Digital Transmission

Physical

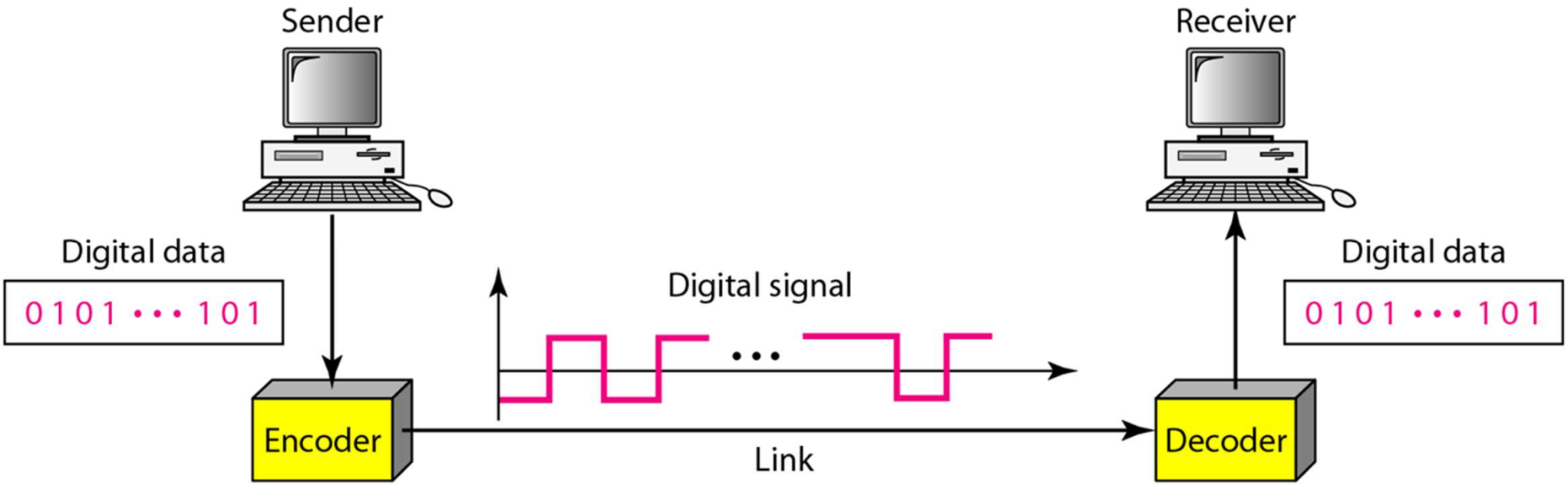
Topics covered in this topic

- Digital-to-Digital Conversion
- Analog-to-Digital Conversion
- Digital Transmission Modes

Digital-to-Digital Conversion

Line Coding

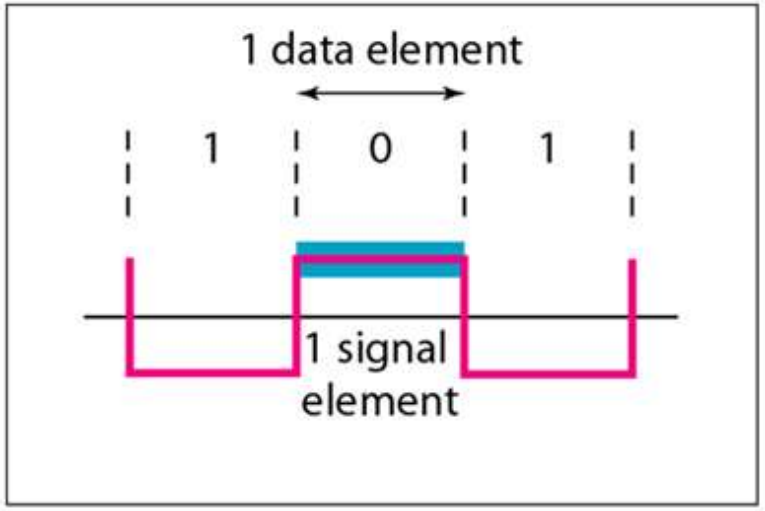
- Convert binary data into digital signals



Data Element and Signal Element

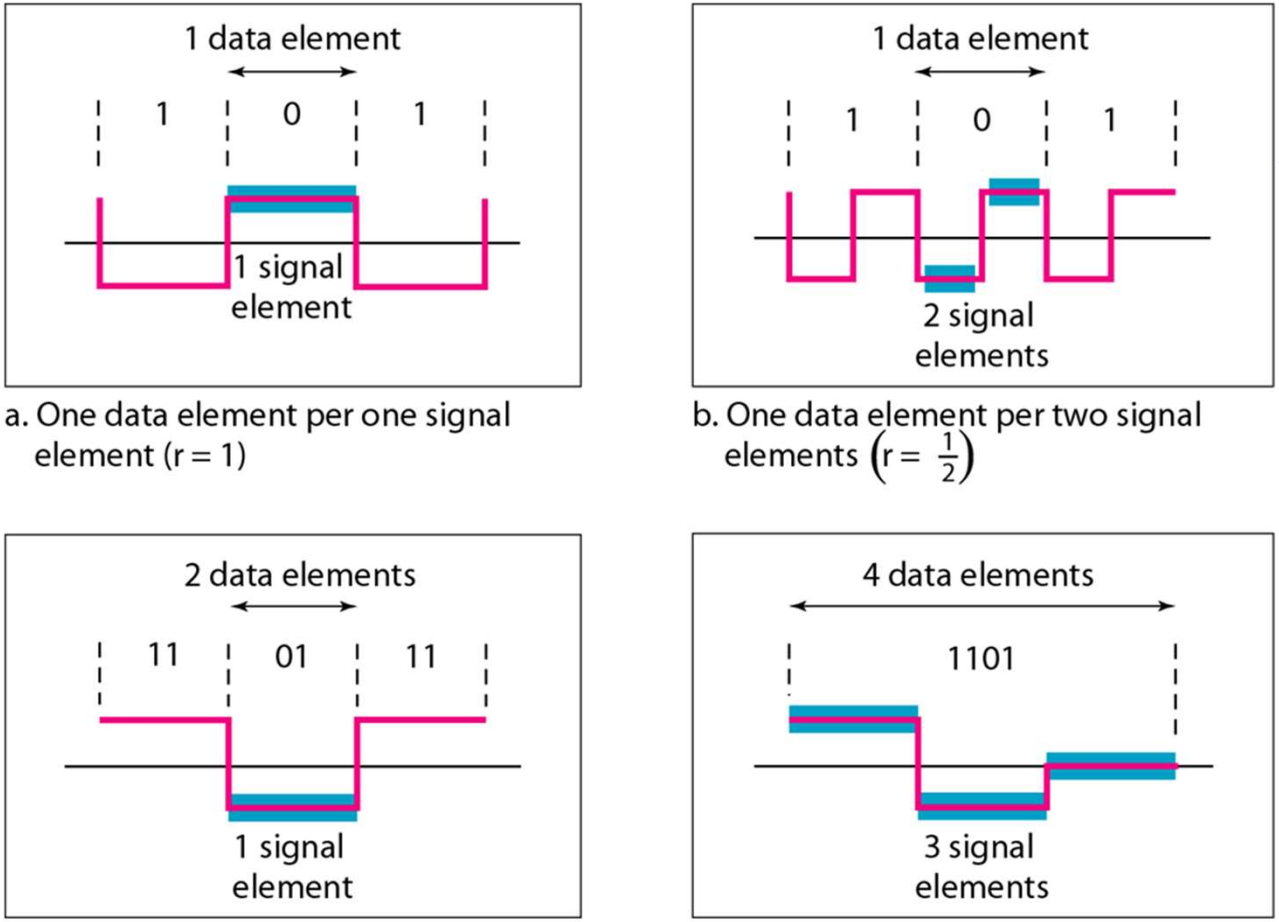
- Data element
  - unit of digital data = bit

- Signal element
  - unit of digital signal



Data Element and Signal Element

- **r** = number of data elements per signal element



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

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

두 개의 준위를 사용해서 한 비트를 표현

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

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

Units of Data and Signal Transmission

- Data transmission rate 일반적으로 쓰는 데이터 전송 속도
  - number of <u>data elements</u> sent in a second
  - unit: bps

- Signal transmission rate
  - number of <u>signal elements</u> sent in a second
  - unit: baud

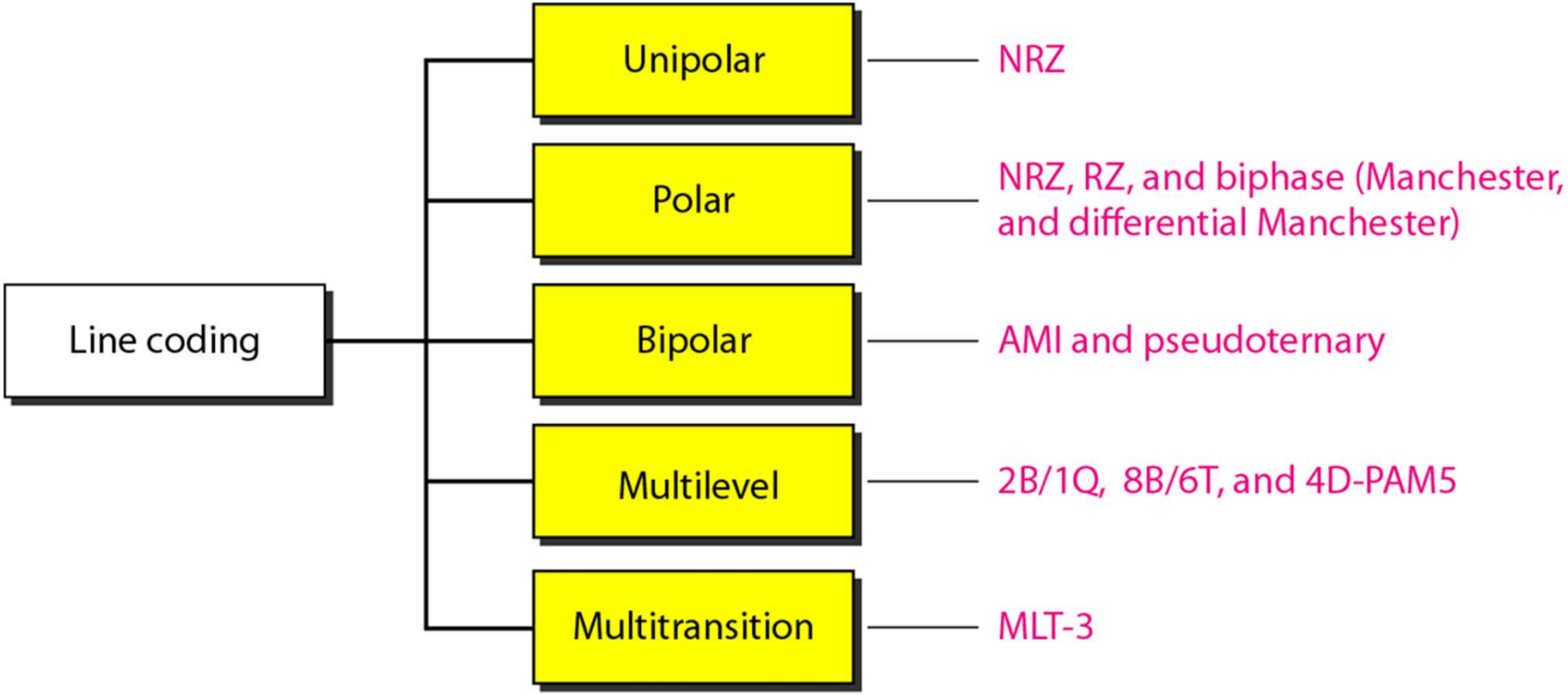
Exercise

- A signal is carrying data in which one data element is encoded as two signal element. If the bit rate is 100kbps, what is the baud rate?

