Xi'an Jiaotong-Liverpool University
西交利物浦大学

MEC208 Instrumentation and Control System

2024-25 Semester 2

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Quiz 3.1 - Answer

What is the non-linearity error as %FSD (full-scale defelction) produced when a $1k\Omega$ potentiometer has a load of $10k\Omega$ and is at one-third of its maximum displacement?

$$error \approx V_s \frac{R_p}{R_L}(x^3 - x^2) = V_S \frac{1k}{10k}\left[\left(\frac{1}{3}\right)^3 - \left(\frac{1}{3}\right)^2\right] = -0.74\% V_S$$

Transform to percentage:

$$error = -0.74\%$$

Outline

Signal Conditioning

- ❑ **What is Signal Condition**
- ❑ **Wheatstone Bridge**
  - Basics
  - Temperature Compensation
- ❑ **Amplifiers**
- ❑ ***Protection Circuit***
- ❑ **Filters**

Protection Circuit

There are many situations where the connection of a sensor to the next unit, e.g. a microprocessor, can lead to the possibility of damage as a result of perhaps a high current or high voltage.

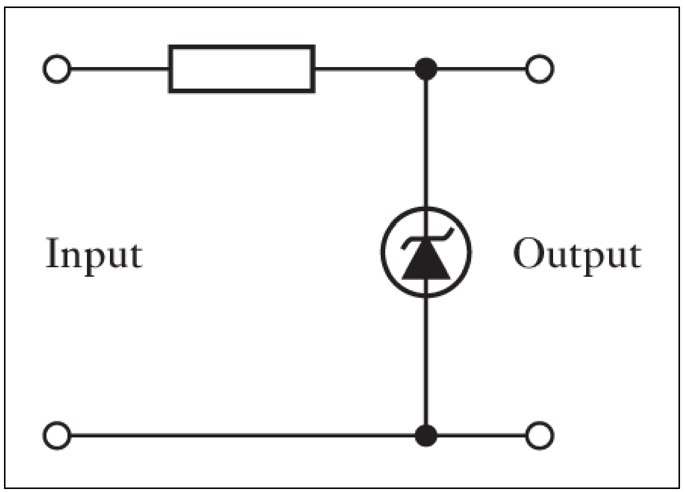

Fig. Zener diode protection circuit.

- Protection from high current by:
  - incorporating in the input line of a series resistor to limit the current to an acceptable level.
- Protection from high voltage by:
  - using a Zener diode circuit. Zener diodes behave like ordinary diodes up to some breakdown voltage when they become conducting. Its resistance drop to a very low value when voltage exceeds some threshold, say 5V.

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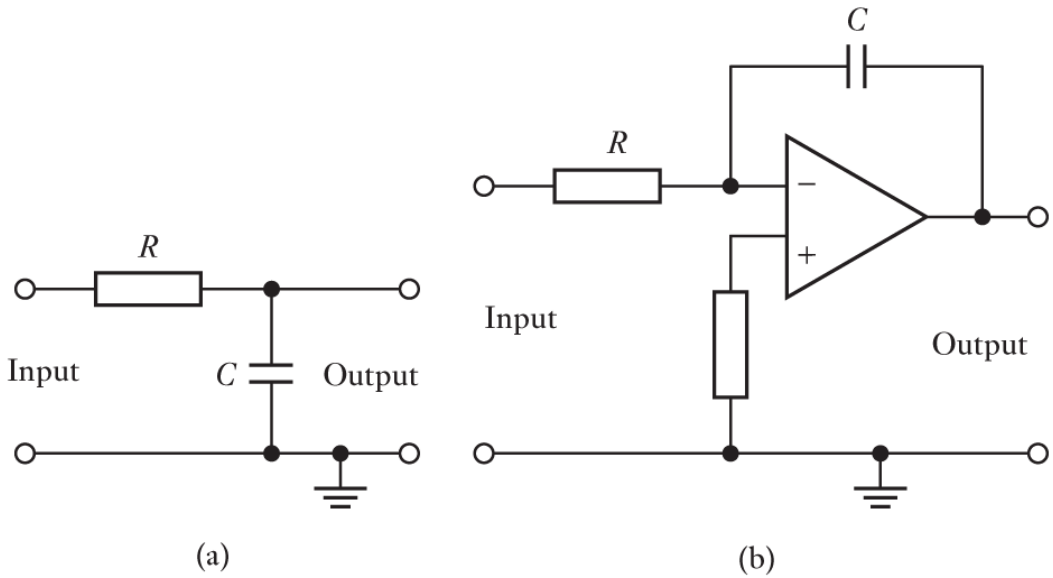
Filtering

The term **filtering** is used to describe the process of removing a certain band of frequencies from a signal and permitting others to be transmitted.

- Passive filter: made up using only resistors, capacitors and inductors;
- Active filter: made up using amplifiers in addition to resistors, capacitors and inductors.



Only need to understand the concept

Fig. Low-pass filter: (a) passive, (b) active using an operational amplifier.

Characteristics of Ideal Filters

Cutoff frequency: the frequency at which the output voltage is 70.7% or attenuated by 3dB of that in the pass band.

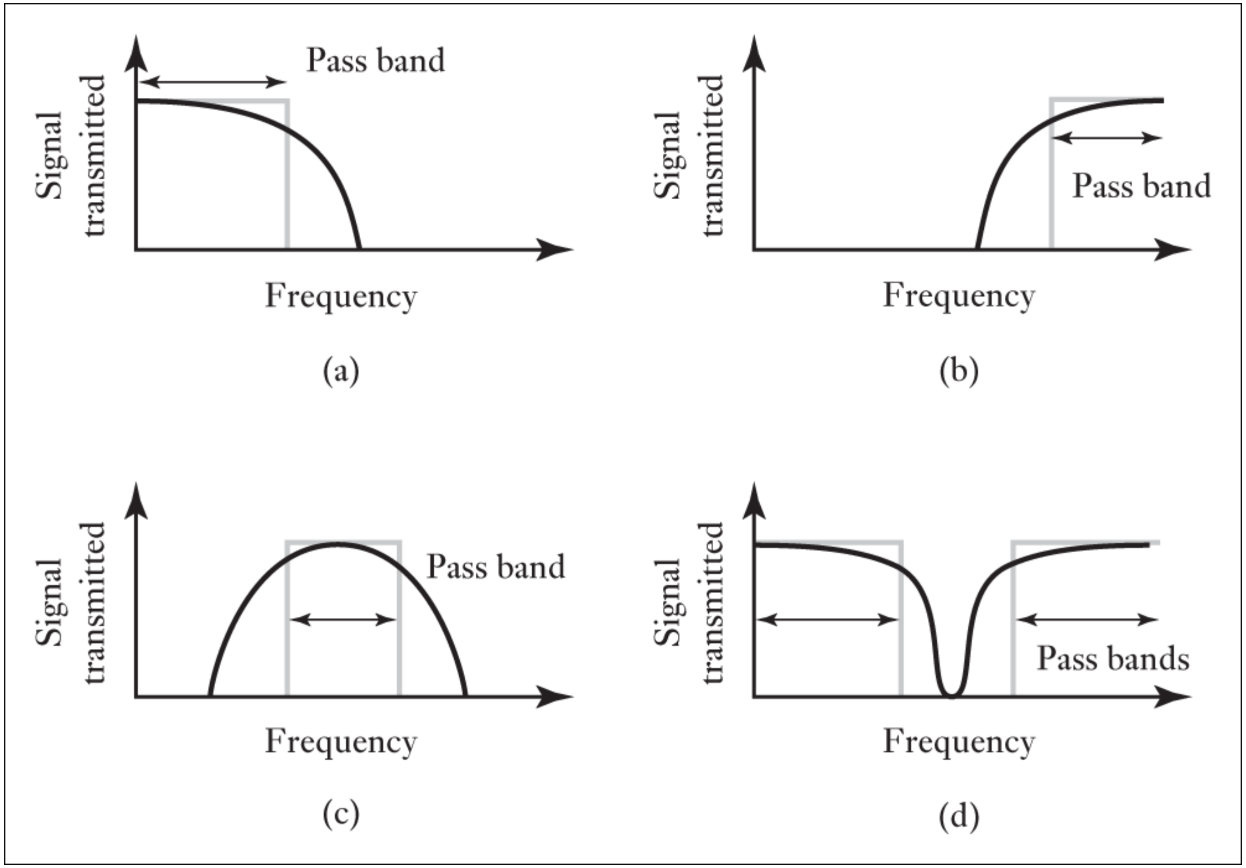


Fig. Filters (a) low-pass, (b) high-pass, (c) band-pass, (d) band-stop.

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- ❑ ***Interference and Noise***

Interference and Noise

Transducers often produce only small amplitude signals that have to be connected to a display device some distance away from the point of measurement. This must be done with care to avoid 'picking up' unwanted noise signal (interference and natural noise) that can corrupt or obscure the required signal.

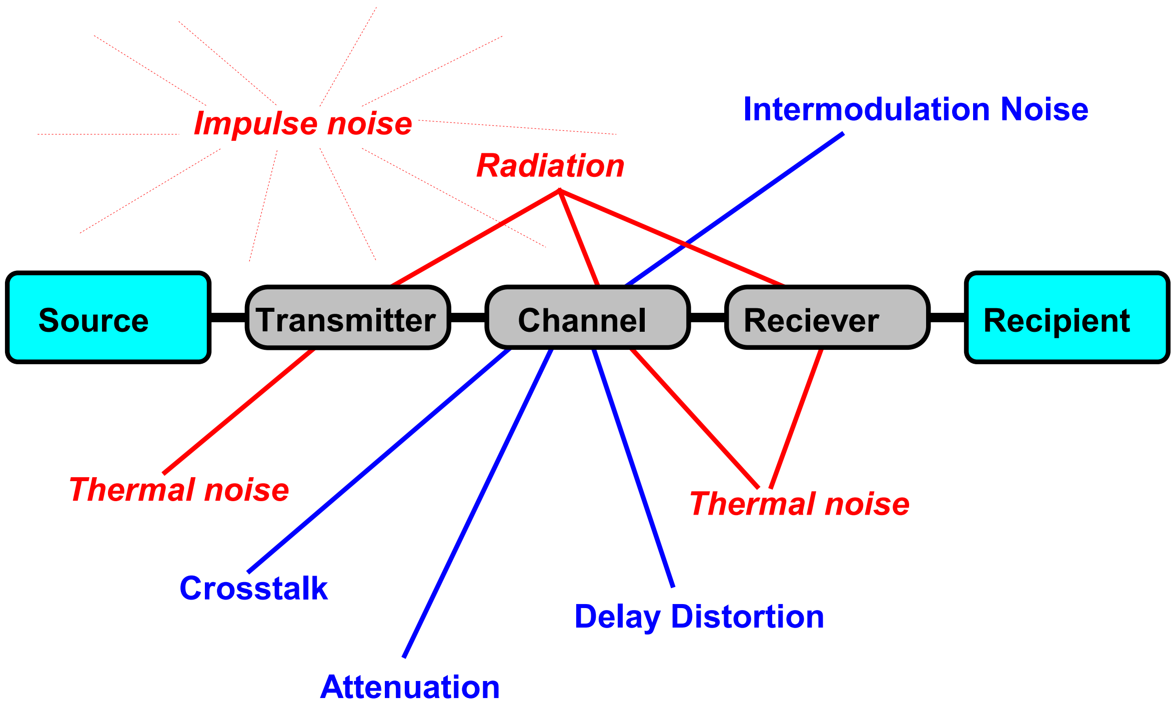
Signal-to-Noise Ratio:
SNR = Signal Power / Noise Power

It is better to prevent the noise being picked up than to try to eliminate it afterwards.

