# Assignment Report

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# 1 Introduction

## 1.1 Transmission system

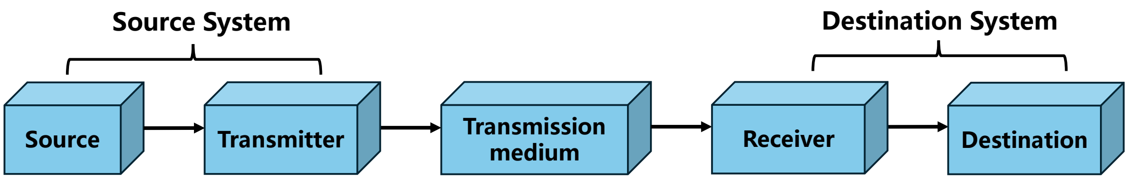



Figure 1: Block diagram of the transmission system

Figure 1 shows the block diagram of the transmission system.

- **Source:** The source convert the information into electrical signals. The source can be a microphone, a camera, a computer, etc.
- **Transmitter:** The transmitter converts the electrical signals into a form suitable for transmission over the channel. The transmitter can be a computer, a mobile phone, a router, etc.
- **Transmission medium:** The transmission medium is the physical path between the transmitter and receiver in a data transmission system. The transmission medium can be wired or wireless. The wired transmission medium includes twisted-pair cable, coaxial cable, and fiber-optic cable. The wireless transmission medium includes radio waves, microwaves, etc.
- **Receiver:** The receiver converts the transmitted signals back into the form that can be understood by the destination.
- **Destination:** The destination is the device that receives the transmitted signals and converts them back into the original form.

## 1.2 Transmission impairments

The most significant impairments are: **Attenuation and attenuation distortion, Delay distortion, Noise**.

### 1.2.1 Attenuation and attenuation distortion

The signal transmitted over any transmission channel will **continue to weaken in strength as the transmission distance grows**. For wired transmission, this reduction in intensity is called attenuation, and this usually changes exponentially. For wireless transmission, the factors leading to attenuation are more complex and depend on the composition of the atmosphere.

The energy loss in attenuation can primarily be categorized into two aspects: First, the energy of the signal is converted into other forms, such as heat; second, the energy in the signal is radiated away, resulting in a decrease in signal strength.

Attenuation distortion refers to the phenomenon where a signal gets distorted during transmission due to varying levels of attenuation across different frequencies. This distortion reduces the intelligibility of the received signal and is particularly noticeable in analog signals.

### 1.2.2 Delay distortion

Delay distortion is for wired transmission, wireless transmission is not affected by this. Delay distortion occurs because the propagation speed of a signal on a cable changes with different frequencies, with the propagation speed being fastest near the center frequency. For digital signals, delay distortion causes some frequencies of one bit to spill over into other bits, resulting in intersymbol interference (ISI). This distortion can be mitigated by using equalizers.

In multimode optical fiber transmission, delay distortion refers to the phenomenon where different modes of light waves propagate at different speeds, causing the output pulse to broaden relative to the input pulse. Figure 2 shows the delay distortion in multimode optical fiber transmission.

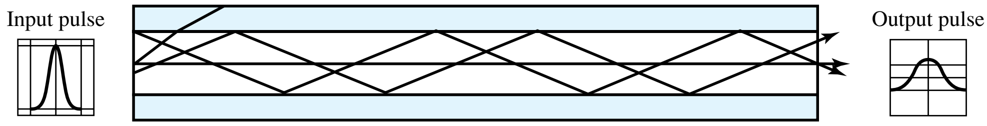



Figure 2: Delay distortion in multimode optical fiber transmission [1]

#### 1.2.3 Noise

Noise is referred as unwanted signals that are introduced into the transmission system between transmission and reception, which distort the received signal alongside the various distortions imposed by the transmission system itself. Noise is the major limiting factor in communications system performance. Noise can be divided into 4 catalogues: **Thermal noise, Intermodulation noise, Crosstalk, Impulse noise**.

**• Thermal noise**

Thermal noise is generated by the random motion of electrons in a conductor and is proportional to the conductor's temperature. This type of noise is uniformly distributed across the bandwidths typically used in communication systems, and hence it is often referred to as white noise. While thermal noise cannot be eliminated, it can be minimized by cooling the conductor. The thermal noise in watts present in a bandwidth of B Hertz can be expressed as:

$$N = kTB$$

where $k = 1.38 \times 10^{-23} J/K$ is Boltzmann's constant.

**• Intermodulation noise**

When signals of different frequencies share the same transmission medium, intermodulation noise is generated, which essentially produces additional signals at frequencies that are the sum or difference of the two original frequencies, or multiples of the original frequencies.

**• Crosstalk**

Crosstalk described the coupling phenomenon between two or more signal lines. It is caused by the electric coupling between adjacent twisted pairs carrying multiple signals.

