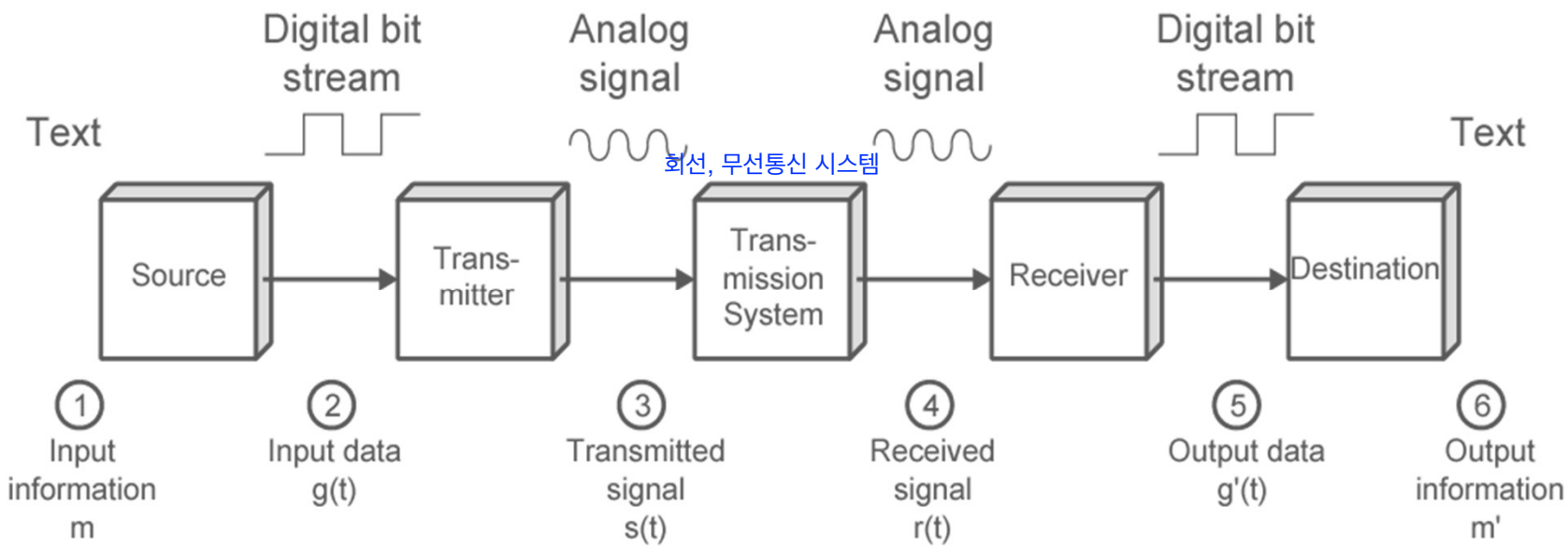
Data and Signals

Physical

Data Communication Model

- Data must be transformed into electromagnetic signals in order to be transmitted.

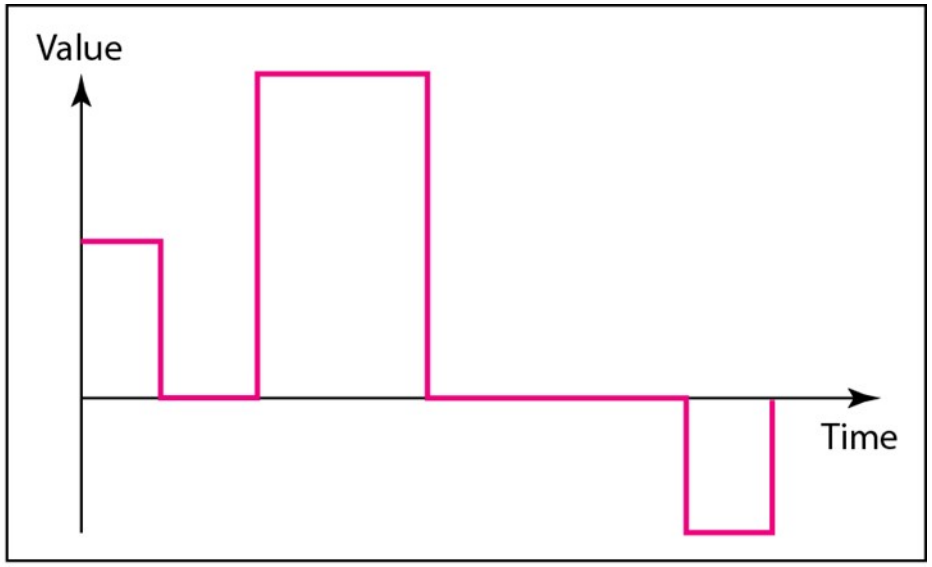


디지털 -> 아날로그
아날로그 -> 디지털로 바뀌면서 통신이 된다

Analog vs. Digital signals

- Analog signals: continuous
- Digital signals: discrete

a. Analog signal

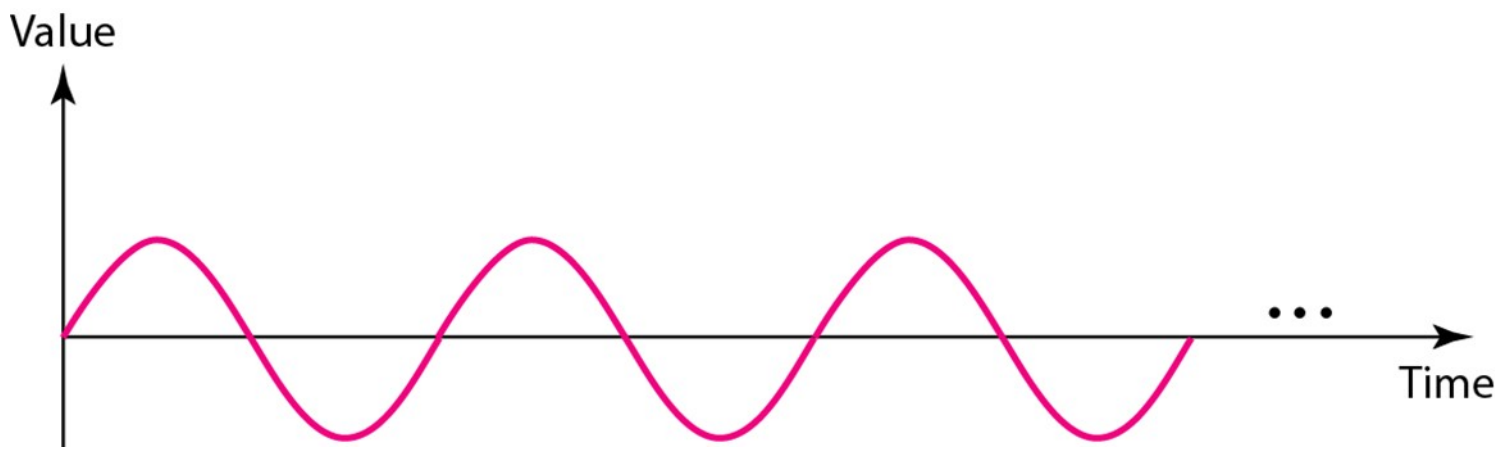


b. Digital signal

Analog Signals

Periodic Signals

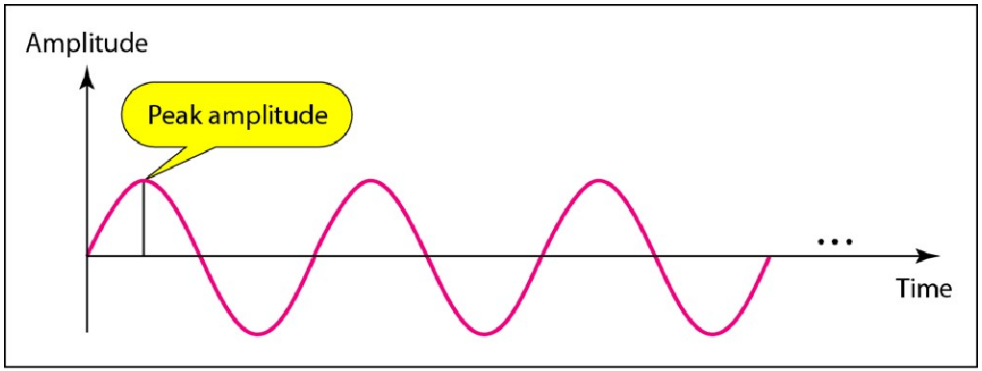
- The same pattern is repeated over time
- Sine wave



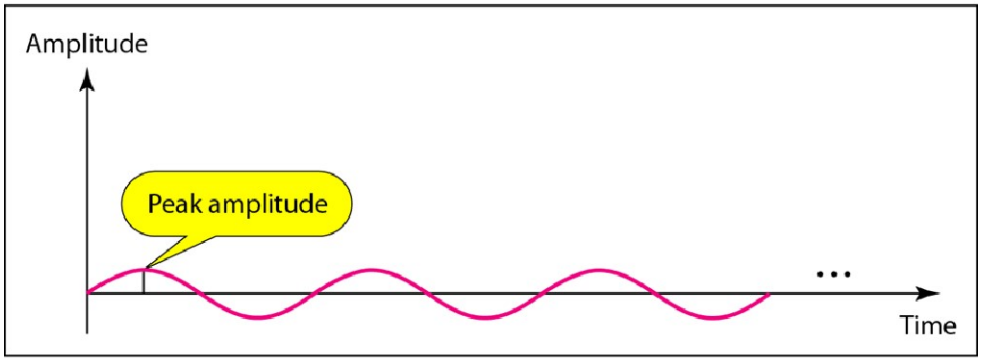
A simple sine wave

Characteristics of Periodic Signals

- Maximum amplitude
  - Absolute of the maximum value



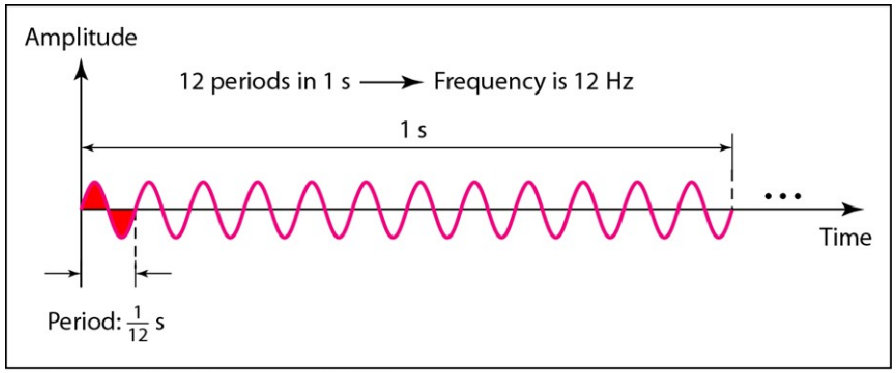
a. A signal with high peak amplitude



b. A signal with low peak amplitude

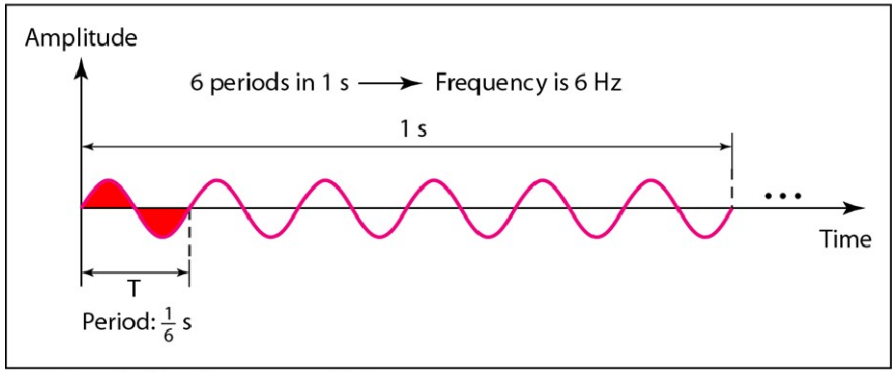
Characteristics of Periodic Signals

- Frequency (*f*) 주파수
  - How many times does the signal oscillate in a second?
  - Unit: Hz



a. A signal with a frequency of 12 Hz

- Period (T) 주기
  - What is the time that the same pattern restarts?
  - Unit: s



b. A signal with a frequency of 6 Hz

Characteristics of Periodic Signals

- Relation between frequency and period
  - frequency is the reciprocal of period

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

Characteristics of Periodic Signals

- Units of period and frequency

Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	10^{-6} s	Megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	Gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	Terahertz (THz)	10^{12} Hz

고주파수 - 파장이 짧아서 직진성이 큼(벽에 튕겨져 나옴)
저주파수 - 파장이 길어서 회절성(퍼지는 거)이 큼

통신에는 저주파수가 유리하지만 이미 주파수가 사용되고 있음. 그래서 새로운 통신 시스템이 나올 때마다 주파수를 올려서 확장함
점차 확장할 수록 가시광선 영역으로 진입

Exercise

- The power we use at home has a frequency of 60Hz. What is the period of this sine wave? 1/60 s

Exercise

- The period of a signal is 100ms. What is its frequency in kilohertz?

0.01khz

10 * 10^-3 s == 1/10s
1/10s의 주파수는 10hz = 0.01khz

Characteristics of Periodic Signals

- Frequency indicates how fast a sine wave oscillates 진동
  - Fast means high frequency
  - Slow means low frequency

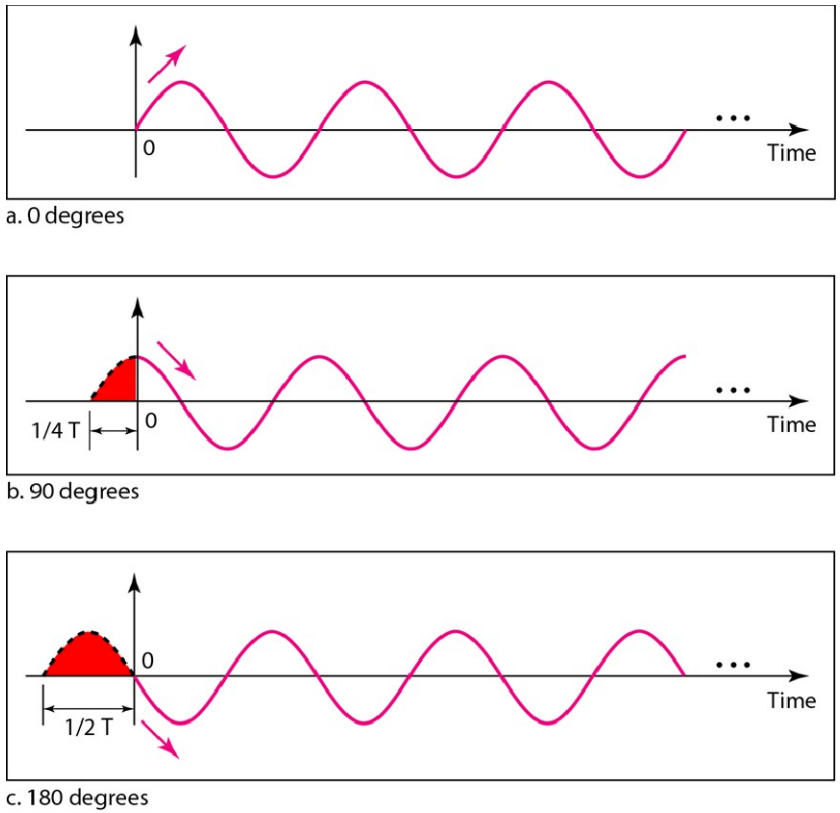
Characteristics of Periodic Signals

- A signal that does not change over time
  - zero frequency
  - period is infinite