Signal processing techniques can be used to effectively to improve SNR:

- i.e., <u>signal averaging</u> is particularly useful when the required signal occupies a range of frequencies, but it works only if the noise is uncorrelated with the required signal.

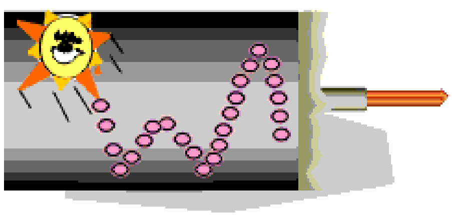
Sources of Noise

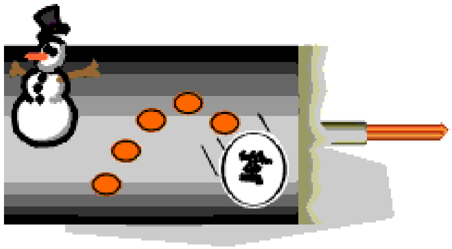


- Unwanted electric signals come from a variety of sources, generally classified as either human interference or naturally occurring noise.
- Noise (unlike distortion) is not correlated with the desired signal.
- Human interference: other electrical apparatus, channel crosstalk etc.
- Natural noise: atmospheric disturbance, extra-terrestrial radiation, random electron motion etc.

Thermal Noise

- Thermal noise is the noise produced by the random motion of charged particles (usually electrons) in conducting media.
- Thermal noise *can be reduced* by cooling the noise source (being applied in some radio receivers using cryogenic coolers, to improve the receiver sensitivity)
- *Cannot be eliminated.*

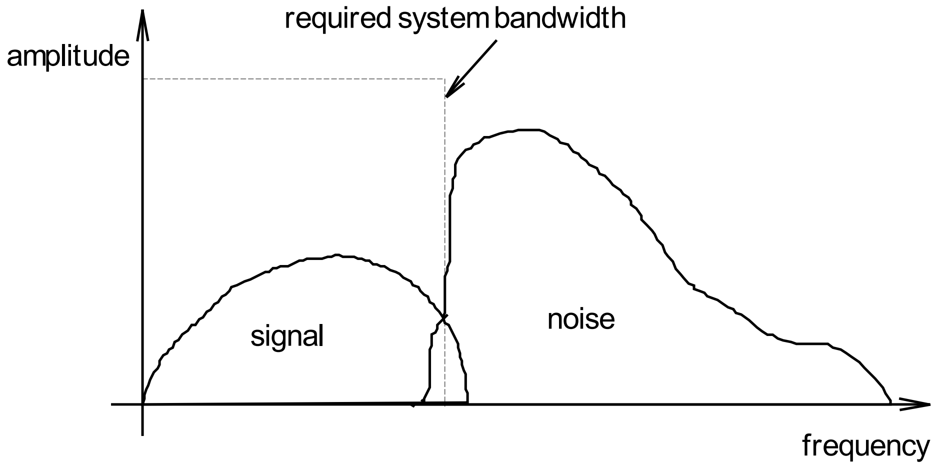


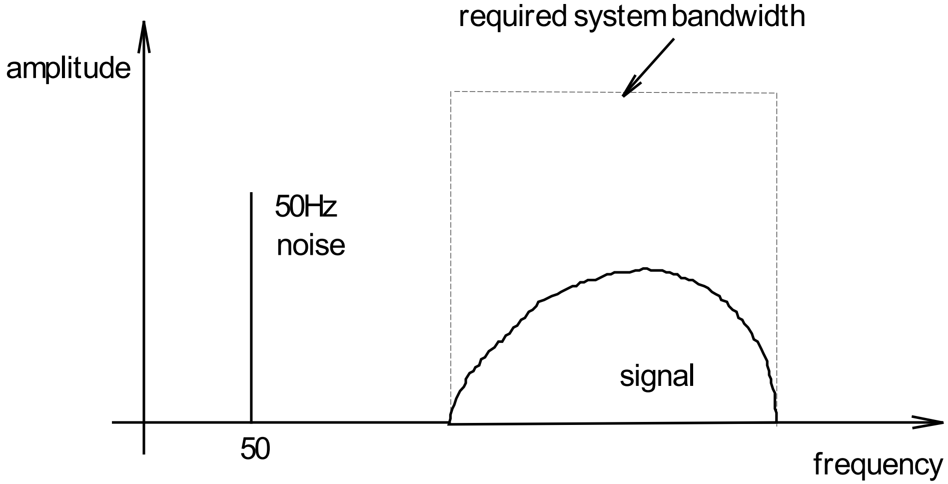


❖ Generally thermal noise can be modeled as a zero mean Gaussian WSS (wide-sense stationary) random process.

❖ The noise is called **White Noise** since all frequency components appear with equal power (white is used in white light for a similar reason).

Noise Elimination – Bandwidth Limiting

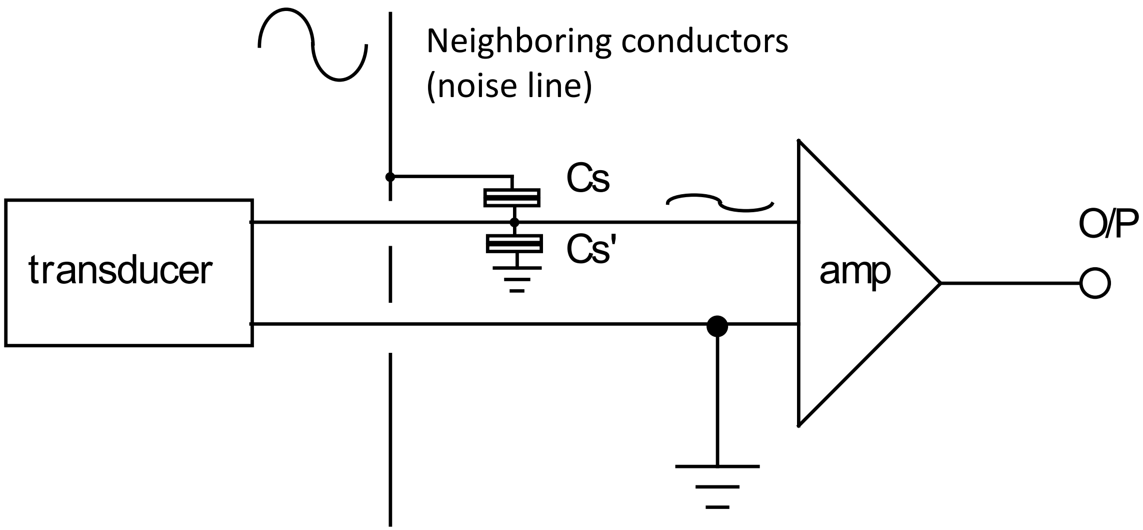




Avoiding Noise ‘pick-up’

Noise is often inadvertently 'picked up' for three main reasons:

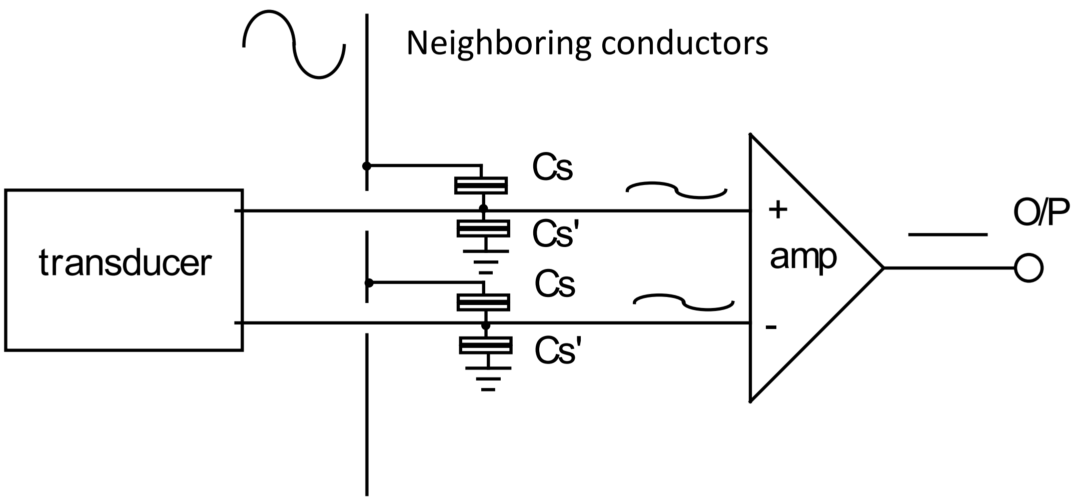
1) ***Noise pick-up by <u>capacitive coupling</u>***



Avoiding Noise 'pick-up'

Avoid capacitive coupling – (i) balance the input

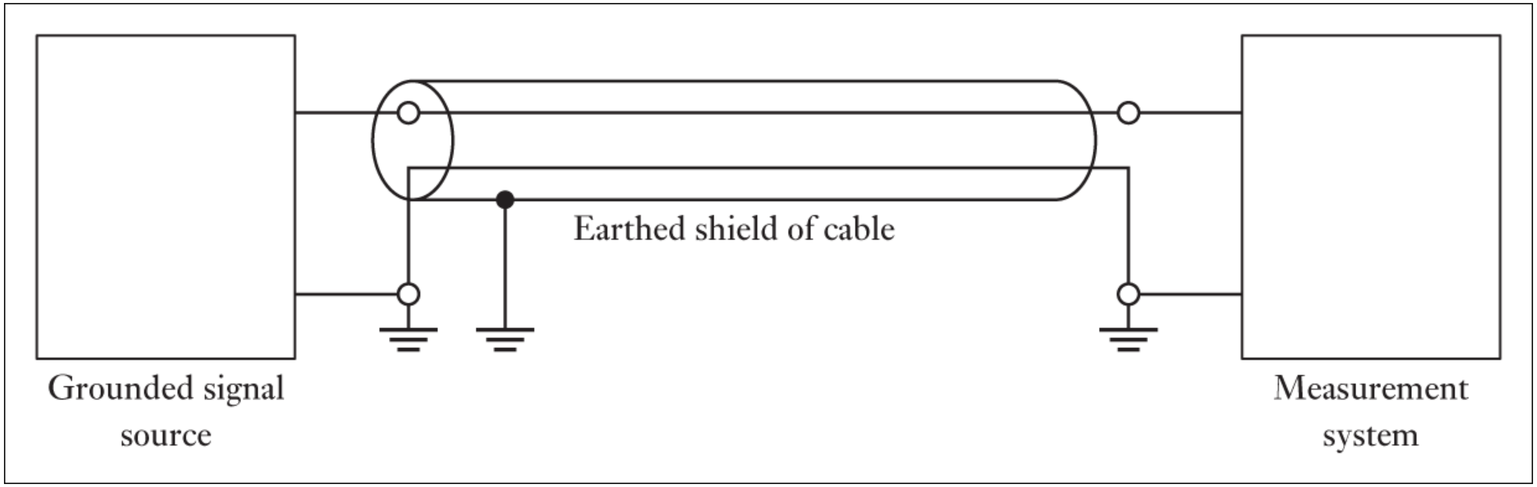
Minimise this problem by using a difference amplifier with high common mode rejection and with both input lines isolated from ground. Then the noise 'pick up' links equally to both inputs and cancels because the amplifier only amplifies *differential* signals and does not amplify common mode signals (ideally).



