Digital Data Transmission

Digital Transmission

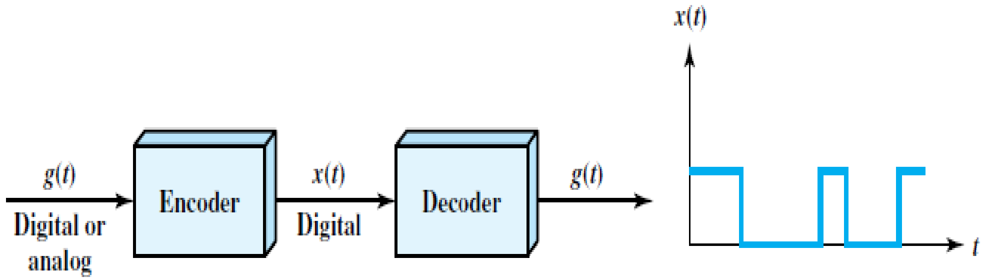
- A computer network is designed to send information from one point to another.
- This information needs to be converted to either a digital signal (digital transmission) or an analog signal (analog transmission).
- In Digital transmission:(1) methods which convert digital data to digital signals (digital-to-digital conversion) and(2) methods which convert analog signals to digital signals (analog-to-digital conversion)

- Both analog and digital information can be encoded as either analog or digital signals.
- The particular encoding that is chosen depends on the specific requirements to be met and the media and communications facilities available.

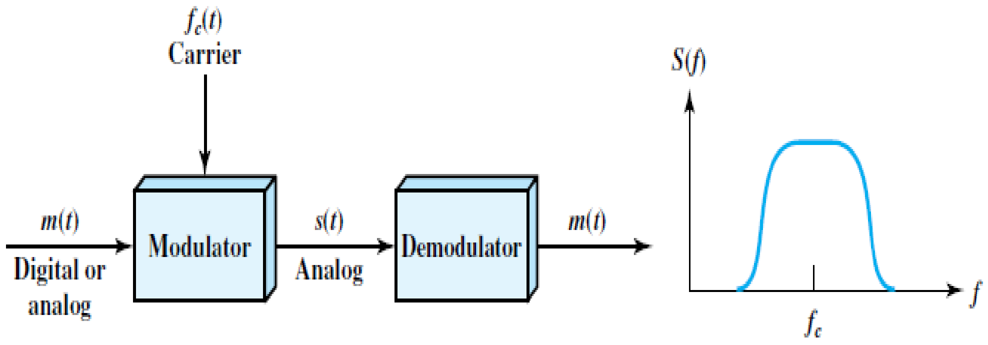
- **Digital data, digital signals:** The simplest form of digital encoding of digital data is to assign one voltage level to binary one and another to binary zero. More complex encoding schemes are used to improve performance, by altering the spectrum of the signal and providing synchronization capability.
- **Digital data, analog signal:** A modem converts digital data to an analog signal so that it can be transmitted over an analog line. The basic techniques are amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). All involve altering one or more characteristics of a carrier frequency to represent binary data.

- **Analog data, digital signals:** Analog data, such as voice and video, are often digitized to be able to use digital transmission facilities. The simplest technique is pulse code modulation (PCM), which involves sampling the analog data periodically and quantizing the samples.
- **Analog data, analog signals:** Analog data are modulated by a carrier frequency to produce an analog signal in a different frequency band, which can be utilized on an analog transmission system. The basic techniques are amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM).

- For **digital signaling**, a data source $g(t)$, which may be either digital or analog, is encoded into a digital signal $x(t)$.The actual form of $x(t)$ depends on the encoding technique and is chosen to optimize use of the transmission medium. For example, the encoding may be chosen to conserve bandwidth or to minimize errors.
- The basis for **analog signaling** is a continuous constant-frequency signal known as the **carrier signal**. The frequency of the carrier signal is chosen to be compatible with the transmission medium being used. Data may be transmitted using a carrier signal by modulation. **Modulation** is the process of encoding source data onto a carrier signal with frequency All modulation techniques involve operation on one or more of the three fundamental frequency domain parameters: amplitude, frequency, and phase.



(a) Encoding onto a digital signal



(b) Modulation onto an analog signal

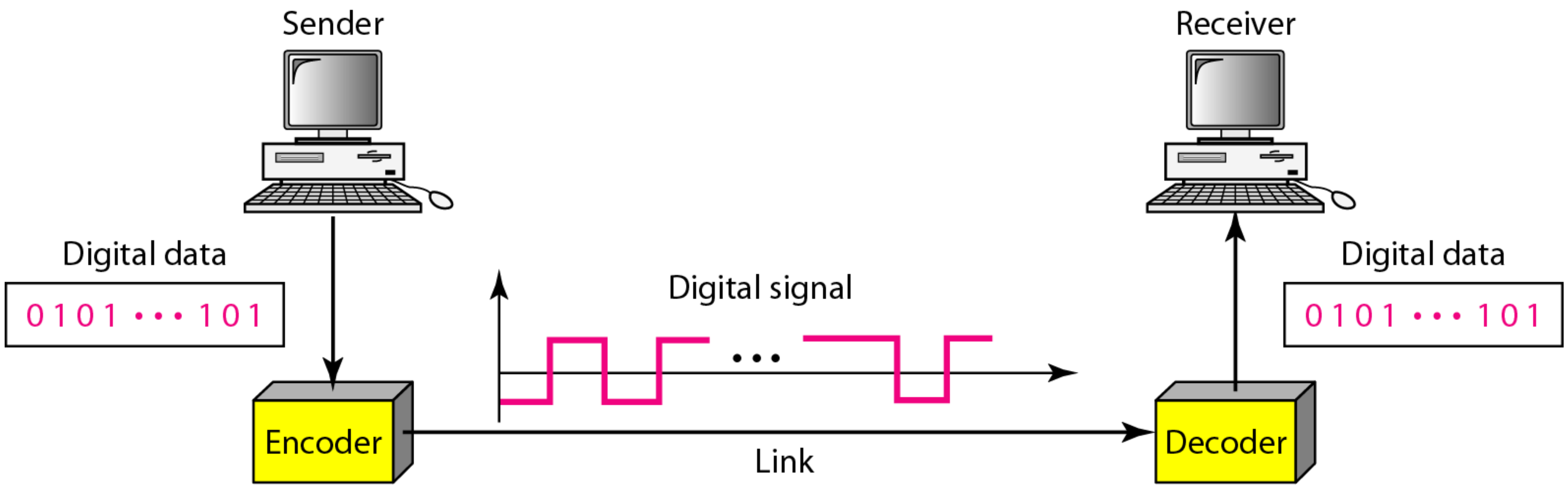
- The input signal $m(t)$ may be analog or digital and is called the modulating signal or **baseband signal**. The result of modulating the carrier signal is called the modulated signal $s(t)$.
- Figure indicates, $s(t)$ is a bandlimited (bandpass) signal. The location of the bandwidth on the spectrum is related to and is often centered on. Again, the actual form of the encoding is chosen to optimize some characteristic of the transmission.

DIGITAL-TO-DIGITAL CONVERSION

- How to convert digital data into digital signals.
- It can be done using line coding, block coding and scrambling. For all communications, line coding is necessary whereas block coding and scrambling are optional.