- A signal that changes instantaneously
  - infinite frequency

Characteristics of Periodic Signals

- Phase 위상
  - The position of the waveform relative to time 0



위상이 같은 신호가 오면 수신이 강화되고
위상이 반대인 신호가 오면 수신이 약화

Characteristics of Periodic Signals

- Units of Phase: Degree vs. Radian

- Degree: 0 – 360°
- Radian: 0 – 2π

- Example
  - 90° = 1/2 π
  - 180° = π
  - 270° = 3/2 π

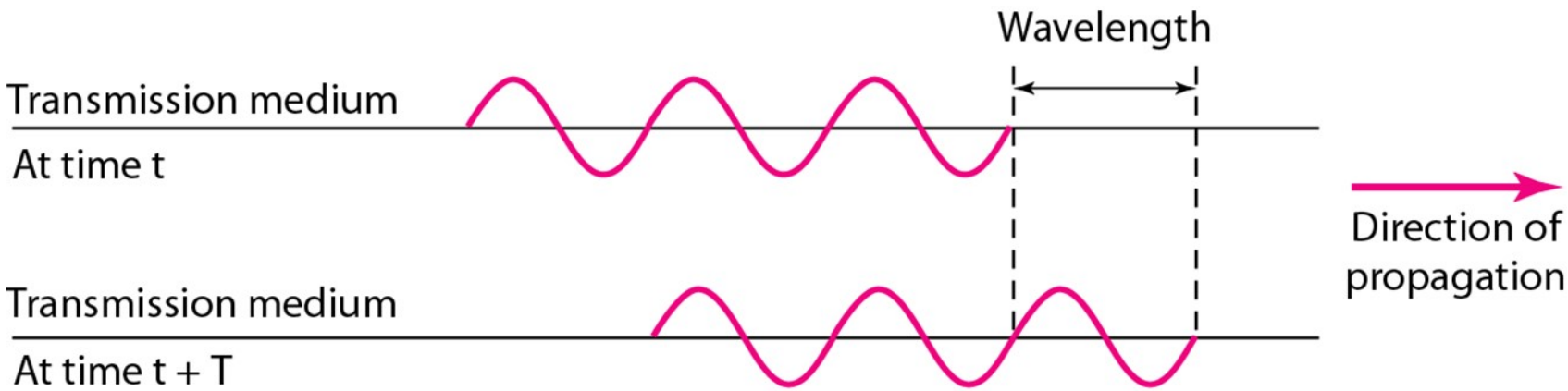
Exercise

- A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

$\pi/3$

Characteristics of Periodic Signals

- wavelength (λ)
  - length of a period (in time)

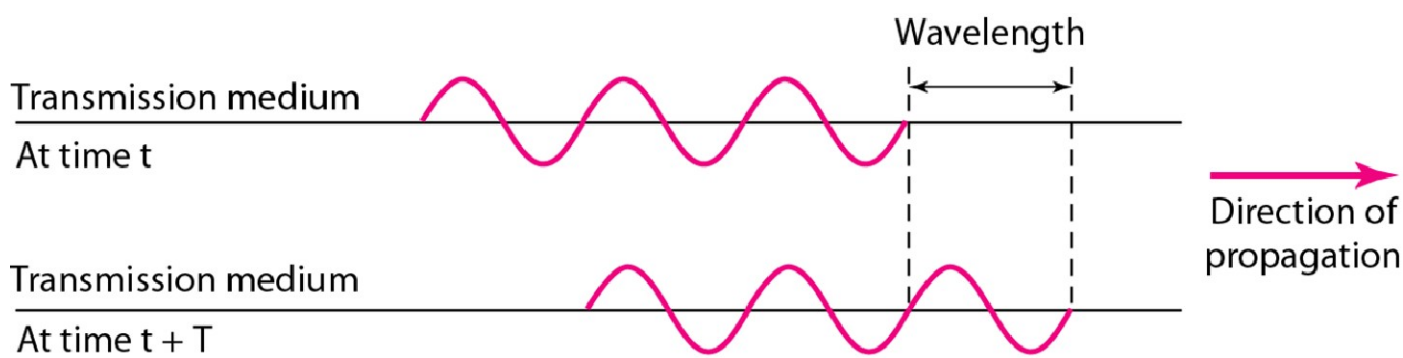


Characteristics of Periodic Signals

- wavelength (λ)
  - wavelength = propagation speed x period
    = propagation speed / frequency
  - λ = c / f
    - c: propagation speed 전파 속도(빛의 속도)

3Ghz의 파장 = 3*10^8 / 3*10^9 = 0.1 m

30Ghz ~ 300Ghz 주파수를 mm파라고 한다. 파장이 mm 단위

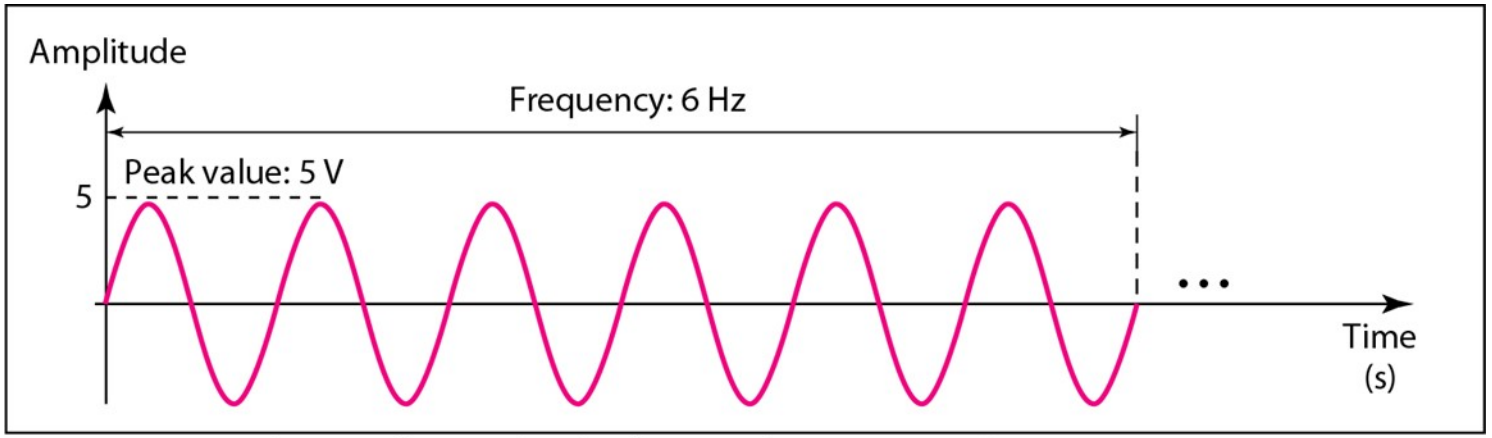


Time domain vs. Frequency domain

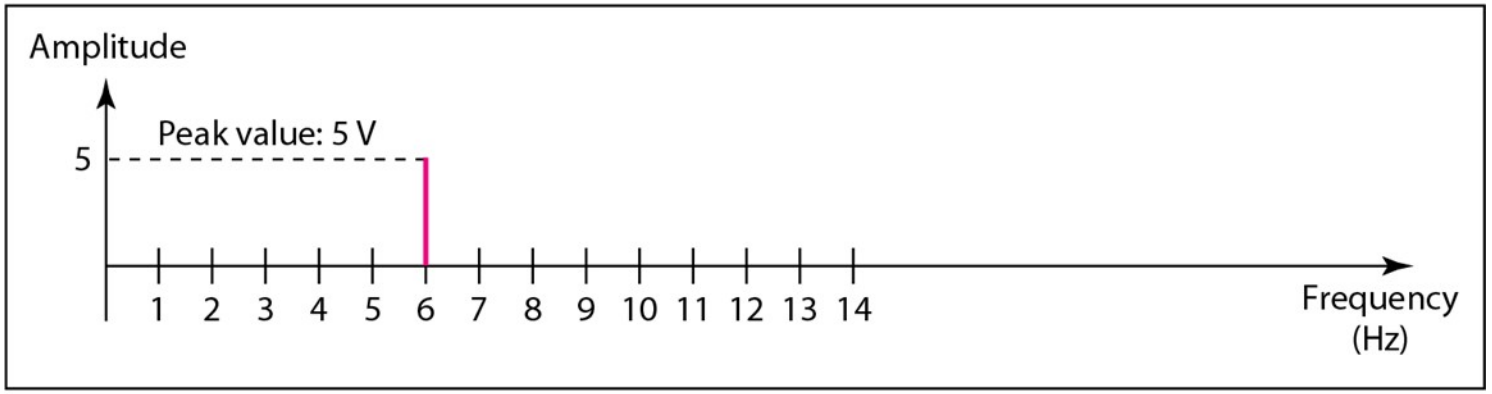
- Time-domain
  - The X-axis of a graph indicates time
- Frequency-domain
  - The X-axis of a graph indicates frequency

Time domain vs. Frequency domain

진폭이 전압



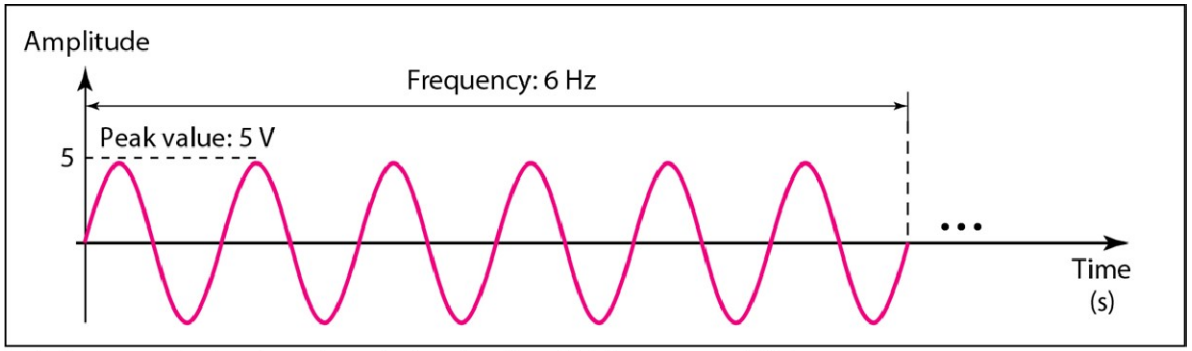
a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)



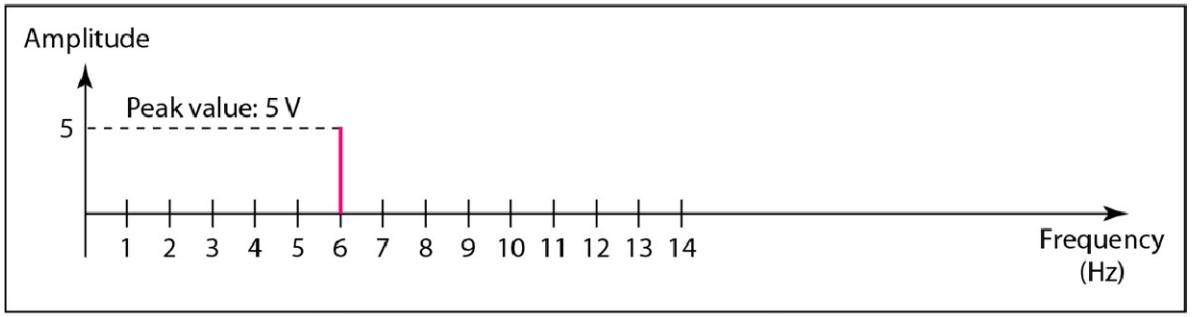
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Time domain vs. Frequency domain

- A simple sine wave becomes a single point in the frequency-domain graph



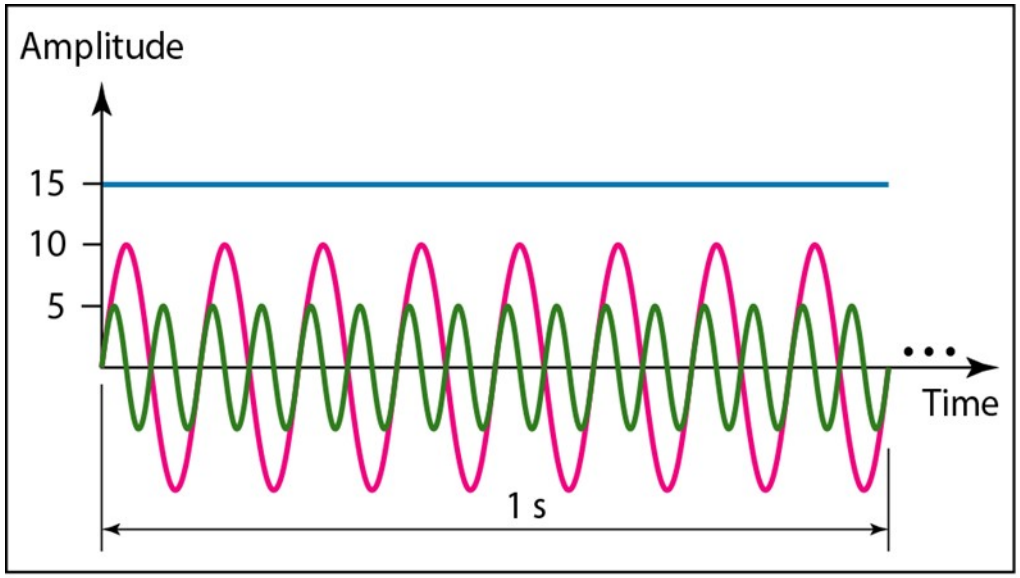
a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)



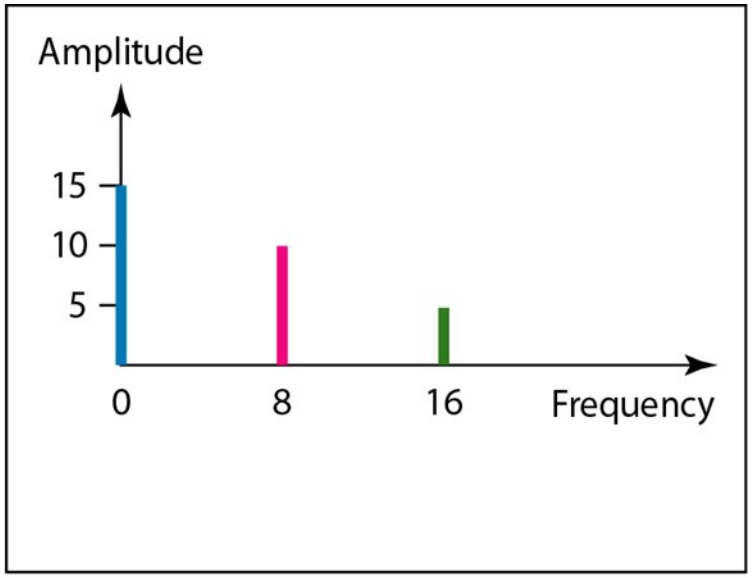
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Frequency domain: merit