200 kbaud/s

Digital-to-Digital Conversion Schemes

아날로그 데이터를 보내고 싶은가, 디지털 데이터를 보내고 싶은가
아날로그 신호로 보내고 싶은가, 디지털 신호로 보내고 싶은가
총 4가지 경우
an(데이터)-an(신호), an-di, di-an, di-di

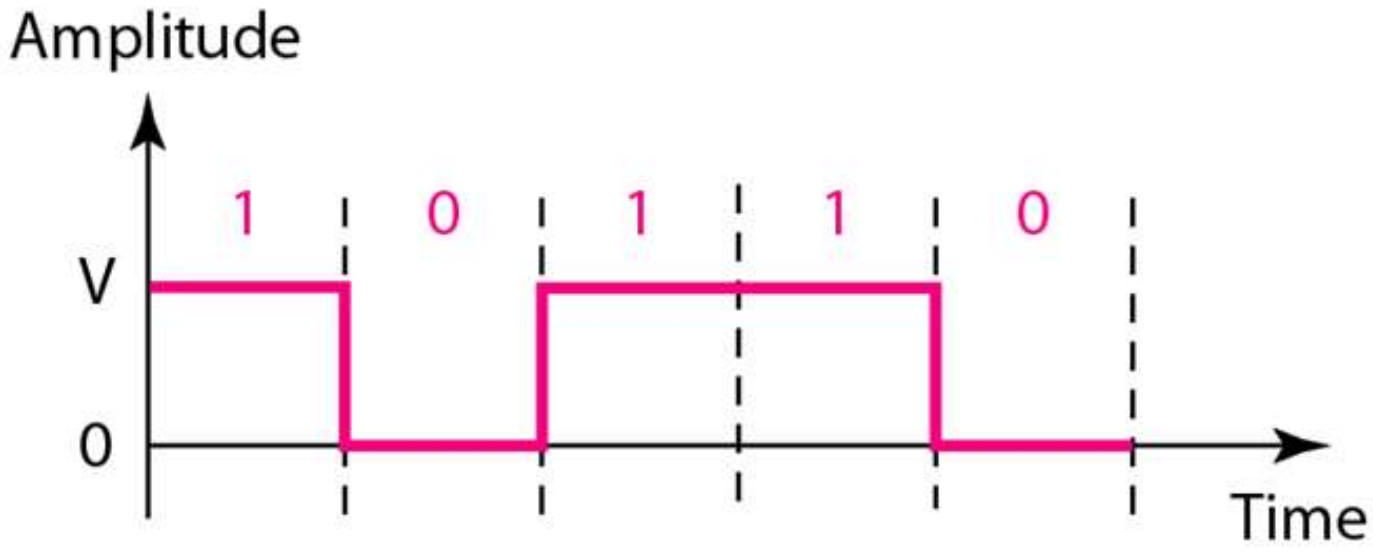


양극 하나만 사용

Unipolar Encoding

- Encode one of the two binary data as 0V

- Unipolar NRZ (non-return-to-zero)
  - Bit 1 → high volt
  - Bit 0 → zero volt



Polar Encoding

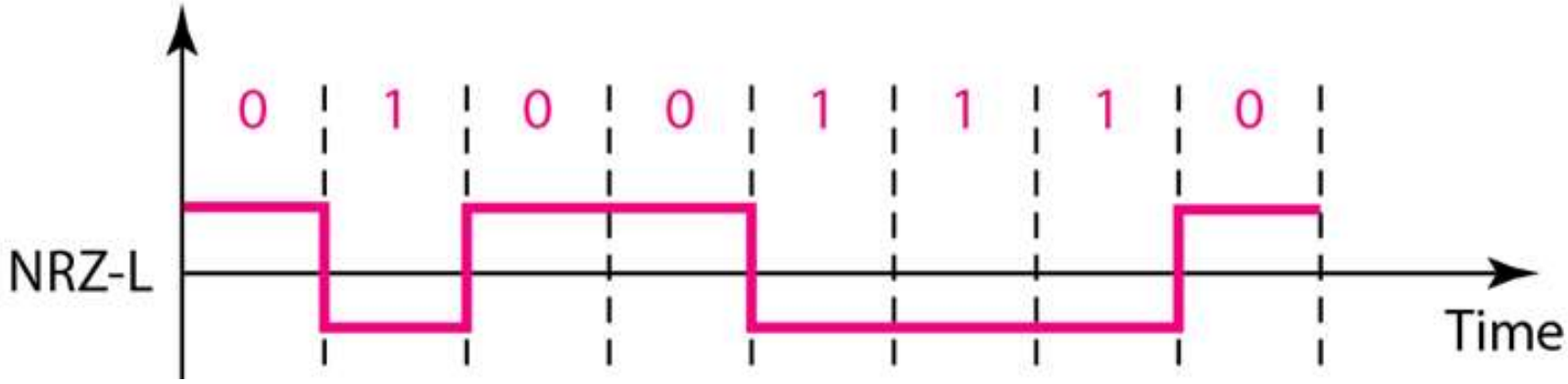
- Use +V, -V for encoding two binary data (Bit 0, Bit 1)

양극 사용

Polar Encoding

- NRZ-L (Level)

송신, 수신 측이 어떤 극이 0,1인지 정할 수 있다



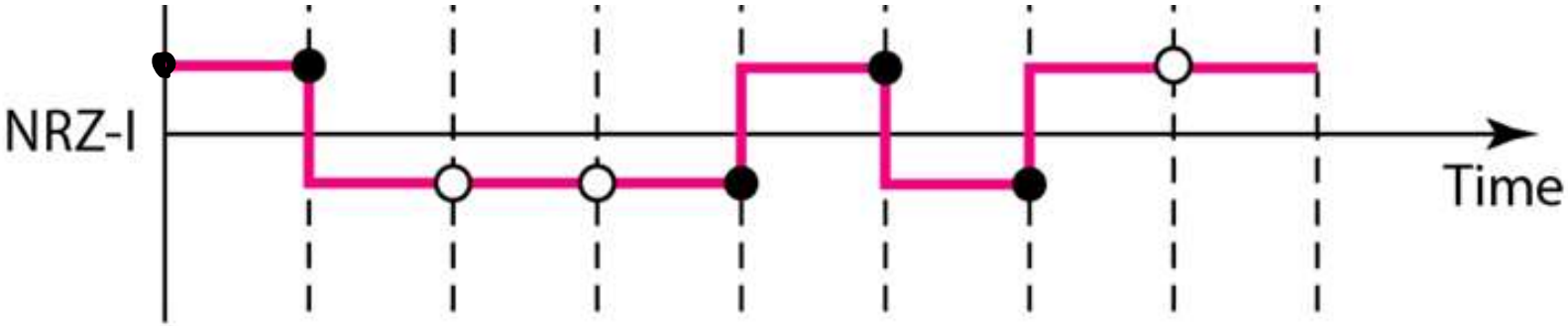
Polar Encoding

- NRZ-I (Inverted)

현재 비트를 보고, 준위를 결정

0은 그대로, 1은 바꾼다

여기가 0인 이유는, 이 전 부분이 1이었기 때문
그럼 맨 처음은? 송수신이 약속한 것으로



^1부분을 표현 -> invert

01001110

하나의 signal component로 하나의 비트를 표현: bps : baud = 1 : 1

DC Component

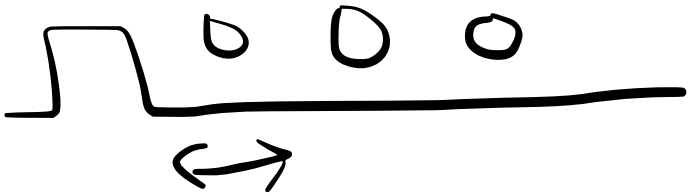
- When the signal stays constant at a certain level for a long time

000000 처럼 보내는 데이터가 하나의 값으로 연속되는 경우에 문제가 발생한다 1. baseline wandering 2. clock drift

  - causes baseline wandering

준위가 높은지 낮은지 판단하는 게 어려움
오는 신호의 전위 평균을 내서 그것보다 높으면 위, 낮으면 아래라고 판단
근데 높은 준위가 계속 나오면 평균(baseline) 준위가 높아지기 때문에 높은 준위를 의미하는 데이터가 왜곡에 의해 조금 낮게 보내지면 이걸 낮은 준위로 인식해버림
또한 연속되지 않더라도 수신된 데이터의 준위가 너무 낮거나 높은게 계속 나오면 평준 준위가 불안정해짐
그래서 평균 준위를 보장하는 방식으로 인코딩해서 보내는데 노력

  - causes clock drift



비트를 표현하는 시간을 정했는데
송신자와 수신자의 clock이 맞지 않는 현상
clock이 안맞아도 중간에 준위가 바뀌면 바뀐게 나오는 시간으로 동기화 되게 해서 맞출수 있는데
하나의 비트가 계속 연속되면 동기화를 할 수 없어서 clock drift가 발생

Baseline wandering

- When the receiver decodes the signal, bit 0 or 1 is decided based on the <u>baseline</u>

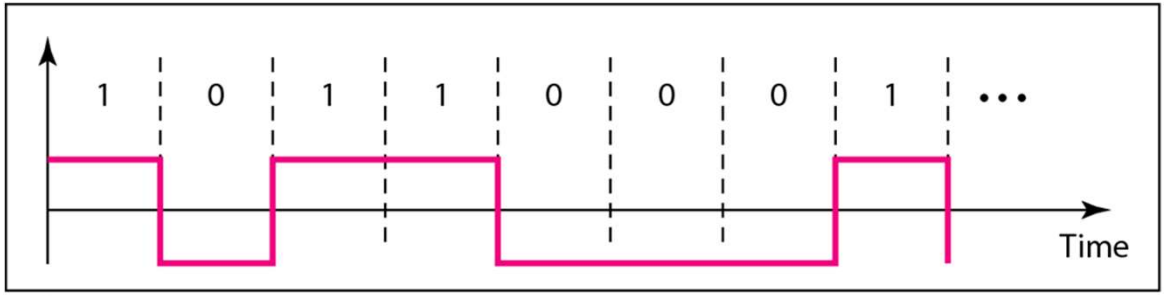
- The baseline is the average level of received signals
  - If Bit 0 → 0V, Bit 1 → 12V, then after some time the average will be near 6V

