figure 4.4 *Line coding schemes*



Unipolar

- In a unipolar scheme, all the signal levels are on one side of the time axis, either above or below.



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

Normalized power

Unipolar

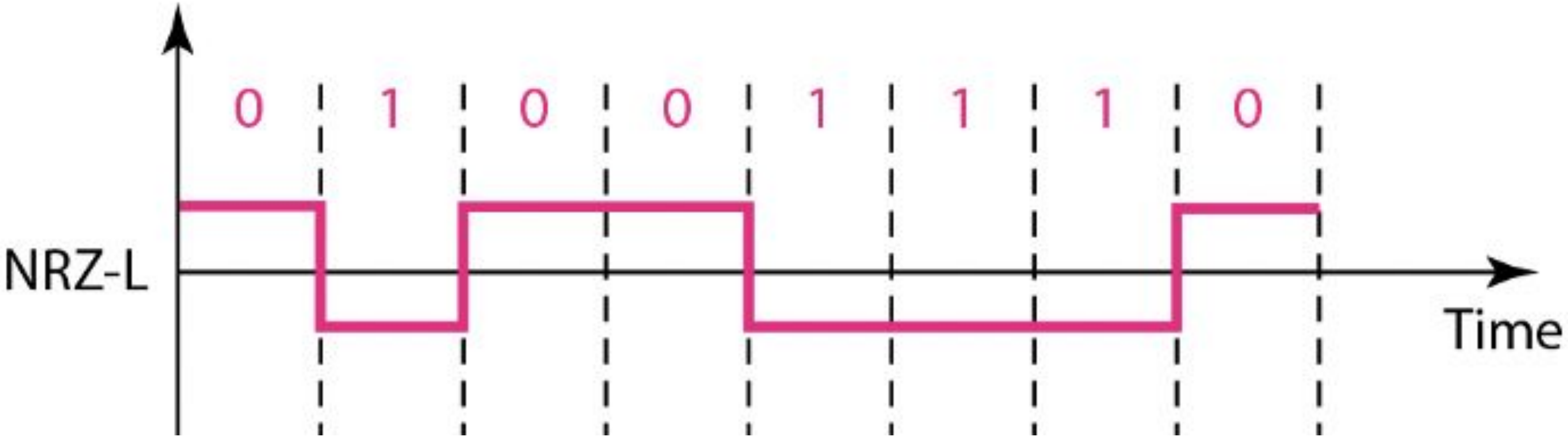
- NRZ (Non-Return-to-Zero) Traditionally, a unipolar scheme was designed as a non-return-to-zero (NRZ) scheme in which the positive voltage defines bit 1 and the zero voltage defines bit 0.
- It is called NRZ because the signal does not return to zero at the middle of the bit.
- Compared with its polar counterpart (see the next section), this scheme is very costly. As we will see shortly, the normalized power (power needed to send 1 bit per unit line resistance) is double that for polar NRZ. For this reason, this scheme is nor- mally not used in data communications today.

Polar - NRZ

- The voltages are on both sides of the time axis.
- Polar NRZ scheme can be implemented with two voltages. E.g. +V for 0 and -V for 1.
- There are two versions:
  - NRZ - Level (NRZ-L)
  - NRZ - Inversion (NRZ-I)

NRZ - Level (NRZ-L)

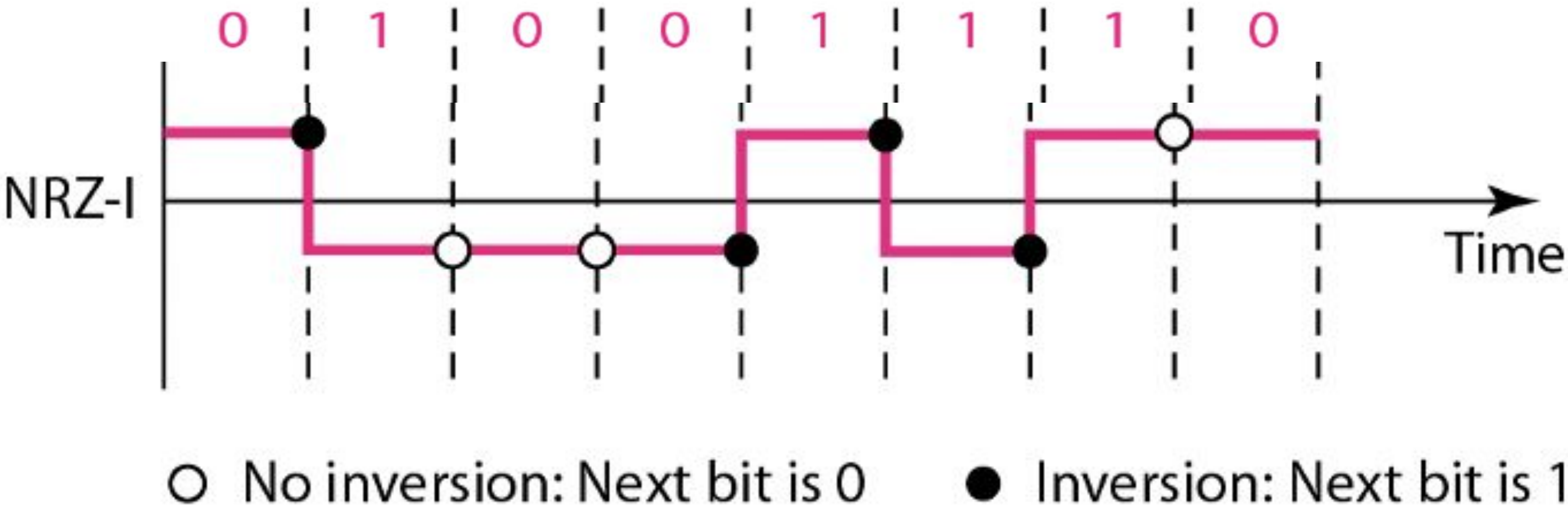
positive voltage for one symbol and
negative for the other



NRZ - Inversion (NRZ-I)

The change or lack of change in polarity determines the value of a

s does not.



Note

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.

Note

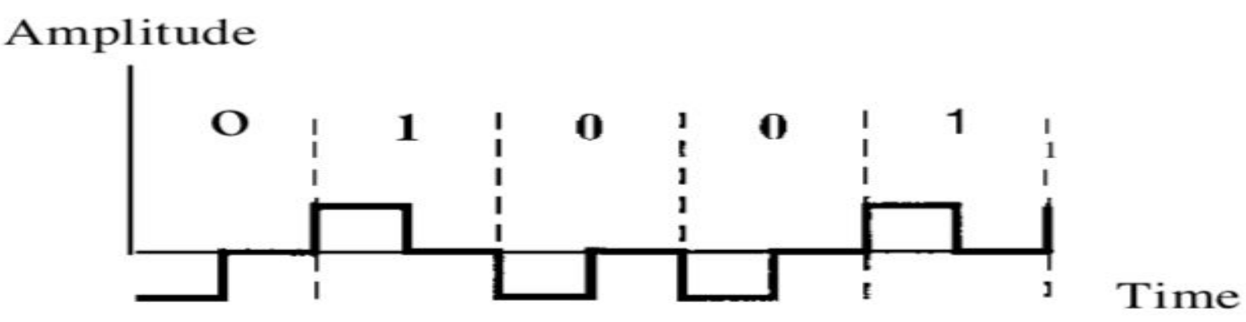
NRZ-L and NRZ-I both have an average signal rate of N/2 Bd.