- The frequency domain is more compact and useful when dealing with more than one sine wave



a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

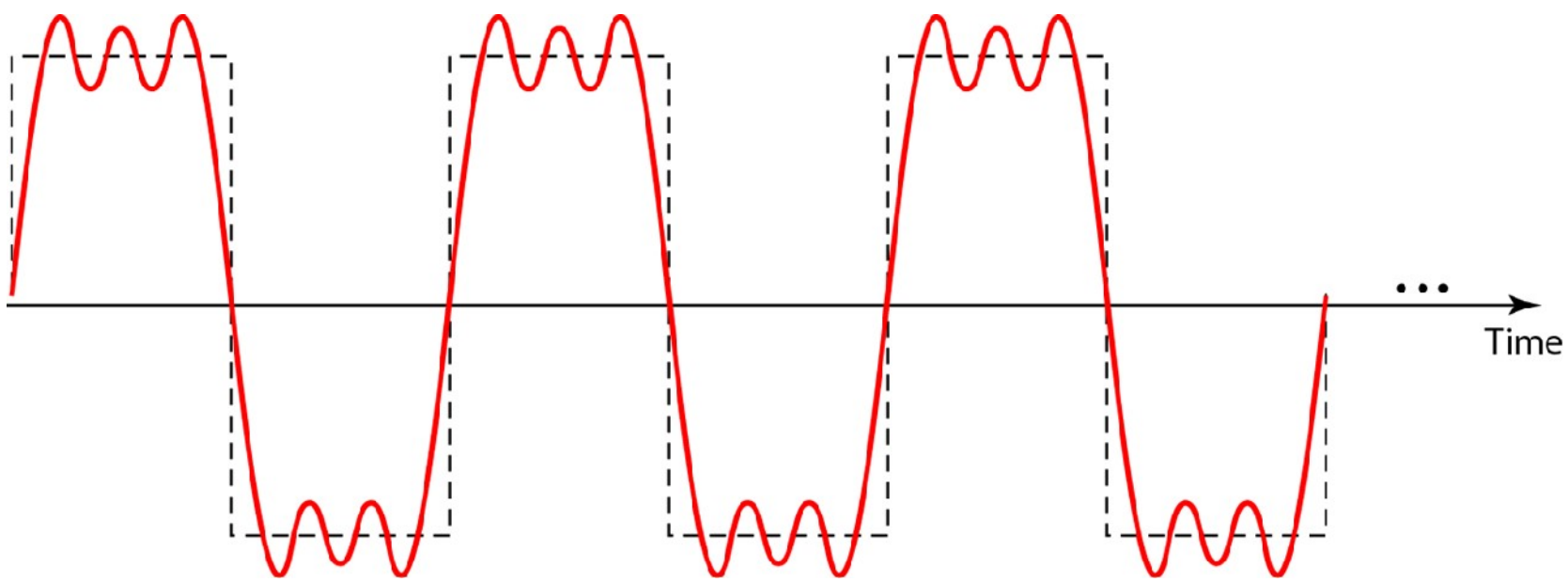


b. Frequency-domain representation of the same three signals

Composite Signals

- Not a simple sine wave

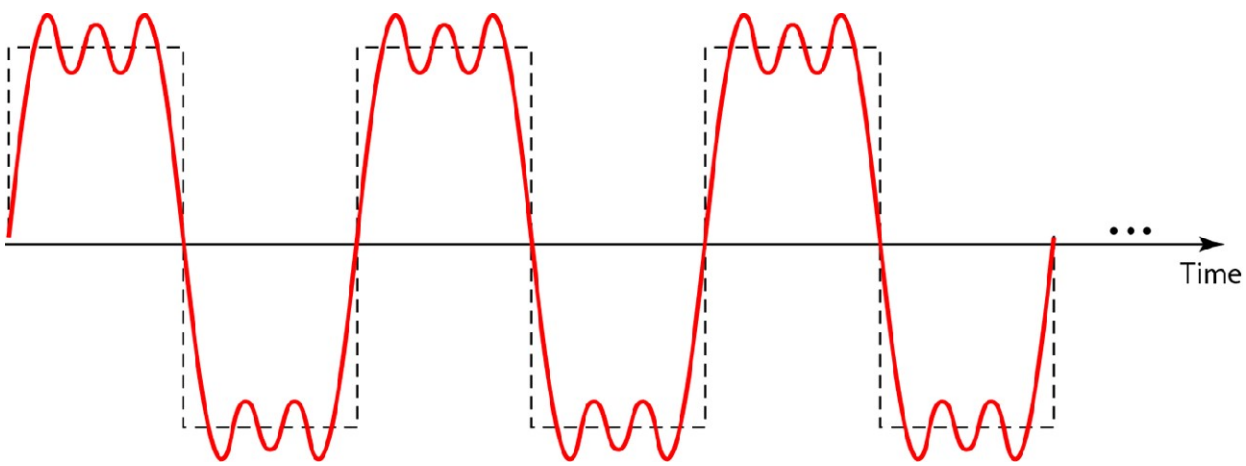
사인 주파수들의 합



Composite Signals

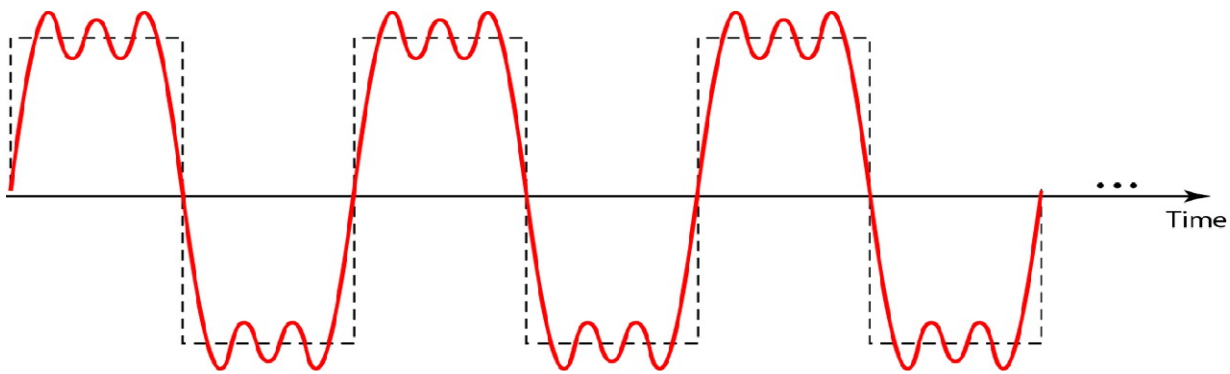
- A composite periodic signal is a composition of multiple simple sine waves with different frequency, amplitude and phase

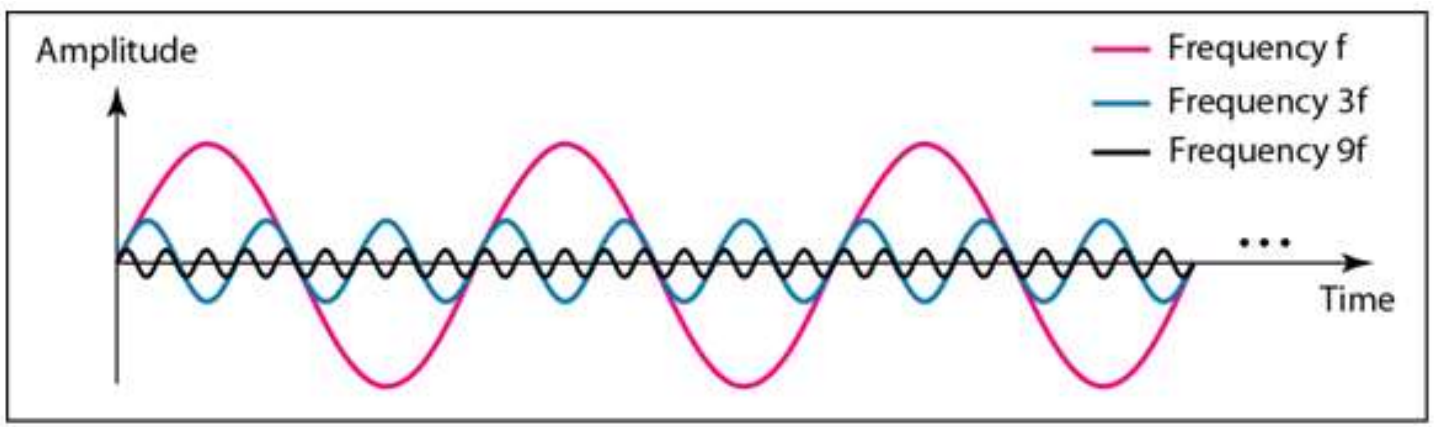
- Can be decomposed into simple sine waves



Composite Signals

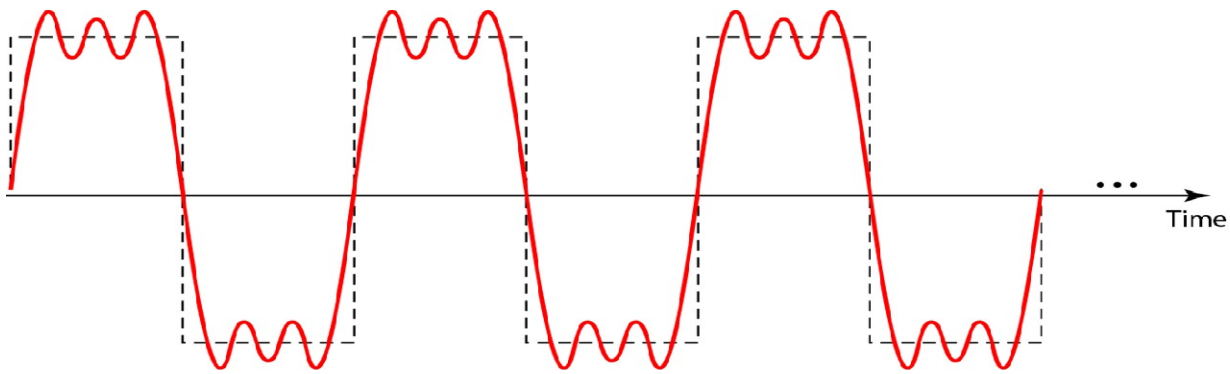
- Time-domain decomposition

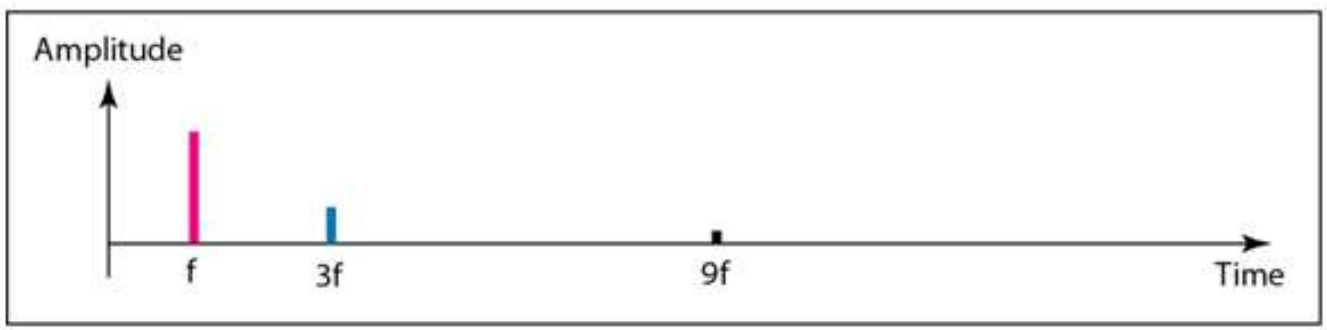




Composite Signals

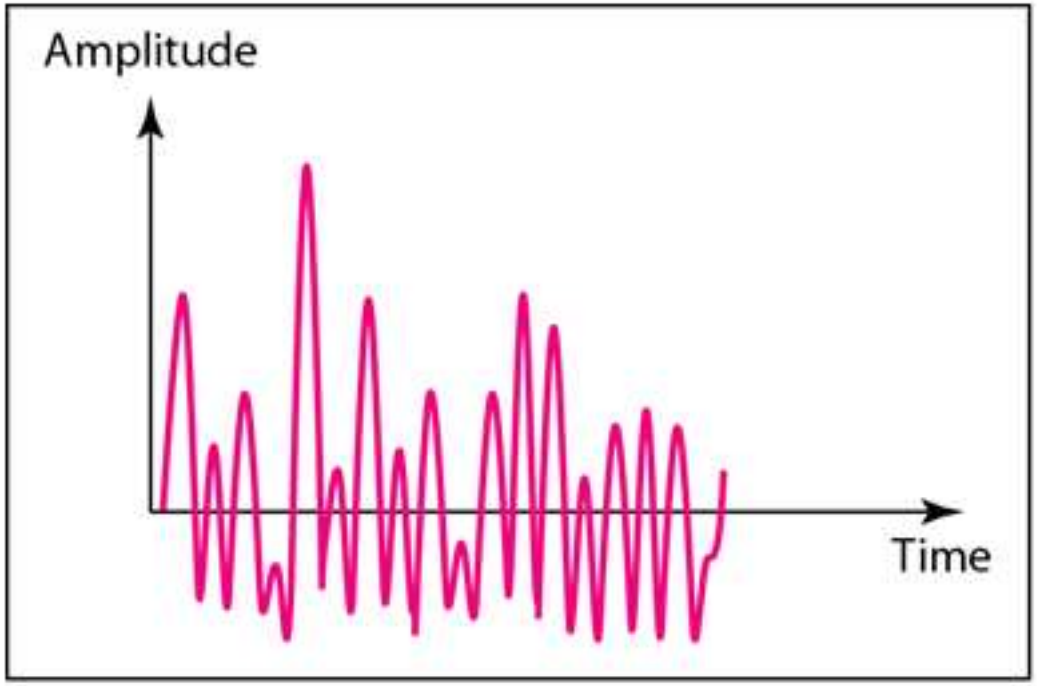
- Frequency-domain decomposition





Composite Signals

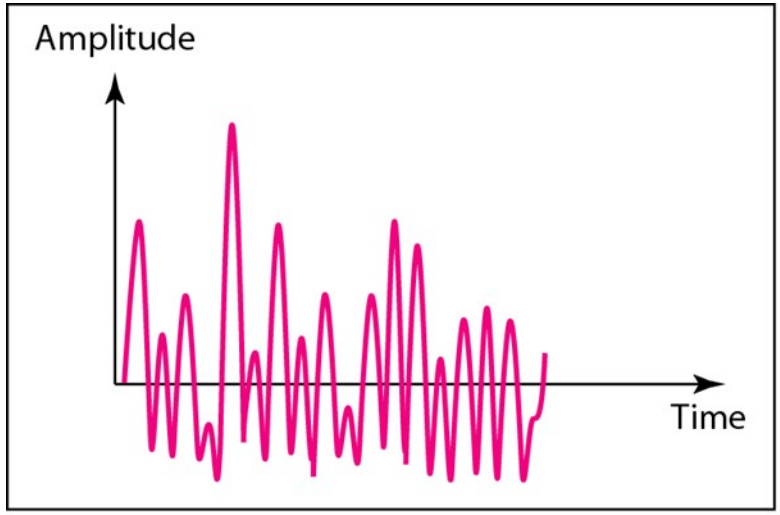
- aperiodic composite signal



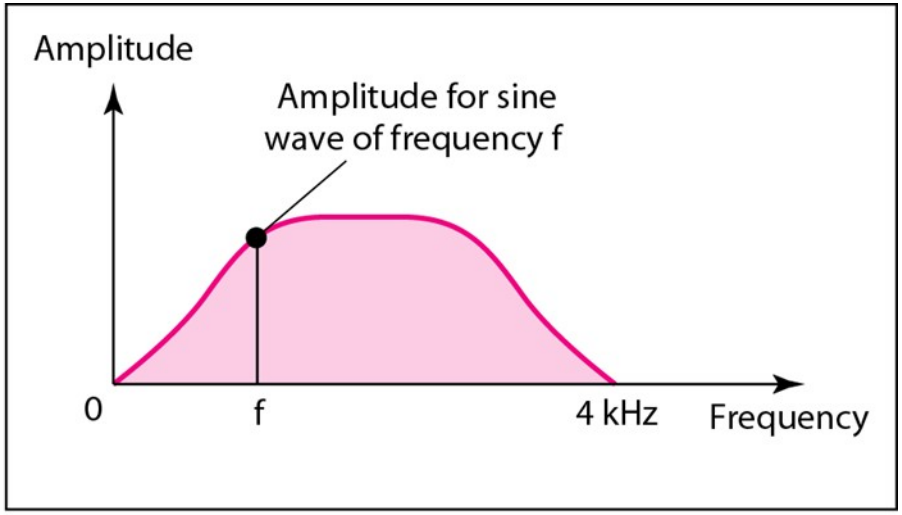
a. Time domain

Composite Signals

- frequency domain of aperiodic composite signal



a. Time domain



b. Frequency domain

사람 목소리는 0 - 4khz 범위라서 음성 정보를 디지털화 할 때 4khz 이상은 삭제한다

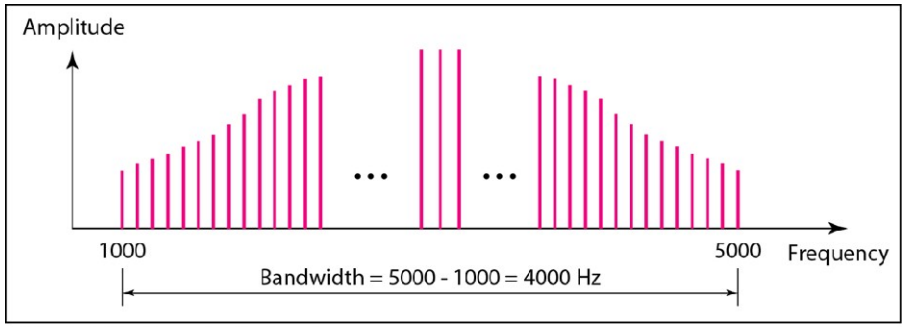
Composite Signals

- If the composite signal is periodic, it will appear in frequency domain as composition of signals with discrete frequencies