Avoiding Noise 'pick-up'

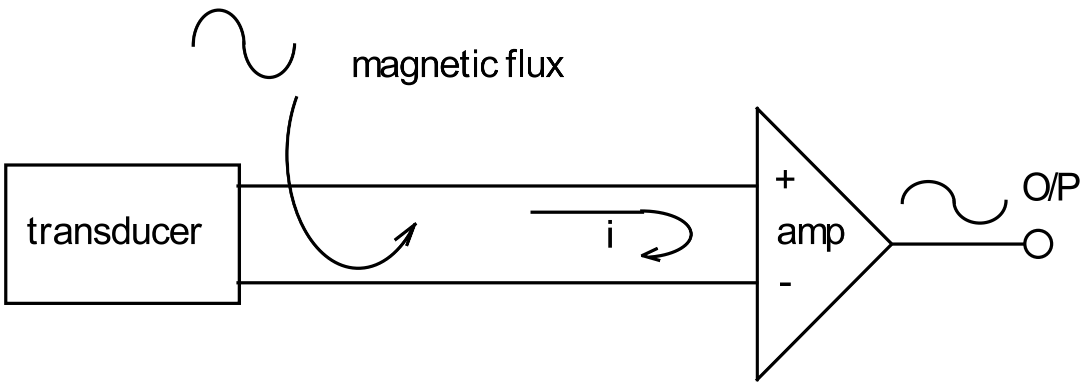
Avoid capacitive coupling – (ii) screen with co-axial cable

Alternatively use screened co-axial cable with the outer sheath grounded. This protects the inner cable from capacitively linking with the noise line.



Avoiding Noise 'pick-up'

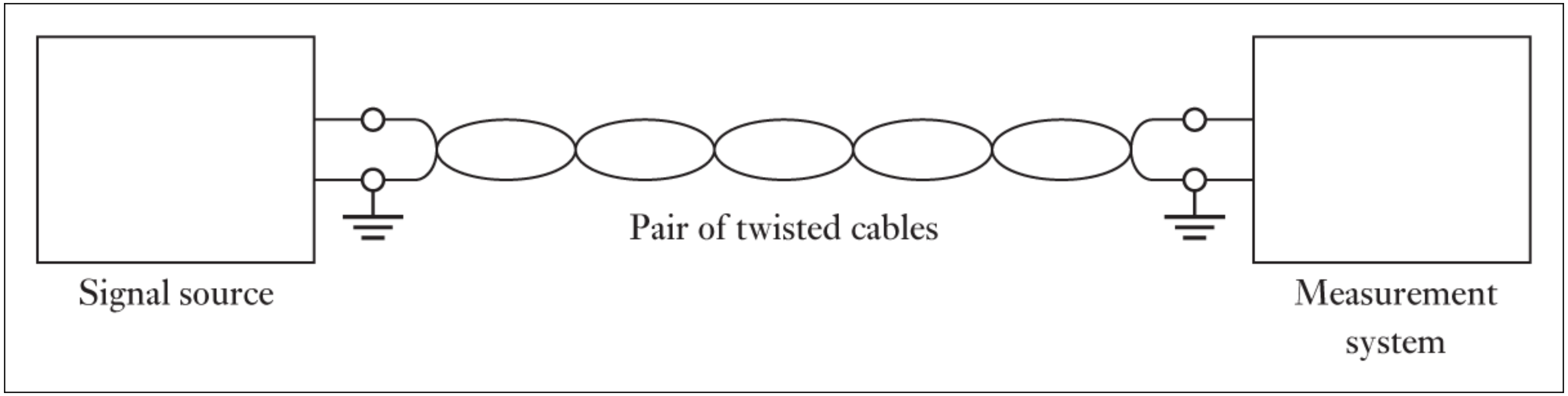
2) ***Noise pick-up by electromagnetic coupling***



Avoiding Noise 'pick-up'

Avoid Electromagnetic coupling – twist the wires

Minimise this pick-up noise by twisting the input lines together.

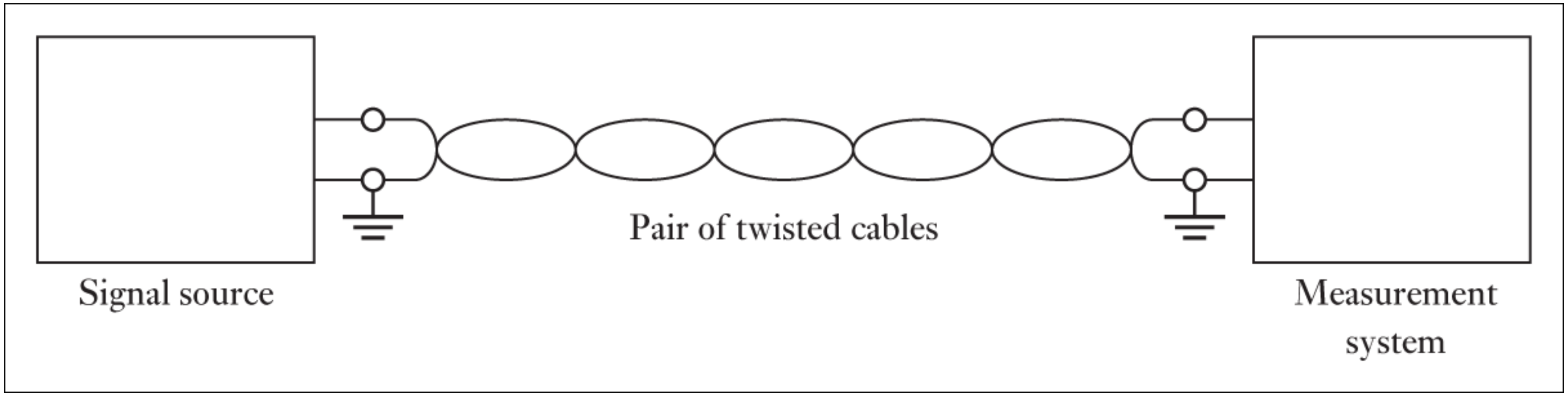


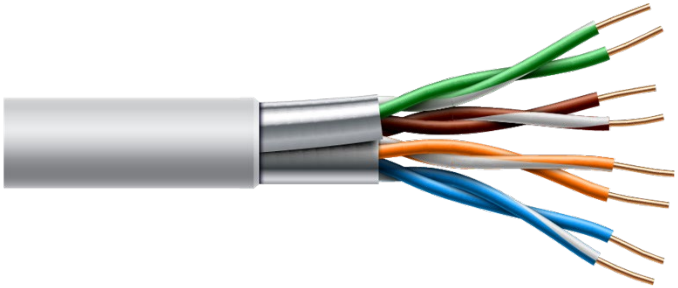
The induced voltages in each loop are reduced by the small area of each loop and are of opposite polarity in each loop and so cancelled.

Avoiding Noise ‘pick-up’

Avoid Electromagnetic coupling – twist the wires

Minimise this pick-up noise by twisting the input lines together.

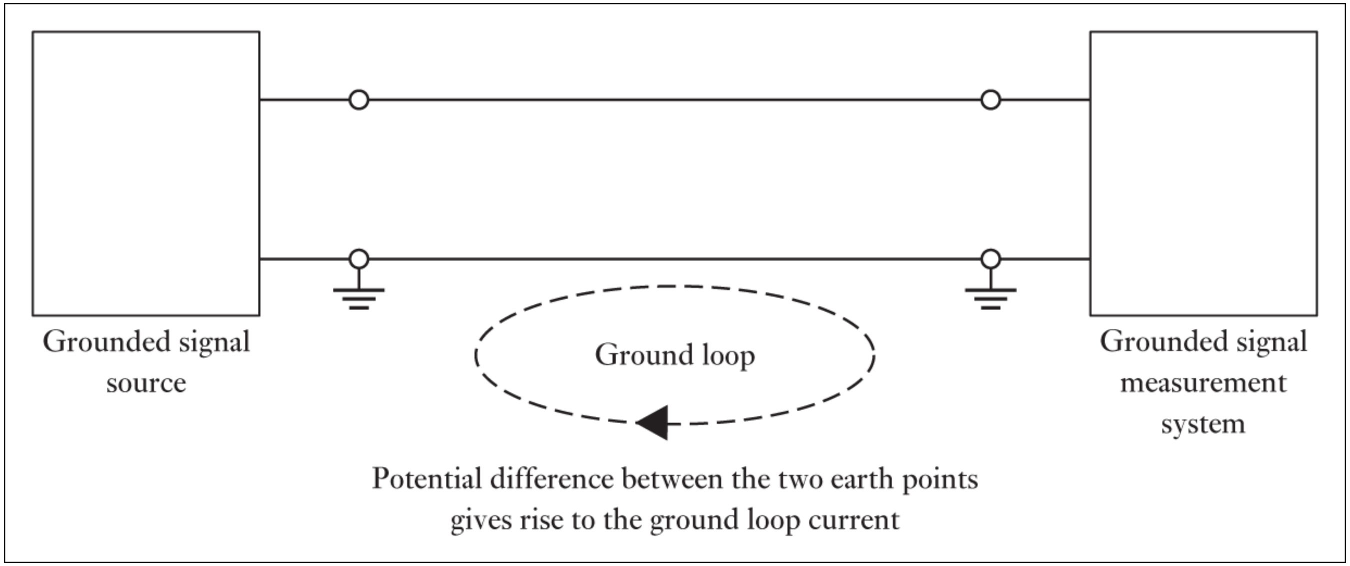




Avoiding Noise ‘pick-up’

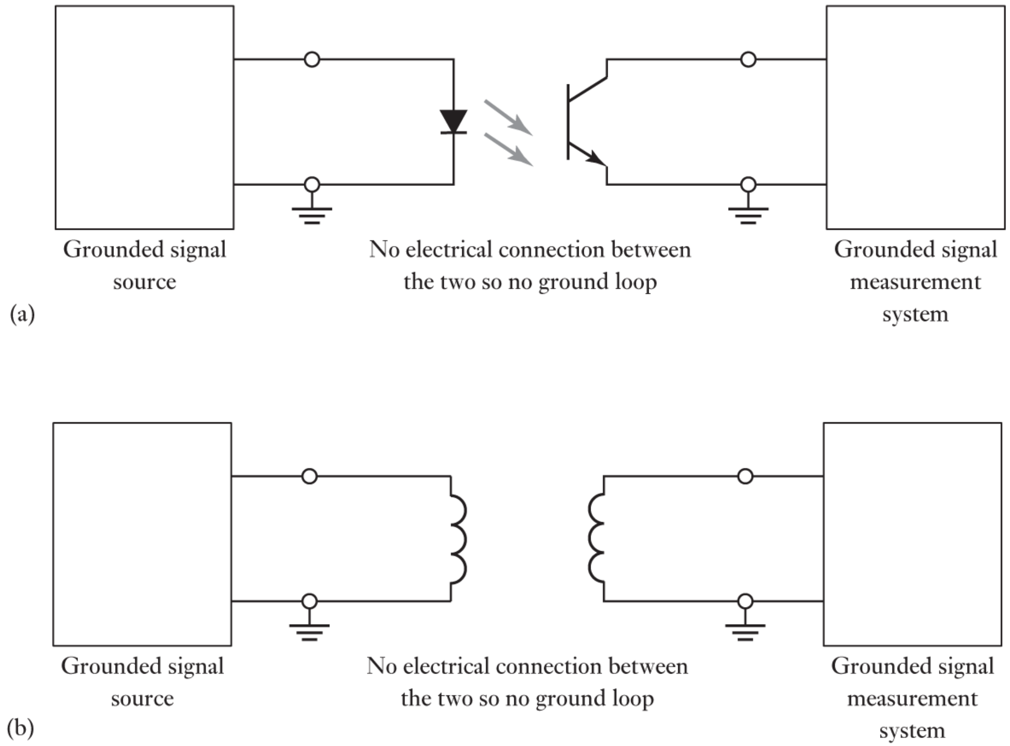
3) *Noise pick-up by Ground loops*

Problems can arise with systems when a circuit has several grounding points. In a large system, multiple grounding is largely inevitable. Unfortunately, there may be potential difference between the two grounding points and thus significant currents (ground-loop currents) can flow between the grounding points through the low but finite ground resistance.