Note

NRZ-L and NRZ-I both have a DC component problem and baseline wandering, it is worse for NRZ-L. Both have no self synchronization &no error detection. Both are relatively simple to implement.

Problem of Polar - NRZ

- The sender and receiver clocks are not synchronized.
- The receiver does not know when one bit has ended and the next bit is starting.
- One solution is the return-to-zero (RZ) scheme, which uses three values: positive, negative, and zero.
- In RZ, the signal changes not between bits but during the bit. In Figure we see that the signal goes to 0 in the middle of each bit. It remains there until the beginning of the next bit.



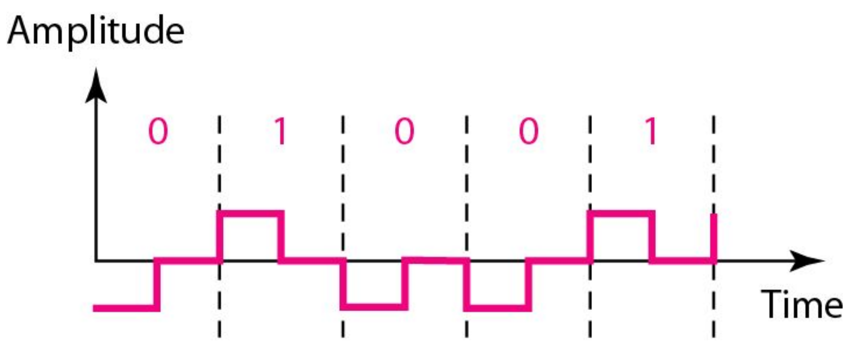
Polar - RZ

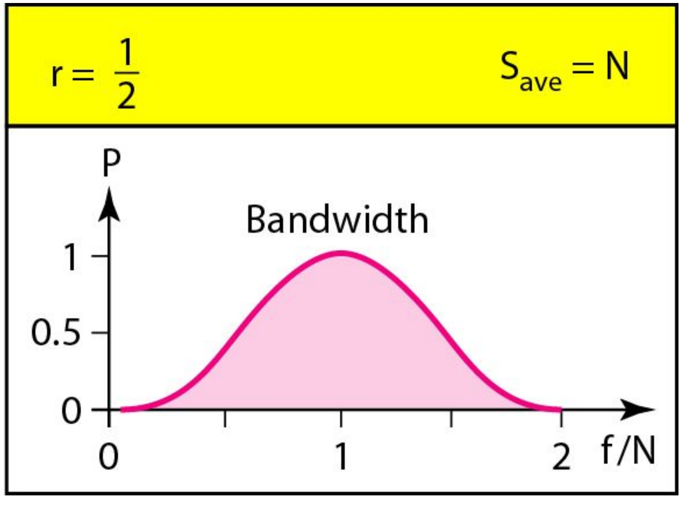
- The Return to Zero (RZ) scheme uses three voltage values. +, 0, -.
- Each symbol has a transition in the middle. Either from high to zero or from low to zero.

Disadvantage of RZ

- This scheme has more signal transitions (two per symbol) and therefore requires a wider bandwidth.
- No DC components or baseline wandering.
- More complex as it uses three voltage level. It has no error detection capability.
- As a result of all these deficiencies, the scheme is not used today. Instead, it has been replaced by the better-performing Manchester and differential Manchester schemes (discussed next).

Figure 4.7 *Polar RZ scheme*





Example 4.4

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

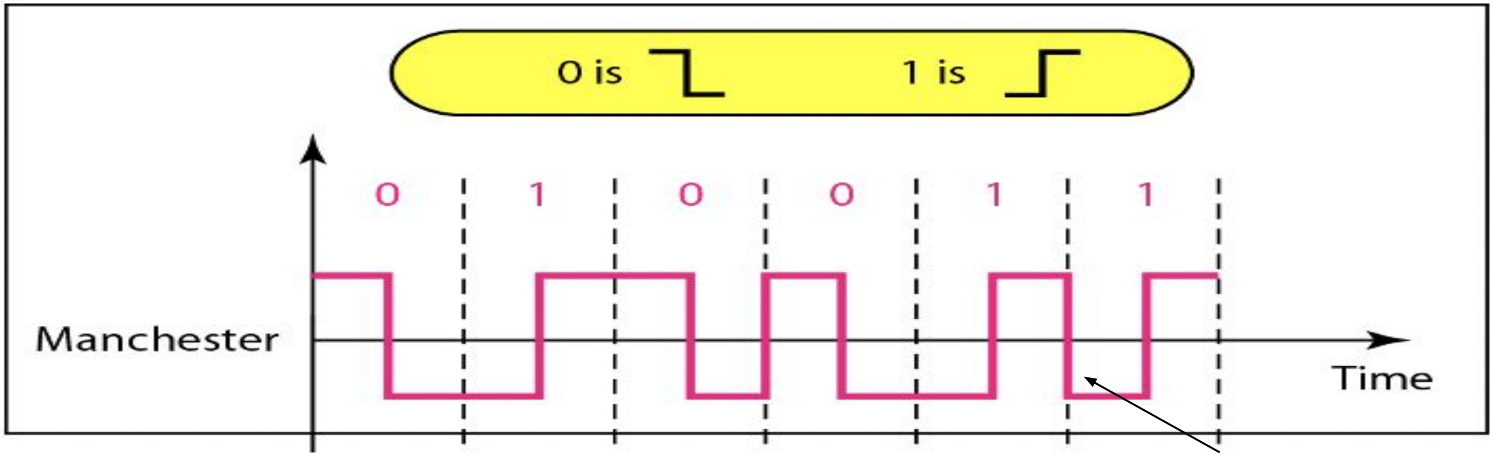
Solution

The average signal rate is S= c x N x R = 1/2 x N x 1 = 500 kbaud. The minimum bandwidth for this average baud rate is B_{min} = S = 500 kHz.

Note c = 1/2 for the avg. case as worst case is 1 and best case is 0

Polar - Biphase: Manchester and Differential Manchester

- Manchester coding consists of combining the NRZ-L (positive voltage for one symbol and negative for the other) and RZ schemes (Every symbol has a level transition in the middle: from high to low or low to high)
- Uses only two voltage levels.



Differential Manchester

- Differential Manchester coding consists of combining the NRZ-I (the change or lack of change in polarity determines the value of a symbol. E.g. a "1" symbol inverts the polarity a "0" does not.) and RZ schemes.
- Every symbol has a level transition in the middle. But the level at the beginning of the symbol is determined by the symbol value. One symbol causes a level change the other does not.