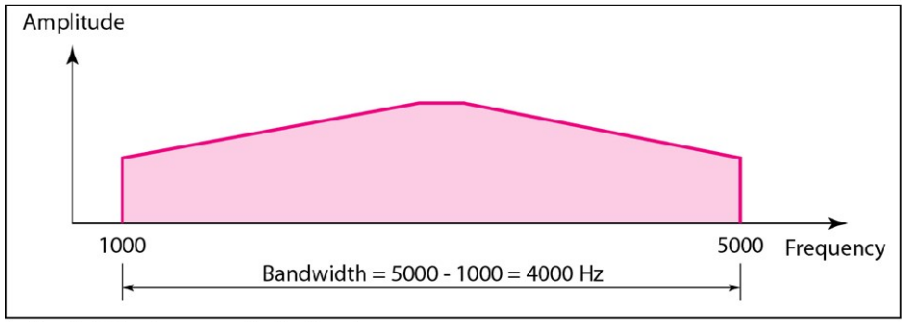
- If the composite signal is aperiodic, it will appear in frequency domain as composition of signals with continuous frequencies

Bandwidth

- Bandwidth is the range of frequencies contained in a composite signal
  - difference between the highest frequency and the lowest frequency



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

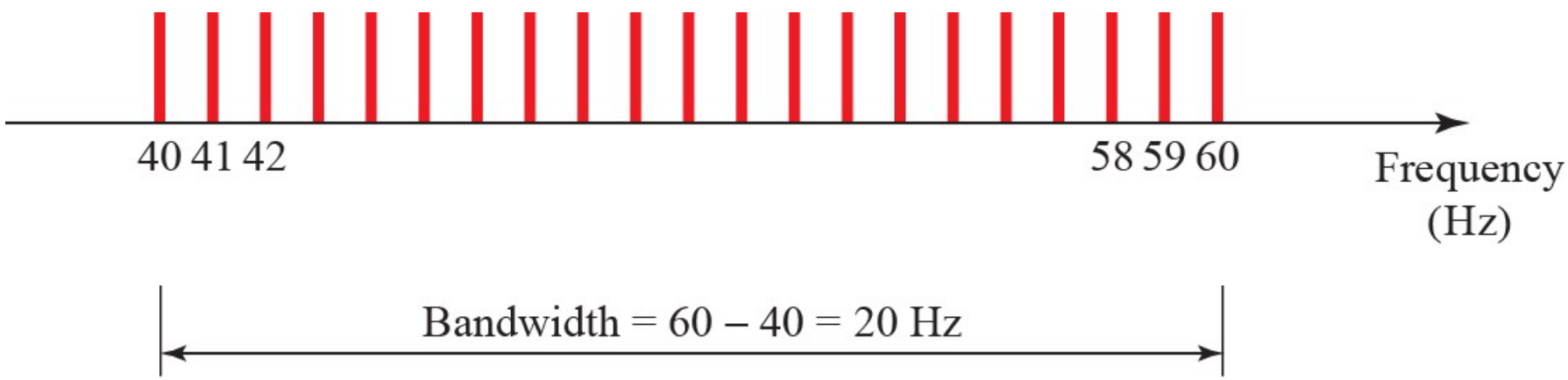
Exercise

- If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900Hz, what is its bandwidth? 900 - 100 = 800hz

- Draw the spectrum, assuming all components have a maximum amplitude of 10V.

Exercise

- A periodic signal has a bandwidth of 20Hz. The highest frequency is 60Hz. What is the lowest frequency? Draw the spectrum if the signal contains all frequencies of the same amplitude.



Aperiodic composite signals

- AM radio
  - Each channel has 10kHz bandwidth
  - 530 – 1700kHz band

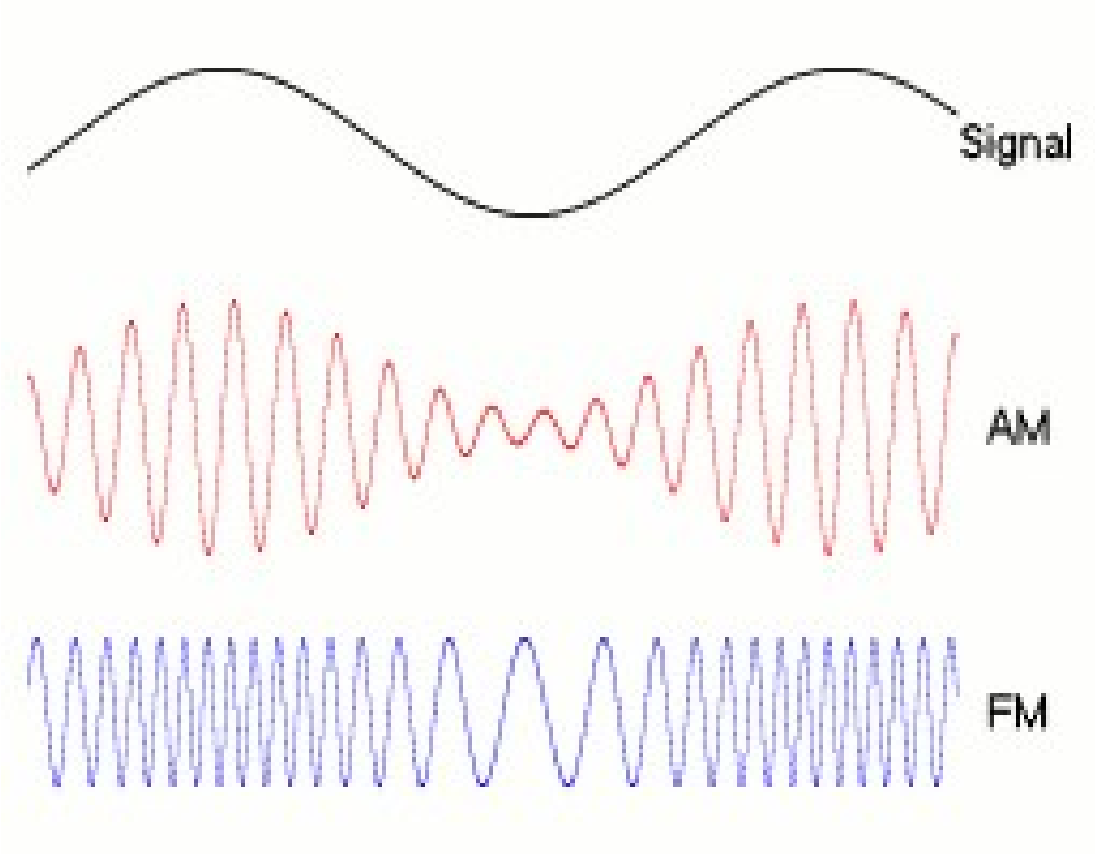
- FM radio
  - Each channel has 200kHz bandwidth
  - 88 – 108MHz band

95.9Mhz 라디오가 있으면
95.9Mhz를 중심으로 양옆 100khz의 범위에서 송출을 함
이 bandwidth가 다른 라디오 채널이랑 겹치지 않아야 함
그래서 항상 .9 처럼 짝수로 라디오 채널이 끝남

AM vs. FM

- AM: Amplitude Modulation
- FM: Frequency Modulation

신호를 am, fm으로 바꿔서 보내는 이유
방송국이 사용할 수 있는 주파수가 정해져 있기 때문에 신호를 여기에 맞춰야함



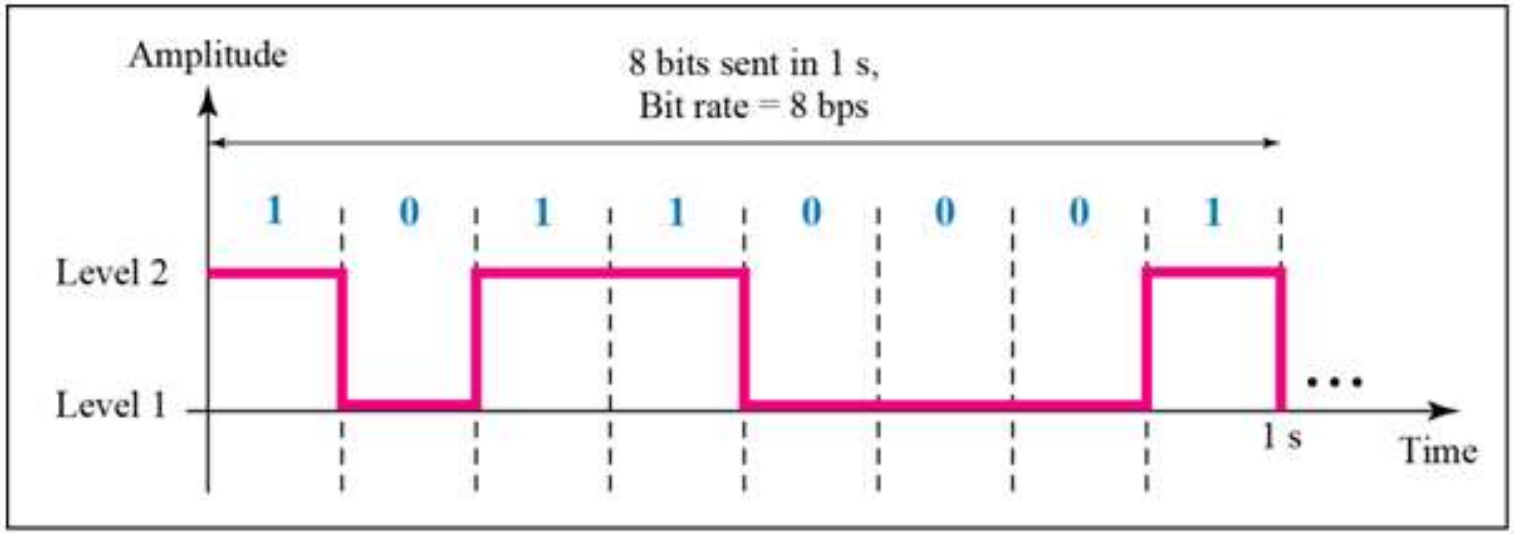
Digital Signals

Digital Signals

- Signals that contain bit information (0, 1) using amplitude, frequency and phase

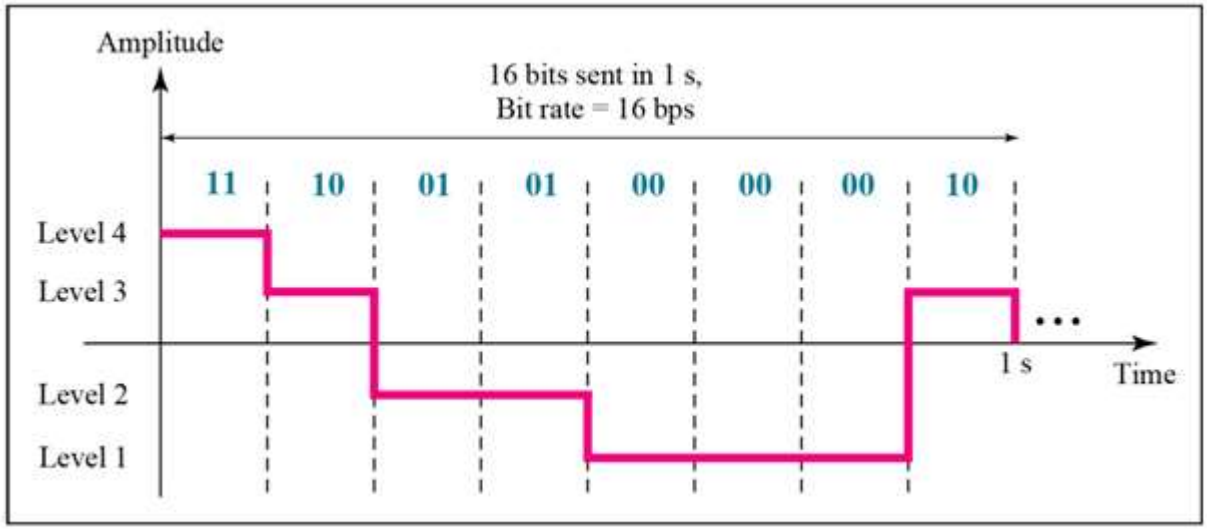
- Example
  - Bit 1 → 5V
  - Bit 0 → 0V

Digital Signals



Digital Signals

- Signal levels can be more than two
  - 4 levels can contain two bits of information
    - Level 1: 00
    - Level 2: 01
    - Level 3: 10
    - Level 4: 11



Exercise

- A digital signal has eight levels. How many bits are needed per level?

2^3

3bits

Transfer rate (bit rate)

- How fast the data is transferred

- Unit: bps (bits per second)

- 1 Kbps = 1000 bps
- 1 Mbps = 1000 Kbps
- 1 Gbps = 1000 Mbps

Exercise

- Assume we need to download text documents at the rate of 100 pages per second. Each page contains 24 lines, and each line contains 80 characters. Each character uses 1 byte. What is the required bit rate of the channel?

100 * 24 * 80 * 8bps

Exercise

- What is the bit rate for high-definition TV (HDTV), which has the following specification?
  - 1920 x 1080 pixels per screen
  - 30 frames per second
  - 1 pixel uses 24 bits (RGB)

1920 * 1080 * 30 * 24 bps 1.492992Gbps

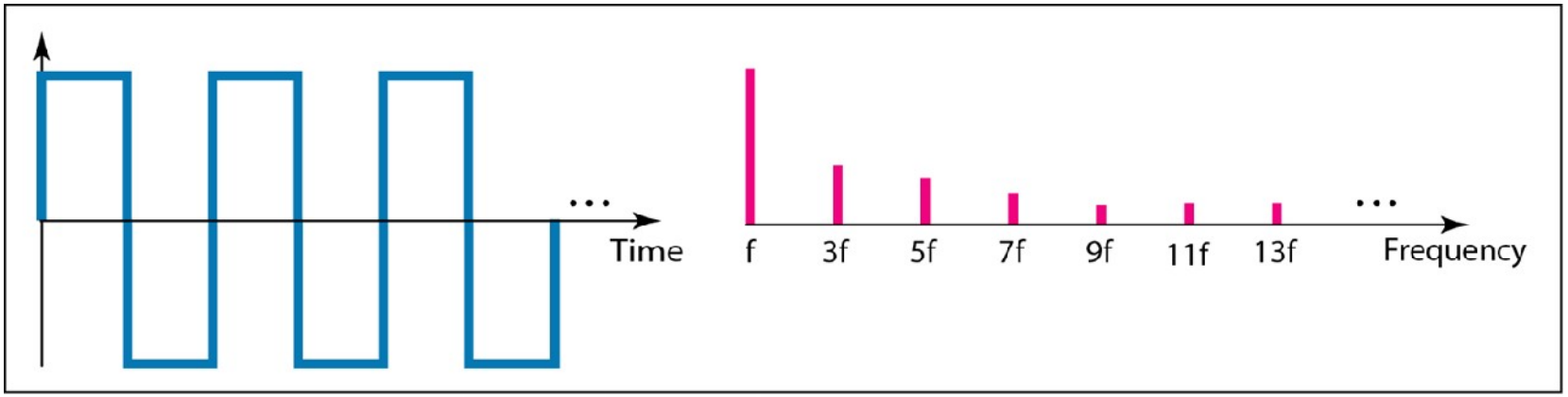
Transmission of Digital Signals

Digital Signals

- How do we transmit digital signals over media?