Avoiding Noise 'pick-up'

Avoid Ground loop coupling – electrical isolation

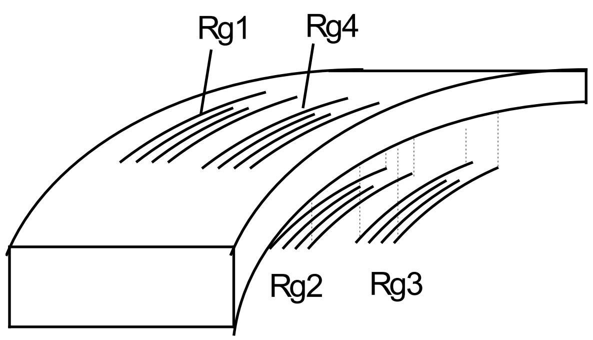


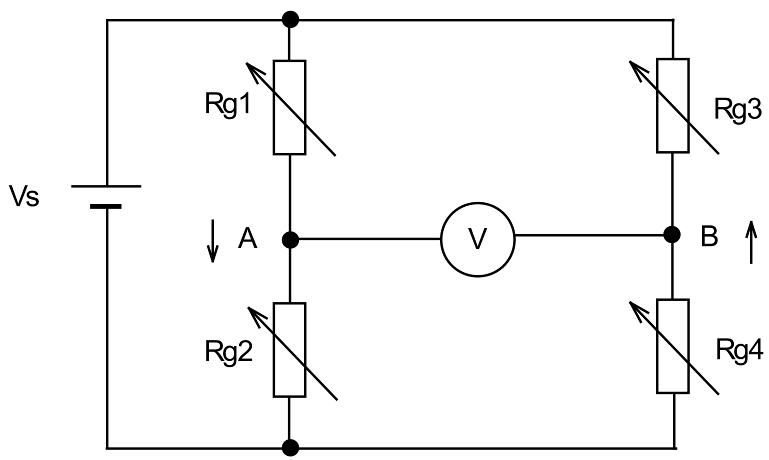
- ✓ Besides, ground loops from multiple point grounding can be minimized if the multiple earth connections are made close together and the common ground has a resistance small enough to make the voltage drops between the earth points negligible.

Quiz 4.1

The strain in a beam subject to tensile stress is to be measured using four strain gauges. The supply voltage to the bridge Vs is 6V, the gauge factor G=2.3, the gauges have a resistance of 200Ω each, Young's modulus of the beam is 250 x 10^9 Newtons/m^2. (hint: Young's modulus=stress/strain)

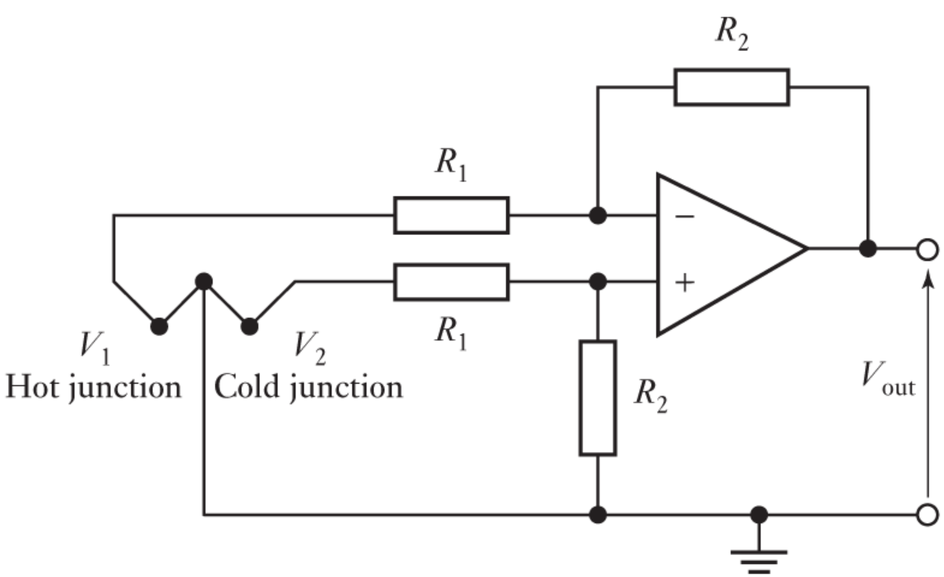
Suppose the measured output voltage from the bridge is 80μV, determine the corresponding strain and stress.





Quiz 4.2

A differential amplifier is used with a copper-constantan thermocouple sensor with sensitivity of $43\mu V/^{o}C$. Suppose $R_1 = 1k\Omega$ and $R_2 = 2.32k\Omega$, the temperature difference between the two thermocouple junctions is 100°C. Find the output voltage of the circuit.



Lecture 5

Outline

Communication System

- ❑ Typical System
- ❑ Transmission Path
- ❑ Industrial Communication
- ❑ Signal Modulation
- ❑ Error Control Methods

Outline

Communication System

- ❑ ***Typical System***
- ❑ **Transmission Path**
- ❑ **Industrial Communication**
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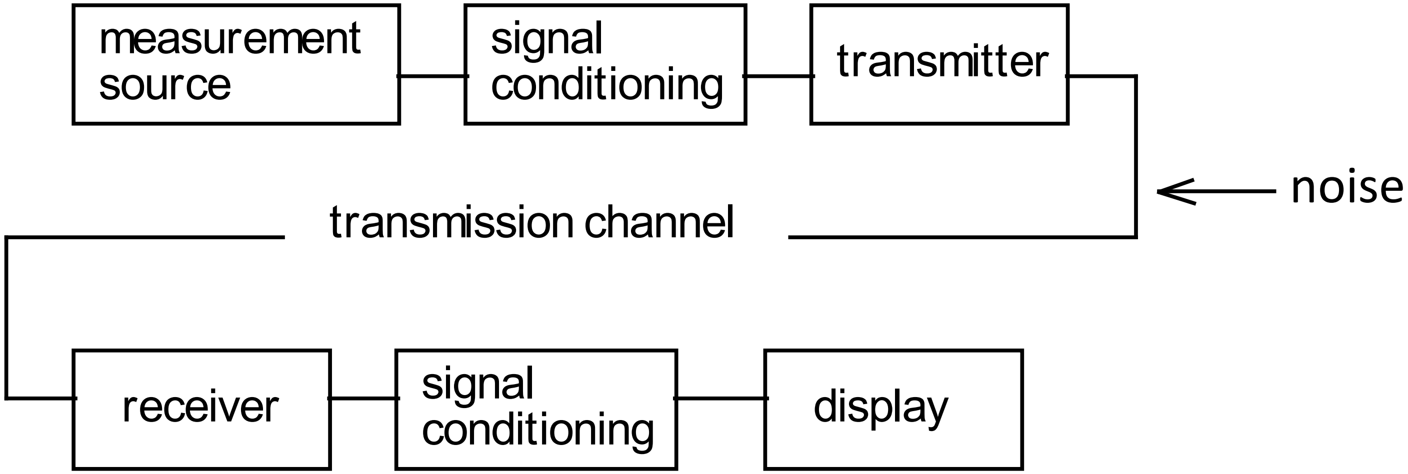
- ❑ **Error Control Methods**

Typical System

- The transducer and associated signal conditioning (bridge circuit, amplifier etc.) is only part of the full measurement system;
- A typical system involves numerous components in the field of electrical engineering including circuits, electronics, electromagnetics, signal processing, microprocessors, and communication networks.

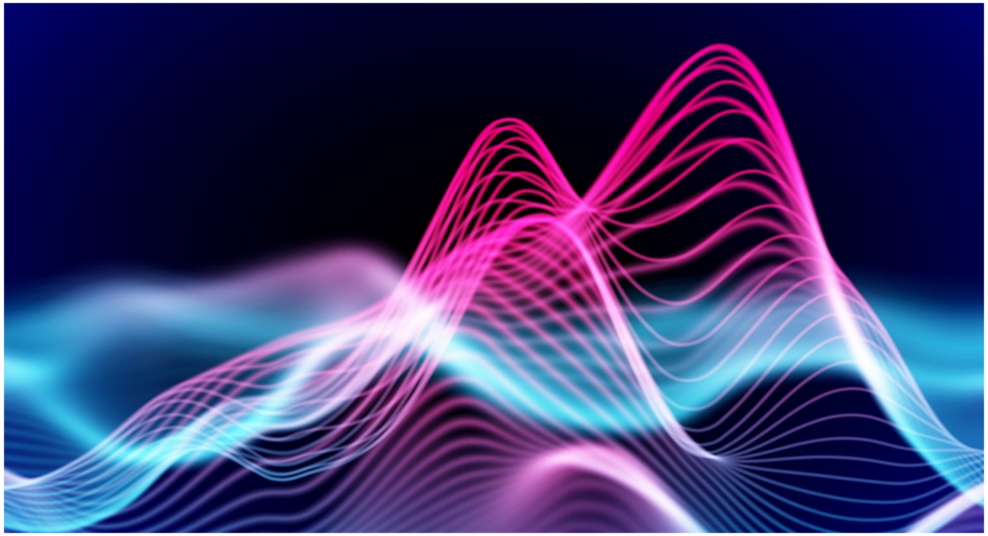


- A communication system coveys information from its source to a destination some distance away.

Information Categories: Analog vs. Digital

There are many kinds of information sources, and information appears in various forms. Information can be identified into two categories: **Analog** and **Digital**.

- An **analog** message is a physical quantity that varies with time, usually in a smooth and continuous fashion.
  - example: acoustic pressure produced when you speak;
  - Since the information resides in a time-varying waveform, an analog communication system should deliver this waveform with a specific degree of fidelity（保真度）;



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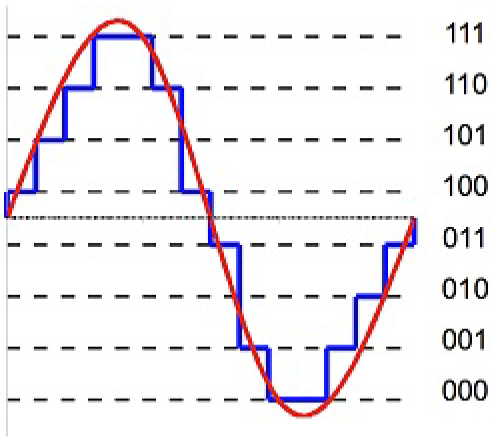
- A **digital** message is an ordered sequence of symbols selected from a finite set of discrete elements.
  - example: keys you press on a computer keyboard;
  - Since the information resides in discrete symbols, a digital communication should deliver these symbols with a specified degree of accuracy in a specified amount of time.