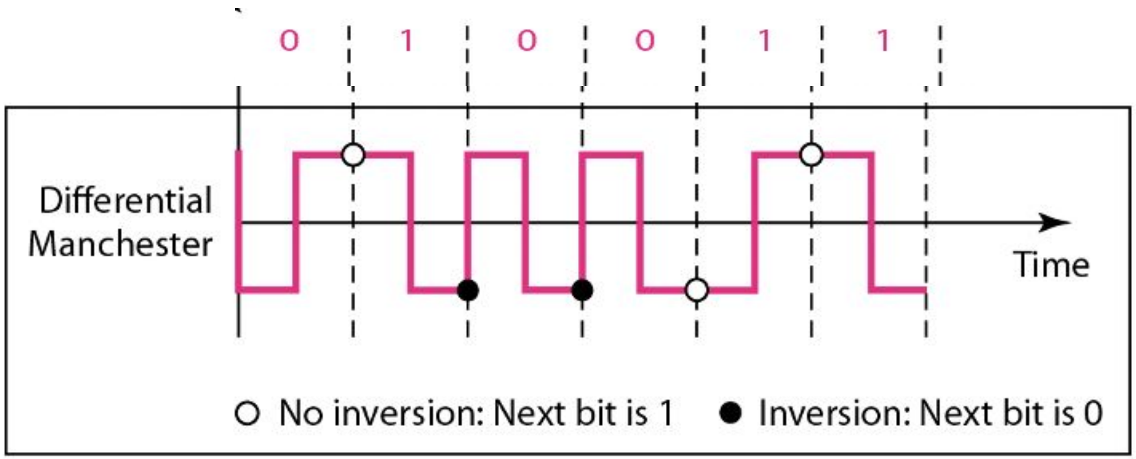
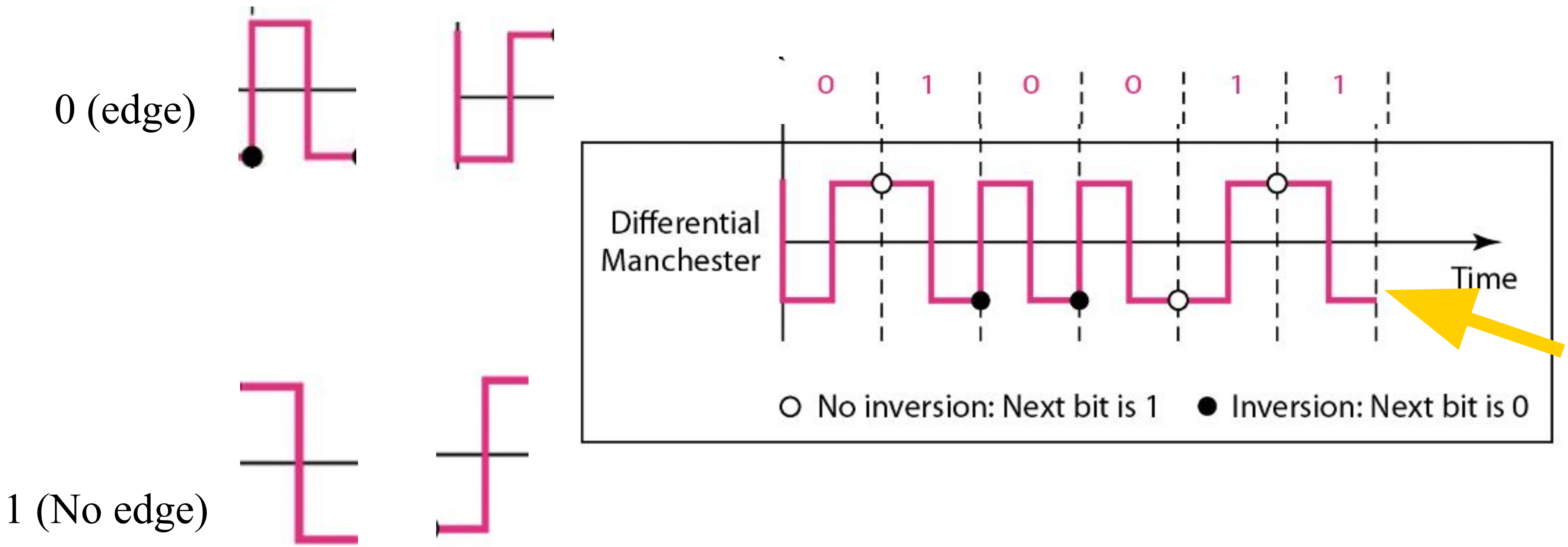


Figure 4.8 *Polar biphase: Manchester and differential Manchester schemes*



- The Manchester scheme overcomes several problems associated with NRZ-L, and differential Manchester overcomes several problems associated with NRZ-I.
- First, there is no baseline wandering. There is no DC component because each bit has a positive and negative voltage contribution.
- **None of these codes has error detection.**

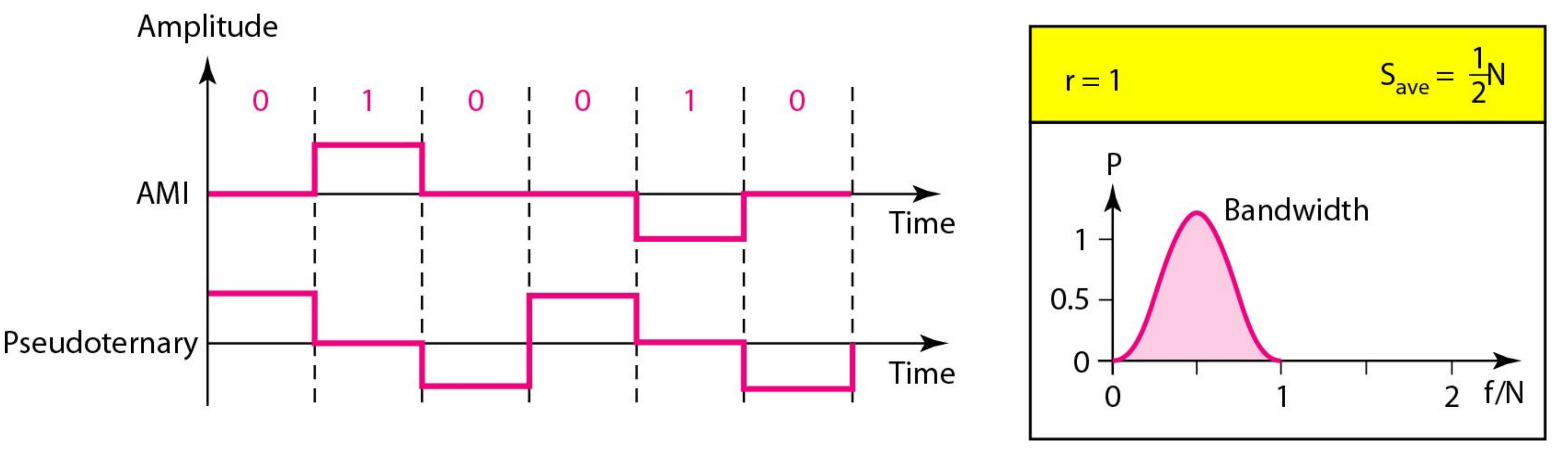
Note

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

Bipolar - AMI and Pseudoternary

- Code uses 3 voltage levels: +, 0, -, to represent the symbols (note not transitions to zero as in RZ).
- Voltage level for one symbol is at “0” and the other alternates between + & -.
- Bipolar Alternate Mark Inversion (AMI) - the “0” symbol is represented by zero voltage and the “1” symbol alternates between +V and -V.
- Pseudoternary is the reverse of AMI.