- If a series of 0 or a series of 1 continues for a long time, the baseline drifts from the average, causing problems when decoding

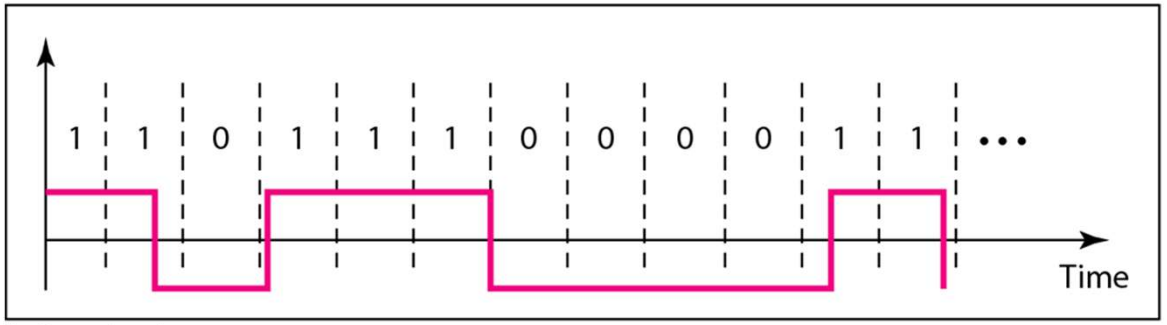
질문: 그럼 반대로 평균 준위가 0에 가까워지면 노이즈에 의해서 0값이 1로 인식되는 문제도 있을 수 있나

Clock Drift

- The speed of clock is slightly different for devices
- Time mismatch of sender and receiver can lead to decoding problems, since the receiver may not know when the signal element ends



a. Sent



b. Received

Self Synchronization

- Even if the speed of clocks is different, the receiver can synchronize clocks if signal changes frequently

- If an encoding scheme enforces signal changes, the scheme is said to have the “self synchronization” property

Self Synchronization

- NRZ-L and NRZ-I do not have self synchronization property, since both of them may generate DC component

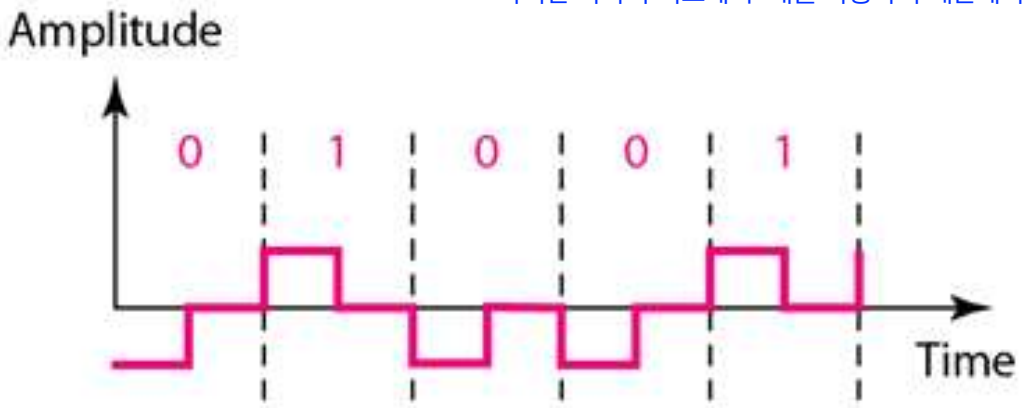
- However, NRZ-I has smaller chance of generating DC component. Thus, NRZ-I is better than NRZ-L in terms of baseline wandering and clock drift

데이터가 0이 계속되는 경우와 1이 계속되는 경우가 있음
nrz-i는 0이 계속되는 경우는 문제지만 1이 계속되는 경우는 해결(1일 때 준위를 바꾸기 때문)

Polar Encoding

- RZ (Return-to-Zero)
  - When encoding a bit, use two signal elements
  - The first element is either LOW or HIGH
  - The second element is 0

한 비트를 표현하는데 두개의 시그널을 사용
clock drift 해결(준위가 두번마다 바뀌니까 self sync)
하지만 하나의 비트에 두 개를 사용하기 때문에 주파수 사용면에서 속도가 떨어짐



Polar Encoding

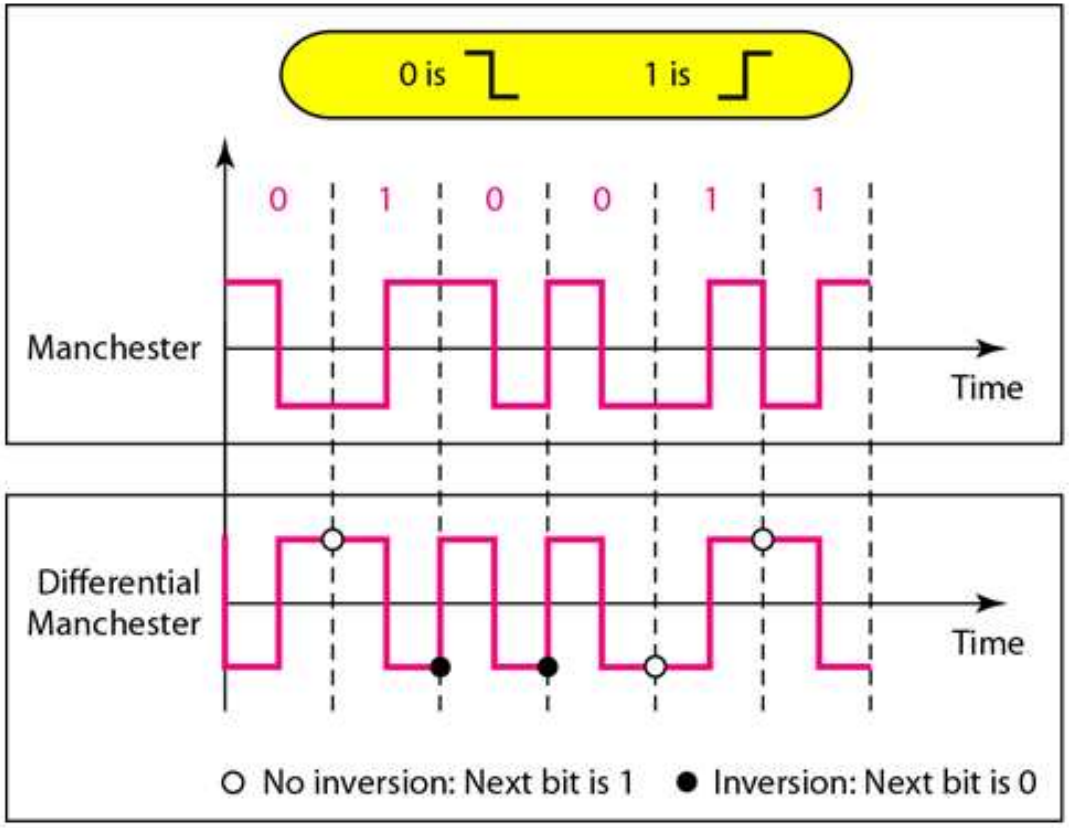
- RZ (Return-to-Zero)
- Pros: self-synchronization
- Cons
  - Two signal elements per data element → lower bit rate
    - requires double baud rate
  - Three signal levels (LOW, 0, HIGH) → lower accuracy
  - Baseline wandering not solved

Polar Encoding

- Manchester, differential Manchester

옛날 이더넷 인코딩 방식

clock drift, baseline 문제 해결
속도만 문제



Polar Encoding

- Manchester, differential Manchester encoding
  - Compared to RZ, smaller signal levels
  - Requires double baud rate (same as RZ)

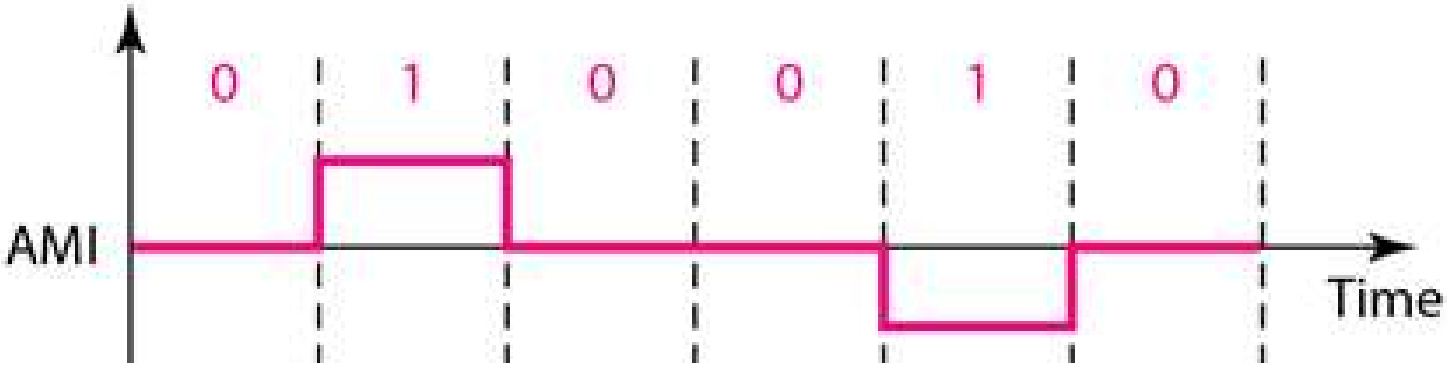
    2개의 준위로 하나의 비트를 표현
  - Signal changes every bit
    - No DC component
    - No baseline wandering
    - No clock drift

Bipolar Encoding

- One of the two binary data is encoded as 0
- The other is encoded using LOW and HIGH

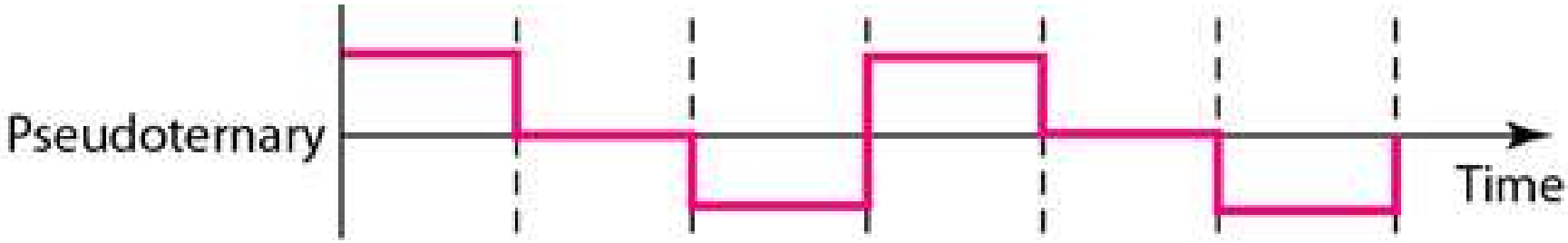
Bipolar Encoding

- AMI (Alternate Mark Inversion)
  - A scheme to remove DC component
  - Bit 0 → 0V
  - Bit 1 → Alternate LOW and HIGH baseline wandering 해결