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Communication System

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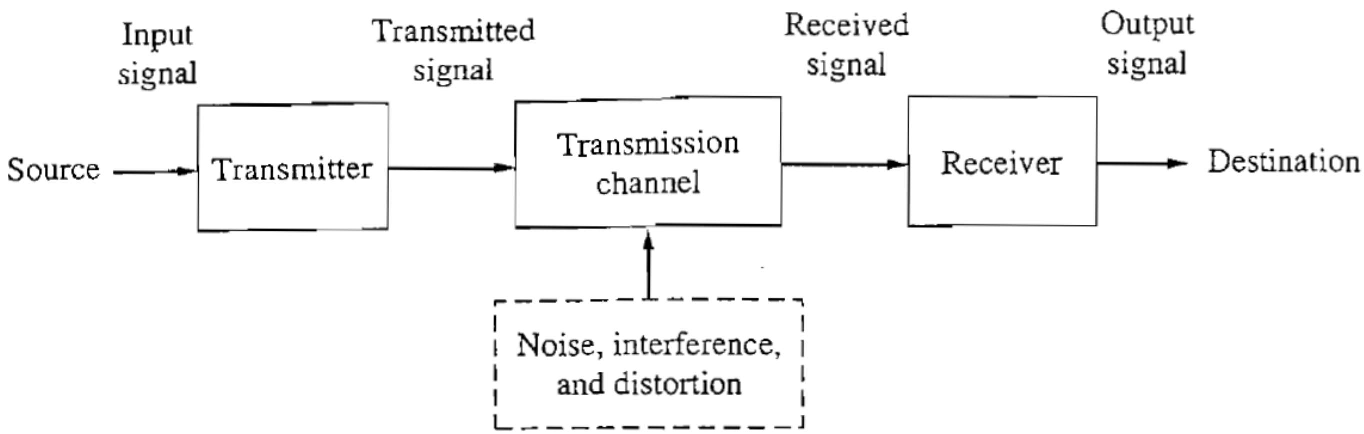
Elements of A Communication System



- The **transmitter** processes the input signal to produce a transmitted signal suited to the characteristics of the transmission channel (modulation, coding);
- The **transmission channel** is the electrical medium that bridges the distance from source to destination;
- The **receiver** operates on the output signal from the channel in preparation for delivery to the transducer at the destination (amplification, demodulation, decoding, filtering).

Elements of A Communication System

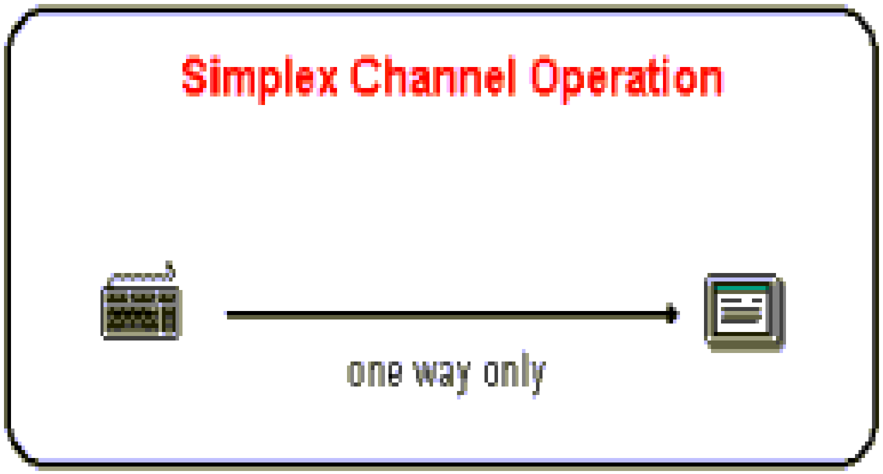
- Every transmission channel introduces some amount of transmission **loss** or 衰减 **attenuation**, the signal power progressively decreased with increasing distance. Attenuation is undesired since it reduces signal strength at the receiver;
- More serious is **distortion**, **interference** and **noise** which appear as alternations of the signal shape.
  - **Distortion**: waveform perturbation caused by imperfect response of the system to the desired signal itself. It disappears when the signal is turned off;
  - **Interference**: contamination by unrelated signals from human sources – other transmitters, power lines, switching circuits and so on;
  - **Noise**: random and unpredictable electrical signals produced by natural processes both internal and external to the system. Filtering reduces noise contamination, but there inevitably remains some amount of the noise that can not be eliminated. This noise constitutes one of the fundamental system limitations.

Simplex, Half and Full Duplex System

Simplex Channel （单工通道）

- Data in a simplex channel is always one way.

Simplex channels are not often used because it is not possible to send back error or control signals to the transmit end.



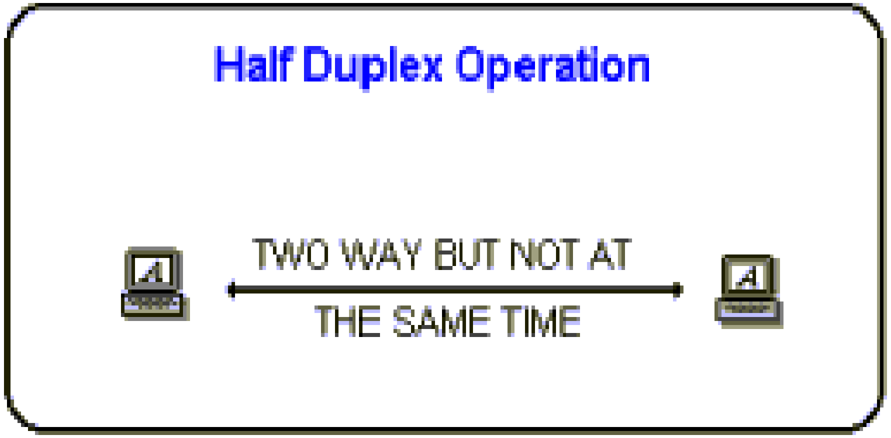
It's like a one way street. Example of simplex transmission is Television, or Radio.

Simplex, Half and Full Duplex System

Half-duplex （半双工通道）

- Data can be sent and received, but not at the same time (i.e. only in one direction at a time)

The channels share the same frequency range for both transmission and reception of data within the available bandwidth. It allows transmission in either direction but not at the same time.



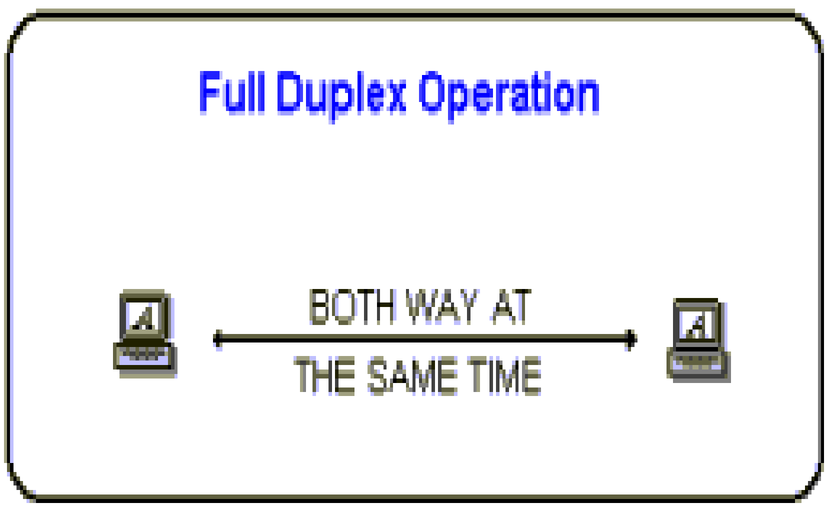
One example of half-duplex is talk-back radio. Only one person can talk at a time.

Simplex, Half and Full Duplex System

Full Duplex （全双工通道）

- Data can be transmitted in both directions simultaneously.

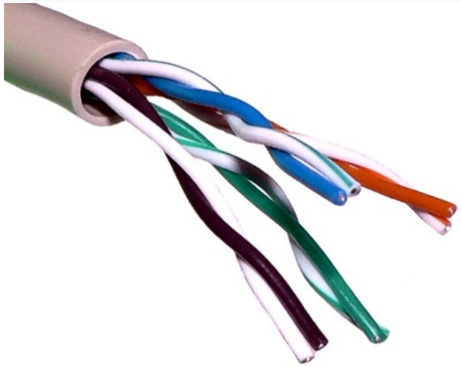
Full-duplex requires one part of the available bandwidth to be dedicated to transmission and another part to reception. In the world of data communications, full duplex allows both way communication simultaneously.



It’s like a two-lane bridge on a two-lane highway. An example is mobile phone.

Typical Transmission Medium and Loss

Transmission Medium	Frequency	Loss dB/km
Open-wire pair (0.3 cm diameter)	1 kHz	0.05
Twisted-wire pair (16 gauge)	10 kHz	2
	100 kHz	3
	300 kHz	6
Coaxial cable (1 cm diameter)	100 kHz	1
	1 MHz	2
	3 MHz	4
Coaxial cable (15 cm diameter)	100 MHz	1.5
Rectangular waveguide (5 × 2.5 cm)	10 GHz	5
Helical waveguide (5 cm diameter)	100 GHz	1.5
Fiber-optic cable	3.6×10^{14} Hz	2.5
	2.4×10^{14} Hz	0.5
	1.8×10^{14} Hz	0.2



- Besides, signal transmission by **radiowave propagation** can eliminate the long cables. It's commonly employed for long-distance communication at frequencies above about 100 MHz.