Line Coding

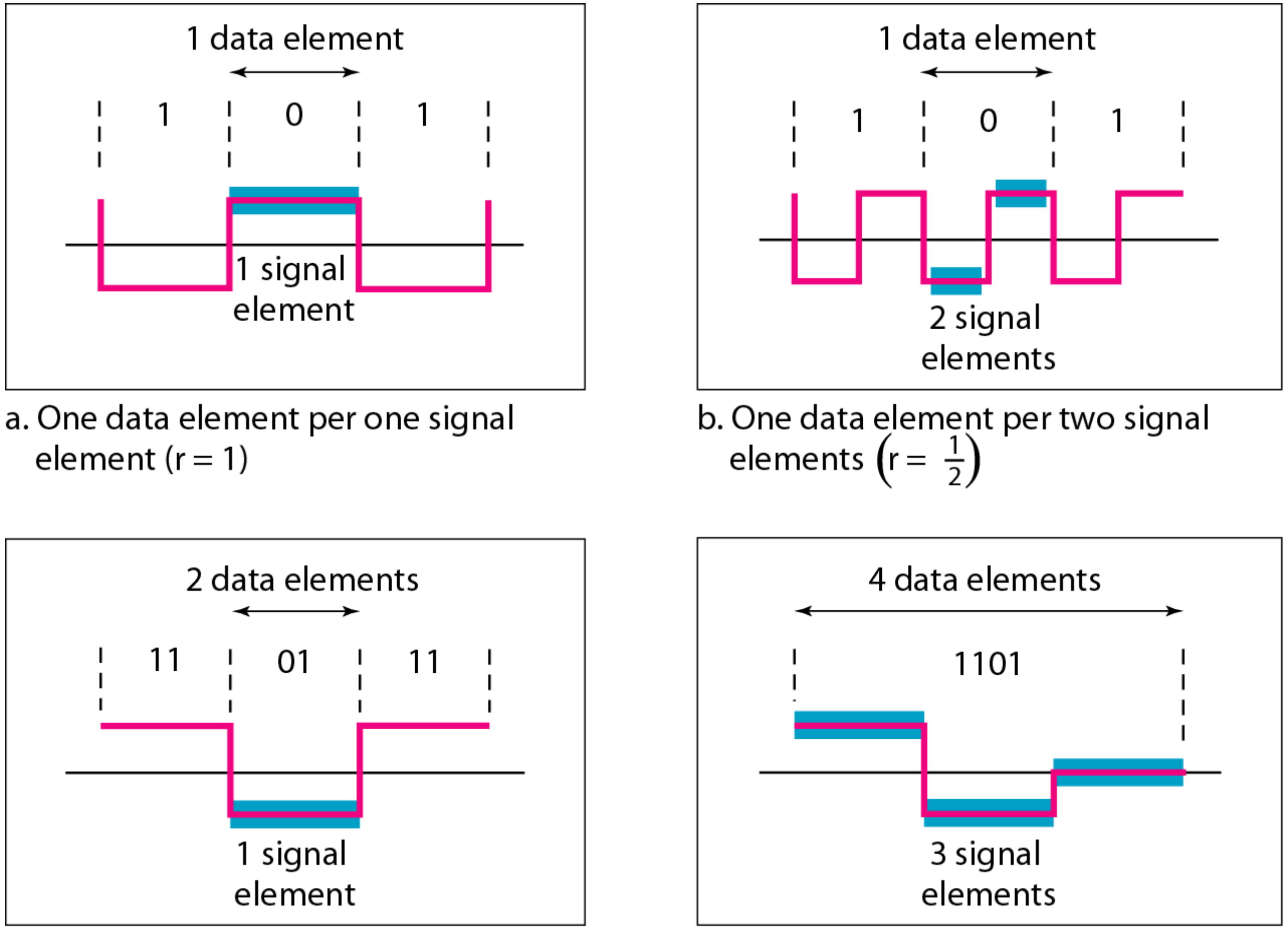
- The process for converting digital data into digital signal is said to be Line Coding. Digital data is found in binary format. It is represented (stored) internally as series of 1s and 0s.



SIGNAL ELEMENT VERSUS DATA ELEMENT

- A data element is the smallest entity that can represent a piece of
- information: this is the bit.
- In digital data communications, a signal element carries data elements.
- A signal element is the shortest unit (time wise) of a digital signal.
- In other words, **data elements are what we need to send, signal elements are what we can send.** Data elements are being carried and signal elements are the carriers.
- The ratio ‘r’ is the number of data elements carried by a signal element.

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

- Fig(a) -one data element is carried by one signal element *(r* = 1).
- Fig (b) - two signal elements (two transitions) to carry each data element *(r* = 1/2).
- Fig (c) - a signal element carries two data elements *(r* = 2).
- Fig (d) - a group of 4 bits is being carried by a group of three signal elements (*r* = 4/3**)**

Common characteristics

- 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

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.

Data rate and Baud rate

- The baud or signal rate can be expressed as:

  $S = c \times N \times 1/r$ bauds

  where N is data rate

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

  r is the ratio between data element & signal element

Line Encoding

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

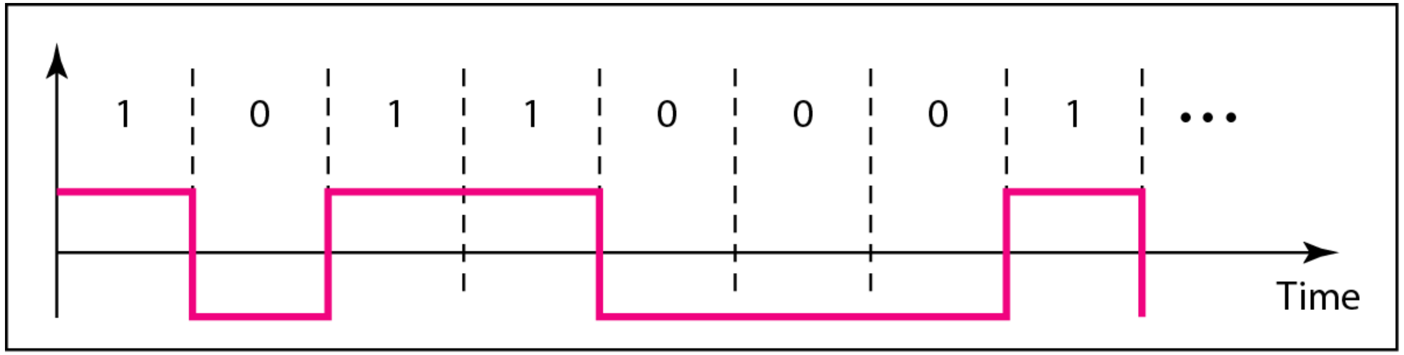
- Baseline wandering
- DC components
- Self synchronization
- Error detection
- Noise and interference
- Complexity

- 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 (A long string of 0s or 1s), the baseline will drift (Baseline wandering) and thus cause errors in detection of incoming data elements.
- A good line encoding scheme will prevent long runs of fixed amplitude.

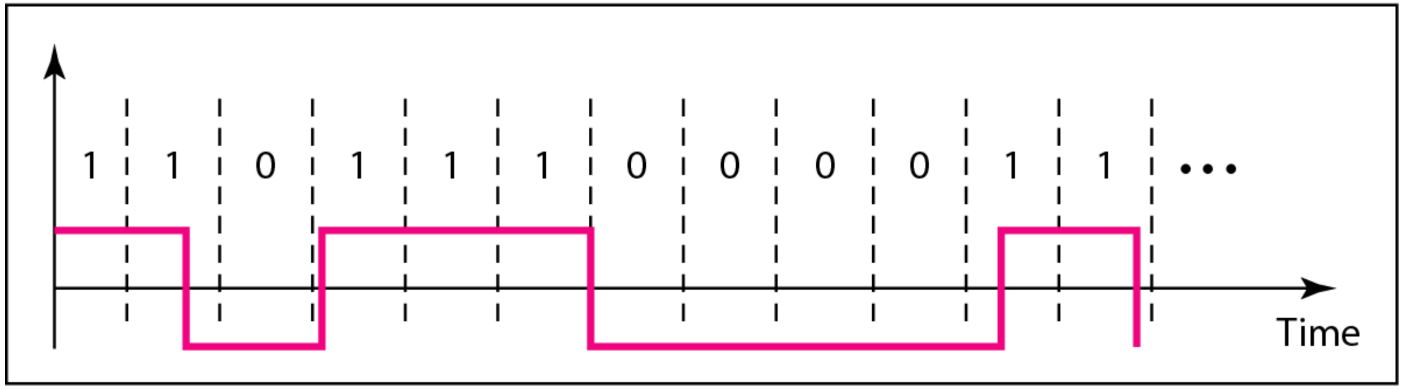
- DC components - when the voltage level remains constant for long periods of time, there is an increase in the low frequencies of the signal. Most channels are bandpass and may not support the low frequencies.
- This will require the removal of the dc component of a transmitted signal.

- 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.