Bipolar Encoding

- Pseudo-ternary encoding
  - 1 → 0V
  - 0 → Alternate between LOW and HIGH



Multilevel Encoding

- Use multiple signals levels to encode data
- Increases transmission speed

- mBnL: Use n signal element to encode m data elements
  - ‘L’ is number of signal levels: the following characters are used
    - B (Binary): 2 levels
    - T (Ternary): 3 levels
    - Q (Quaternary): 4 levels

- $2^m \leq L^n$

Multilevel Encoding

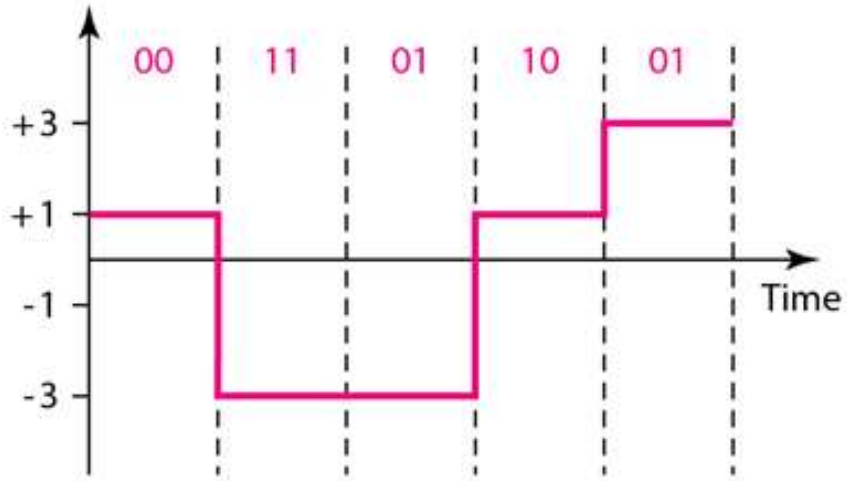
- 2B1Q 레벨을 여러개 씀
  - 2 bits are encoded into a single signal element
  - 4 signal levels (Q)
  - Used in DSL

00이 계속 나오면 계속 1 준위가 됨 - baseline wondering 해결 못함

앞에 준위에 의해 현재 준위가 결정

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

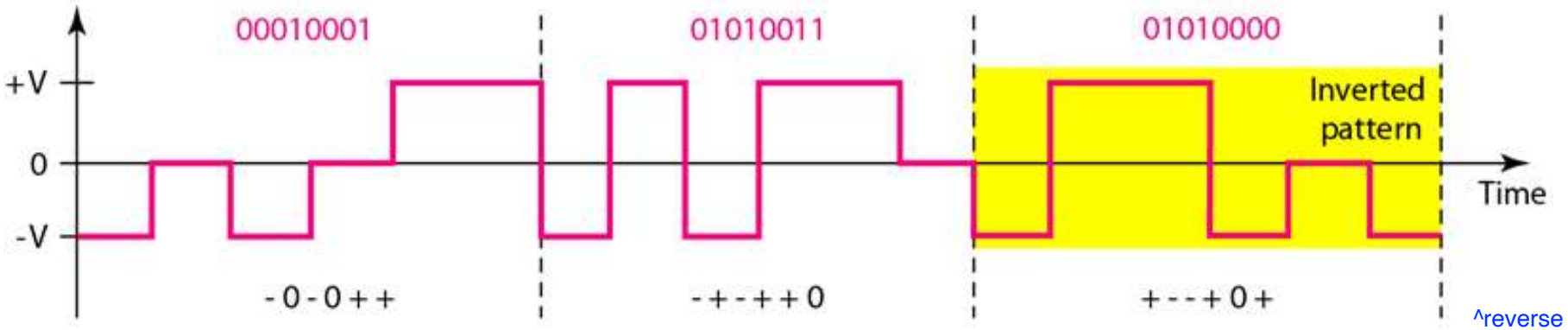
^앞에가 00이고 1준위니까
11인 현재는 -3준위

Multilevel Encoding

- 8B6T
  - Used in 100BASE-4T 100Mbps 이더넷의 표준
  - 8 bits are encoded into 6 three-level signal element
  - 6 signal elements are designed so that
    - The element has the same number of '+'s and '-'s, or
    - The element has one more '+'s than '-'s

2^8비트가 256가지 경우
3^6승은 이것보다 크다, 즉 3개의 준위로 8비트를 표현할 수 있다
하지만 -와 +준위의 개수가 같게하는 경우 까지 포함하면 256이 안됨
+하나까지 많은 것은 허용

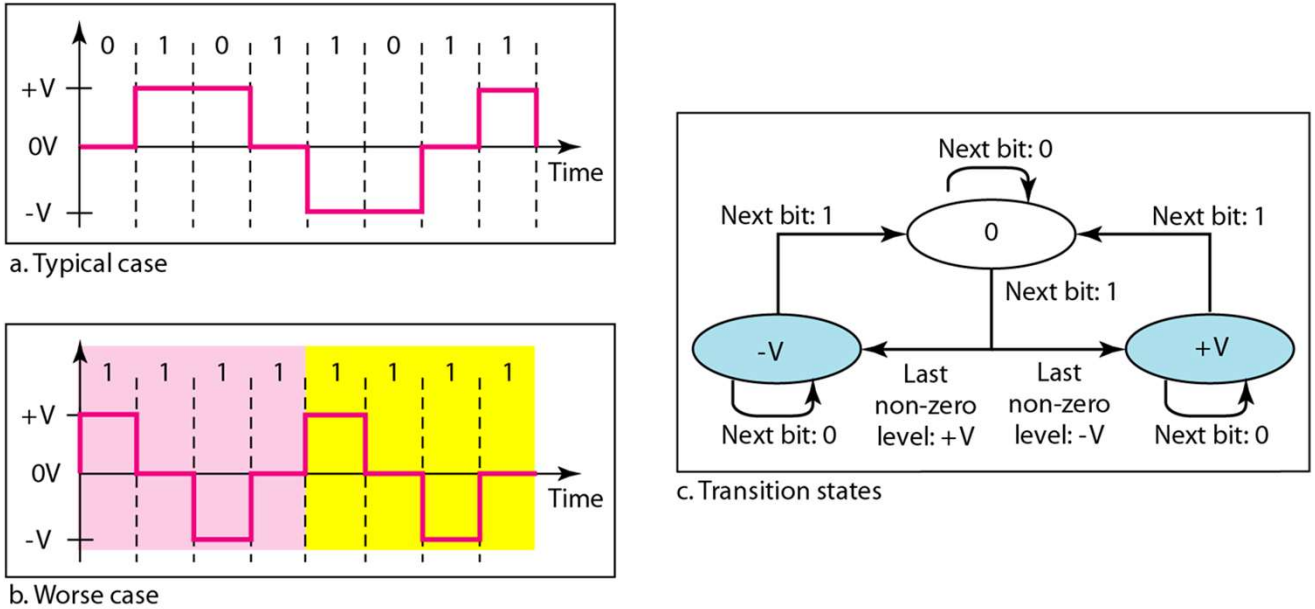
  - If there are two back-to-back signal elements with one more '+', than the second signal element is reversed



+준위가 많은 시그널이 두 개 연속으로 오면 뒤에 오는 시그널이 reverse
그 다음부터 다시 정상으로 받음

MLT-3

- Used in LAN
  - If the next bit is 0, no signal level change
  - If the next bit is 1 and the current signal level is nonzero, then signal level is 0
  - If the next bit is 1 and the current signal level is 0, then signal level is the inverse of most recent nonzero level

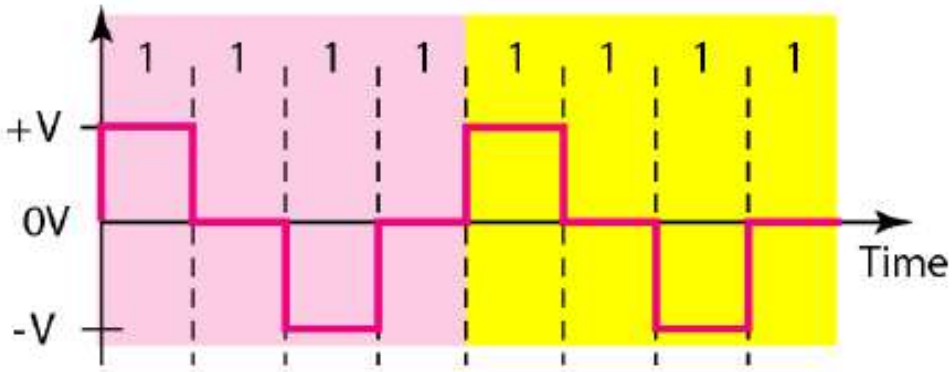


MLT-3

- Advantage 다른애들은 1/2임

  1/2이란 얘기는 한 번 출렁일 때 2비트감
  한번 출렁일 때 4비트가 간다 -> 1/4

  – Fundamental frequency is 1/4 of transfer rate.



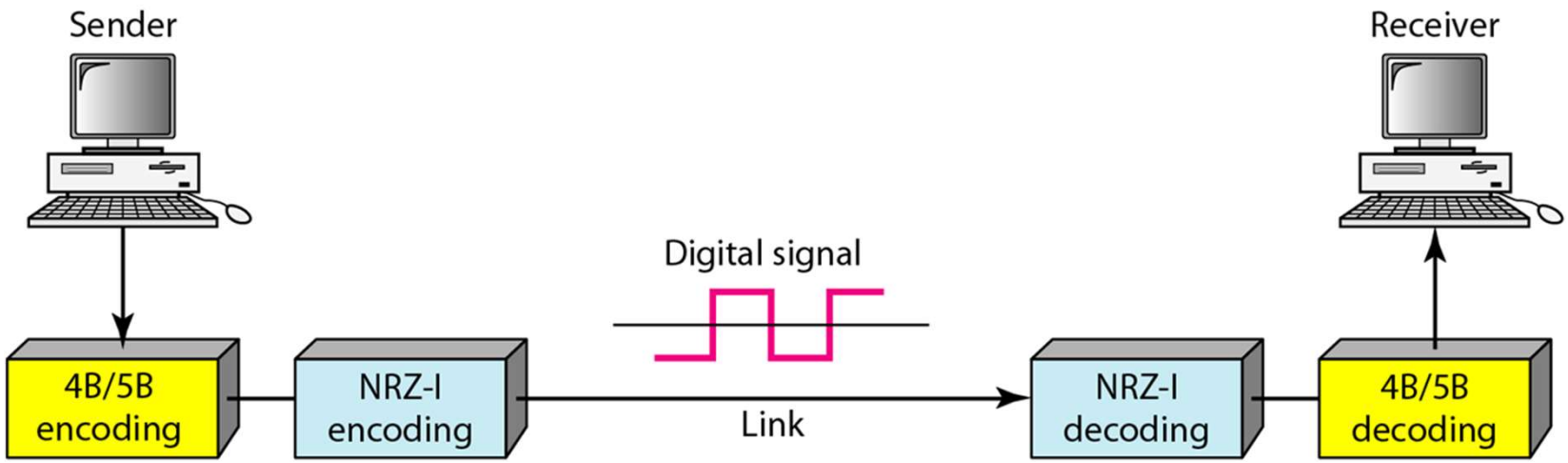
- Drawback
  – Does not support self-synchronization (for long string of zeros)
  – More complex than NRZ-I due to use of three levels and complex transition rules

Block Coding

- Convert <u>m bits of data</u> into <u>n bits of data</u> (block code)
- called mB/nB coding
- $m < n$
- Goal: self-synchronization, error detection, etc.