Figure 4.9 *Bipolar schemes: AMI and pseudoternary*



Bipolar pros and cons

- It is a better alternative to NRZ.
- Has no DC component or baseline wandering.
- Has no self synchronization because long runs of “0”s results in no signal transitions.
- No error detection.

Multilevel Schemes

- In these schemes we increase the number of data bits per symbol thereby increasing the bit rate.
- Since we are dealing with binary data we only have 2 types of data element a 1 or a 0.
- We can combine the 2 data elements into a pattern of “m” elements to create “2^m” symbols.
- If we have L signal levels, we can use “n” signal elements to create L^n signal elements.

Code C/Cs

- Now we have 2^m symbols and L^n signals.
- If $2^m > L^n$ then we cannot represent the data elements, we don't have enough signals.
- If $2^m = L^n$ then we have an exact mapping of one symbol on one signal.
- If $2^m < L^n$ then we have more signals than symbols and we can choose the signals that are more distinct to represent the symbols and therefore have better noise immunity and error detection as some signals are not valid.

Note

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

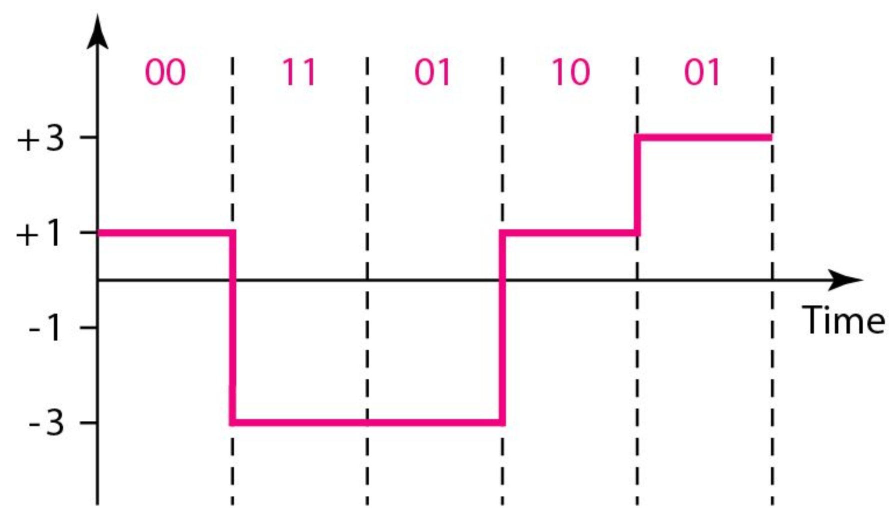
Representing Multilevel Codes

- We use the notation mBnL, where m is the length of the binary pattern, B represents binary data, n represents the length of the signal pattern and L the number of levels.
- L = B binary, L = T for 3 ternary, L = Q for 4 quaternary.

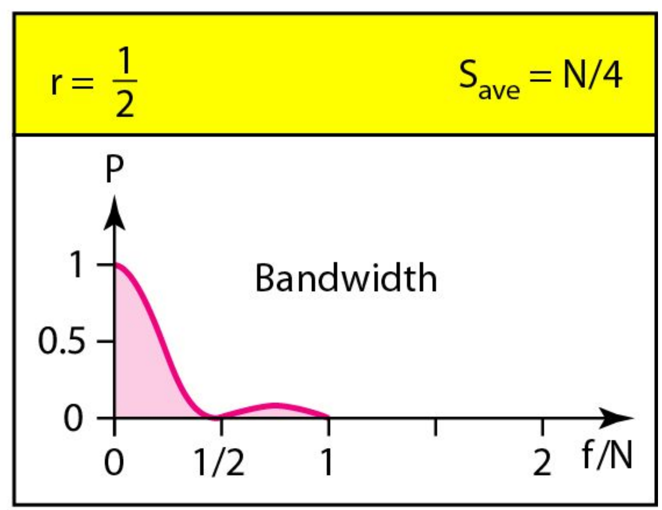
Figure 4.10 *Multilevel: 2B1Q scheme*

	Previous level: positive	Previous level: negative
Next bits	**Next level**	**Next level**
00	+1	-1
01	+3	-3
10	-1	+1
11	-3	+3

Transition table



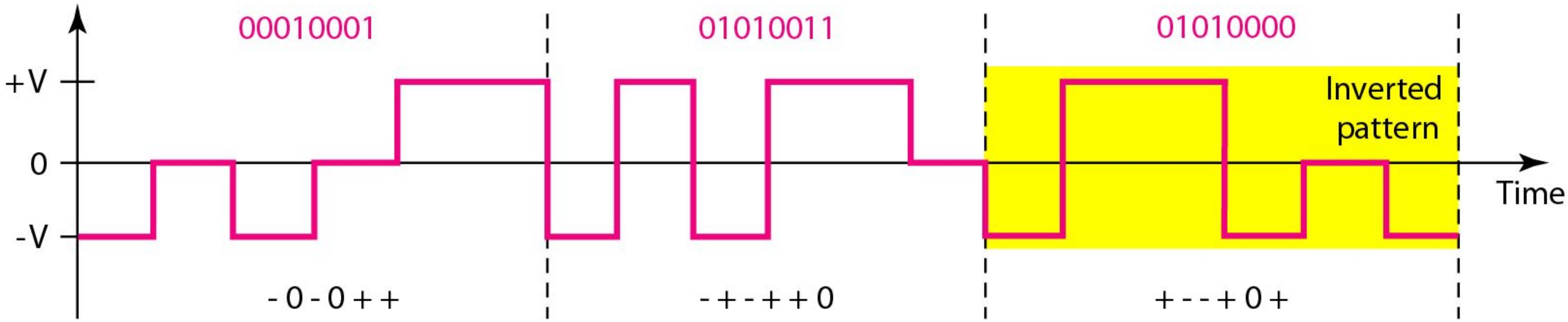
Assuming positive original level



Redundancy

- In the 2B1Q scheme we have no redundancy and we see that a DC component is present.
- If we use a code with redundancy we can decide to use only "0" or "+" weighted codes (more +'s than -'s in the signal element) and invert any code that would create a DC component. E.g. '+00++-' -> '-00--+'
- Receiver will know when it receives a "-" weighted code that it should invert it as it doesn't represent any valid symbol.