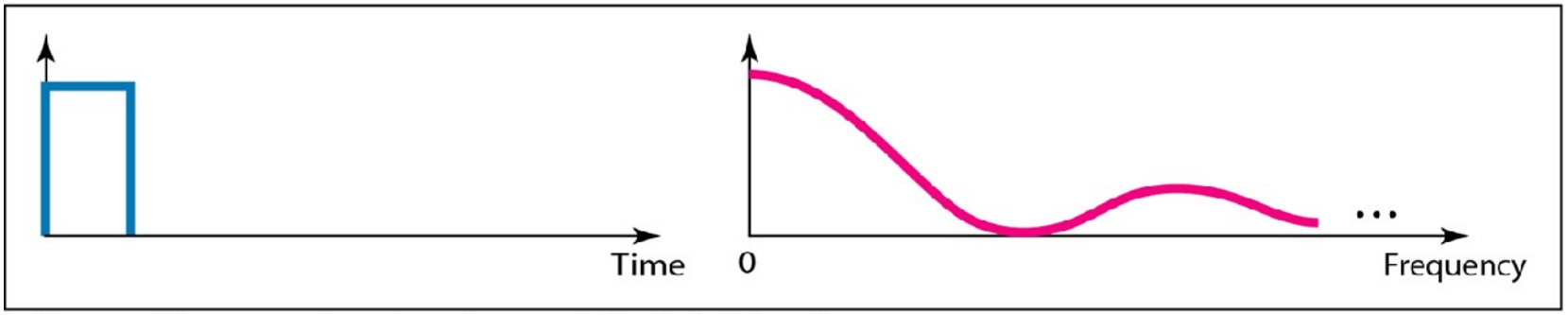
Digital Signals

- Time domain and frequency domain of a digital signal



a. Time and frequency domains of periodic digital signal

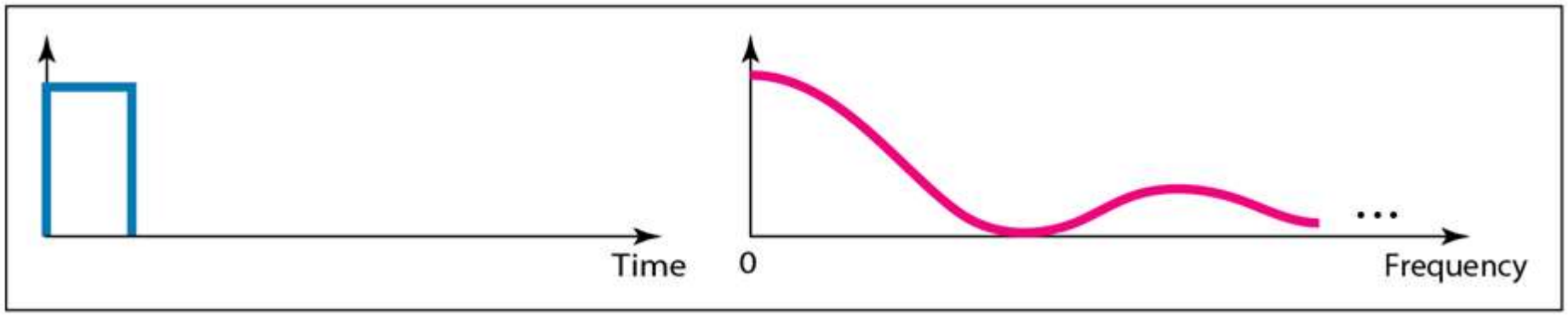
보내고 싶은 모양을 사인 그래프의 합으로 나타낸다



b. Time and frequency domains of nonperiodic digital signal

Digital Signals

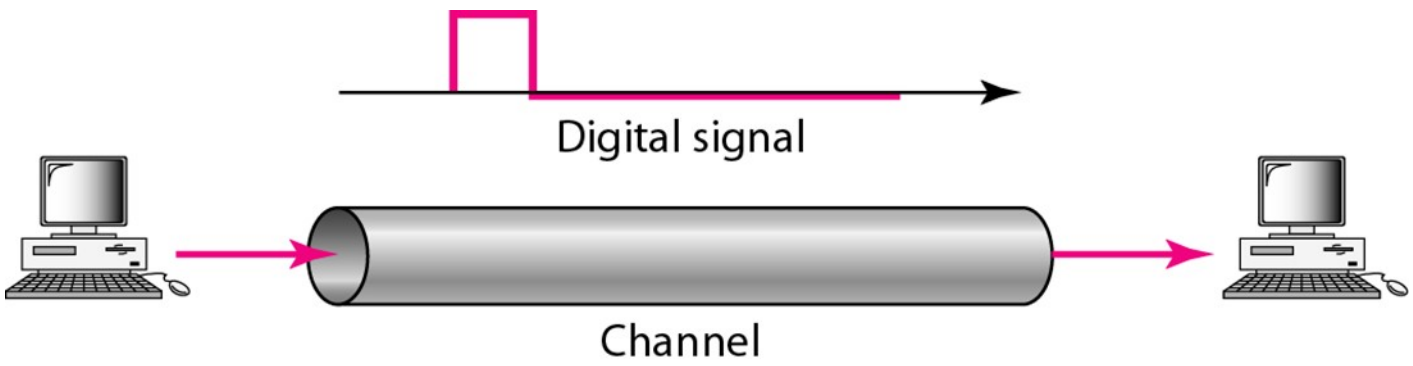
- A digital signal is a composite analog signal with infinite bandwidth



Baseband Transmission

- The simplest way to transmit a digital signal is to transmit "as it is".
- This is known as baseband transmission

기저대역 전송
신호를 있는 모양 그대로 만들어서 전송

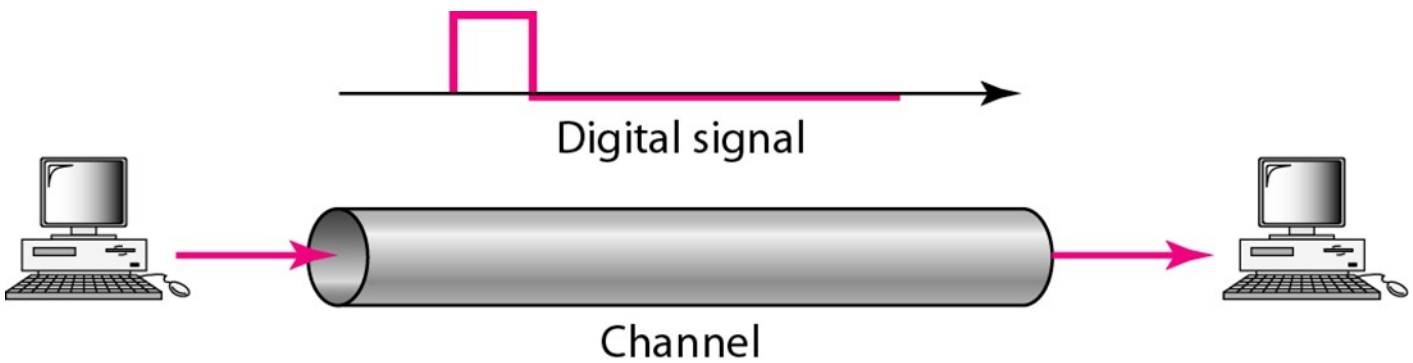


Baseband Transmission

완전한 네모 모양을 만들려면 고주파까지 무한대로 더해야 하는데 현실적이지 않음

- To transmit digital signal "as it is", we need a channel with infinite bandwidth

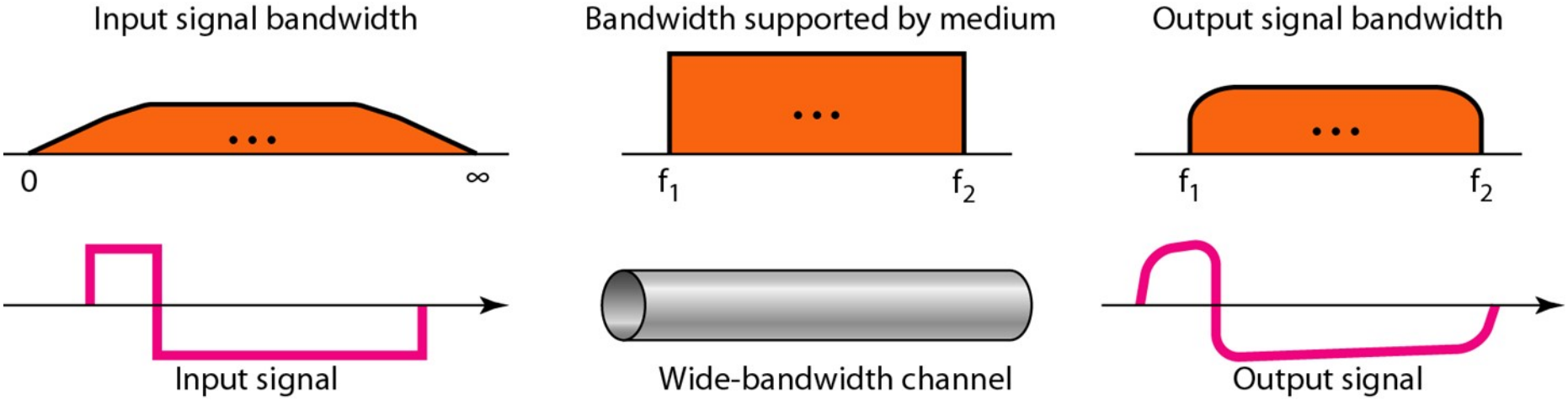
- Low-pass channel: channel that can pass signals from zero frequency



Baseband Transmission

- Real-life media cannot have infinite bandwidth
- Some frequency components are cut from the original signal, leaving an approximate signal

회선이 전달할 수 있는 주파수 영역이 있기 때문에 무한히 주파수를 더해서 네모 모양을 만들었어도 전달되지 않는 주파수 영역이 빠지면서 수신하면 모양이 바뀐다



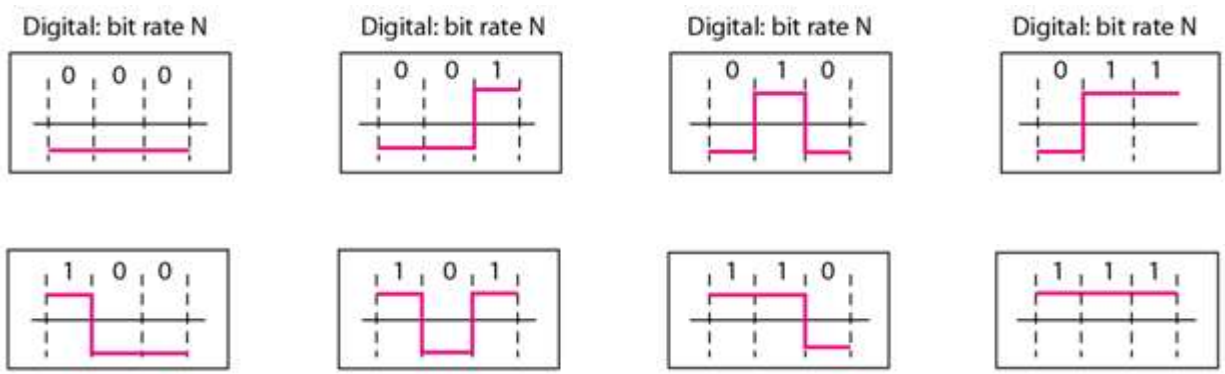
Baseband Transmission

- The more bandwidth we use, we get an approximate signal that is closer to the original

Approximation of Digital Signals

- Suppose we encode 3 bits into the following signals

- These signals need infinite bandwidth to be passed as original forms



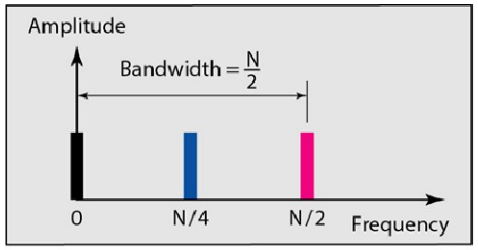
Approximation of Digital Signals

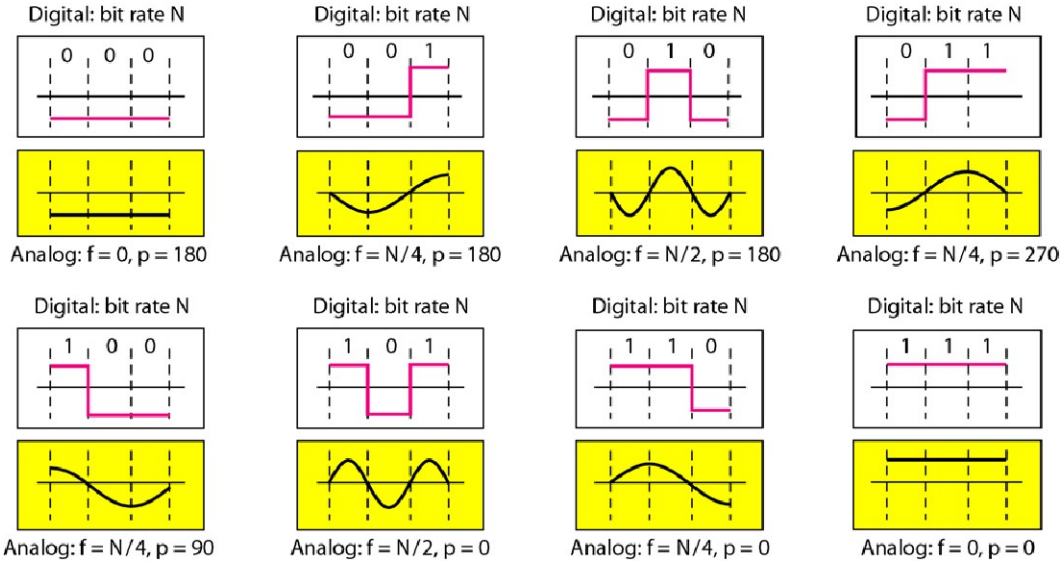
- We approximate signals as follows

N - 1초에 몇 비트를 전송할 수 있는가

  – We need a bandwidth of N/2 Hz, where N is the transfer rate

완벽한 네모 디지털 신호를 보낼 수 없으니 최대한 비슷하게 만들어서 보냄
상대적으로 주파수를 덜 사용해서 만들 수 있다

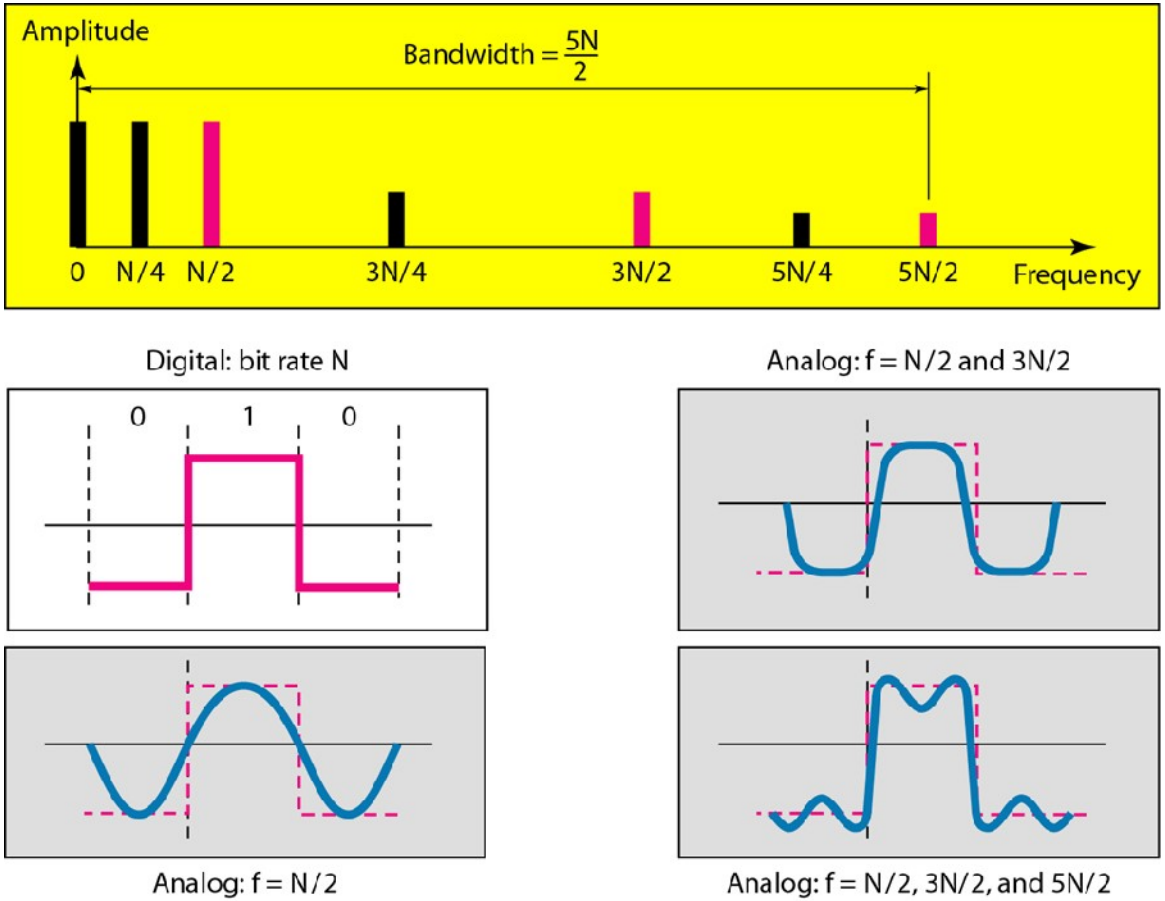




Approximation of Digital Signals

- If we use more bandwidth, we can create better approximates

높은 주파수를 계속 더할 수록 디지털 신호와 비슷해진다
원래 의도한 디지털 신호와 비슷해질 수록 수신이 의도대로 됨



Approximation of Digital Signals

- Basically, bandwidth needed for baseband transmission is proportional to transfer rate
- More bandwidth provides better approximation – increased accuracy

Bit Rate	*Harmonic 1*	*Harmonics 1, 3*	*Harmonics 1, 3, 5*
$n = 1$ kbps	$B = 500$ Hz	$B = 1.5$ kHz	$B = 2.5$ kHz
$n = 10$ kbps	$B = 5$ kHz	$B = 15$ kHz	$B = 25$ kHz
$n = 100$ kbps	$B = 50$ kHz	$B = 150$ kHz	$B = 250$ kHz

baseband인 0hz에다가 주파수들을 더하는 것

Summary: Baseband Transmission

- Baseband transmission is a way to transmit a digital signal in its original form
- To transmit undistorted digital signal, we need infinite bandwidth (which is impossible)
- Transfer rate is proportional to bandwidth
- To send data at N bps, we need at least N/2 bandwidth
  - If we have a bandwidth f, maximum transfer rate is 2f

Exercise

낮은 주파수만 통과시키는 채널

- What is the required bandwidth of a low-pass channel if we need to send 1Mbps by using baseband transmission?