Effect of lack of synchronization



a. Sent

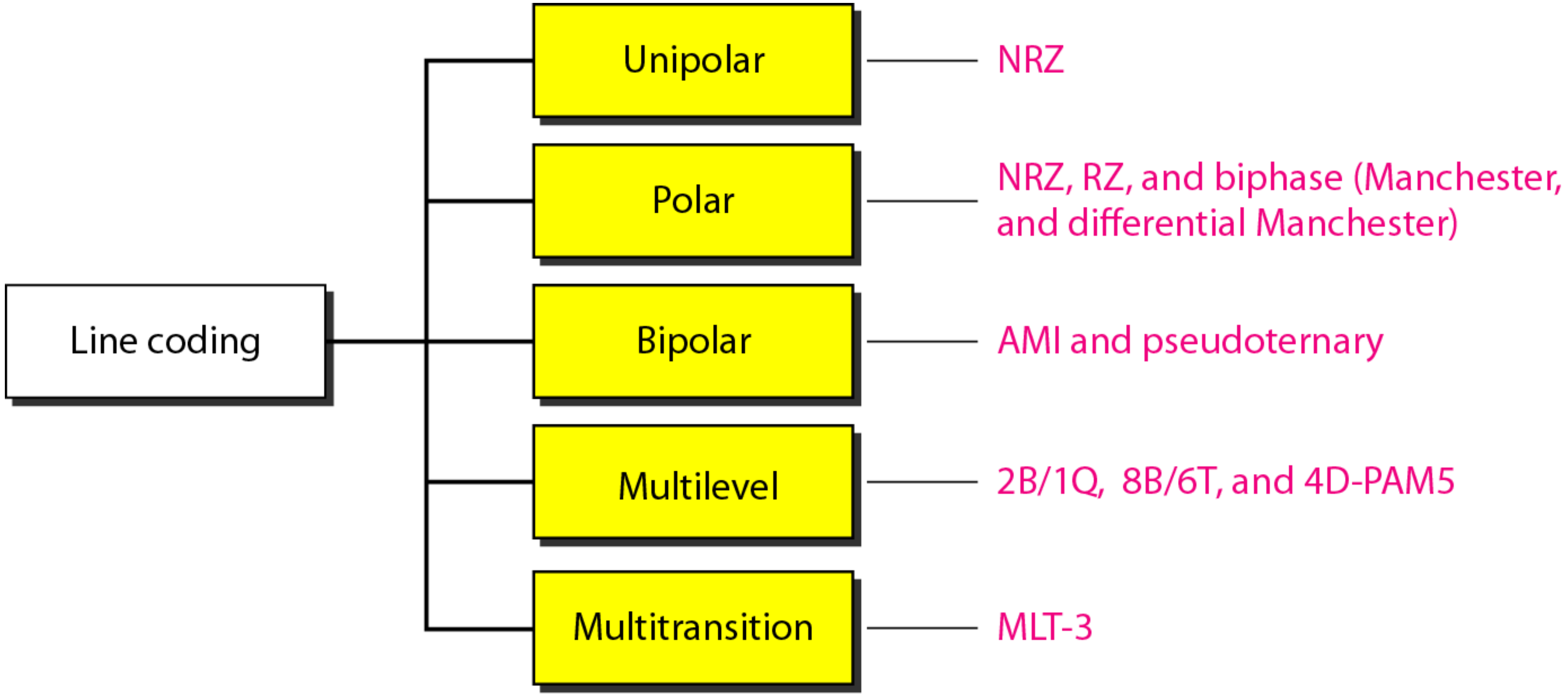


b. Received

- 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.

- 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.
- 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.

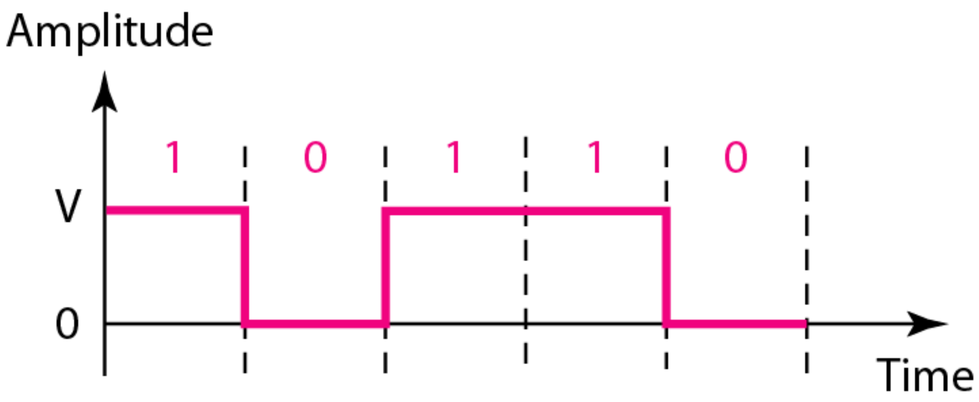
Line coding schemes



Unipolar

- All signal levels are on one side of the time axis - either above or below
- NRZ - Non Return to Zero scheme is an example of this code. 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.
- The signal level does not return to zero during a symbol transmission i.e., the signal does not return to zero at the middle of the bit.
- Scheme is prone to baseline wandering and DC components. It has no synchronization or any error detection. It is simple but costly in power consumption.

Unipolar NRZ scheme



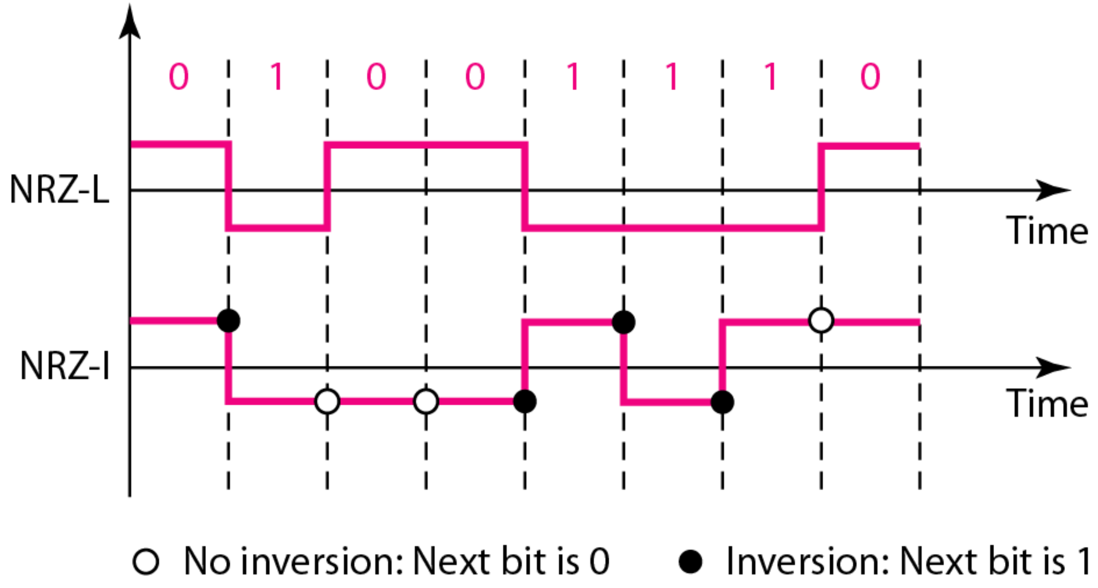
$$\frac{1}{2}V^2 + \frac{1}{2}(0)^2 = \frac{1}{2}V^2$$

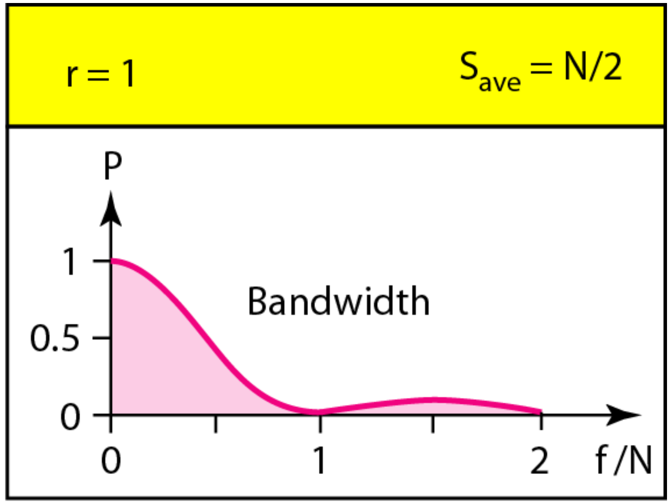
Normalized power

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 1 and -V for 0.
- There are two versions:
  - 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 symbol. If there is no change, the bit is 0, if there is a change, the bit is 1.