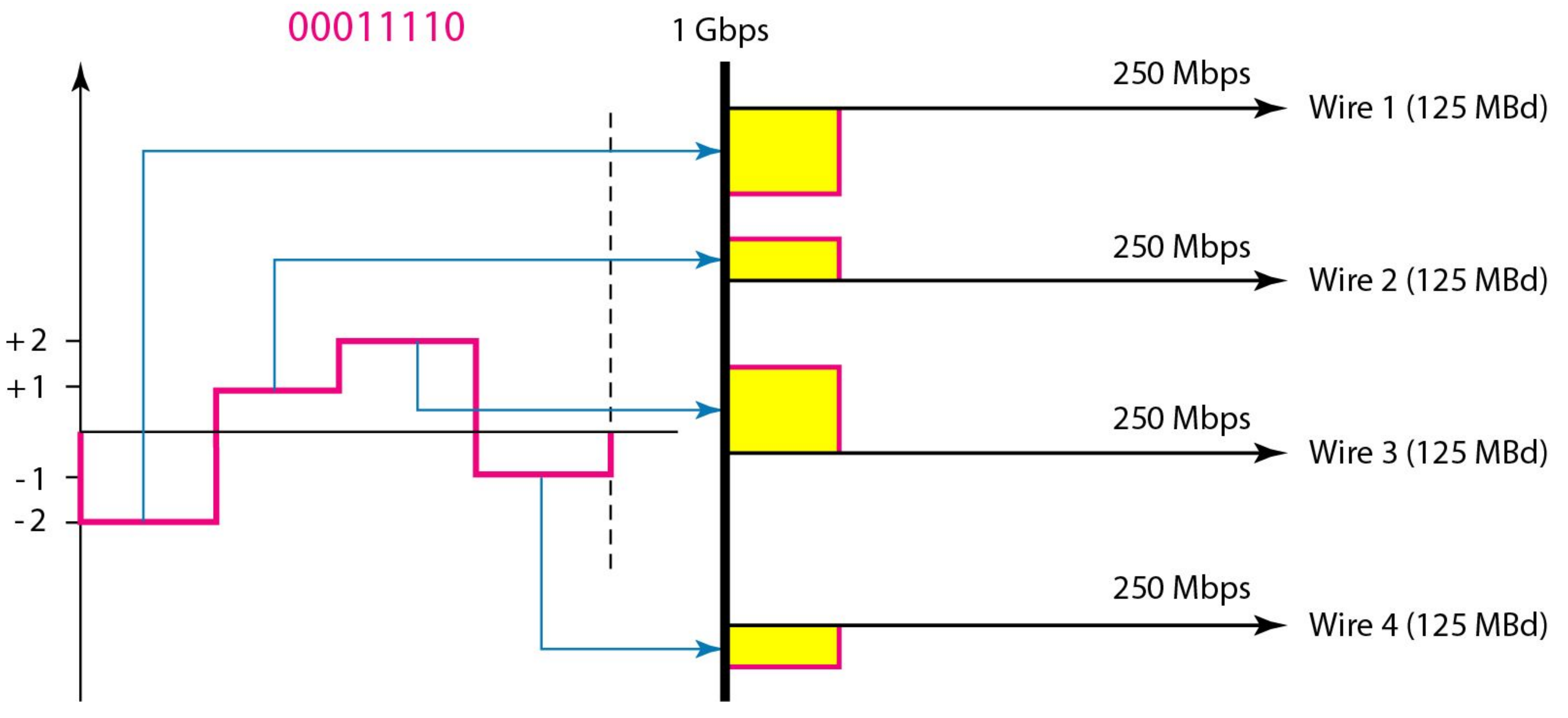
Figure 4.11 *Multilevel: 8B6T scheme*



Multilevel using multiple channels

- In some cases, we split the signal transmission up and distribute it over several links.
- The separate segments are transmitted simultaneously. This reduces the signalling rate per link -> lower bandwidth.
- This requires all bits for a code to be stored.
- xD: means that we use ‘x’ links
- YYYz: We use ‘z’ levels of modulation where YYY represents the type of modulation (e.g. pulse ampl. mod. PAM).
- Codes are represented as: xD-YYYz

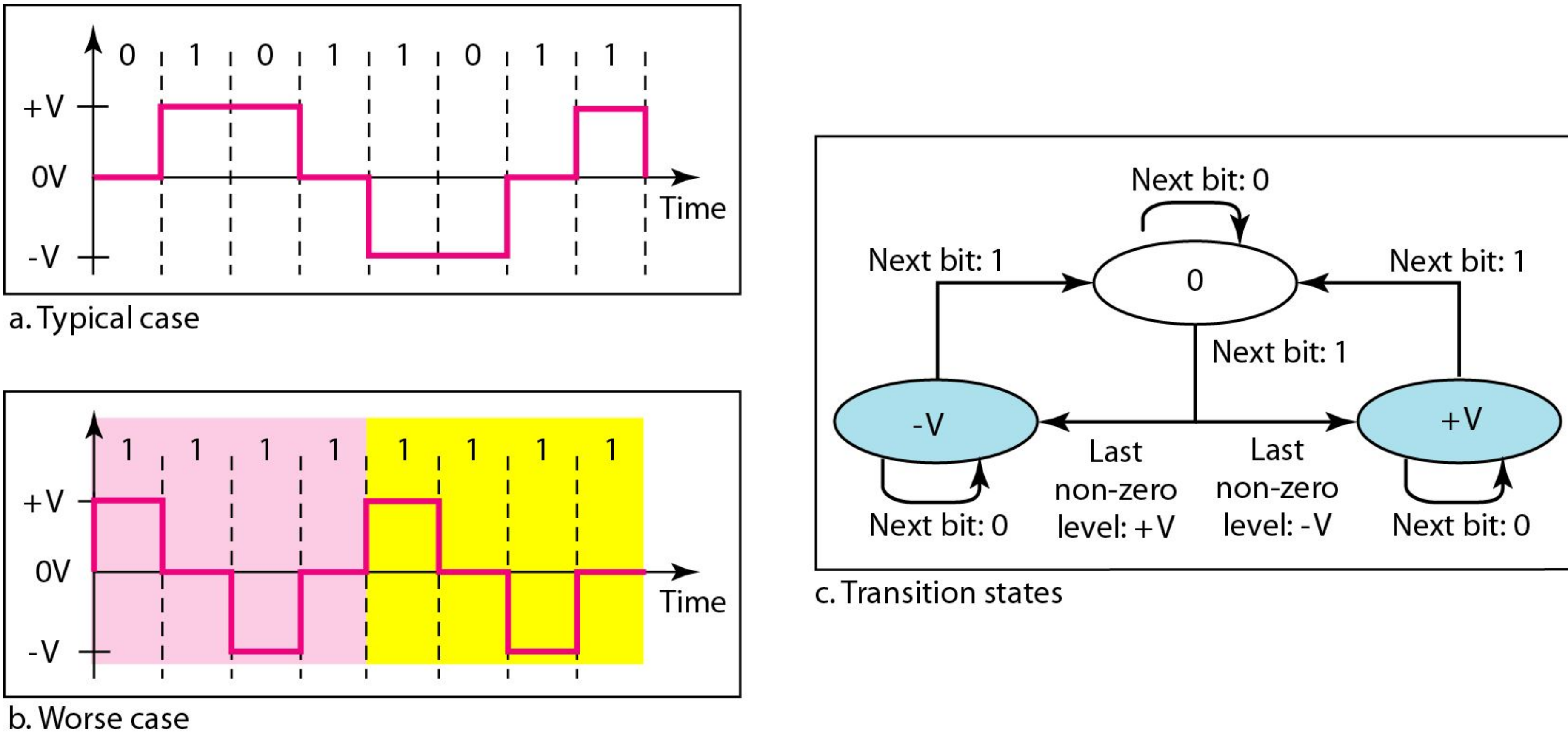
Figure 4.12 *Multilevel: 4D-PAM5 scheme*