0 - 500khz

- We have a low-pass channel with bandwidth 100kHz. What is the maximum bit rate of this channel?

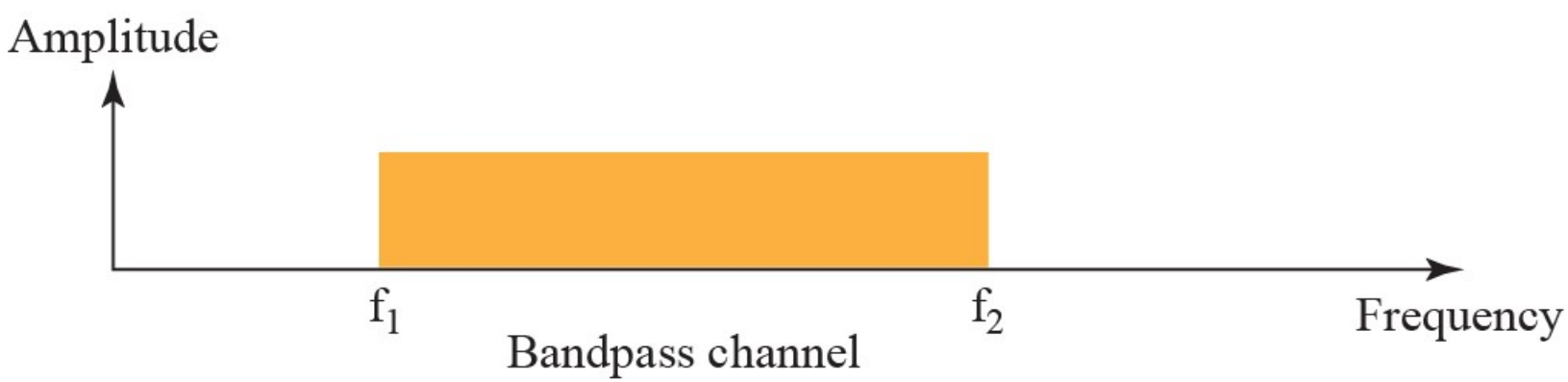
200kbps

특정 대역폭의 주파수들을 사용해서 신호를 만들기

Band-pass channel

- Passes frequencies from f_1 to f_2 (f1 > 0)

- A realistic channel

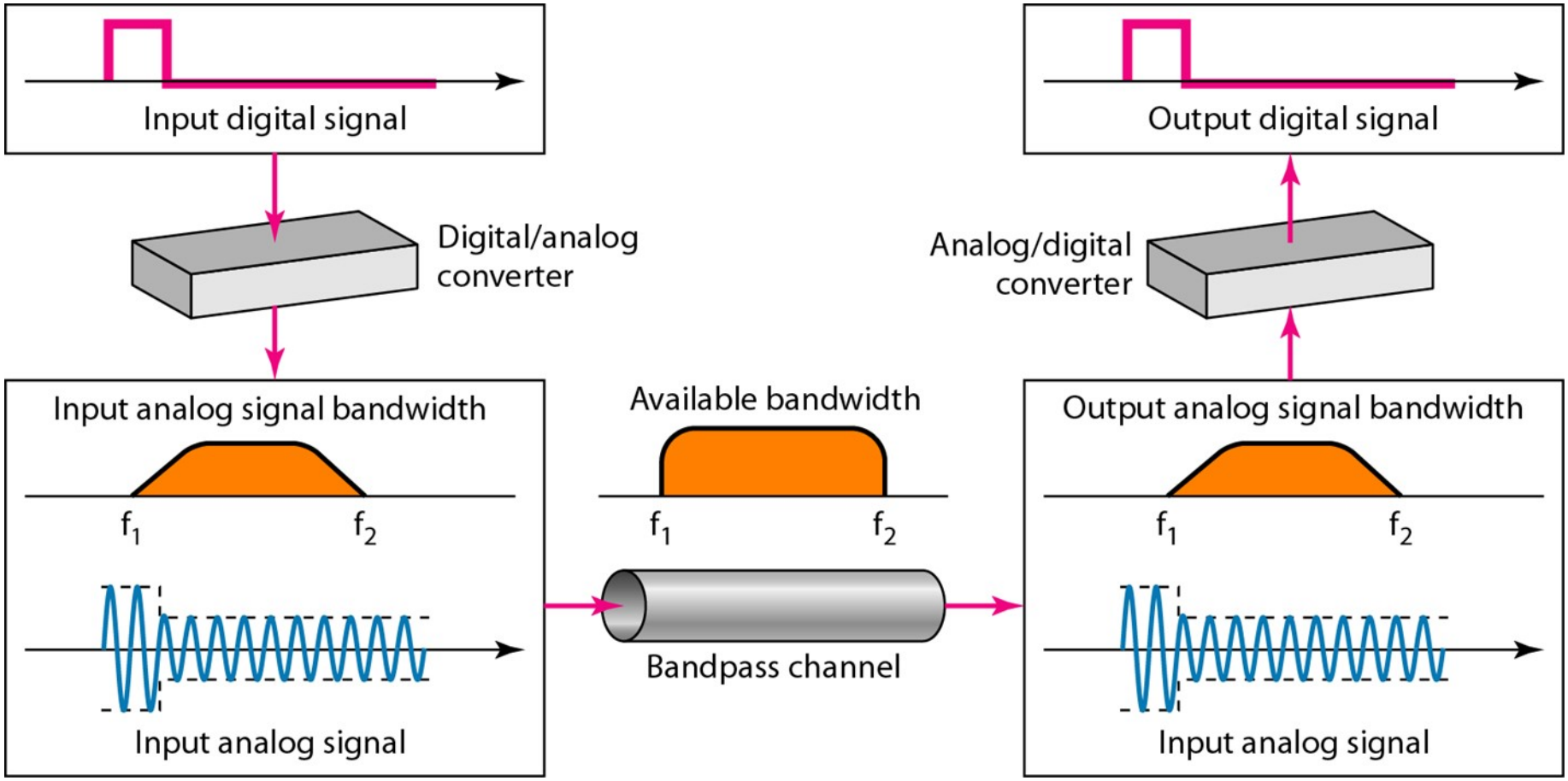


Modulation

- In order to transmit signals through band-pass channel, we need to modulate signals

- Modulate digital signals into analog signals

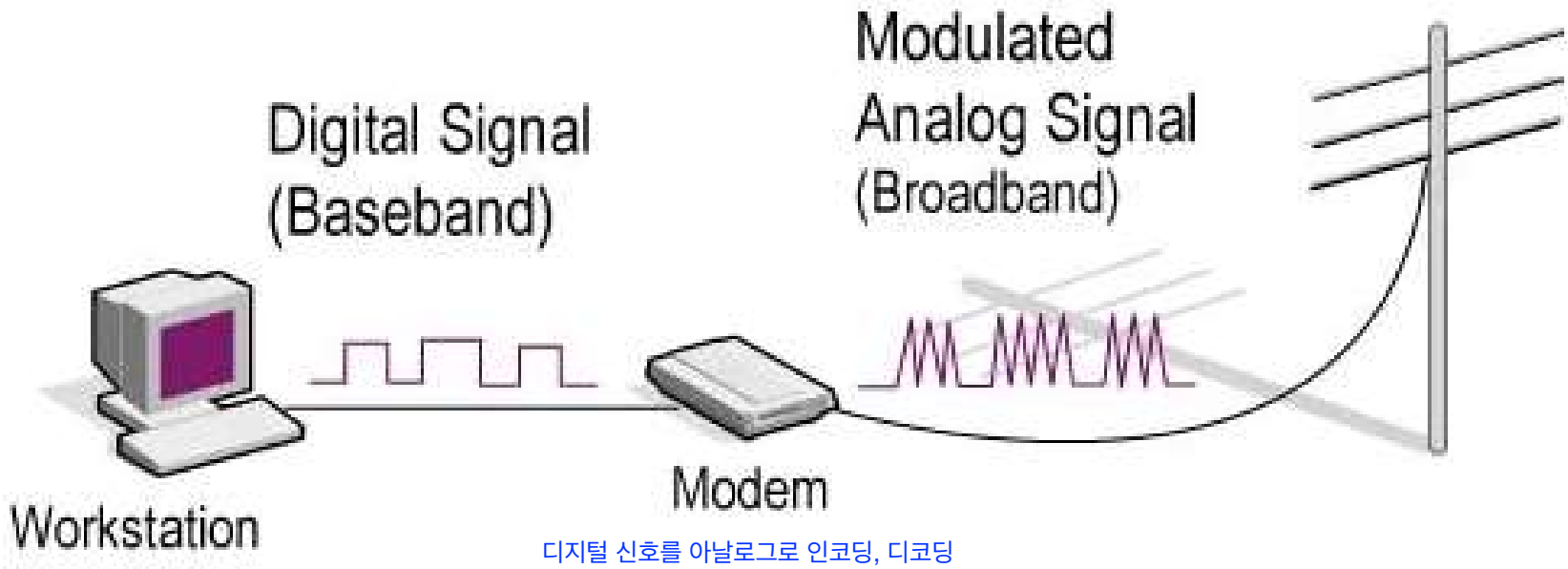
Band-pass Transmission using Modulation



출렁이는 진폭을 조절해서 디지털 신호처럼 보이게 설정
baseband를 사용하지 않기 때문에 진폭 자체를 디지털 신호처럼 만들 수는 없고
대신 출렁이는 부분을 조절해서 0,1을 표현

Example: Baseband vs. Broadband

- Broadband uses bandpass transmission
- Ethernet uses baseband transmission



디지털 신호를 아날로그로 인코딩, 디코딩

bandpass 로 통신하는 걸 브로드밴드라함

Example: mobile communication in Korea

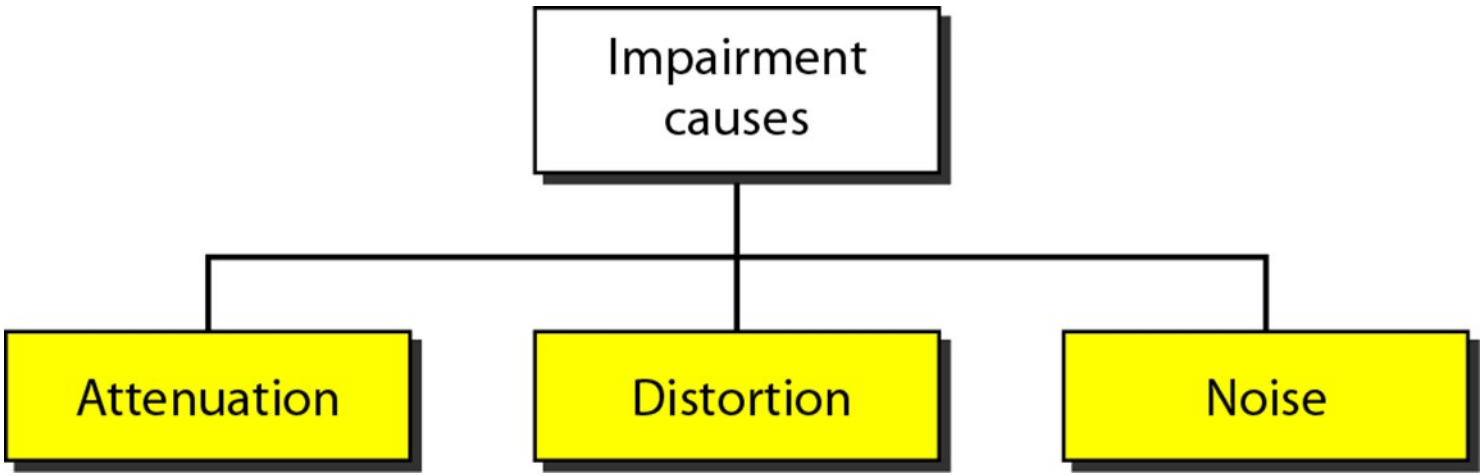
- SKT
  - 20MHz in 800MHz band: 2G
  - 10MHz in 800MHz band: LTE
  - 20MHz in 1.8GHz band: LTE
  - 60MHz in 2.1GHz band: 3G
  - 30MHz in 2.3GHz band: Wibro
- KT
  - 10MHz in 800MHz: LTE
  - 20MHz in 900MHz: LTE
  - 20MHz in 1.8GHz: LTE (previously 2G)
  - 40MHz in 2.1GHz: 3G
  - 30MHz in 2.3GHz: Wibro
- LG
  - 20MHz in 800MHz: LTE
  - 20MHz in 1.8GHz: 2G
  - 20MHz in 2.1GHz: LTE

Transmission Impairment

Transmission Impairment

- Imperfect media causes signal impairment
- The signal at the beginning of the medium is not the same as the signal at the end of the medium

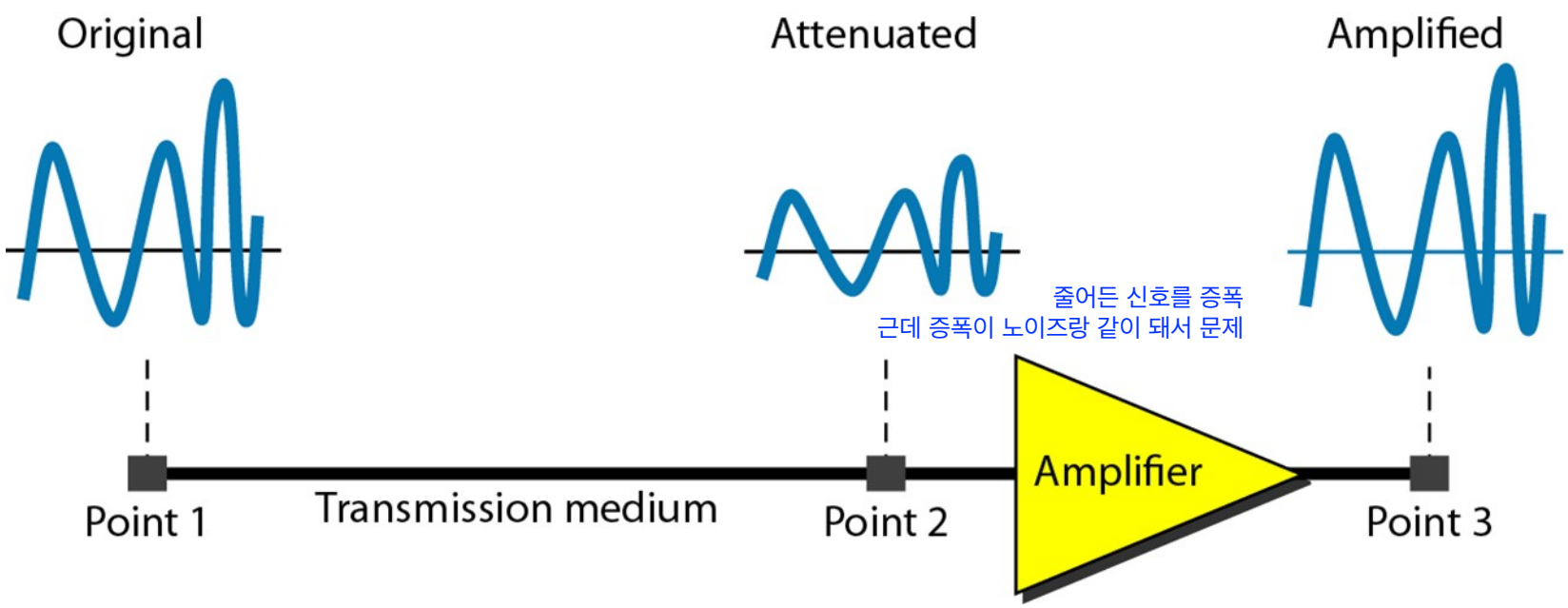
수신을 어렵게하는 요인들



신호 감쇠
신호는 에너지기 때문에 열로 바뀜

Attenuation

- Loss of energy as the signal travels through media
- Signals can be amplified using amplifiers