Block Coding

- 4B/5B
  - NRZ-I shows good transmission rate (r = 1), but has synchronization problem
  - If series of 0s continues, synchronization problem can occur
  - The goal of 4B/5B is to avoid continuous 0s



Block Coding

- 4B/5B
  - Convert 4-bit data into 5 bits so that
  - In the bit stream, “0000” does not appear
  - 0010010110011010000011000 (X)

Block Coding

- 4B/5B
  - 4-bit data: 0000, 0001, 0010, …, 1110, 1111
  - We need to convert 4-bit data into 5-bit block codes
  - Among 5 bits, the first 2 bits must include at least one ‘1’, and the last 3 bits must include at least one ‘1’.

    앞의 2비트중 하나는 1이어야 하고
    뒤의 3비트중 하나는 1이어야 함
  - How many 5-bit codes exist, that satisfy the previous condition?
  - Is this block coding possible? How can we prove this?

Block Coding

- Example block coding

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		

Example

- Suppose signal is transmitted at 1M baud

80%

- What is the data rate if NRZ-I + 4B/5B is used?

800kbps

- What is the data rate if Manchester Encoding is used?

500kbps

Scrambling

ami도 0이 연속되는 게 문제

- AMI encoding alternates LOW and HIGH signals in order to remove DC component

- However, since bit 0 is encoded into 0V, synchronization problem can occur if a series of 0 continues

- Scrambling is a scheme that removes continuous 0 without incurring overhead

Scrambling

- B8ZS (Bipolar with 8 Zero Substitution)
  - Used mainly in North America

0이 8개가 나오면 이렇게 바꿔준다

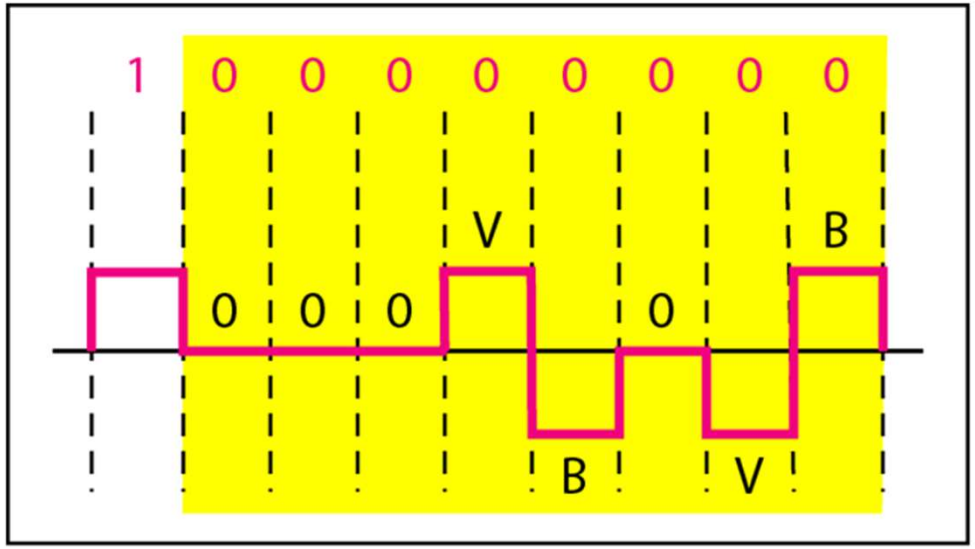
- 00000000 → 000VB0VB

비트 수를 늘리지 않고도 self sync
하지만 준위를 3개 쓰고 있어서 가능

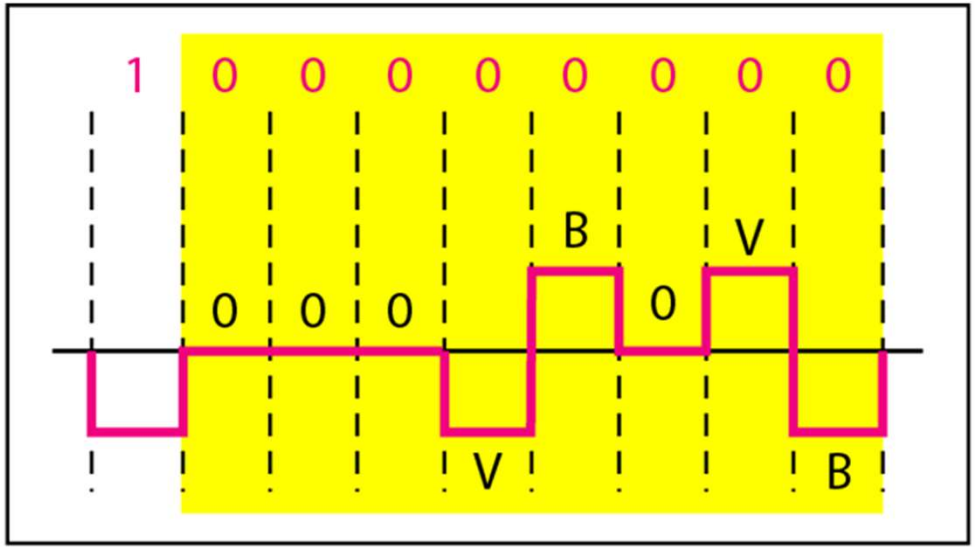
- V (Violation): a non-zero level that violates AMI rule
- B (Bipolar): a non-zero level that obeys AMI rule

Scrambling

ami에서 1을 나타낼 때는 전에 1을 나타내던 bit의 inverse를 해야 하는데
V부분에서는 inverse를 하지 않고 있음. 그래서 violation
violation이 나왔을 때 시스템은 “어 이거 원래는 전에 온 1을 나타내는 signal component의 inverse가 돼야 하는데 아니네? 그럼 이 부분은 scrambling 이겠군”이라고 생각



a. Previous level is positive.

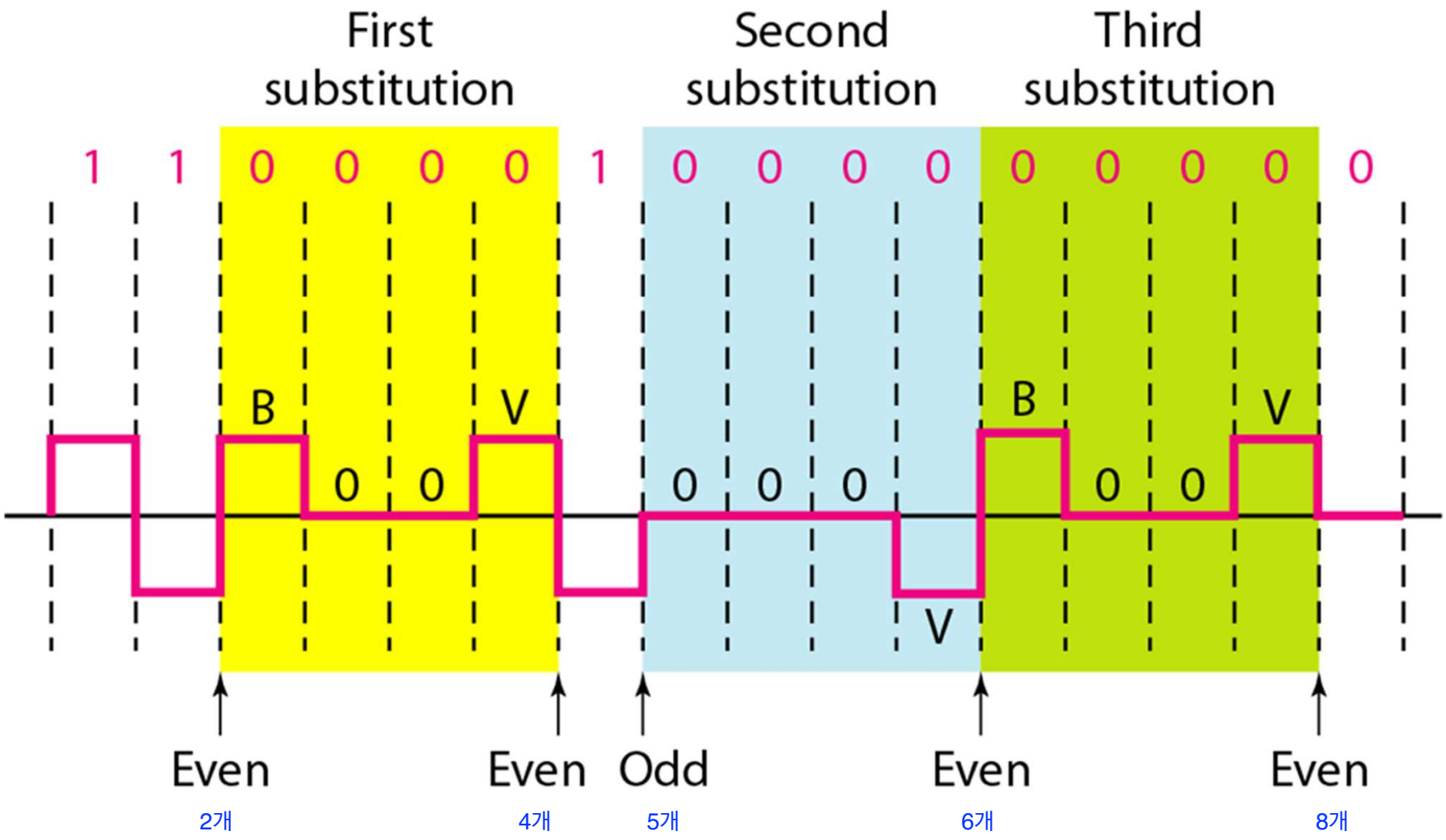


b. Previous level is negative.