Multitransition Coding

- Because of synchronization requirements we force transitions. This can result in very high bandwidth requirements -> more transitions than are bits (e.g. mid bit transition with inversion).
- Codes can be created that are differential at the bit level forcing transitions at bit boundaries. This results in a bandwidth requirement that is equivalent to the bit rate.
- In some instances, the bandwidth requirement may even be lower, due to repetitive patterns resulting in a periodic signal.

Figure 4.13 *Multitransition: MLT-3 scheme*



MLT-3

- Signal rate is same as NRZ-I
- But because of the resulting bit pattern, we have a periodic signal for worst case bit pattern: 1111
- This can be approximated as an analog signal a frequency 1/4 the bit rate!

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

Block Coding

- For a code to be capable of error detection, we need to add redundancy, i.e., extra bits to the data bits.
- Synchronization also requires redundancy - transitions are important in the signal flow and must occur frequently.
- Block coding is done in three steps: division, substitution and combination.
- It is distinguished from multilevel coding by use of the slash - xB/yB.
- The resulting bit stream prevents certain bit combinations that when used with line encoding would result in DC components or poor sync. quality.

Note

**Block coding is normally referred to as *m*B/*n*B coding;
it replaces each *m*-bit group with an *n*-bit group.**

Figure 4.14 *Block coding concept*

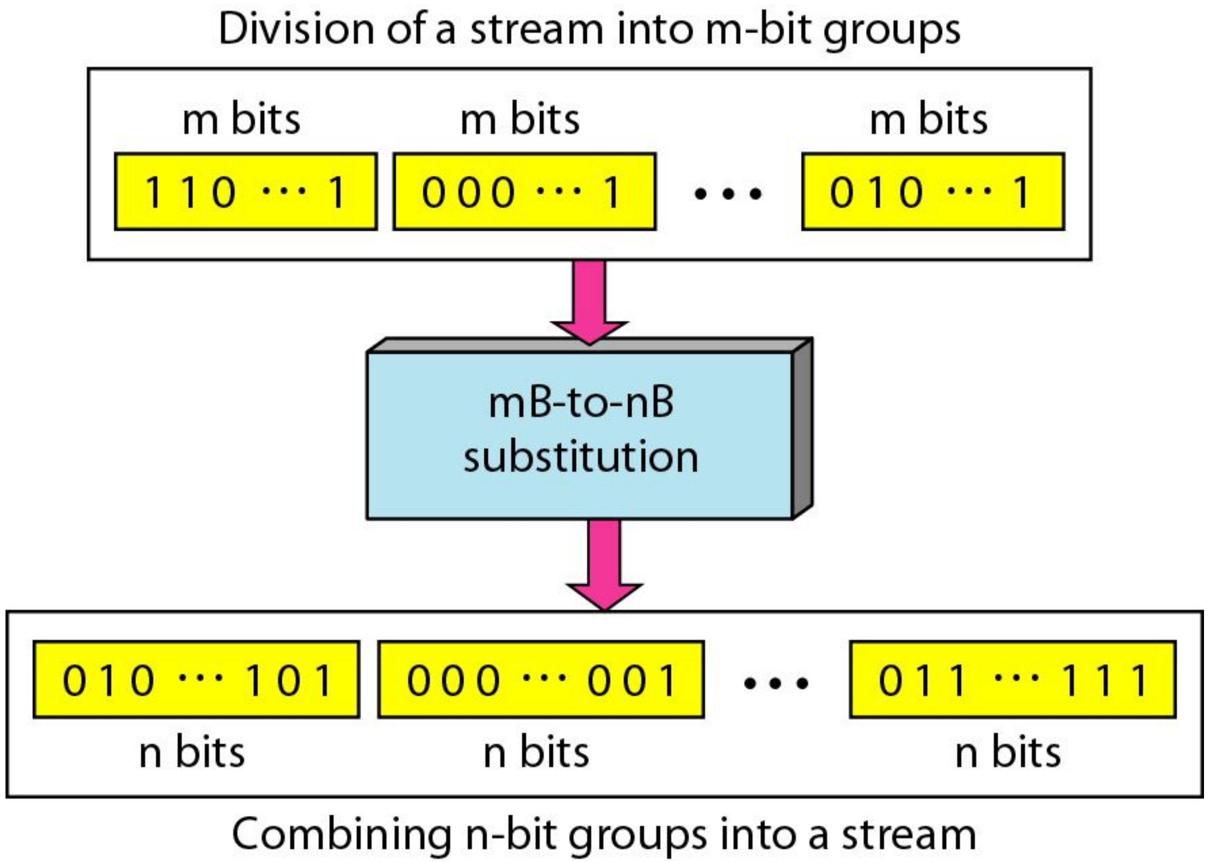


Figure 4.15 *Using block coding 4B/5B with NRZ-I line coding scheme*

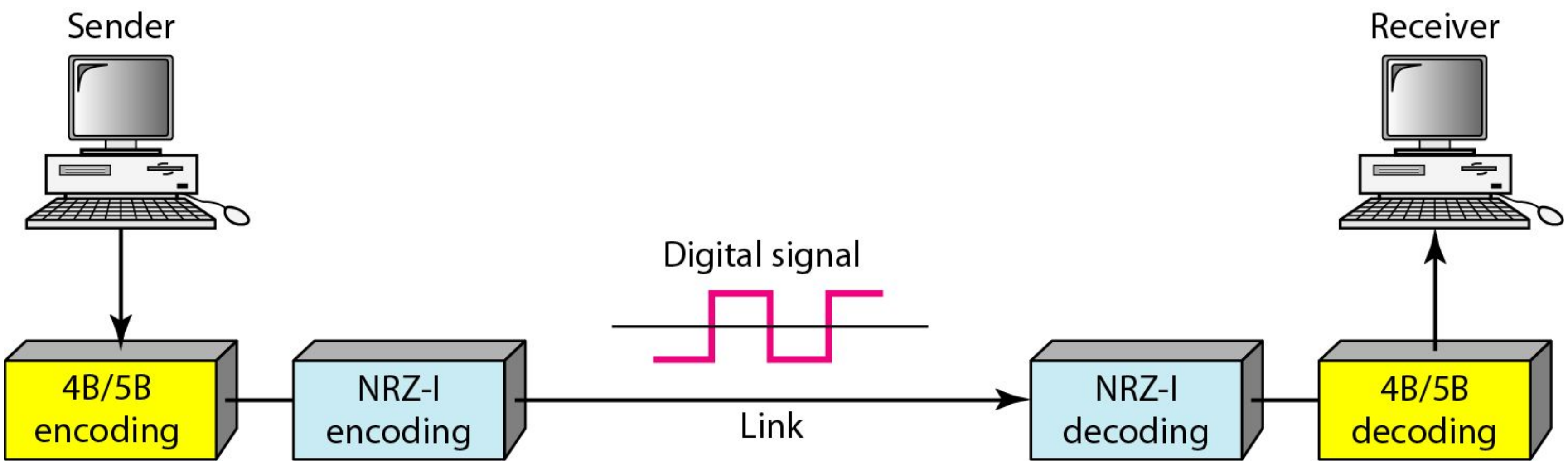
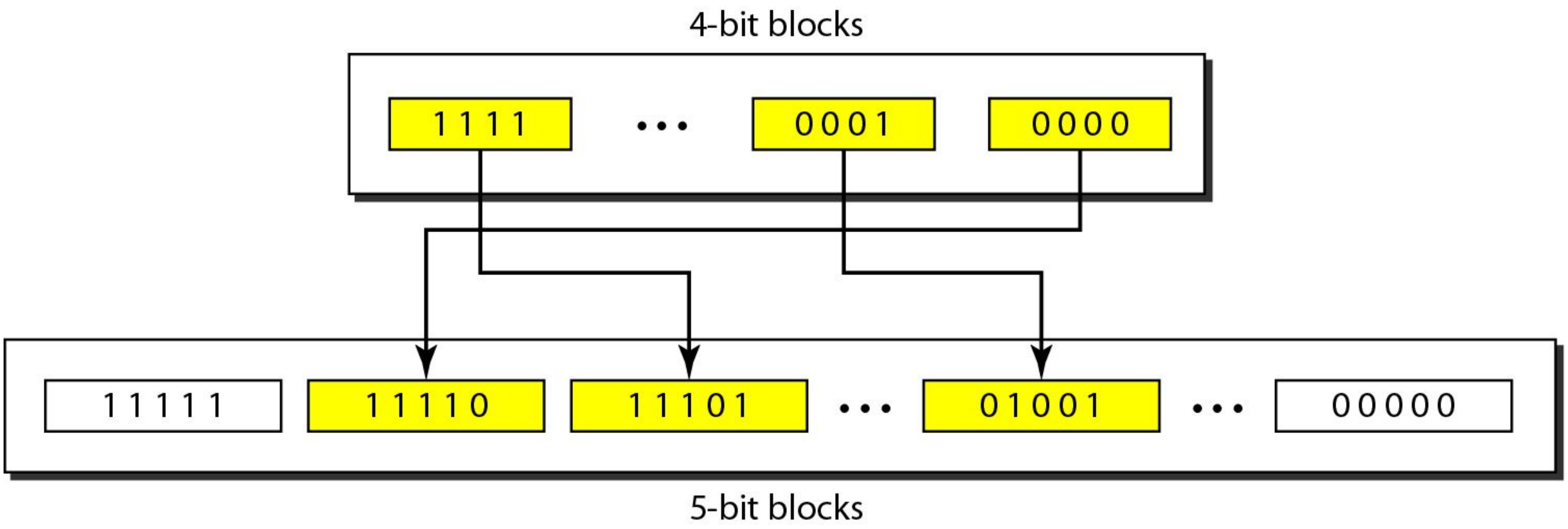


Table 4.2 *4B/5B mapping codes*

Data Sequence	*Encoded Sequence*	*Control Sequence*	*Encoded Sequence*
0000	11110	Q (Quiet)	00000
0001	01001	I (Idle)	11111
0010	10100	H (Halt)	00100
0011	10101	J (Start delimiter)	11000
0100	01010	K (Start delimiter)	10001
0101	01011	T (End delimiter)	01101
0110	01110	S (Set)	11001
0111	01111	R (Reset)	00111
1000	10010		
1001	10011		
1010	10110		
1011	10111		
1100	11010		
1101	11011		
1110	11100		
1111	11101		

Figure 4.16 *Substitution in 4B/5B block coding*



Redundancy

- A 4 bit data word can have 24 combinations.
- A 5 bit word can have 25=32 combinations.
- We therefore have 32 - 26 = 16 extra words.
- Some of the extra words are used for control/signalling purposes.

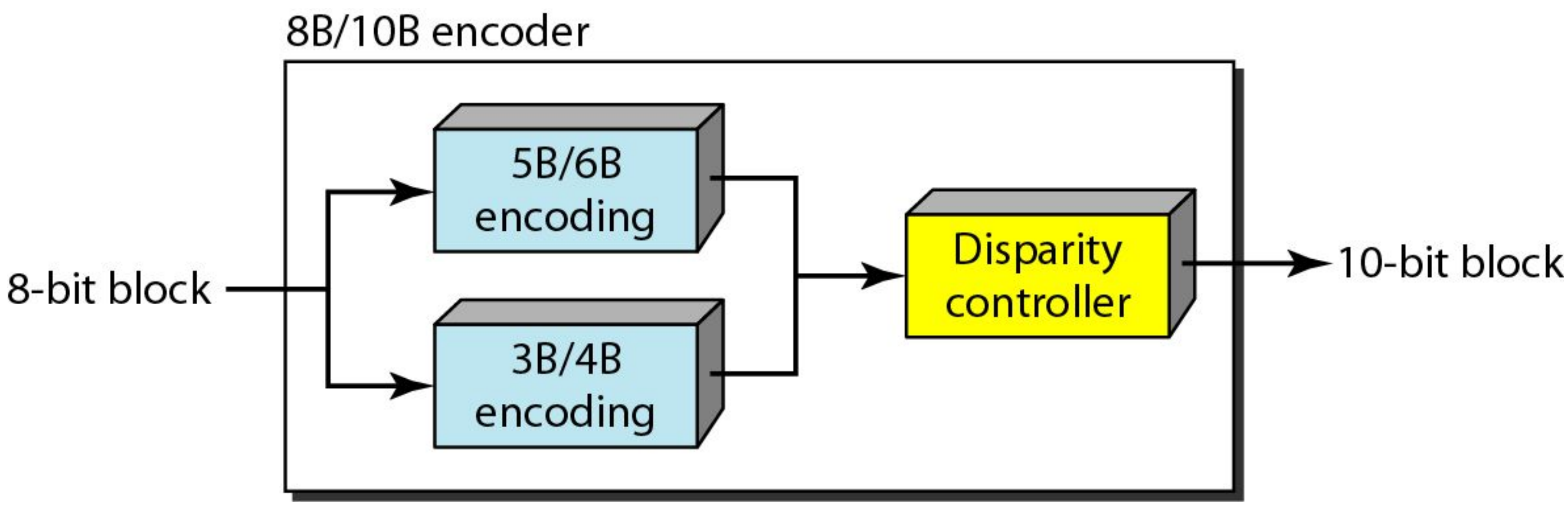
Example 4.5

We need to send data at a 1-Mbps rate. What is the minimum required bandwidth, using a combination of 4B/5B and NRZ-I or Manchester coding?