Polar NRZ-L and NRZ-I schemes



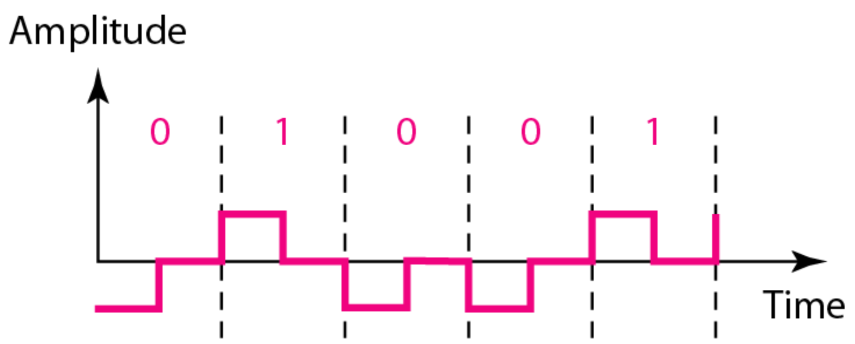


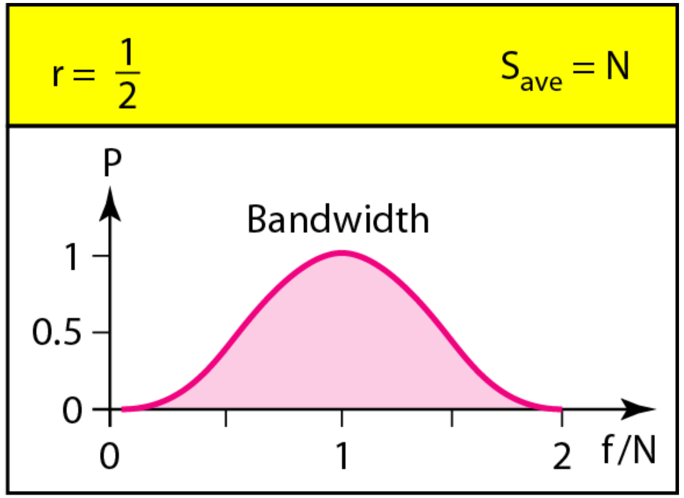
- In NRZ-L the level of the voltage determines the value of the bit.
  In NRZ-I the inversion or the lack of inversion determines the value of the bit.
- NRZ-L and NRZ-I both have an average signal rate of N/2 Bd.
- NRZ-L and NRZ-I both have a DC component problem and baseline wandering, it is worse for NRZ-L. Both have no self synchronization &no error detection. Both are relatively simple to implement.

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.
- This scheme has more signal transitions (two per symbol) and therefore requires a wider bandwidth.
- No DC components or baseline wandering.
- Self synchronization - transition indicates symbol value.
- More complex as it uses three voltage level. It has no error detection capability.

Polar RZ scheme

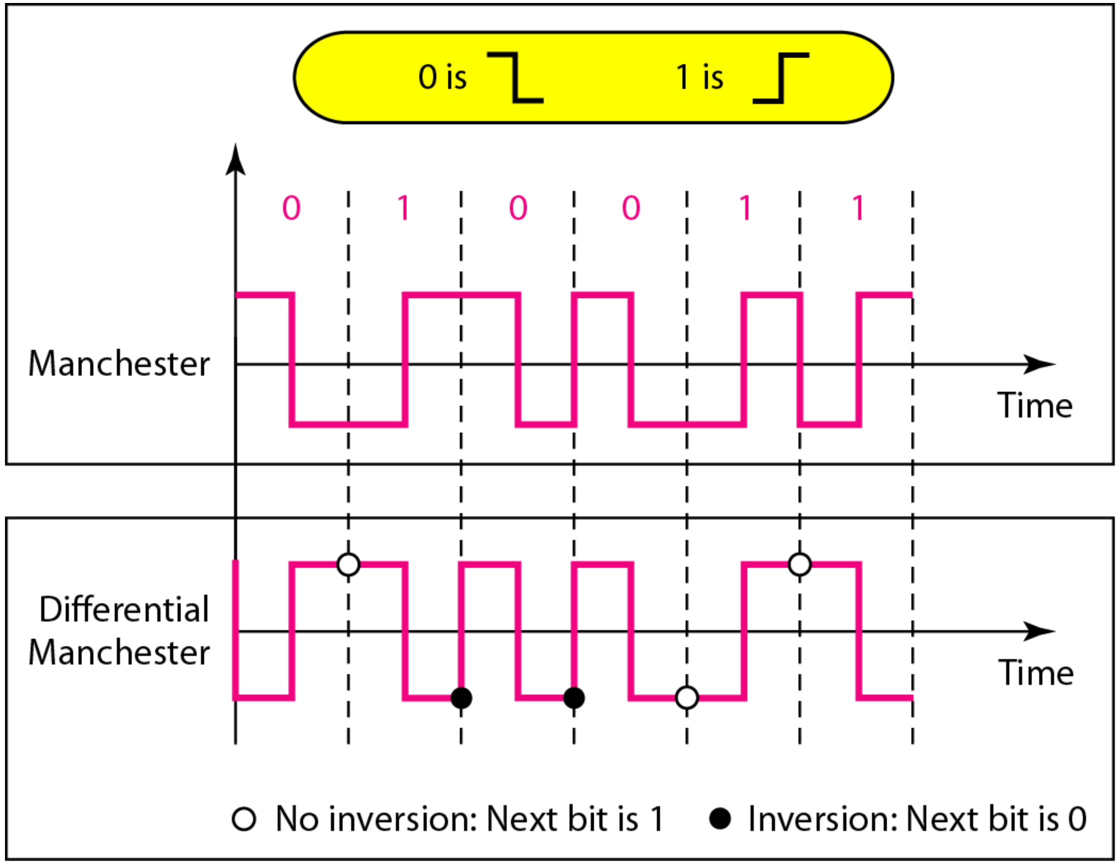


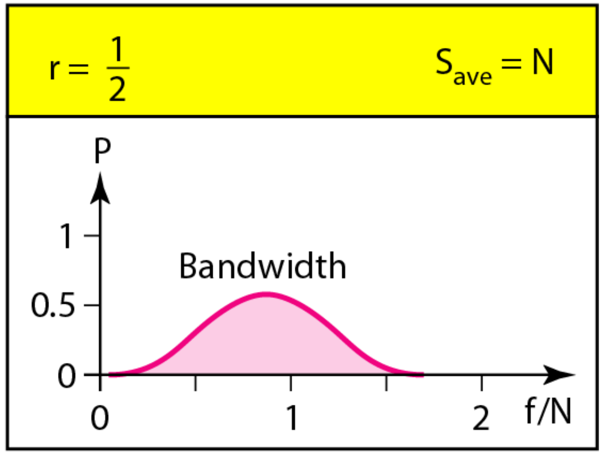


Polar - Biphase: Manchester and Differential Manchester

- Manchester coding consists of combining the NRZ-L 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 coding consists of combining the NRZ-I 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.

Polar biphase: Manchester and differential Manchester schemes





- In Manchester and differential Manchester encoding, the transition at the middle of the bit is used for synchronization.
- The minimum bandwidth of Manchester and differential Manchester is 2 times that of NRZ. The is no DC component and no baseline wandering. None of these codes has error detection.