Scrambling

- HDB3 (High-Density Bipolar 3-Zero)
  - Used in places other than North America
- 0000 → 000V, or 0000 → B00V
- After previous substitution, number of non-zero signal elements is odd → 000V
- After previous substitution, number of non-zero signal element is even → B00V

Scrambling


First substitution
Second substitution
Third substitution
1 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0
B
V
0 0
0 0 0
V
B
V
0 0
Even
Even
Odd
Even
Even
2개
4개
5개
6개
8개

Case Study: Ethernet Physical Layer

Ethernet

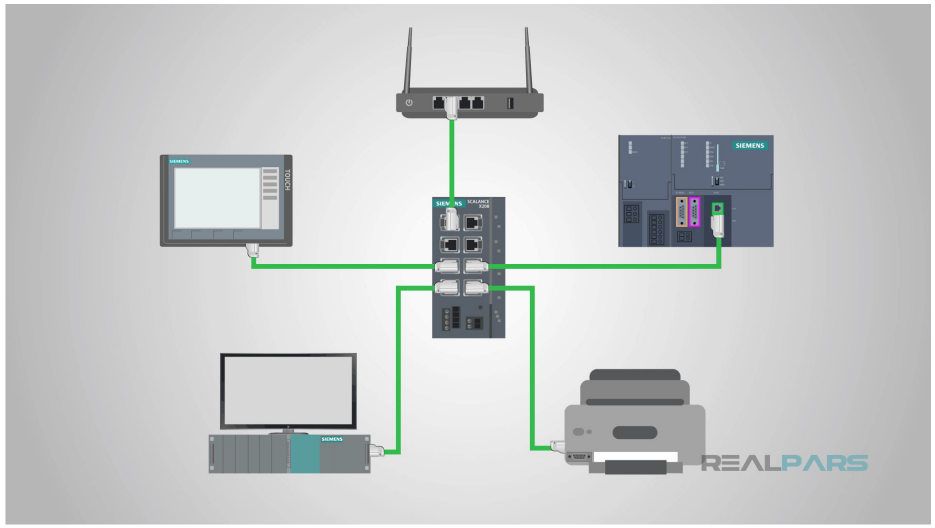
- A family of wired networking technologies commonly used in local area networks (LAN), metropolitan area networks (MAN), and wide area networks (WAN)

와이파이 라우터의 구멍 중에서
wan 적힌 걸 벽에 연결하고
lan 적힌 걸 컴퓨터에 연결

Ethernet

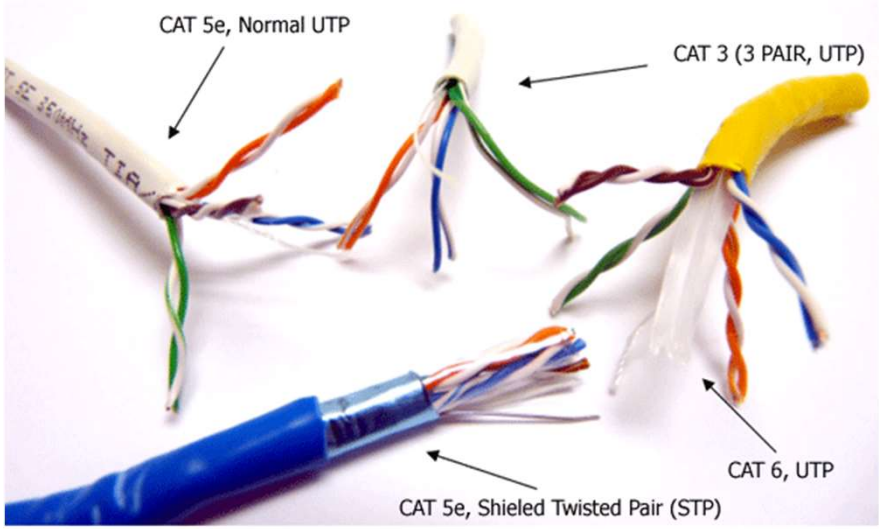
- Standardized by IEEE 802.3 division
  - Wi-Fi is IEEE 802.11

- Covers physical layer and data link layer



Ethernet Cable

케이블도 속도 제한이 있음



칼론 CAT5 10M 랜선 랜케이블, 그레이, 1개

넥시 CAT.6 UTP 케이블 3m, 화이트, 1개

CATEGORY	SHIELDING	MAX TRANSMISSION SPEED (AT 100 METERS)	MAX BANDWIDTH
Cat 3	Unshielded	10 Mbps	16 MHz
Cat 5	Unshielded	10/100 Mbps	100 MHz
Cat 5e	Unshielded	1000 Mbps / 1 Gbps	100 MHz
Cat 6	Shielded or Unshielded	1000 Mbps / 1 Gbps	>250 MHz
Cat 6a	Shielded	10000 Mbps / 10 Gbps	500 MHz
Cat 7	Shielded	10000 Mbps / 10 Gbps	600 MHz
Cat 8	Shielded	25 Gbps or 40Gbps *	2000 MHz

Ethernet Standards

- Major standard variants
  - 10BASE5: 10Mbps, baseband transmission, max 500m
    - Uses RG-8 thick cable
  - 10BASE2: 10Mbps, baseband transmission, max 200m
    - Uses RG-8 thin cable
  - 10BASE-T: 10Mbps, baseband transmission, twisted pair
    - max segment length about 100m
  - 100BASE-TX: 100Mbps, full-duplex communication using two twisted pairs, called "Fast Ethernet"
  - 1000BASE-T: 1Gbps, uses 4 twisted pairs, 5-level coding
  - 10GBASE-T: 10Gbps
  - etc.

Ethernet Standards

- 10BASE-5, 10BASE-2, and 10BASE-T uses Manchester Encoding
- 100BASE-TX uses MLT-3 encoding + 4B/5B
  - In order to achieve 100Mbps, we need 125Mbaud due to 4B/5B encoding.
  - We use MLT-3, which is possible to implement using 1/4 of data rate as fundamental frequency
  - 125 * 1/4 = 31.25MHz is needed.
  - Since cat 5 supports up to 100MHz, 100Mbps is achievable with cat 5 cables.
- 1000BASE-T uses 8B1Q4 and 4D-PAM5

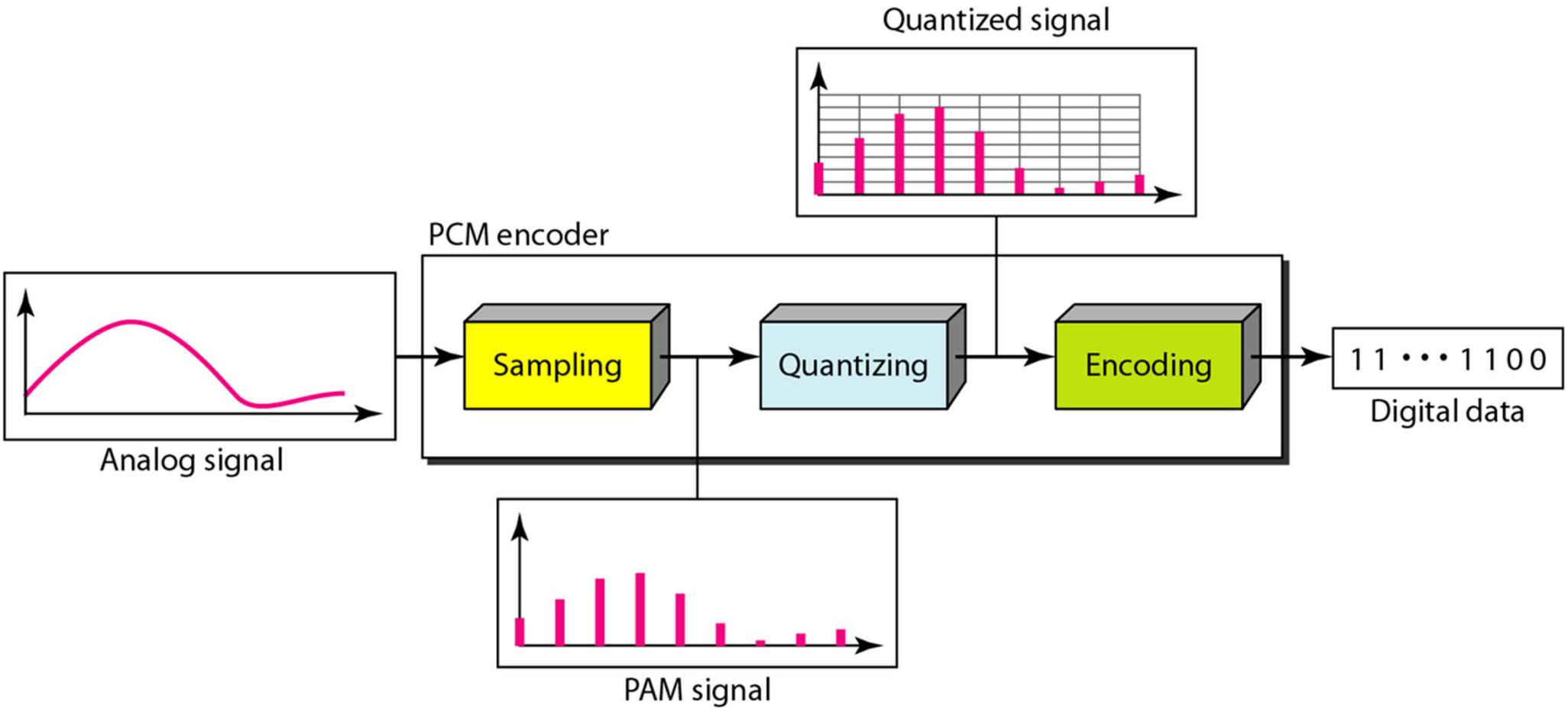
Analog-to-Digital Conversion

Analog-to-Digital Conversion

- Multimedia data such as voice, music, movie, etc. are originally analog data

- In order to transmit and receiver, the analog data should be converted to digital data

Pulse Code Modulation (PCM)



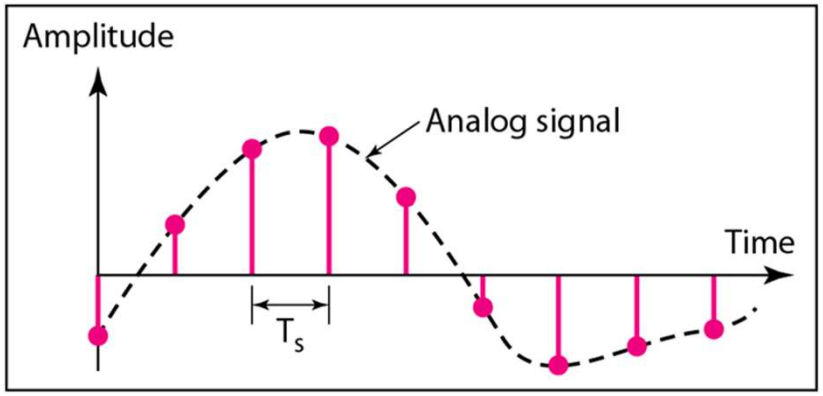
Pulse Code Modulation (PCM)

- The most basic analog-to-digital conversion scheme
  - Sample analog data
  - Quantize signals
  - Encode signals into digital bitstream