Units for signal strength: decibel (dB)

- $dB = 10 \log_{10}(P_2/P_1)$ 두 신호 세기의 비율

- indicates <u>ratio</u> of two signal strengths

Example

- Suppose a signal travels through a transmission media and its power is reduced to one half. This means that $P_2 = 0.5P_1$. In this case, the attenuation can be calculated as:

log2 = 0.3010
log1/2 = -0.3010

$$10 \log_{10} P_2/P_1 = 10 \log_{10} (0.5\ P_1)\ /P_1 = 10 \log_{10} 0.5 = 10 \times (-0.3) = -3\ \text{dB}.$$

소리가 10배 -> + 10db
소리가 5배 -> 10db - 3db = 7db

- A loss of 3dB (-3dB) is equivalent to losing one-half the power

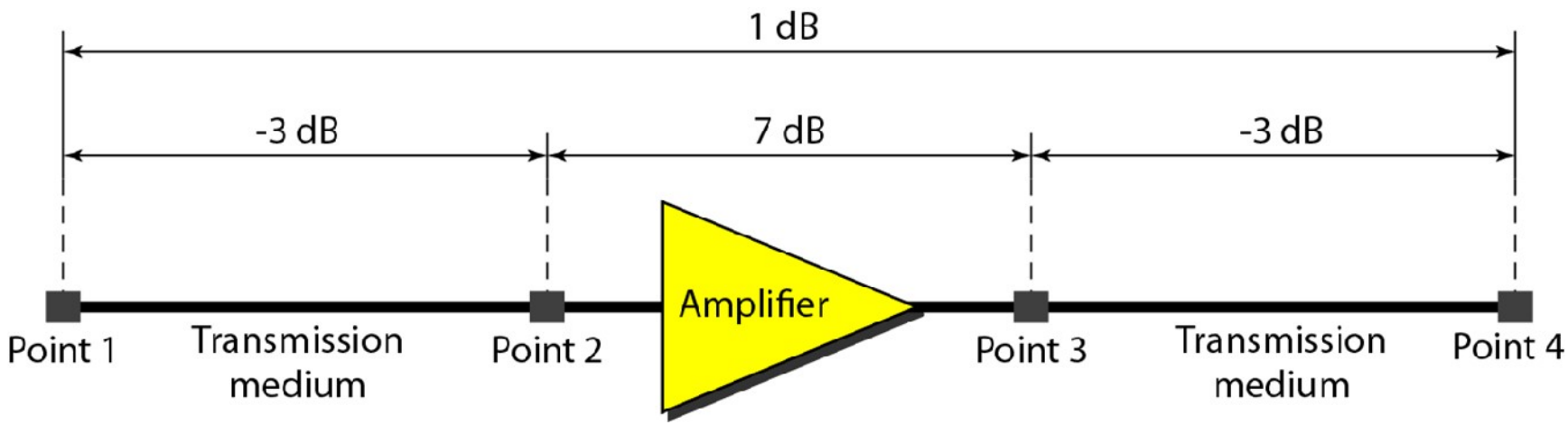
Example

- A signal travels through an amplifier and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification can be calculated as:

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1} = 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

Benefit of using dB

- One reason that engineers use the decibel to measure the changes in signal strength is that decibel numbers can be added (or subtracted) when we are measuring several points instead of just two.



db 뒤에 물 붙이면 절댓값으로 쓰임
dbw - 1watt를 기준으로 하는 비율 통신 세계에서 1watt는 큰값 db로 쓸 때도 있음. 다만 수업에서는 db는 소리의 비율이라는 뜻으로 사용
dbm - 1 milli watt를 기준으로 하는 비율

dBm

- dBm is used to measure signal power in milliwatts
- $dBm = 10 \log_{10} P_m$
- P_m: power in milliwatt unit
- 1mW = 0dBm
- 10mW = 10dBm
- 100mW = 20dBm

200mW - 20 + 3 = 23dbm
보통 핸드폰이 전송하는 신호의 크기

46dbm - 40000mW = 40W

-20dbm ~ -40dbm이 신호가 잘 받는 구간
0.0001mw
-90dbm - 0.00000002mw 약전기도 받음

Example

- The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with -0.3dB/km has a power of 2mW, what is the power of signals at 5km?

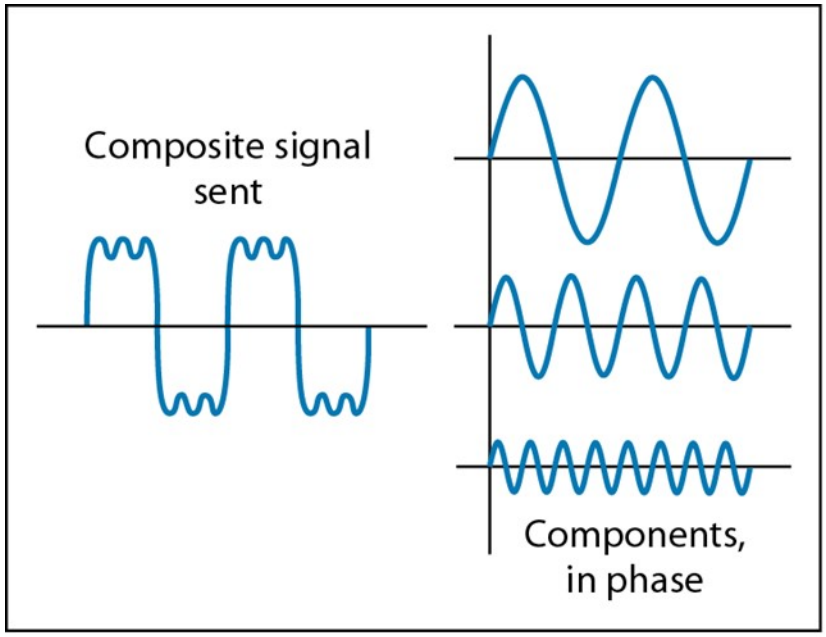
$$\text{dB} = 10 \log_{10} (P_2 / P_1) = -1.5 \quad \longrightarrow \quad (P_2 / P_1) = 10^{-0.15} = 0.71$$

$$P_2 = 0.71 P_1 = 0.7 \times 2 \text{ mW} = 1.4 \text{ mW}$$

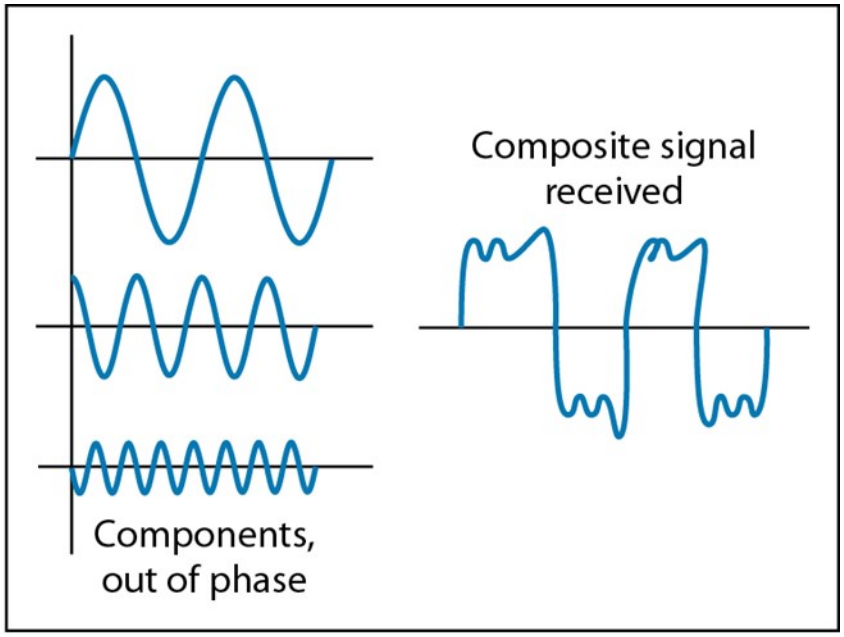
Distortion

도플러 효과처럼 이동하면 신호가 달라질 수 있음

- Signal changes its form or shape



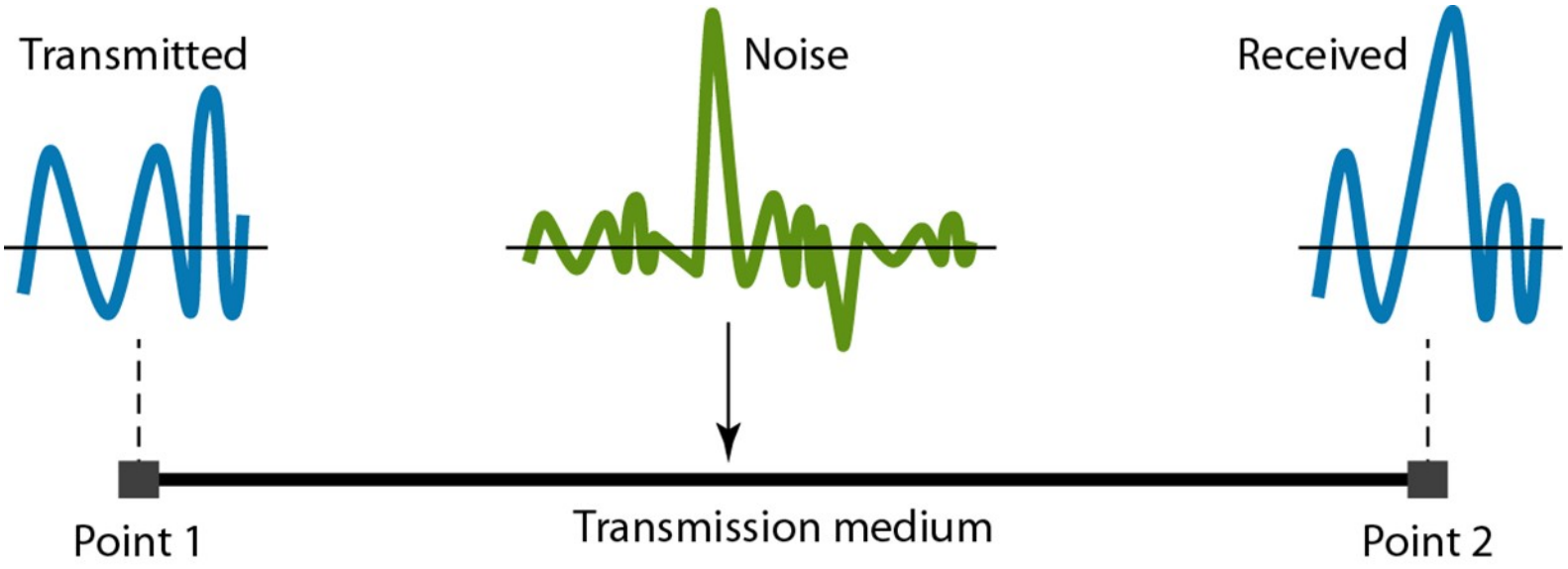
At the sender



At the receiver

Noise

- Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal



신호와 노이즈의 전력비

Signal-to-Noise Ratio (SNR)

- SNR = signal power / noise power
- Units may be in W scale (ratio) or dB scale

Exercise

10000uW

- The power of a signal is 10mW and the power of the noise is 1uW; what are the values of SNR and SNR_{dB}?

10000

10*log10000 = 40

Example

- What is the SNR and SNR_{dB} for a noiseless channel?

노이즈가 없으면 SNR이 무한대로 가서 엄청 적은 신호로도 받을 수 있다

$$\text{SNR} = (\text{signal power}) / 0 = \infty \longrightarrow \text{SNR}_{\text{dB}} = 10 \log_{10} \infty = \infty$$

SNR이 무한히 크다 -> 작은 signal power로도 통신할 수 있다

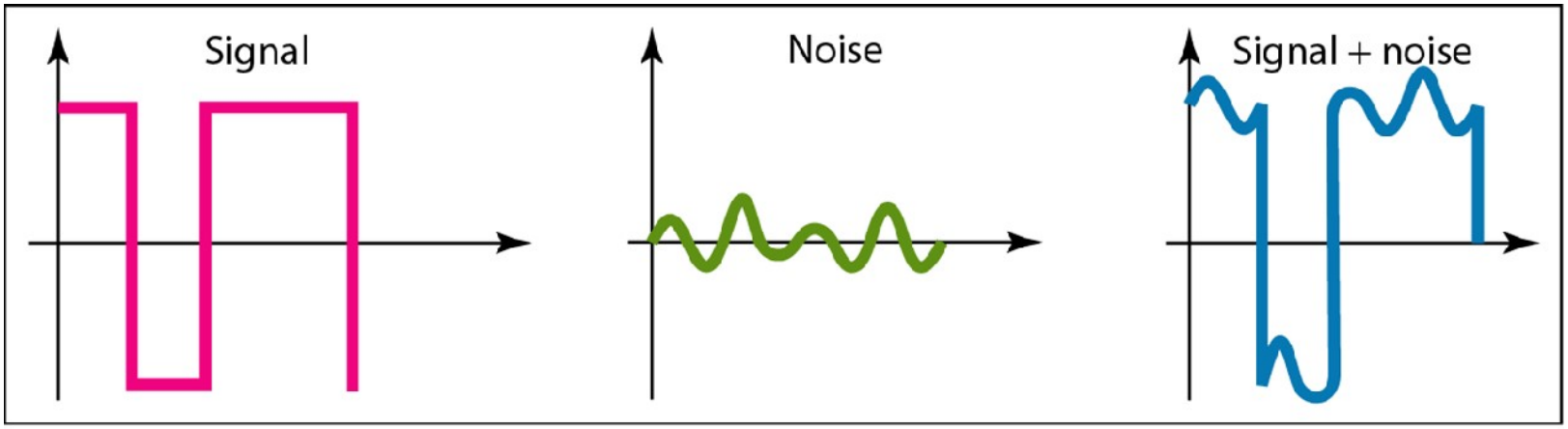
- This is an ideal case; it can never happen in real life.

수신에 중요한 요소 1. 절대적인 수신 크기 2. SNR

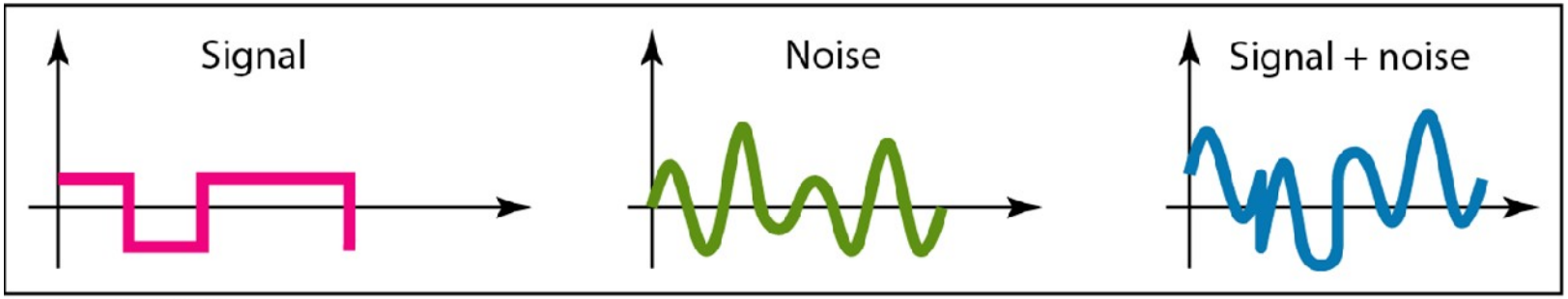
receiver sensitivity 수신감도
하드웨어마다 스펙이 다름

Impact of noise on signal

- If SNR is too low, signal cannot be recovered



a. Large SNR



b. Small SNR

Data Rate Limits

Data Transfer Rate (Bit Rate)

- Data transfer rate is dependent upon the following three:

- Bandwidth
- Number of signal levels
- Channel quality (noise level)

Nyquist Equation

- When assuming noiseless channel

bandwidth 신호 레벨

- Data rate = $2 \times B \times \log_2 L$ data rate를 이론적으로 계산한 값(노이즈 없을 때)

- B: bandwidth
- L: number of signal levels

- What is we use too many signal levels?
  - Accuracy is degraded

Exercise

- Consider a noiseless channel with a bandwidth of 3000Hz transmitting a signal with two signal levels. What is the maximum bit rate?