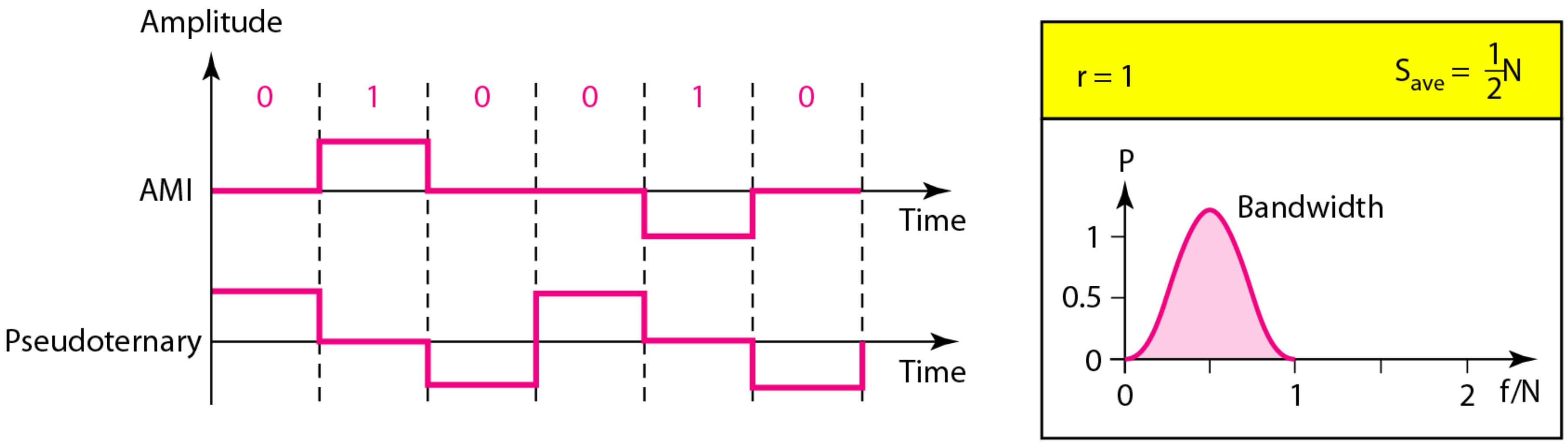
Bipolar

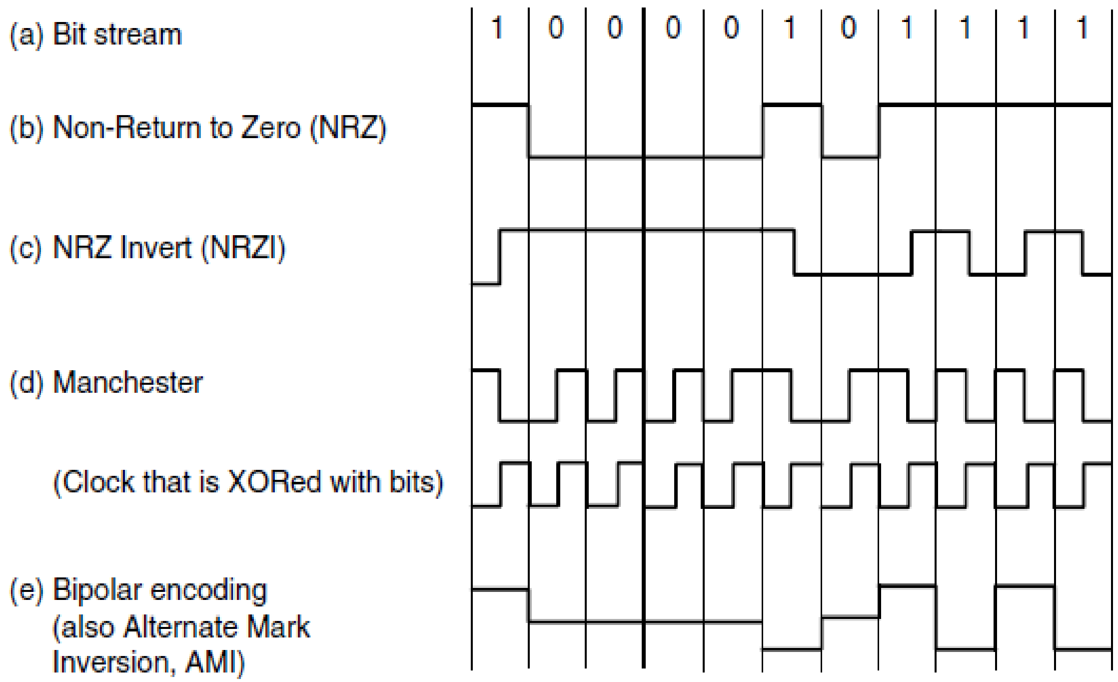
- It is a better alternative to NRZ.
- Has no DC component or baseline wandering.
- Has no self synchronization because long runs of “0”s results in no signal transitions.
- No error detection.

Bipolar - AMI and Pseudoternary

- Code uses 3 voltage levels: - +, 0, -, to represent the symbols (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.

Bipolar schemes: AMI and pseudoternary




(a) Bit stream
1 0 0 0 0 1 0 1 1 1 1
(b) Non-Return to Zero (NRZ)
(c) NRZ Invert (NRZI)
(d) Manchester
(Clock that is XORed with bits)
(e) Bipolar encoding
(also Alternate Mark
Inversion, AMI)

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

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

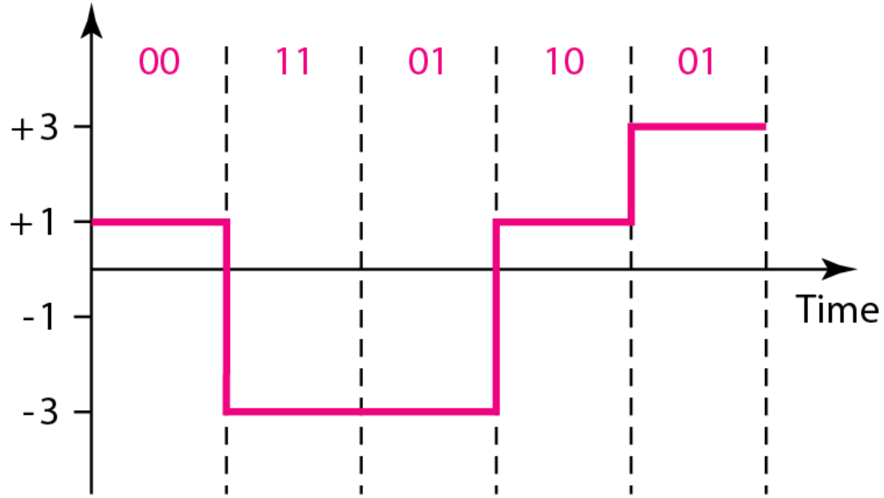
Representing Multilevel Codes

- 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.

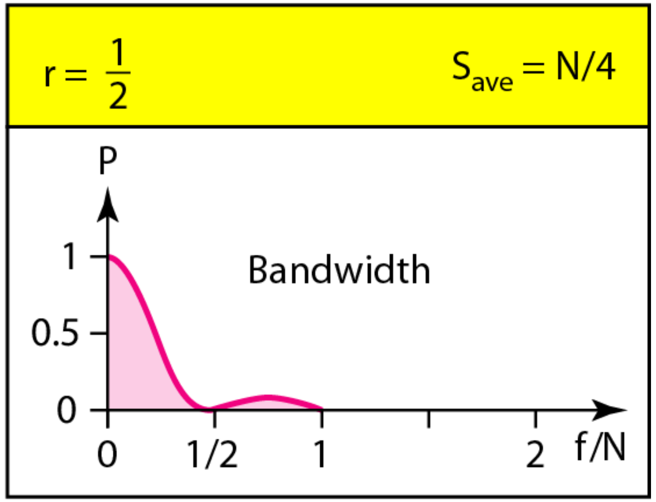
Multilevel: 2B1Q scheme

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

Transition table



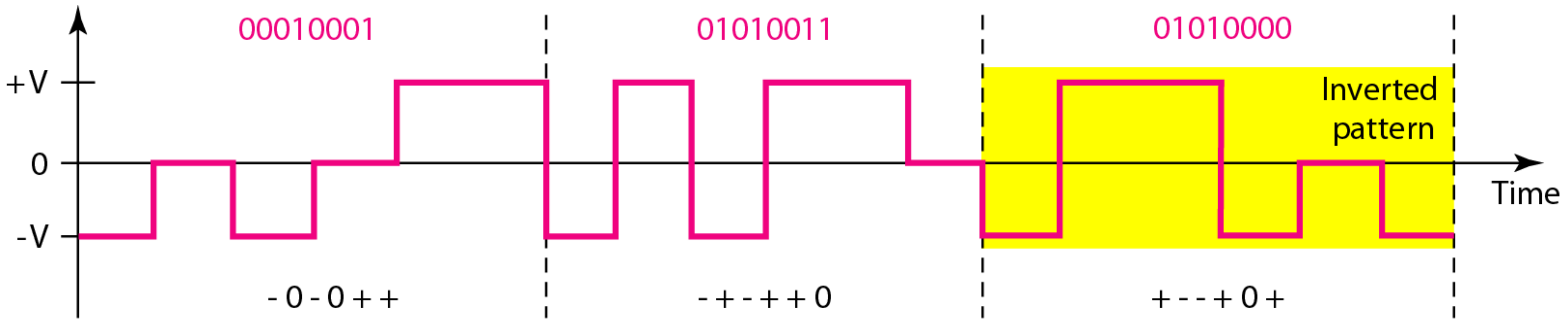
Assuming positive original level



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.