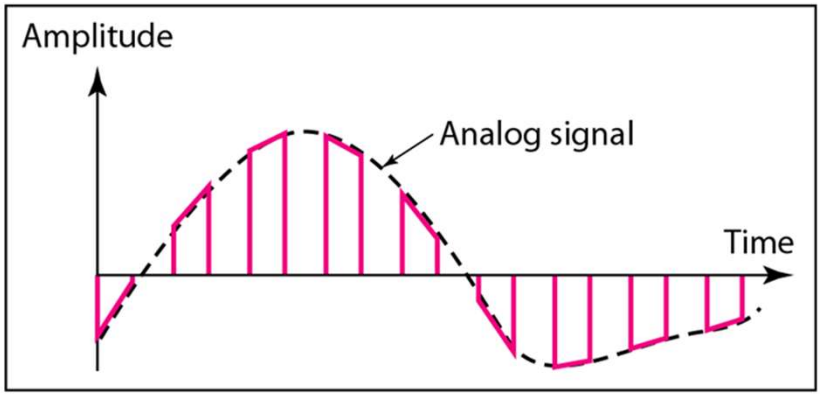
Sampling

- Periodically read signal amplitude

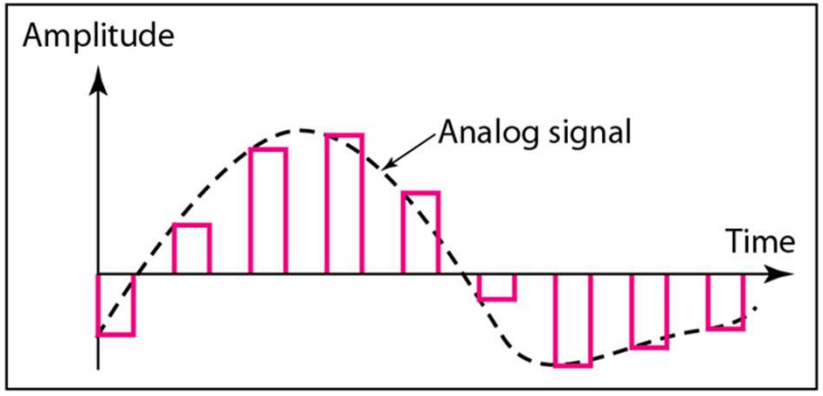
일정 시간 간격으로 아날로그 신호의 진폭을 따옴 -> 딴 점들을 연결



a. Ideal sampling



b. Natural sampling



c. Flat-top sampling

Sampling

- Sampling period
  - What is the period that the signal is sampled?

- Sampling rate

  10000hz = 1초에 만번 샘플링샘

  - How many times the signal is sampled in a second

- Sampling period x sampling rate = 1

Sampling

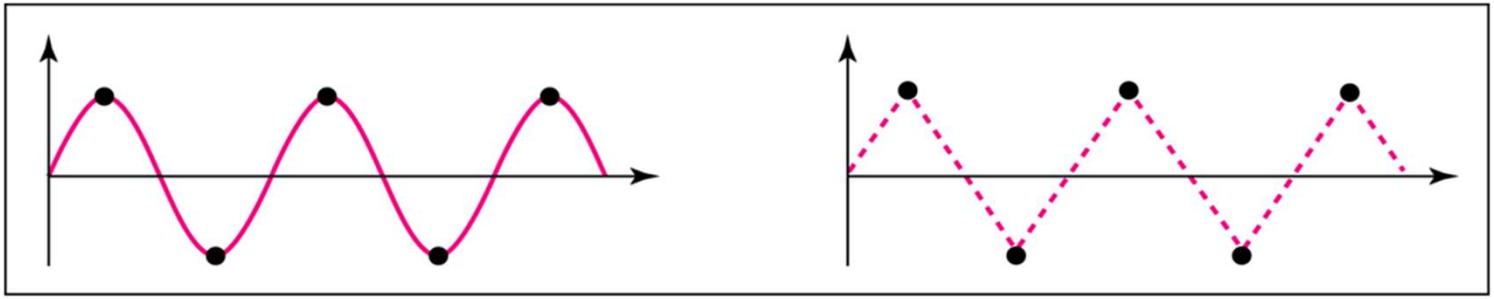
- Nyquist theorem

샘플링을 두배로 해야 복원이 됨

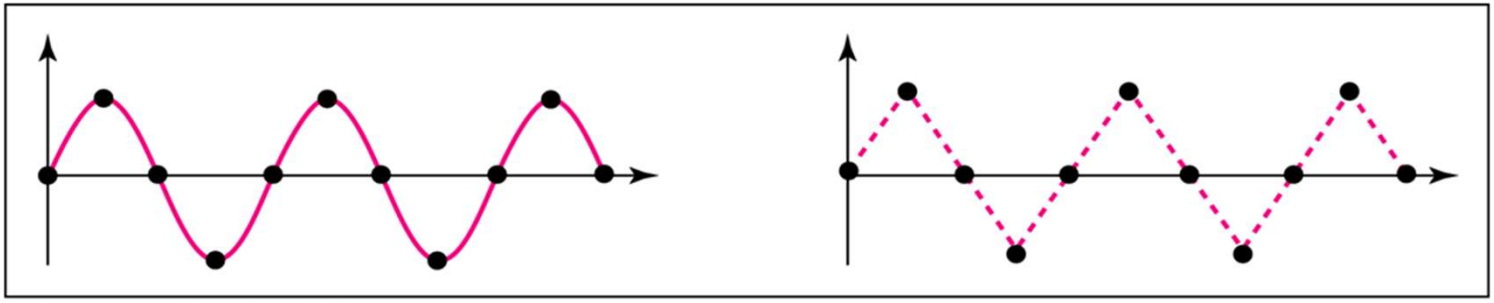
  - The sampling rate should be higher than twice the maximum frequency of the signal

한 번 진동하는데 위 아래가 두 개 있으니

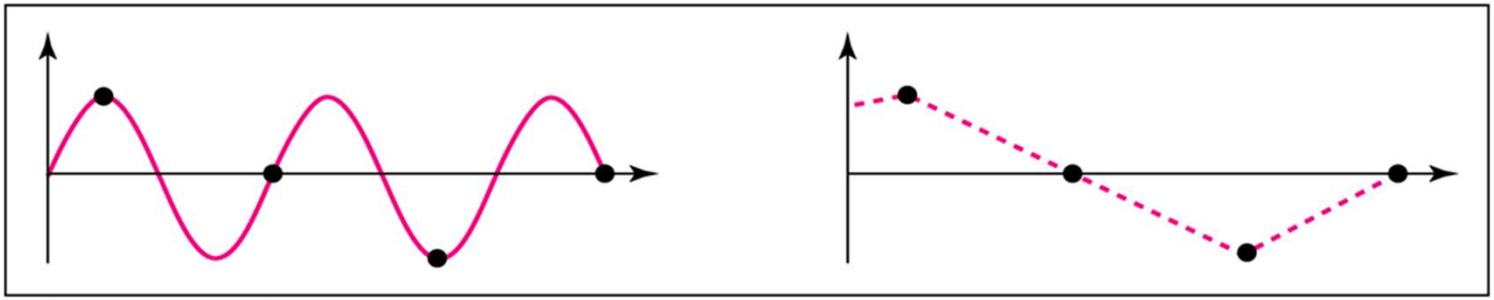
Sampling



a. Nyquist rate sampling: $f_s = 2\ f$



b. Oversampling: $f_s = 4\ f$



c. Undersampling: $f_s = f$

Example

- Telephone companies digitize voice by assuming a maximum frequency of 4000 Hz. What is the minimum sampling rate?

8000hz

Example

- A complex low-pass signal has a bandwidth of 200kHz. What is the minimum sampling rate for this signal?

400khz

Quantizing

- The scheme to determine signal levels in a discrete manner

시그널을 어떤 디지털 준위로 표현할 것인가

Quantizing

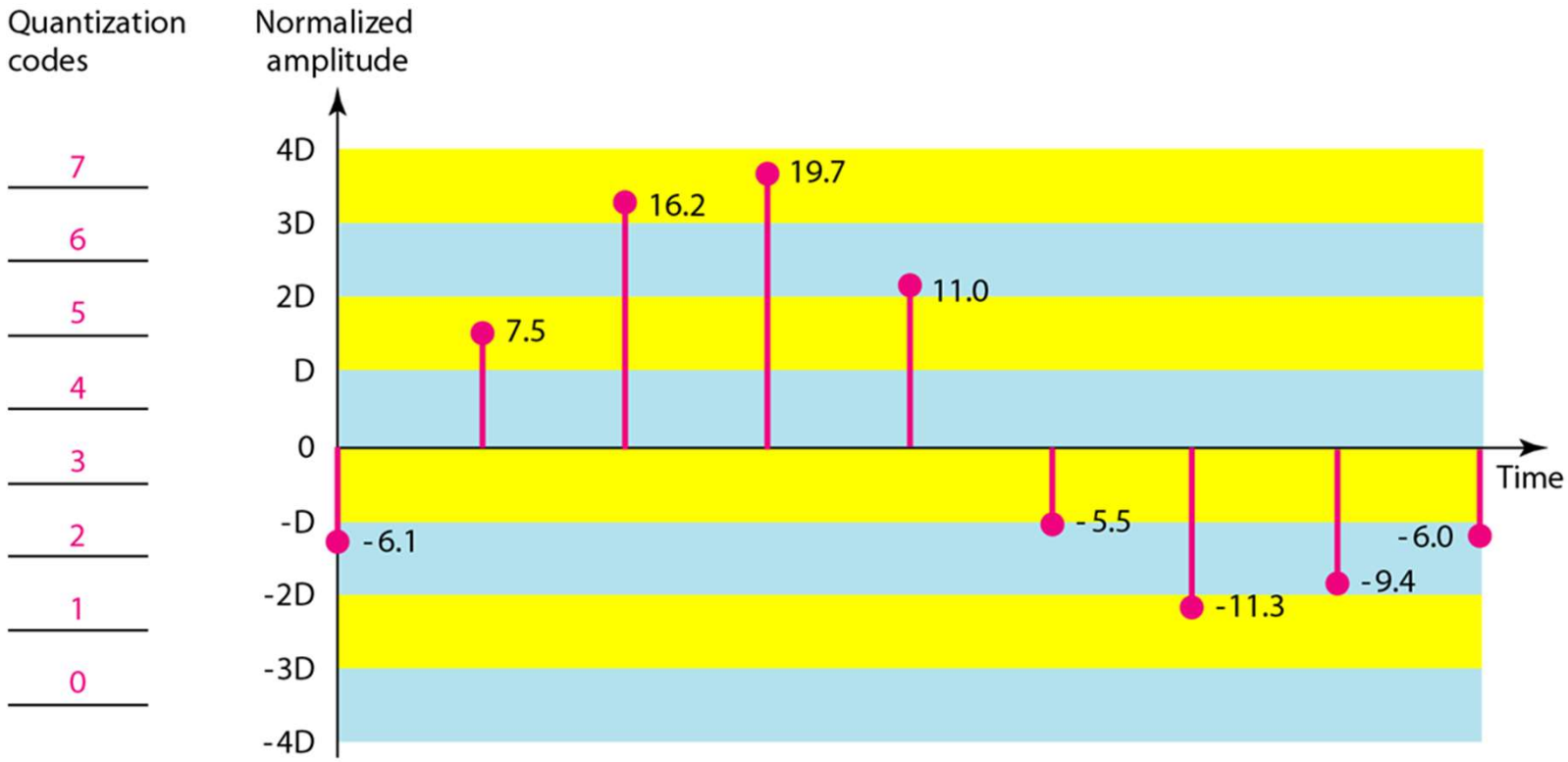
- The sampled signal level can be anywhere between minimum and maximum amplitude

- We need to quantize the signal into discrete signal levels in order to encode them into a digital bit stream

Quantizing

- Suppose the analog signal has amplitude between V_{min} and V_{max}
- Divide the range (V_{min}, V_{max}) into L sections of size D
- D = (Vmax – Vmin) / L
- Assign quantized code for each section

Quantizing



Normalized PAM values	-1.22	1.50	3.24	3.94	2.20	-1.10	-2.26	-1.88	-1.20
Normalized quantized values	-1.50	1.50	3.50	3.50	2.50	-1.50	-2.50	-1.50	-1.50
Normalized error	-0.38	0	+0.26	-0.44	+0.30	-0.40	-0.24	+0.38	-0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

Quantizing

- Quantization Error 퀀타이즈 에러를 노이즈라 생각할 수 있음
  - Difference between real value and quantized value
  - $-D/2 \leq \text{error} \leq D/2$
  - As number of quantization levels increases, quantization error decreses

비트를 많이써서 원본에 가깝게 하면 snr이 높음

- Quantization error affects SNR_{dB} as follows:

- $SNR_{dB} = 6.02n_b + 1.76dB$
  - n_b: bits per sample

Exercise

- What is the SNR_{dB} in the previous example?