$2 * 3000 * \log_2(2) = 6000$

Exercise

- Consider a noiseless channel with a bandwidth of 3000Hz transmitting a signal with <u>four</u> signal levels. What is the maximum bit rate?

  2 * 3000 * log2(4) = 6000

  시그널 레벨을 두 배로 하면 두배 더 빠르다

Example

- We need to send 265kbps over a noiseless channel with a bandwidth of 20kHz. How many signal levels do we need?

1초에 256k개의 비트를 보내야 할 때, 20kHz 대역폭을 사용하면 98.7 레벨 이상을 사용해야 한다

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L \longrightarrow \log_2 L = 6.625 \longrightarrow L = 2^{6.625} = 98.7 \text{ levels}$$

- The number of levels need to be a power of 2, so the answer is 128 levels (280kbps)

시그널 레벨은 2의 지수승으로 한다

레벨을 많이 쓰는 게 쉬운 게 아니다
전압의 준위가 레벨이다
2개 쓸 때는 0V, 5V
4개는 0V, 1.5V, 3.0V, 4.5V
레벨이 많으면 그만큼 전력량이 차이가 덜 나기 때문에 쉽게 외곡된다

Shannon Capacity

노이즈를 생각해서 최대로 낼 수 있는 전송속도

- Maximum bit rate in a noisy channel

- $C = B \times \log_2(1+SNR)$

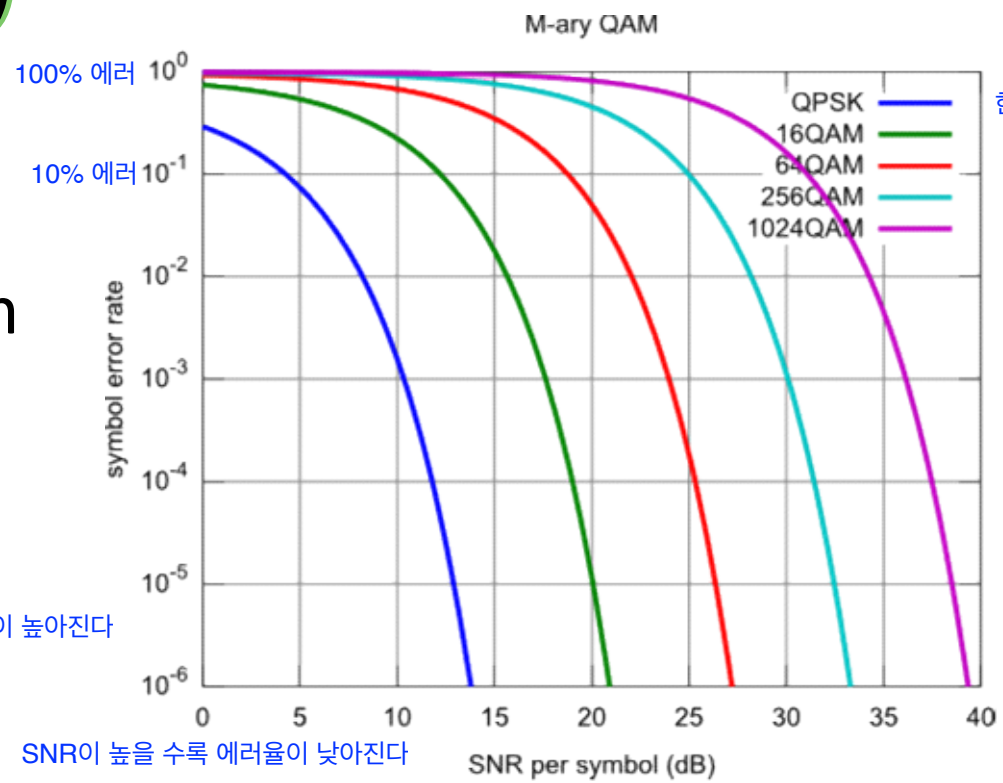
SNR이 높으면 전송속도도 빨라진다

오른쪽 줄로 갈수록 전송속도가 더 빠른 인코딩 방식

channel capacity

- C: capacity (maximum bit rate)
- B: bandwidth

전송속도를 높이기 위해서 빡센 인코딩을 하면 그걸 전송하기 위한 필요 SNR이 높아진다



SNR이 높을 수록 에러율이 낮아진다

Example

- Consider an extremely noisy channel in which SNR is zero. What is the maximum bit rate for this channel?

  SNR이 0이면 신호가 없거나 노이즈만 있음

watt

$$C = B \log_2 (1 + \text{SNR}) = B \log_2(1 + 0) = B \log_2 1 = B \times 0 = 0$$

- In other words, we cannot send or receive any data through this channel.

Example

- We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000Hz (300 – 3300Hz) assigned for data communications. The signal-to-noise ratio is usually 3162.

- The channel capacity is:

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2(1 + 3162) = 3000 \times 11.62 = 34{,}860 \text{ bps}$$

Example

- Suppose SNR is 36dB, and channel bandwidth is 2MHz. What is the channel capacity?

snr을db 단위로 주면
이렇게 snr을 계산

$$\mathrm{SNR_{dB}} = 10 \log_{10}\mathrm{SNR} \longrightarrow \mathrm{SNR} = 10^{\mathrm{SNR_{dB}}/10} \longrightarrow \mathrm{SNR} = 10^{3.6} = 3981$$

$$C = B \log_2(1 + \mathrm{SNR}) = 2 \times 10^6 \times \log_2 3982 = 24\ \mathrm{Mbps}$$

Example

- When the SNR is very high, we can assume that SNR+1 is almost the same as SNR. In these cases, the theoretical channel capacity can be simplified as follows.

- $C = B \times (SNR_{dB} / 3)$ 앞의 식에서는 watt의 SNR를 썼는데 이 식에서는 SNRdb를 사용

- For the previous example,

- $C = 2MHz \times (36 / 3) = 24Mbps$

Performance

Bandwidth

- Two meanings of bandwidth
  - The size in frequency domain of a channel (Hz)

Bandwidth can be considered as a subset of channel capacity term. When bandwidth is measured, the maximum volume of information that can be accurately transferred per unit of time is taken into account.
For example, channel capacity may be very high, but low signal quality would make bandwidth low as well.

  - The maximum bit rate (bps)

bandwidth의 두가지 쓰임새 hz는 주파수의 대역폭
bps는 전송속도 즉 이때 bandwidth는 최대로 보낼 수 있는 bps

- Example
  - Bandwidth of a line is 4kHz. This line has 56Kbps of bandwidth.

Throughput

전송률
제대로 수신자가 데이터를 받은 크기

- The actual data transfer rate (bps)
  - Throughput < Bandwidth
    실제 수신한 양 최대로 보낼 수 있는 전송량

- Example
  - A network with bandwidth of 10Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

$$\text{Throughput} = (12{,}000 \times 10{,}000) / 60 = 2 \text{ Mbps}$$

2000kbps == 2Mbps

  - Throughput of this network is 1/5 of its bandwidth

Delay

송신자가 어떤 비트를 전송한 시점과 수신자가 그 비트를 받은 시점

- Duration between the time the first bit of a message leaves the source and the time the last bit of the message is received at the destination

- Delay = transmission delay + propagation delay + queuing delay + processing delay

Delay Components

- Transmission delay
  - Duration between the time the first bit leaves the source and the time the last bit leaves the source
- Propagation delay
  - Duration of time a bit travels from source to destination
  - distance / speed of travel
- Queuing delay
  - Time waiting for other packets ahead of the packet
- Processing delay
  - Time used by system to process the message

Delay Components

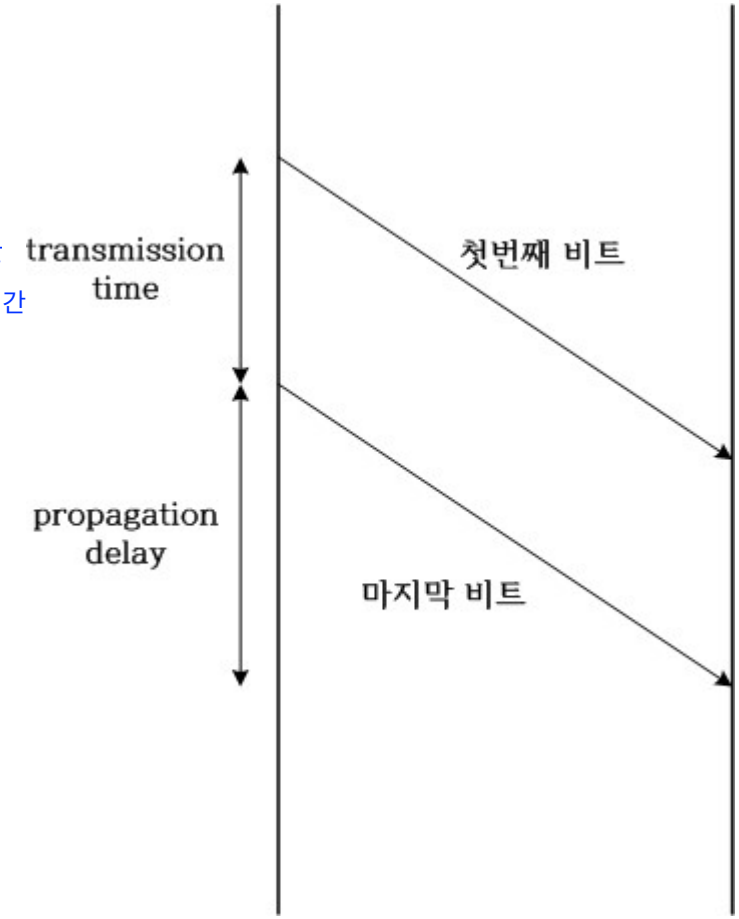
Transmission delay is how long it takes to get all the bits into the wire in the first place (it's packet_length/data_rate).

Propagation delay is how long it takes one bit to travel from one end of the "wire" to the other (it's proportional to the length of the wire, crudely).

비트 내용(프레임)을 전송하는데 걸리는 시간

통신을 할 때 프레임에 비트를 몰아서 쏘는데 이 시간

신호가 수신자까지 이동하는 시간



Example

- What is the propagation time if the distance between the two points is 12,000km? Assume the propagation speed to be 2.4 x 10^8m/s in cable.

시간 거리 속도

$$\text{Propagation time} = (12{,}000 \times 10{,}000) / (2.4 \times 2^8) = 50 \text{ ms}$$

^km니까 1000임 오타

- A bit can go over the Atlantic Ocean in only 50ms if there is a direct cable

Example

bandwidth가 1Gps다 -> 1초에 10^9 bit를 전송할 수 있다

- What are the propagation time and the transmission time for a 2.5KB message if the bandwidth of the network is 1Gbps? Assume that the distance between the sender and the receiver is 12,000km and that the signal travels at 2.4 x 10^8m/s

$$\text{Propagation time} = (12{,}000 \times 1000) / (2.4 \times 10^8) = 50 \text{ ms}$$

$$\text{Transmission time} = (2500 \times 8) / 10^9 = 0.020 \text{ ms}$$

프레임의 크기 / 회선의 bandwidth(최대 전송

^byte를 bit로 변환

1Gps bandwidth에서 2500*8 bit의 데이터를 0.02ms의 속도로 보낼 수 있다

- Message is short and the bandwidth is large

→ Propagation time is the dominant factor

Example

- What are the propagation time and the transmission time for a 5MB message if the bandwidth of the network is 1Mbps? Assume that the distance between the sender and the receiver is 12,000km and the signal travels at 2.4 x 10^8m/s

$$\text{Propagation time} = (12{,}000 \times 1000) / (2.4 \times 10^8) = 50 \text{ ms}$$

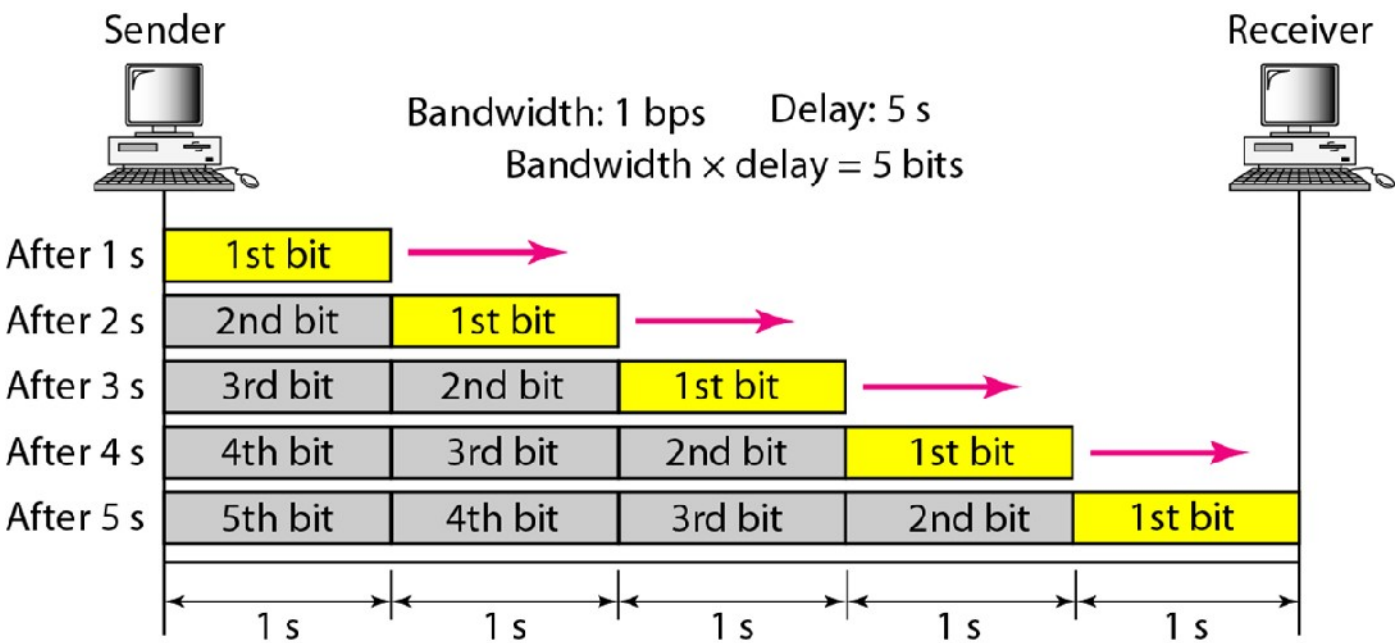
$$\text{Transmission time} = (5{,}000{,}000 \times 8) / 10^6 = 40 \text{ s}$$

- Message is long and bandwidth is small

→ Transmission time is the dominant factor

Bandwidth-Delay Product

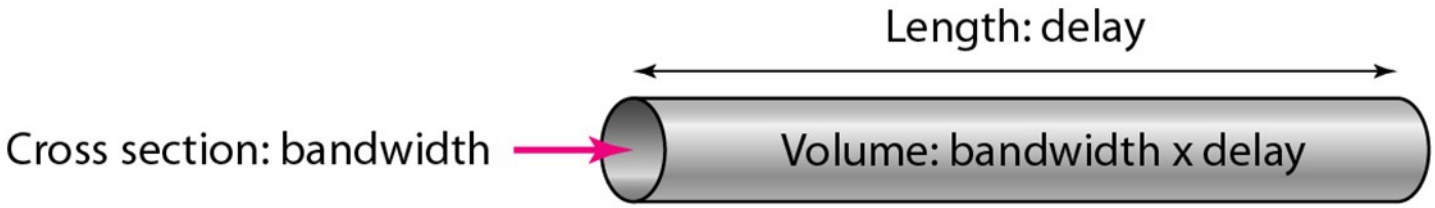
- Bandwidth-delay product represents the "volume" of the channel
  - How much data can be fit into the channel between sender and receiver



채널을 채우는 데이터 양을 구할 수 있다

Bandwidth-Delay Product

- The channel can be thought as a pipe
- Bandwidth-delay product is the number of bits that fills up the pipe



Exercise

- Suppose bandwidth of a link is 10Mbps, and the delay is 50ms. What is the amount of data to fill up this channel?

500kbit

송신자가 얼마나 빠른 속도로 전송할지 판단할 때 사용

End of Chapter