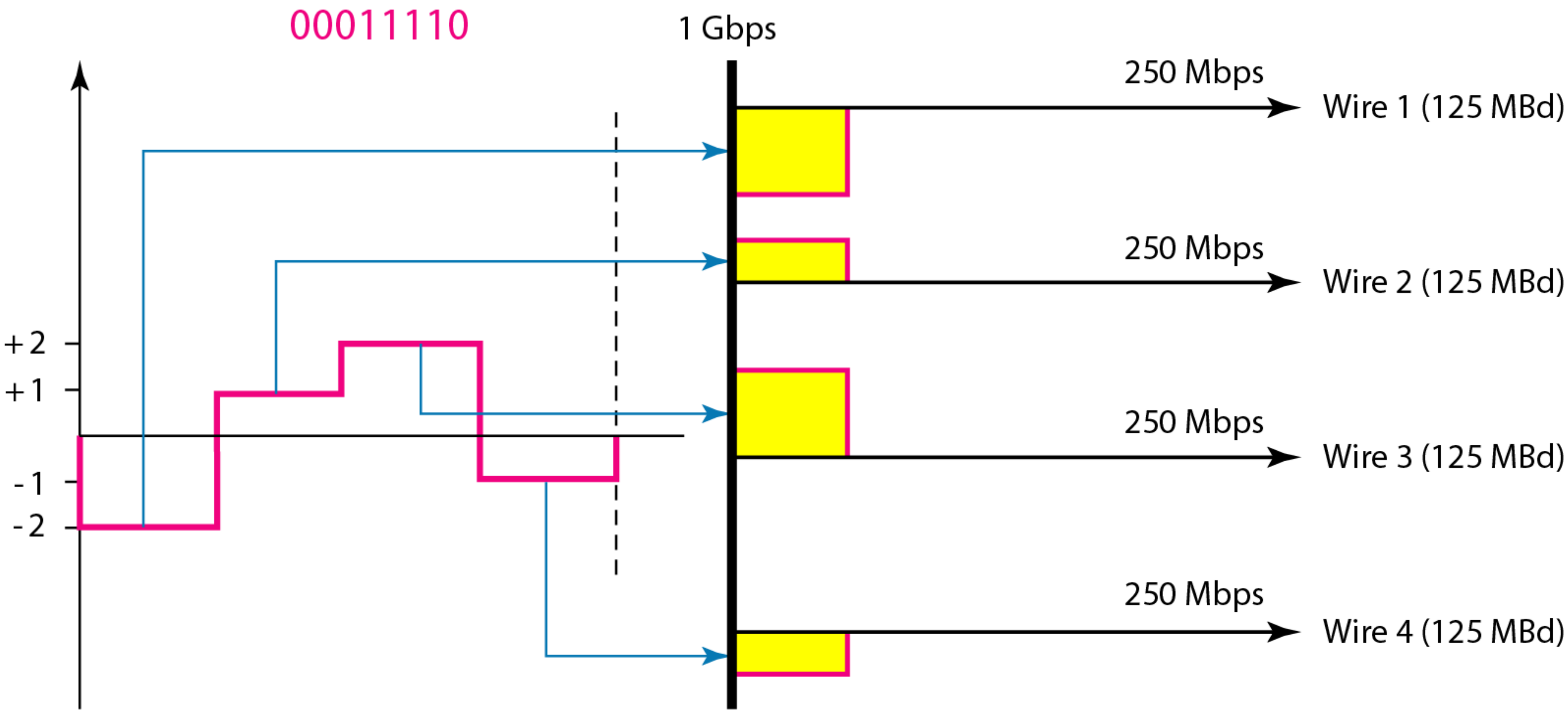
Multilevel: 8B6T scheme



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

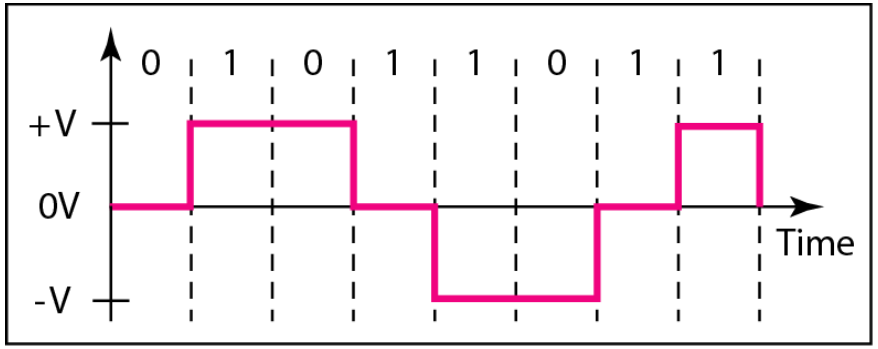
Multilevel: 4D-PAM5 scheme



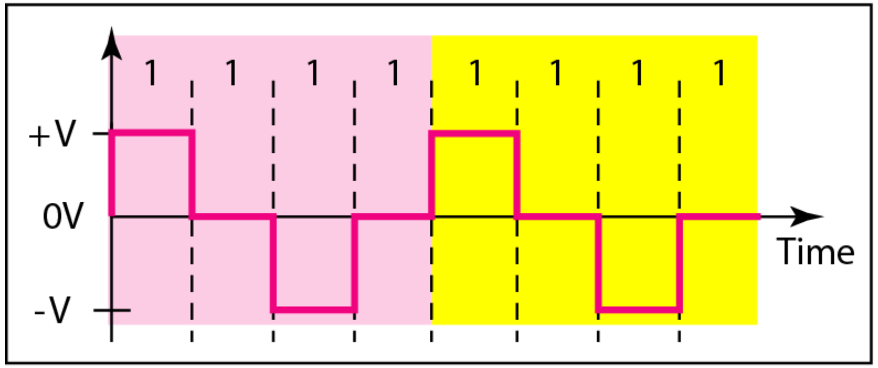
Multitransition Coding

- Because of synchronization requirements we force transitions. This can result in very high bandwidth requirements -> more transitions than 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.

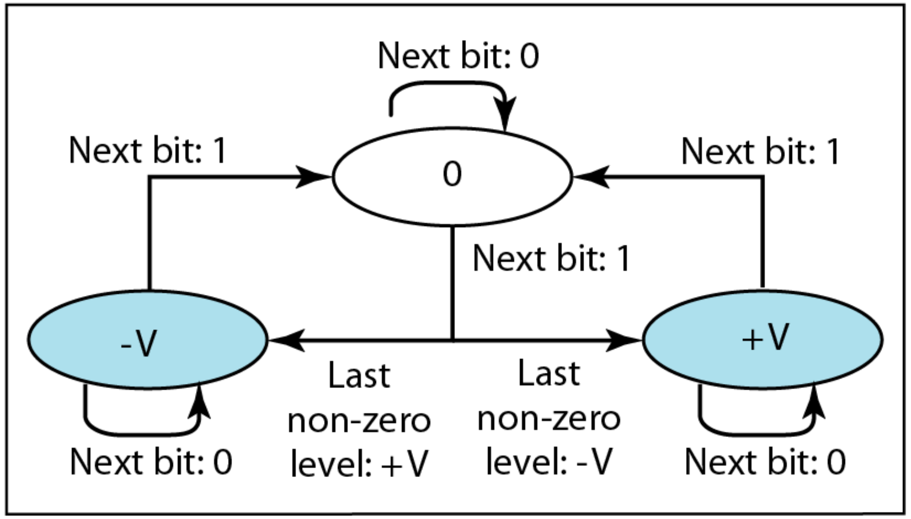
Multitransition: MLT-3 scheme



a. Typical case



b. Worse case



c. Transition states

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!