**• Impulse noise**

Impulse noise is a random, instantaneous, high-amplitude signal that can be caused by various factors, such as lightning strikes, power line interference, and electromagnetic interference. The frequency and amplitude of the impulse signal are uncertain and **difficult to predict**, and the **randomness is particularly strong**.

# 2 Question and Solution

## 2.1 Question 1

### 2.1.1 Basic theory of twin-wire line

**(a) Distribution parameter effect**

When the geometric length L of the transmission line and the minimum wavelength $\lambda_{min}$ of the electromagnetic wave it transmits satisfy $L \geq \frac{\lambda_{min}}{100}$, the transmission line becomes a long line.

When high-frequency signals pass through the transmission line, a **distributed parameter effect** will occur. That is, there will be a series distributed inductance $L$ at each point along the line, the series distributed resistance

$R$ of the wire will increase, a parallel distributed capacitance $C$ will be generated between the lines, and a parallel distributed conductance $G$ will exist between the wires.

**(b) Transmission line equation**

Due to the existence of the distributed parameter effect, the transmission line can be regarded as a series of infinitely many circuit units, each with parameters $L, R, C, G$. The transmission line equation can be obtained using circuit analysis methods.

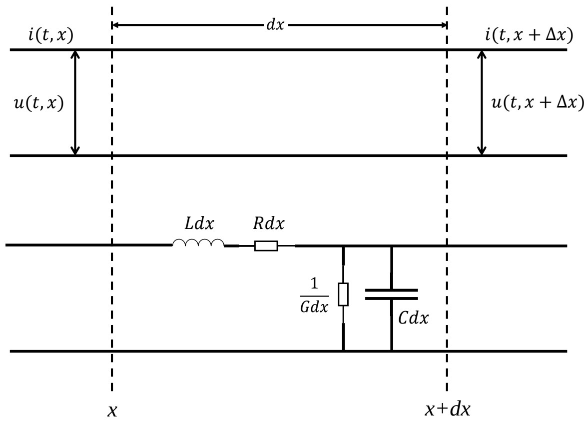



Figure 3: Equivalent circuit of transmission line

Figure 3 shows the equivalent circuit of the transmission line. According to the Kirchhoff's law:

$$\begin{cases} u(t,x) = u(t,x+\Delta x) + L\Delta x \frac{\partial i(t,x)}{\partial t} + R\Delta x \cdot i(t,x) \\ i(t,x) = i(t,x+\Delta x) + C\Delta x \frac{\partial u(t,x+\Delta x)}{\partial t} + G\Delta x \cdot u(t,x+\Delta x) \end{cases} \tag{1}$$

By simplifying Equation 1, it can obtain:

$$\begin{cases} \frac{u(t,x)-u(t,x+\Delta x)}{\Delta x} = L\frac{\partial i(t,x)}{\partial t} + R \cdot i(t,x) \\ \frac{i(t,x)-i(t,x+\Delta x)}{\Delta x} = C\frac{\partial u(t,x+\Delta x)}{\partial t} + G \cdot u(t,x+\Delta x) \end{cases}$$

let $\Delta x \to 0$, then:

$$\begin{cases} -\frac{\partial u(t,x)}{\partial x} = L\frac{\partial i(t,x)}{\partial t} + R \cdot i(t,x) \\ -\frac{\partial i(t,x)}{\partial x} = C\frac{\partial u(t,x)}{\partial t} + G \cdot u(t,x) \end{cases} \tag{2}$$

Equation 2 is called the **telegraph equation**. By rewriting the instantaneous values of voltage and current in the form of complex numbers, we can obtain:

$$\begin{cases} -\frac{\partial U}{\partial x} = (R + j\omega L) \cdot I \\ -\frac{\partial I}{\partial x} = (G + j\omega C) \cdot U \end{cases} \tag{3}$$

Equation 3 is the transmission line equation. It can be seen that the transmission line equation is a set of **first-order partial differential equations**. The solution of the transmission line equation can be obtained by solving the differential equations.

### 2.1.2 Basic characteristic parameters of the transmission line

Consider a sine wave propagating on a transmission line where the amplitude of the wave decreases with distance due to energy loss. The corresponding equation is:

$$v = Ve^{-\alpha x} sin(\omega t - \beta x)$$

where $v$ is the voltage at the point $x$ and time $t$, $V$ is the amplitude of the voltage, $\alpha$ is the attenuation constant, $\beta$ is the phase constant, $\omega$ is the angular frequency and $x$ is the distance from the reference point. Using a phasor representation:

$$\begin{cases} V_x = V_0 e^{(-\alpha + j\beta)x} \\ I_x = V_0 e^{(-\alpha + j\beta)x} \end{cases}$$