Outline

Communication System

- ❑ **Typical System**
- ❑ **Transmission Path**
- ❑ ***Industrial Communication***
- ❑ **Signal Modulation**
- ❑ **Error Control Methods**

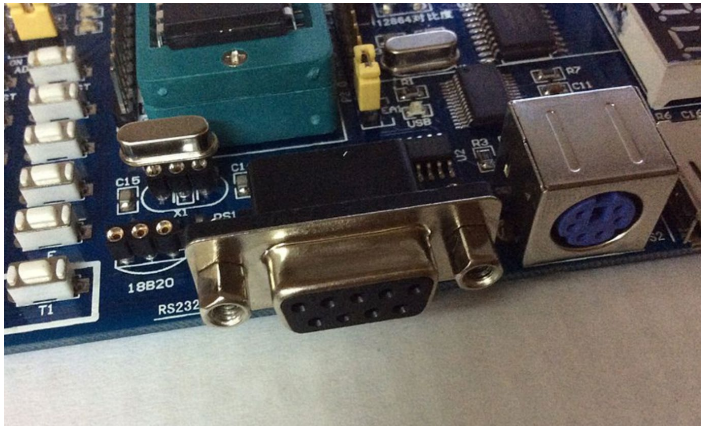
Industrial Communication

- It is critical in automation and control, ensuring that sensors, controllers (PLCs), and actuators coordinate reliably and in real time.
  - Effective communication improves efficiency, safety, and flexibility in manufacturing and process industries.
- Industrial communication methods can be categorized into
  - Serial communication (串口)
  - Fieldbus communication (现场总线)
  - Ethernet-based communication (以太网)
  - Wireless communication

Serial Communication

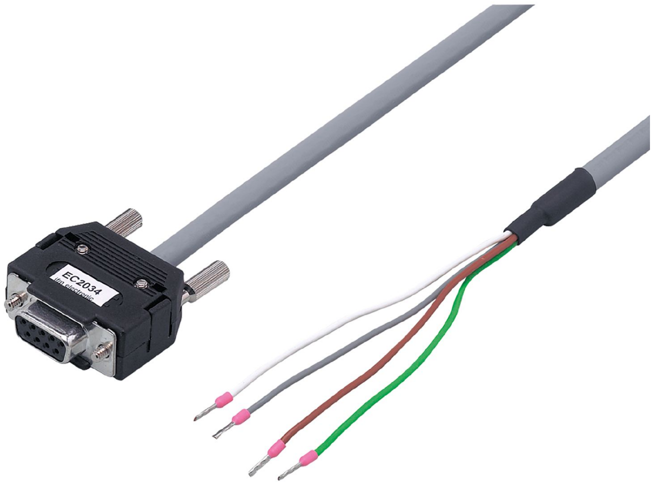
- Serial communication refers to sending data one bit at a time over a single channel.
  - It is simple and cost-effective for connecting industrial devices. Common serial communication includes RS-232, RS-485, and RS-422.

Type	Distribution	Speed	Distance
RS-232	Point-to-point	~115 kbps	15m
RS-422	One-way multi-drop	~10 Mbps	1200m
RS-485	Multi-drop	~10 Mbps	1200m



Fieldbus Communication

- Fieldbus protocols are industrial network systems designed for real-time distributed control, predating Ethernet. They replace bundles of point-to-point wires with a single serial bus that links multiple field devices (sensors, actuators, motors) to controllers, which have reduced wiring and improved reliability.
- Common fieldbus protocols include Modbus, Profibus, and **CAN Bus**

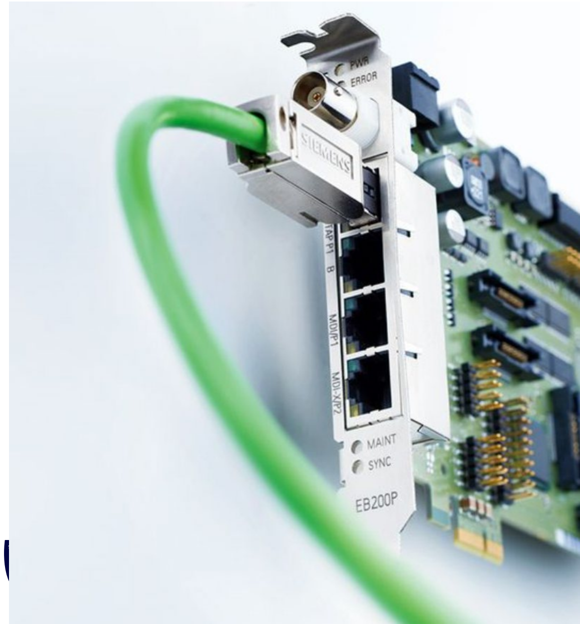


Fieldbus Communication – CAN Bus

- **C**ontroller **A**rea **N**etwork is a fieldbus originally developed for automotive use, now also common in industrial machinery. It is a message-based bus where each node (device) can broadcast frames to all others with priority arbitration
  - CAN provides error detection, fault confinement, and high reliability via differential signaling
  - Standard CAN bus operates up to 1 Mbps (distances of tens of meters), suitable for connecting microcontrollers, drives, or smart sensors in real-time.
  - CAN's benefit is its robustness and real-time capability – it excels at fast, short messages (e.g. sensor readings or motor commands) with very low latency, making it invaluable in vehicles and modern machines.

Ethernet-based Communication

- Ethernet-based industrial protocols leverage standard network technology (IEEE 802.3 Ethernet) for automation, combining high bandwidth and integration with enterprise networks.
- Traditional Ethernet had limitations for real-time control (due to nondeterministic collision handling), but modern standards and full-duplex switching have enabled Ethernet to meet industrial timing demands.
  - Fast speed: 100 Mbps or 1 Gbps



Wireless Communication

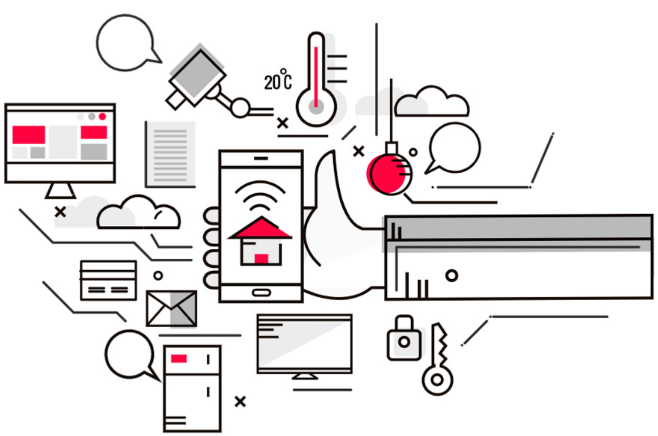
- Wireless communication methods are increasingly used in industrial settings to connect devices where cabling is impractical.
  - They enable mobility, easy retrofit of sensors, and connectivity across long distances or rotating equipment.
- Key wireless technologies in industry include Wi-Fi, Bluetooth, Zigbee, and 5G

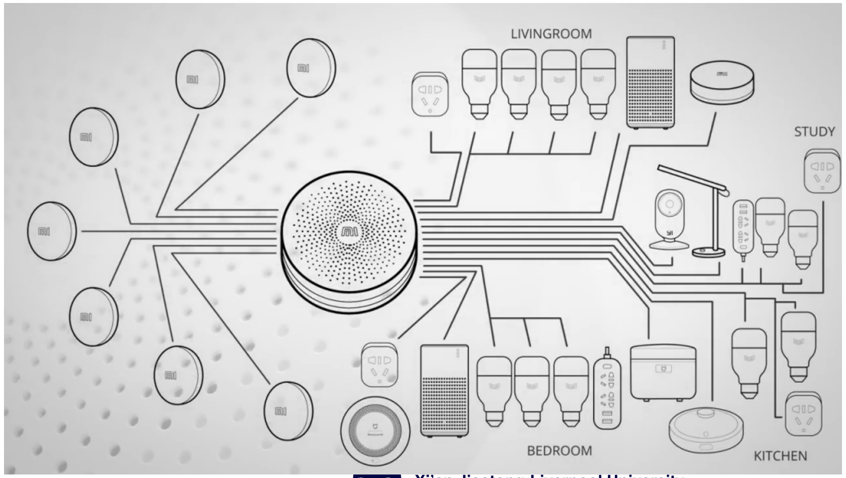
Wireless Communication – Zigbee

- Zigbee: A low-power, mesh networking protocol based on IEEE 802.15.4, widely used in industrial wireless sensor networks. Zigbee is designed for reliable, short-range communication with very low data rates and minimal energy use.
  - Ideal for IoT sensors that report periodically
  - In a Zigbee mesh, nodes can relay data for each other, extending coverage and providing redundancy.

zigbee

Xiaomi





Outline

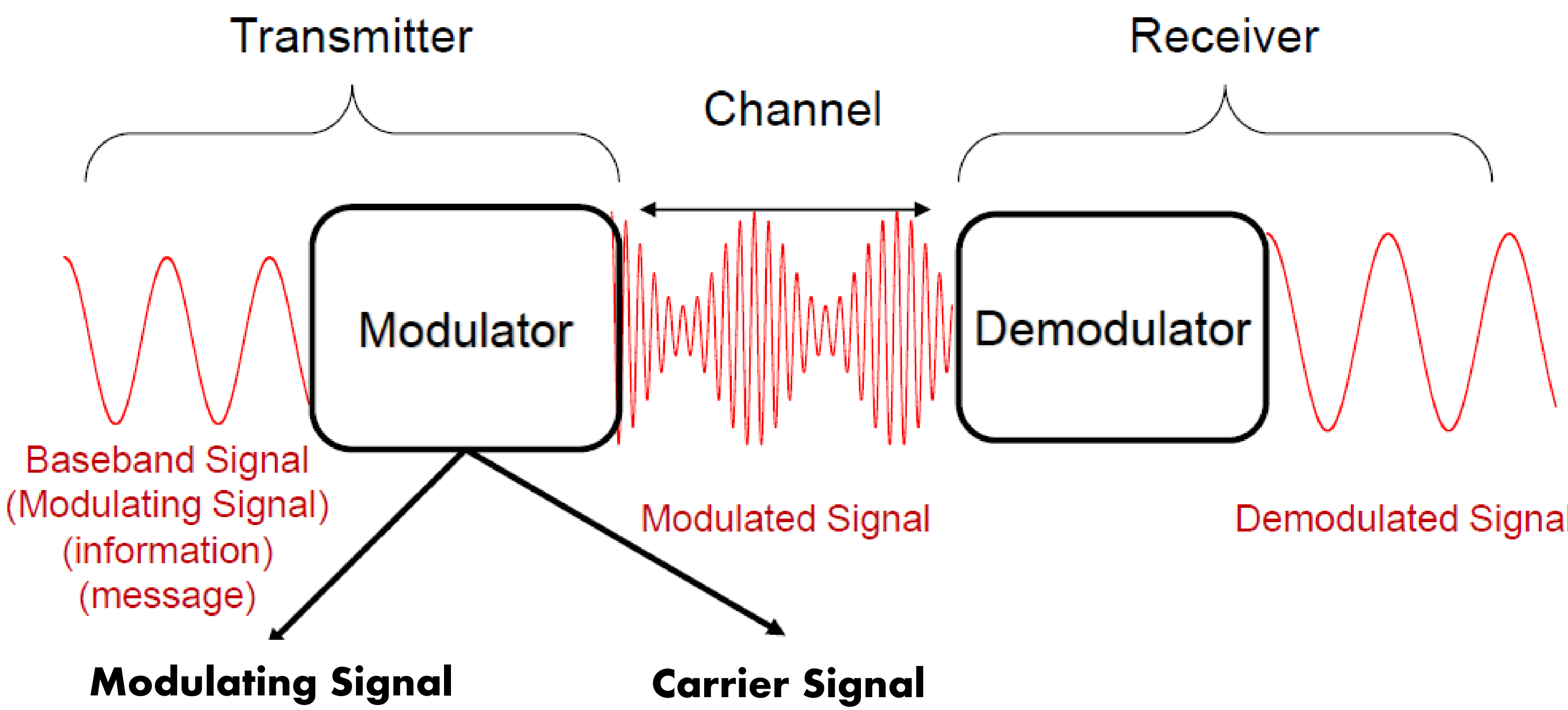
Communication System

- Typical System
- Transmission Path
- Industrial Communication
- *Signal Modulation*
- Error Control Methods

What is Modulation?

Modulations are operations performed at the transmitter to achieve efficient and reliable information transmission.