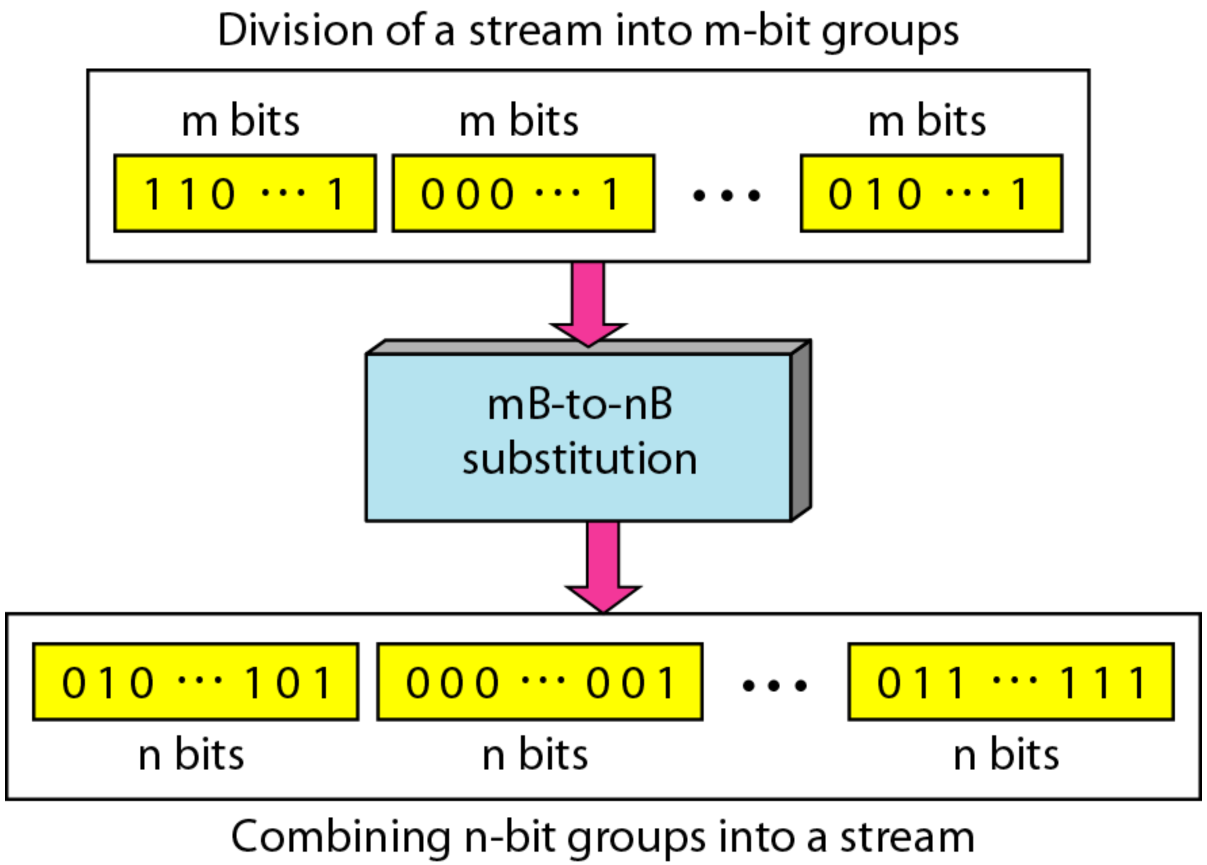
Summary of line coding schemes

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

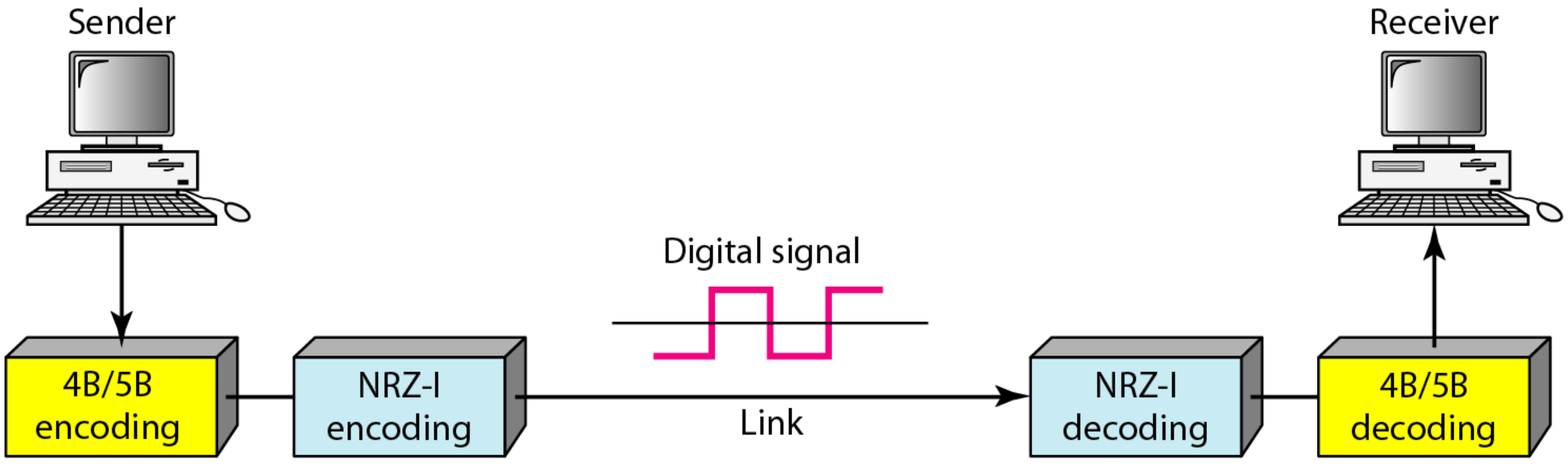
Block Coding

- 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 represented by slash notation, mB/nB. Means, m-bit block is substituted with n-bit block where n > m. Block coding involves three steps:
    1. Division
    2. Substitution
    3. Combination.
- After block coding is done, it is line coded for transmission.
- 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.

Block coding concept



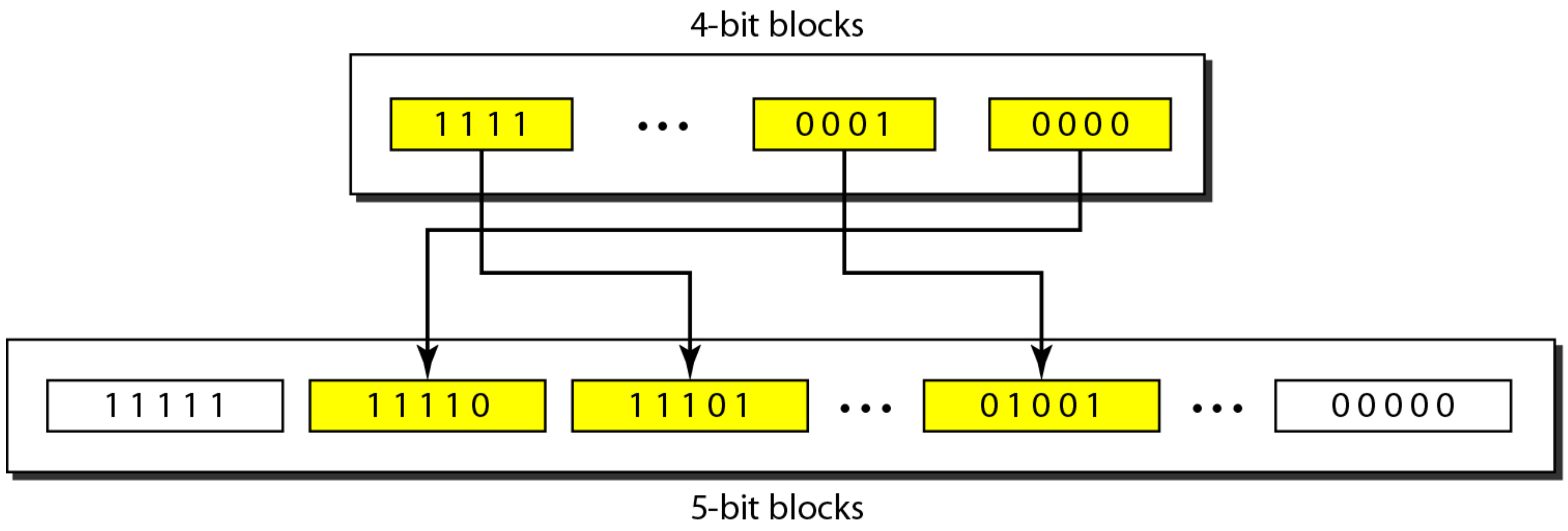
Using block coding 4B/5B with NRZ-I line coding scheme