Solution

First 4B/5B block coding increases the bit rate to 1.25 Mbps. The minimum bandwidth using NRZ-I is N/2 or 625 kHz. The Manchester scheme needs a minimum bandwidth of 1.25 MHz. The first choice needs a lower bandwidth, but has a DC component problem; the second choice needs a higher bandwidth, but does not have a DC component problem.

Figure 4.17 *8B/10B block encoding*



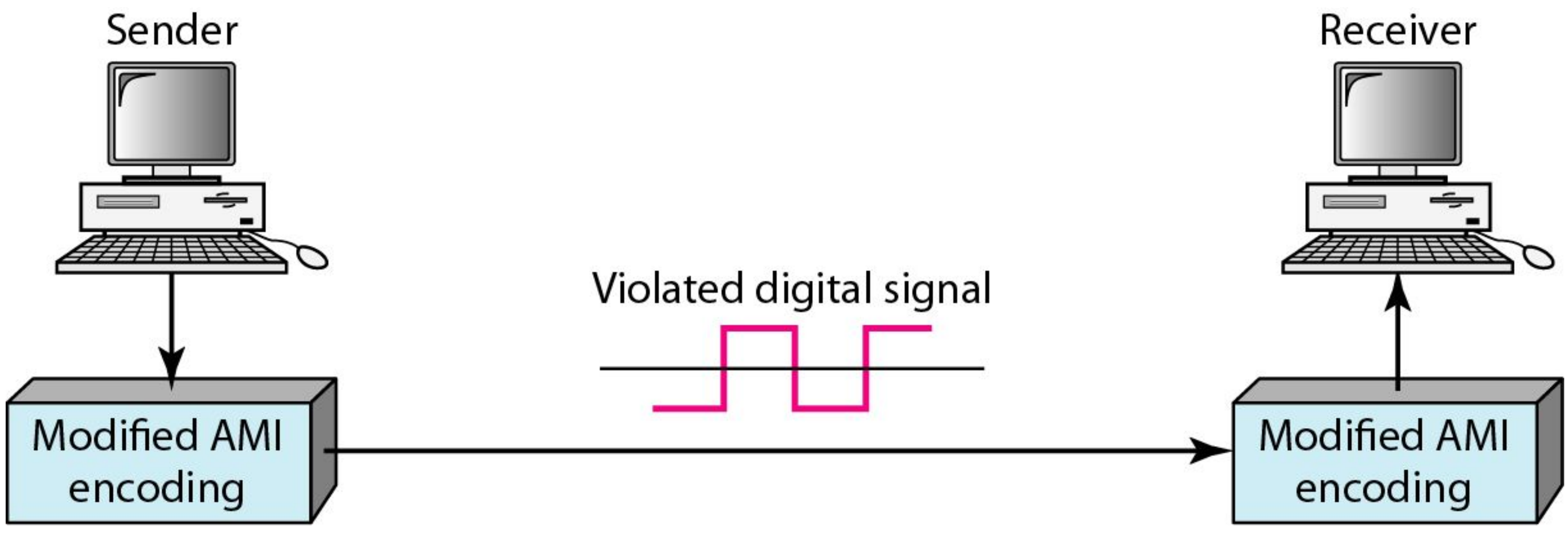
More bits - better error detection

- The 8B10B block code adds more redundant bits and can thereby choose code words that would prevent a long run of a voltage level that would cause DC components.

Scrambling

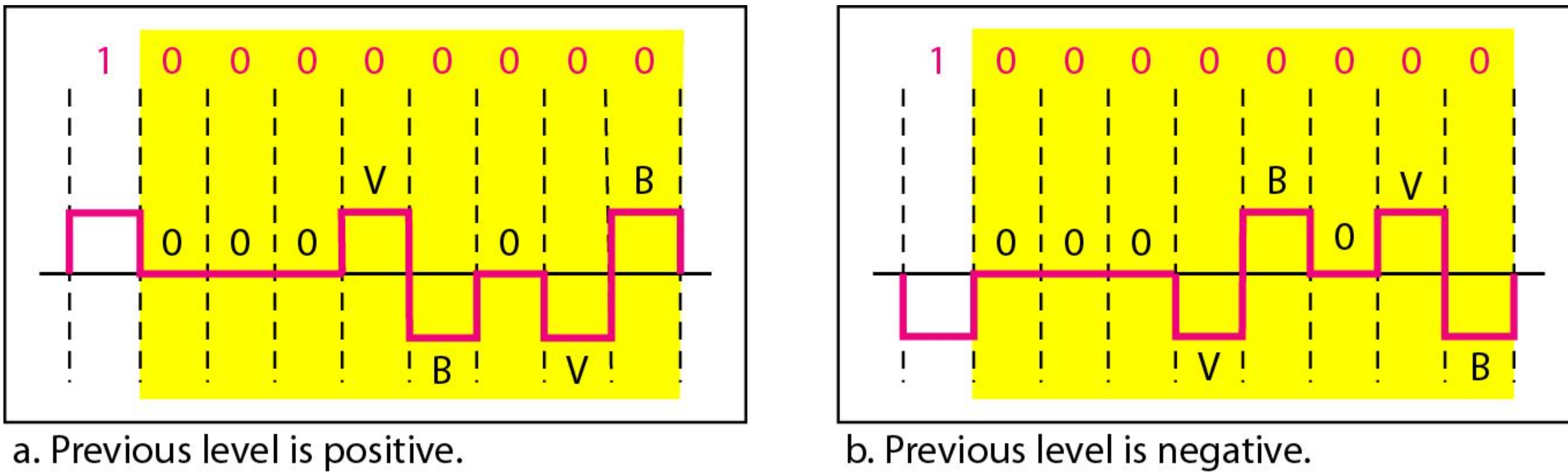
- The best code is one that does not increase the bandwidth for synchronization and has no DC components.
- Scrambling is a technique used to create a sequence of bits that has the required c/c’s for transmission - self clocking, no low frequencies, no wide bandwidth.
- It is implemented at the same time as encoding, the bit stream is created on the fly.
- It replaces ‘unfriendly’ runs of bits with a violation code that is easy to recognize and removes the unfriendly c/c.

Figure 4.18 *AMI used with scrambling*



For example: B8ZS substitutes eight consecutive zeros with 000VB0VB.
The V stands for violation, it violates the line encoding rule
B stands for bipolar, it implements the bipolar line encoding rule

Figure 4.19 *Two cases of B8ZS scrambling technique*



HDB3 substitutes four consecutive zeros with 000V or B00V depending on the number of nonzero pulses after the last substitution.

If # of non zero pulses is even the substitution is B00V to make total # of non zero pulse even.

If # of non zero pulses is odd the substitution is 000V to make total # of non zero pulses even.

Figure 4.20 *Different situations in HDB3 scrambling technique*