Exercise

- A telephone subscriber line must have an SNR_{dB} above 40. What is the minimum number of bits per sample?

telephone line bandwidth : 4khz
minimum sampling rate : 8khz

snr = 6.02 * bits per sample + 1.76
40 = 6.02 * bits per sample + 1.76
bits per sample = 6.35 -> 7

Encoding

- Convert quantized levels into bit patterns

- If there are L levels, $n_b = \log_2 L$

Encoding

- Unit: bit rate

- Bit rate = sampling rate x n_b

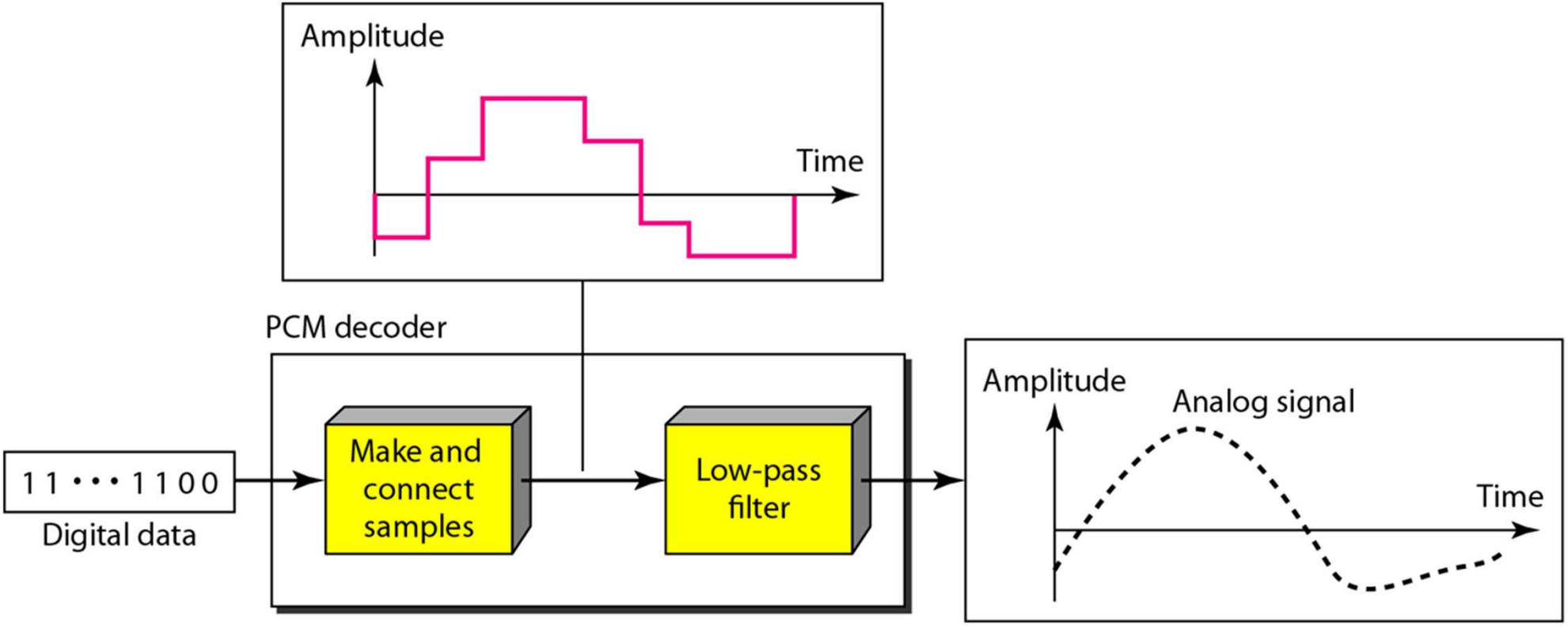
각 샘플의 비트 수(퀀타이즈 정도)

Exercise

- We want to digitize the human voice. The frequency of human voice is between 0 and 4000Hz. What is the bit rate, assuming 8 bits per sample?

bandwidth : 4000hz
sampling rate : 8000hz
bit rate : 8000 * 8 = 64000

PCM Decoder

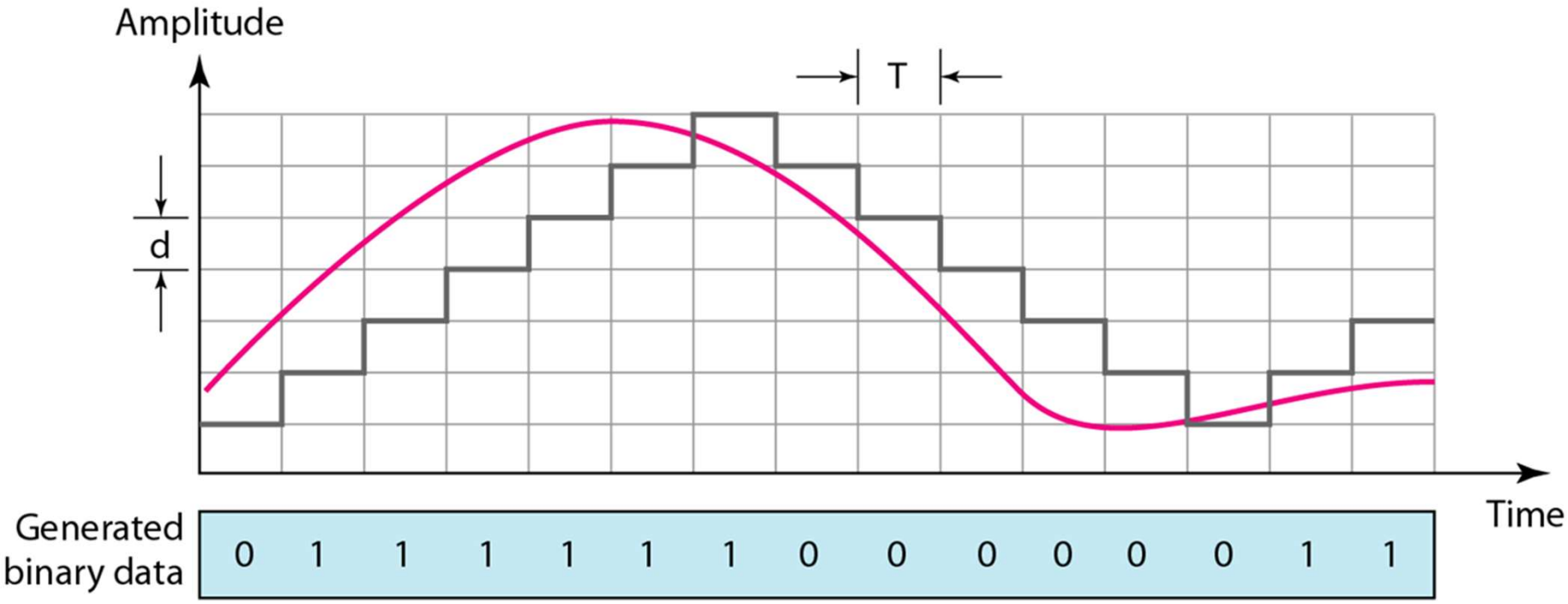

Amplitude
Time
PCM decoder
1 1 • • • 1 1 0 0
Digital data
Make and connect samples
Low-pass filter
Amplitude
Analog signal
Time

Delta Modulation

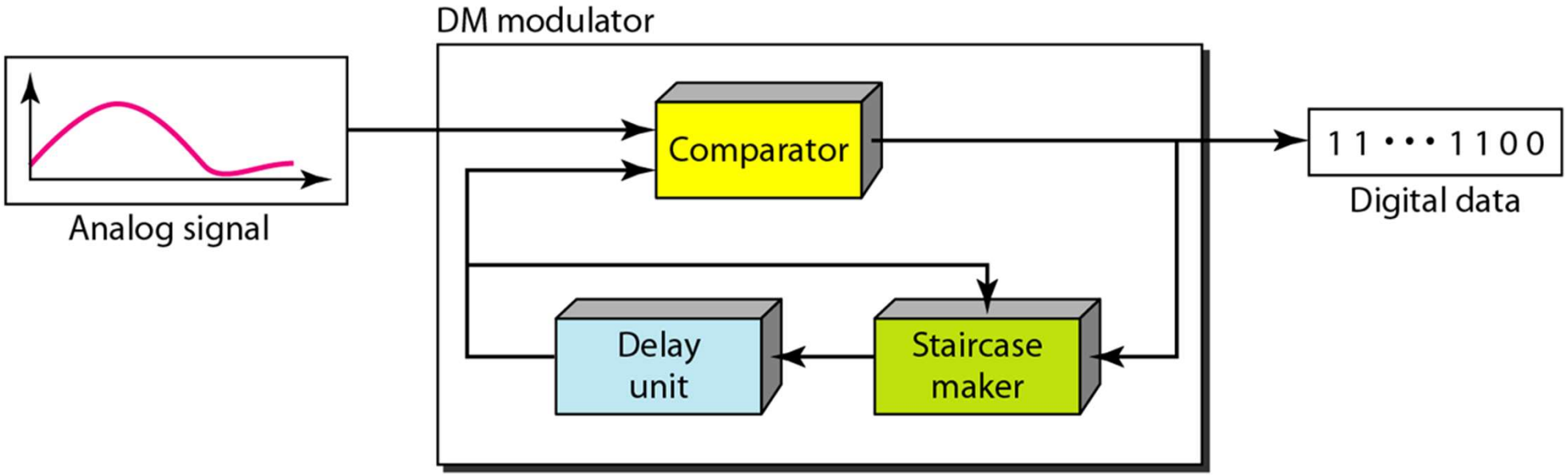
- PCM finds the value of the signal amplitude for each sample
- Delta Modulation finds the change from the previous sample
- Delta Modulation is simpler than PCM

Delta Modulation

- 1: signal amplitude increased from last sample
- 0: signal amplitude decreased from last sample



Delta Modulation



End of Chapter