- Modulation involves two waveforms: a modulating signal that represents the message, and a carrier wave that suits the particular application;
- Modulation is a reversible operation, i.e., the message can be retrieved by the complementary process of **demodulation** at the receiver.



Why Modulation?

The primary purpose of modulation in a communication system is to generate a modulated signal suited to the characteristics of the transmission channel.

Practical benefits of modulation:

- ✓ **For efficient transmission**: signal transmission over appreciable distance always involves a traveling electromagnetic wave; the transmission efficiency depends upon the frequency of the signal been transmitted;
- ✓ **To overcome hardware limitations**: performance of hardware often depends upon the frequency involved, modulation permits designer to place a signal in some frequency range that avoids hardware limitations (cost and availability);
- ✓ **To reduce noise and interference**: certain types of modulation have the valuable property of suppressing both noise and interference;
- ✓ **For frequency assignment**: allows receiving many signals at the same time, but the desired signal can be separated from the other signals by filtering;
- ✓ **For multiplexing**: modulation allows multiplexing which is the process of combining several signals for simultaneous transmission on one channel.

Types of Modulation

Continuous-wave (CW) modulation system:

- **Amplitude Modulation (AM)**
- **Frequency Modulation (FM)**

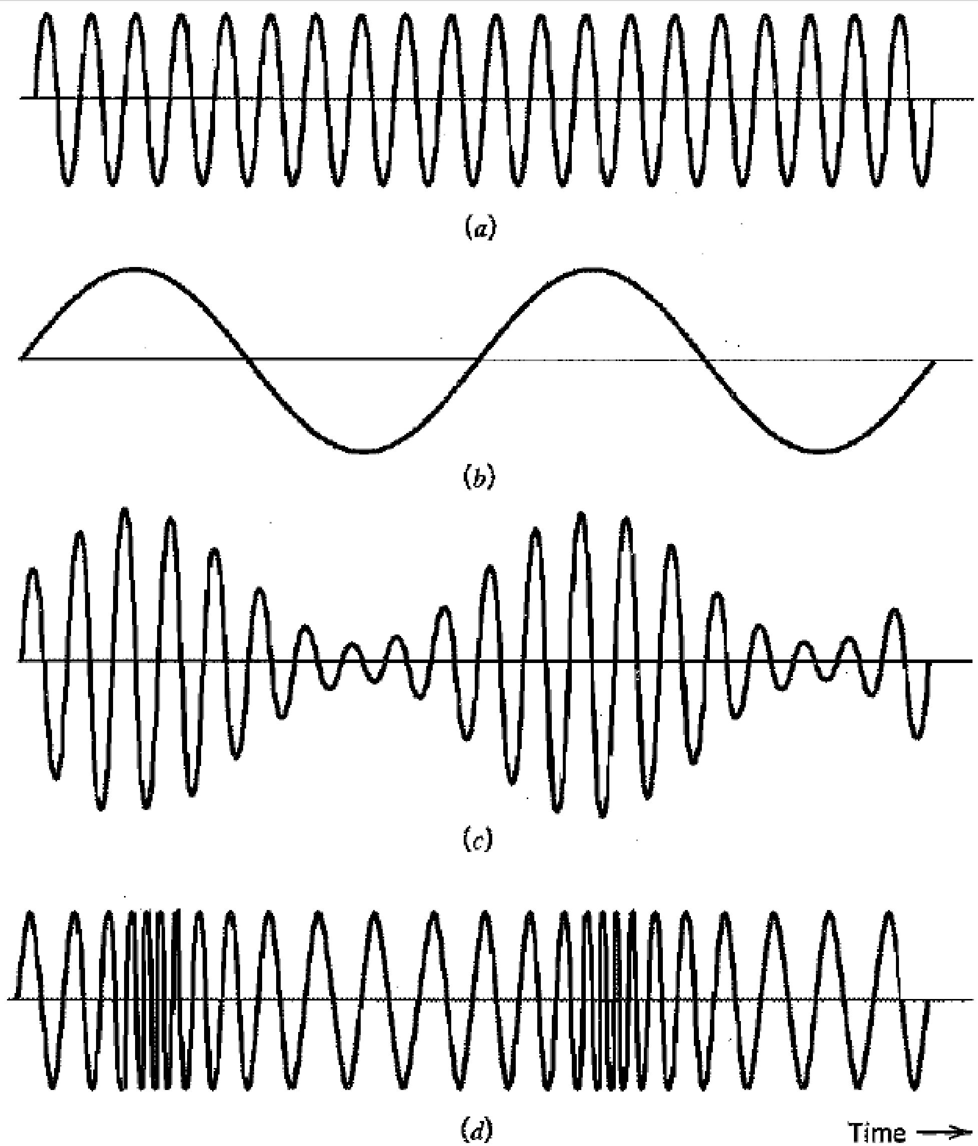
- The carrier in these systems is often a sinusoidal wave modulated by an analog signal (smooth and continuous).
- Involves direct frequency translation of the message spectrum.

Digital modulation system:

- **Pulse Code Modulation (PCM)**

- An electric signal satisfying certain requirements can be reproduced from an appropriate set of instantaneous samples;
- Sampling makes it possible to transmit a message in the form of pulses, rather than a continues signal.

AM vs. FM



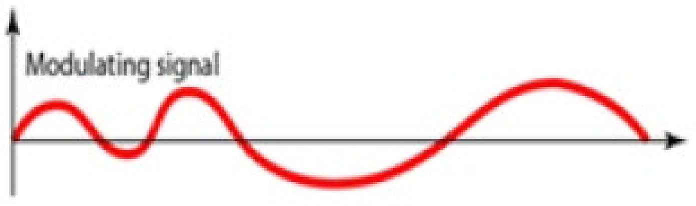
Carrier

Message

Amplitude Modulation signal

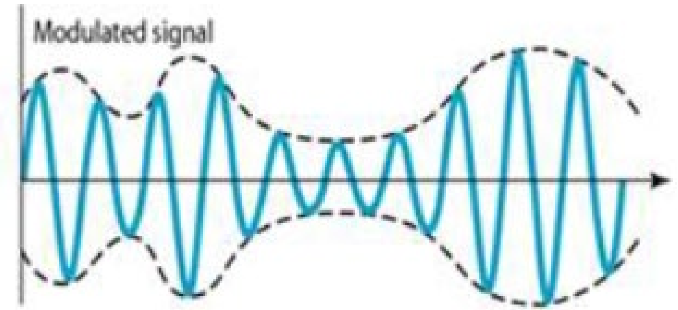
Frequency Modulation signal

Amplitude Modulation (AM)



Message (modulating signal)

Carrier



Modulated signal

The unique property of AM is that the **envelope** of the modulated signal has the same shape as the message.

Modulation Index

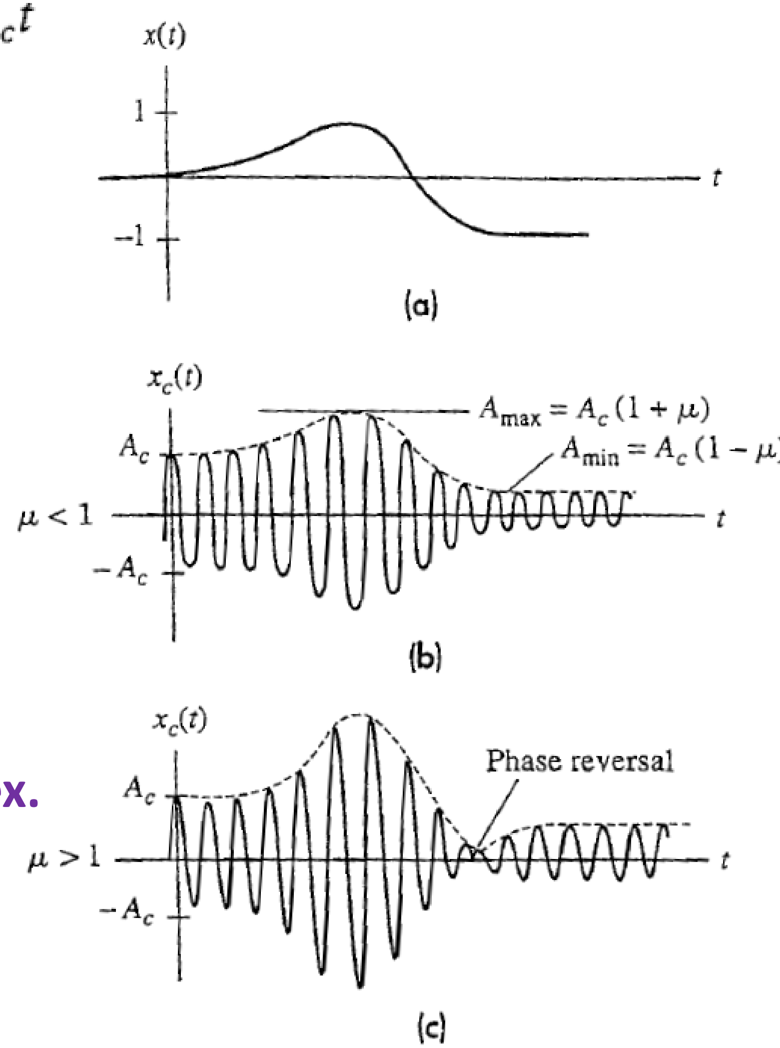
Assume message signal is $x(t)$, carrier is $A_c \cos \omega_c t$

Modulation by $x(t)$ produced the modulated envelop:

$$A(t) = A_c[1 + \mu x(t)]$$

Completed AM signal is:

$$x_c(t) = A_c[1 + \mu x(t)] \cos \omega_c t$$



***μ* is a positive constant called modulation index.**

μ < 1: Under-modulation.
μ > 1: Over-modulation with phase reversals and envelop distortions;

Frequency Modulation (FM)

Frequency modulation, or conversion, is also used to shift a modulated signal to a new carrier frequency (up or down) for amplification or other processing.

In this case, frequency of the output (modulated signal) (f_o) is varied with change in the amplitude of modulating signal (message)($A_m(t)$):

$$f_o(t) = f_c + kA_m(t)$$

where f_o = instantaneous modulated frequency
f_c = carrier frequency
A_m = modulating signal amplitude

$$\Delta f(t) = f_o(t) - f_c = kA_m(t)$$

Δf is called the frequency deviation.
Δf_{max} = $kA_{m,max}$ is the maximum frequency deviation.

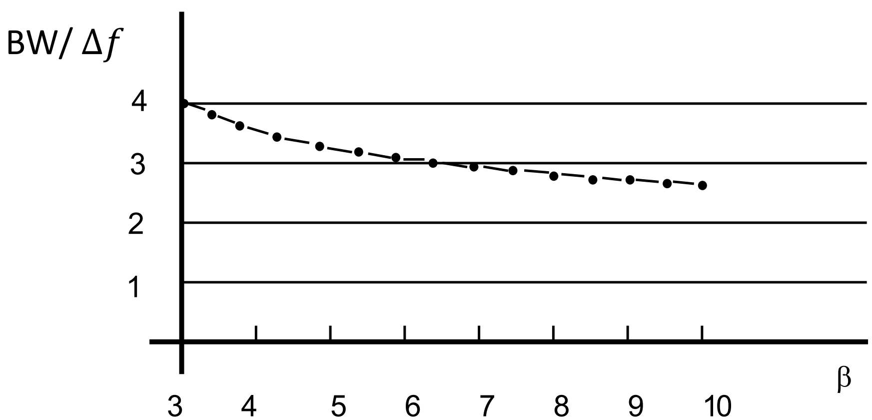
Frequency Modulation (FM)

The bandwidth (BW) occupied by an FM signal depends on the modulation index: β and is usually greater than for AM.

$$\boldsymbol{\beta} = \frac{maximum\ frequency\ deviation}{maximum\ frequency\ of modulating\ signal} = \frac{\Delta f_{max}}{f_m}$$

For β < 0.2, BW ~ $2f_m$ (same as AM)
For β > 10, BW ~ $2(\Delta f + f_m)$

For $\beta \in [3,10]$ the bandwidth can be estimated from the graph below.