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		

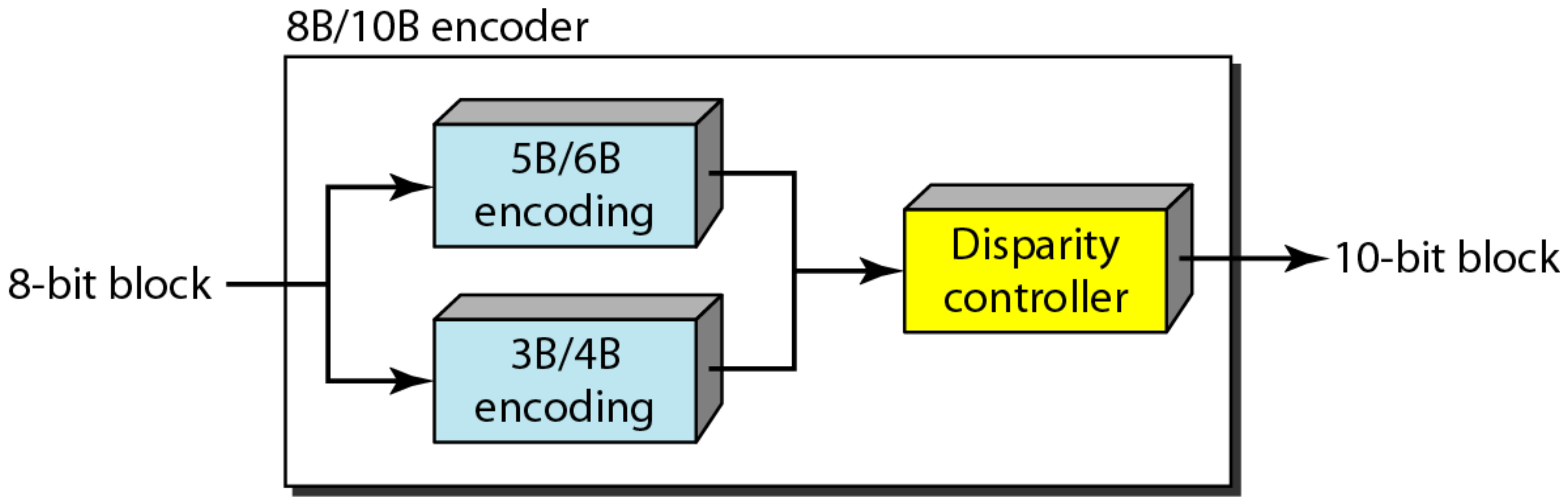
Substitution in 4B/5B block coding



Redundancy

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

8B/10B block encoding



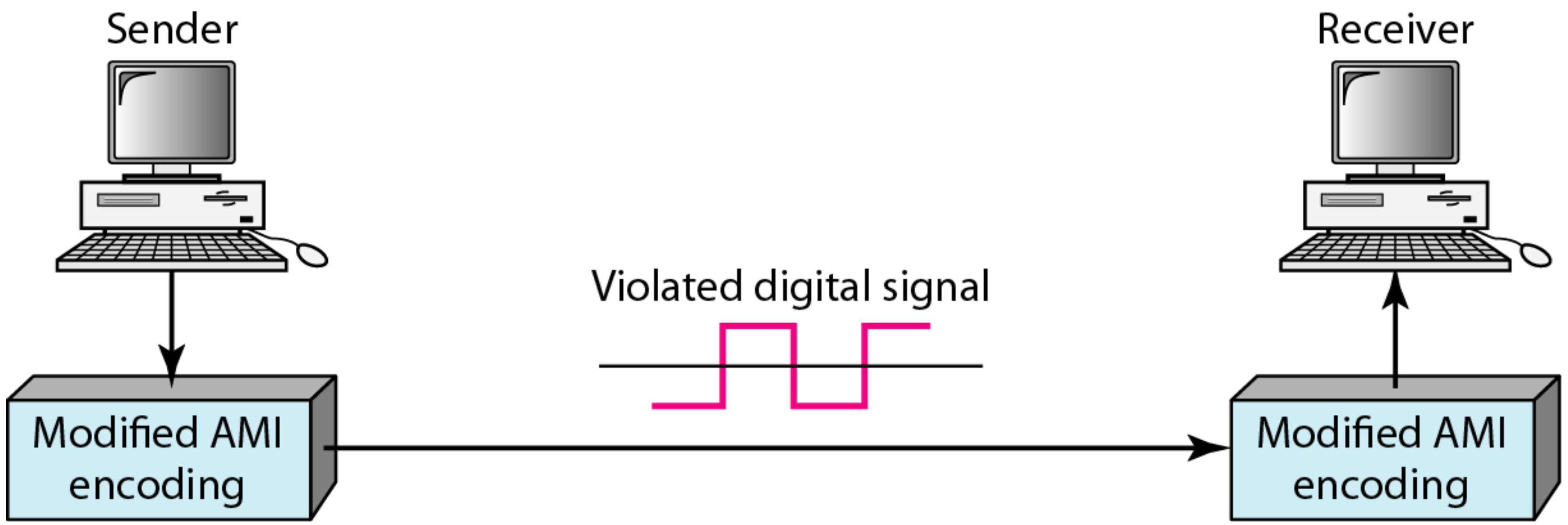
More bits - better error detection

- 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

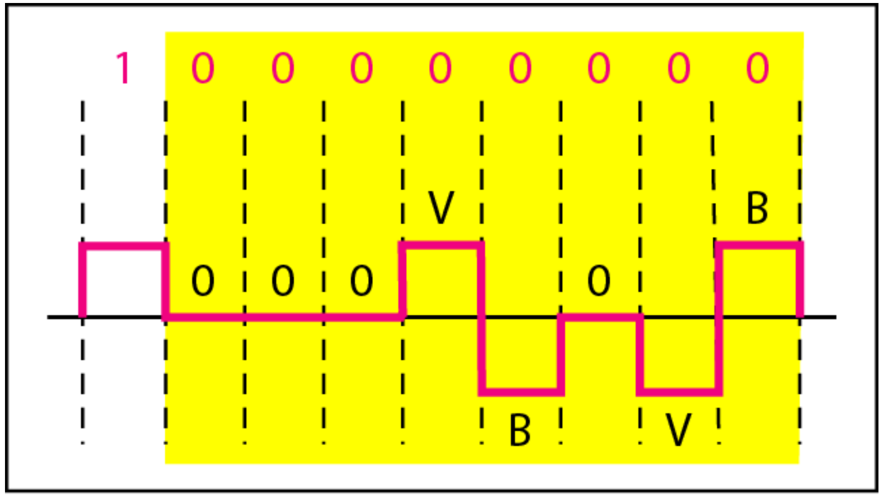
- The best code is one that does not increase the bandwidth for synchronization and has no DC components.
- Scrambling is a technique used to create a sequence of bits that has the required characteristics for transmission - self clocking, no low frequencies, no wide bandwidth.
- It is implemented at 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 characteristics.

AMI used with scrambling

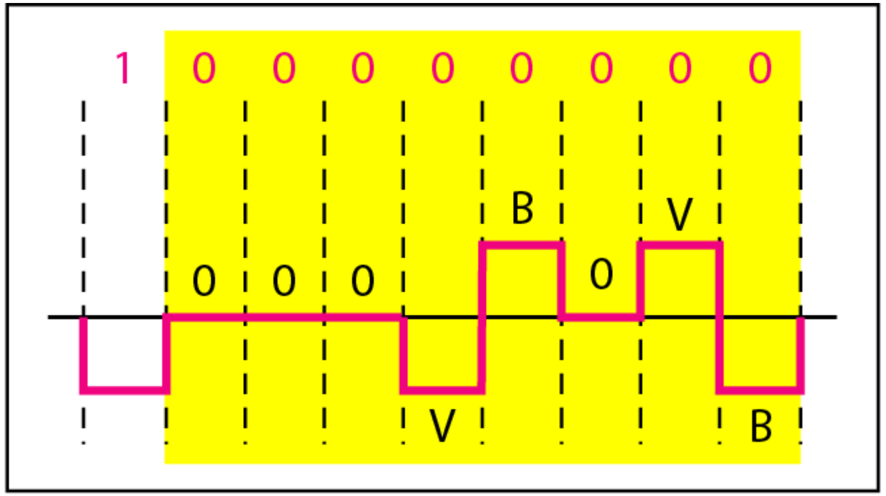


- For example: B8ZS substitutes eight consecutive zeros with 000VB0VB.
- The V stands for violation, it violates the line encoding rule
- B stands for bipolar, it implements the bipolar line encoding rule

Two cases of B8ZS scrambling technique



a. Previous level is positive.



b. Previous level is negative.

- 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.

Different situations in HDB3 scrambling technique