Pulse Code Modulation (PCM)

Pulse Code modulation (PCM) converts continuous-time signal into a sequence of pulses (discrete-time signal).

Advantages:

- The transmitted power can be concentrated into short bursts instead of being generated continuously; thus the system designer has greater latitude for equipment selection, and may choose devices such as lasers and high-power microwave tubes that operates only on a pulsed basis;
- The time interval between pulses can be filed with sample values from other signals, a process called time-division multiplexing (TDM).

Disadvantages:

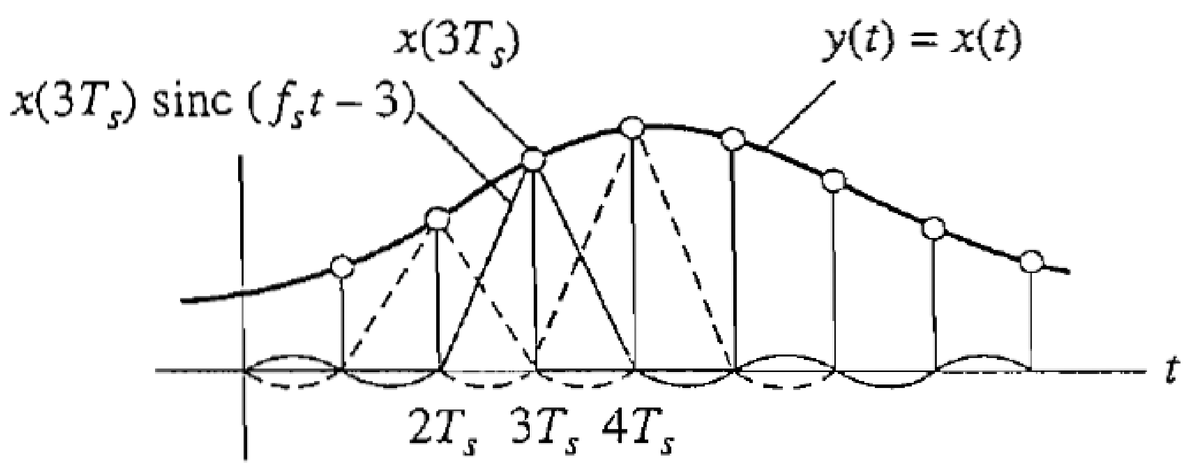
- Require very large transmission bandwidth compared to the message bandwidth.

Nyquist or Shannon's Sampling Theorem

Nyquist criterion or Shannon's sampling theorem:

When the signal is reconstructed from the samples, it is only when the sampling rate is at least **twice** that of the highest frequency in the analogue signal that the original analogue signal can be completely reconstructed.

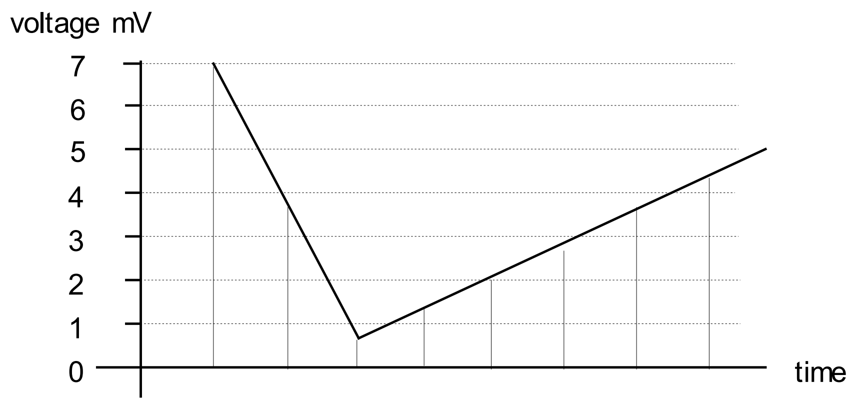
Nyquist rate: twice the highest frequency in the analogue signal.



Ideal reconstruction.

Covert to Binary Code

The sampled values are then converted into a binary number using an ADC (analogue to digital converter) so the samples are represented by groups of binary pulses, corresponding to the 0s and 1s.



Sampled voltages	7	3	0	1	2	2	3	4	(mV)
Binary equivalent	111	011	000	001	010	010	011	100	(3-bit code)

In practice, a code with more bits would be used. The number of bits (N) used to code the signal determines the **resolution** of the system.

$$Resolution = \frac{Signal\ Range}{2^N - 1}$$

Example 5.1

Consider a thermocouple giving an output of 0.5 mV/^{o}C, what will be the word length required when its output passes through an ADC if temperatures from 0^{o}C to 200^{o}C to be measured with a resolution of 0.5^{o}C?

The full-scale output from the sensor is:

$$200 \times 0.5 = 100\ mV$$

With a word length n, this voltage will be divided into $\frac{100}{2^n-1} mV$ steps.

For a resolution of 0.5^{o}C, we must be able to detect a signal from the sensor of:

$$0.5 \times 0.5 = 0.25\ mV$$

Thus we require:

$$0.25 = \frac{100}{2^n - 1}$$

Hence $n = 8.6$. Thus a 9-bit word length is required.

Outline

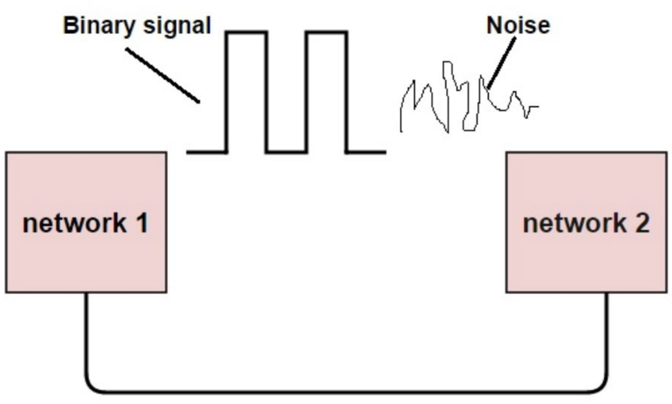
Communication System

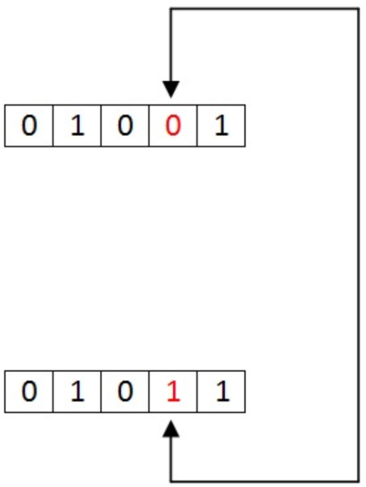
- ❑ **Typical System**
- ❑ **Transmission Path**
- ❑ **Industrial Communication**
- ❑ **Signal Modulation**
- ❑ ***Error Control Methods***

Data Transmission Error in Digital Systems

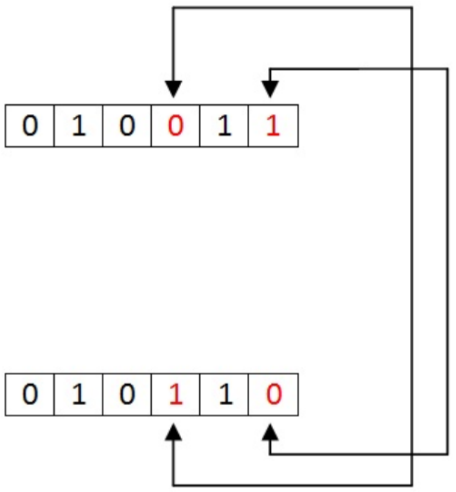
- In digital instrumentation systems, the analog signals will be changed into digital sequence (in the form of bits);
- The transmission of **digitised** information requires an acceptable bit error rate that depends on the accuracy required. For example, with speech an error rate of 1 in 10^5 bits is acceptable;
- The data errors will cause loss of important / secured data. In instrumentation systems, it is usually the case that any uncorrected error at all is a disaster - even one bit of change in data may affect the whole system's performance.

In many cases, methods of error control is essential.





Single bit error



Multiple bit error

Error Control Methods

Generally two approaches:

1. Feedback Error Control

- only contains sufficient information to detect when errors are present and then to request a re-transmission so that the information is sent again (e.g. **parity check**, block sum check etc.).

2. Forward Error Control

- each transmitted character or frame contains additional (redundant) information so that the receiver can not only detect when errors are present but also correct these errors (e.g. **Hamming codes**, **chain codes** etc.)

Both require an overhead that increases the number of bits sent and therefore increases the bandwidth of the transmission path required to achieve a given data rate.

Parity Check Code（奇偶检验码）

An extra bit is attached to the word and is made either 0 or 1 so that the total number of 1 in that word is always even (even parity).

If a single error occurs then the number of 1's becomes odd and a signal is sent back to the transmitter to request re-transmission of the word.

- Example:

Message (data word)	1010	
Code word (even parity)	10100	(parity bit: 0)
Code word (odd parity)	10101	(parity bit: 1)

The bandwidth requirement is increased only marginally provided the signal-to-noise ratio is high (so only a very few words need to be re-transmitted) :

$$BW = f_{max} \cdot (N + 1)$$

where f_{max} is the maximum frequency of signal, N is the number of bits required to represent the signal sample.

------ However it has limited error detection capabilities and no error correction is possible.

Even vs. Odd Parity

Even Parity（偶校验）

- If data has even number of 1's, the parity bit is 0. E.g. data is 10000001 -> parity bit 0
- Odd number of 1's, the parity bit is 1. E.g. data is 10010001 -> parity bit 1

Odd Parity（奇校验）

- If data has odd number of 1's, the parity bit is 0. E.g. data is 10011101 -> parity bit 0
- Even number of 1's, the parity bit is 1. E.g. data is 10010101 -> parity bit 1

3 bit data			Message with even parity		Message with odd parity	
A	B	C	Message	Parity	Message	Parity
0	0	0	000	0	000	1
0	0	1	001	1	001	0
0	1	0	010	1	010	0
0	1	1	011	0	011	1
1	0	0	100	1	100	0
1	0	1	101	0	101	1
1	1	0	110	0	110	1
1	1	1	111	1	111	0

Quiz 5.1

A thermocouple is used to measure temperature from 50 ^oC to 250 ^oC. The output voltage is then passed through an ADC for further transmission.

1) If 8 digits are used to represent the signal, what's the resolution of the system?
2) If the sensitivity of the thermocouple is 0.2 mV/ ^oC, to detect a signal of 0.1 mV, how many digits are required?

Thank You！