The expression $\alpha + j\beta$ is called the propagation constant and is given the symbol $\gamma$. Then the equation can be rewritten as:

$$\begin{cases} V_x = V_0 e^{-\gamma x} \\ I_x = V_0 e^{-\gamma x} \end{cases} \tag{4}$$

Differentiating Equation 4 with respect to $x$ gives:

$$\begin{cases} \frac{\partial V_x}{\partial x} = -\gamma V_0 e^{-\gamma x} = -\gamma V_x \\ \frac{\partial I_x}{\partial x} = -\gamma I_0 e^{-\gamma x} = -\gamma I_x \end{cases}$$

Combining this with Equation 2 gives:

$$\begin{cases} -\gamma V_x = (R + j\omega L) I_x \\ -\gamma I_x = (G + j\omega C) V_x \end{cases} \tag{5}$$

**(a) Characteristic impedance**

The characteristic impedance $Z_0$ of a transmission line is defined as **the ratio of the voltage to the current at any point on the line**. The characteristic impedance is given by:

$$Z_0 = \frac{V_x}{I_x} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{6}$$

**(b) Propagation constant**

The propagation constant $\gamma$ is defined as **the rate at which the amplitude of the wave decreases with distance**. Multiplying the sides of two equation in Equation 5 gives:

$$\gamma^2 V_x I_x = (R + j\omega L)(G + j\omega C) V_x I_x$$

Then we can get the propagation constant:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{7}$$

The propagation constant $\gamma$ describes the parameters of attenuation and phase change of the **incident wave** and **reflected wave** per unit length on the transmission line.

**(c) Reflecion coefficient**

The coefficient of reflection $\Gamma$ is defined as **the ratio of the reflected wave to the incident wave**. The coefficient of reflection is given by:

$$\Gamma = \frac{V_r}{V_i} = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{8}$$

where $Z_L$ is the load impedance.

- **When $\mathbf{Z_L = Z_0}$**: The transmission line is matched, and the reflection coefficient is zero.
- **When $\mathbf{Z_L > Z_0}$**: The reflected voltage phase is the same as the incident voltage.
- **When $\mathbf{Z_L < Z_0}$**: The reflected voltage phase is opposite to the incident voltage.

**(d) Voltage standing wave ratio, VSWR**

The voltage standing wave ratio (VSWR) is defined as **the ratio of the maximum voltage to the minimum voltage on the transmission line**. The VSWR is given by:

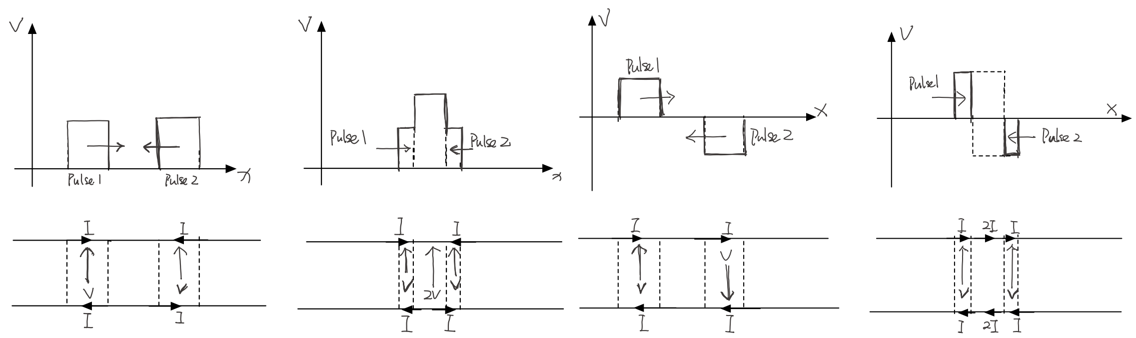
$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{9}$$

When the amplitudes of the incident wave and the reflected wave are the same, the signal cannot propagate, this type of wave is called **standing wave**. When the amplitude of the reflected wave is less than that of the incident wave, the signal can propagate, this type of wave is called **partial standing wave**.

### 2.1.3 Reflection

When the load resistance $Z_L$ is equal to the characteristic impedance $Z_0$, i.e., $Z_L = Z_0$, the transmission line is called a matched transmission line. At this time, there is no reflection of voltage and current waves on the transmission line, i.e., $\Gamma = 0$. When $Z_L \neq Z_0$, the transmission line is called an unmatched transmission line. At this time, the voltage and current waves on the transmission line will be reflected, i.e., $\Gamma \neq 0$. The case of impedance mismatch will be discussed below.

**(a) Two-way propagation of pulses**




(a) Same polarity (b) Opposite polarity

Figure 4: Two-way propagation of pulses

Figure 4 shows the two-way propagation of pulses. If the amplitudes of two rectangular pulses are in the same direction, the voltage adds and the current subtracts when they meet. If the amplitudes of the rectangular pulses are in opposite directions, the voltage subtracts and the current adds when they meet.

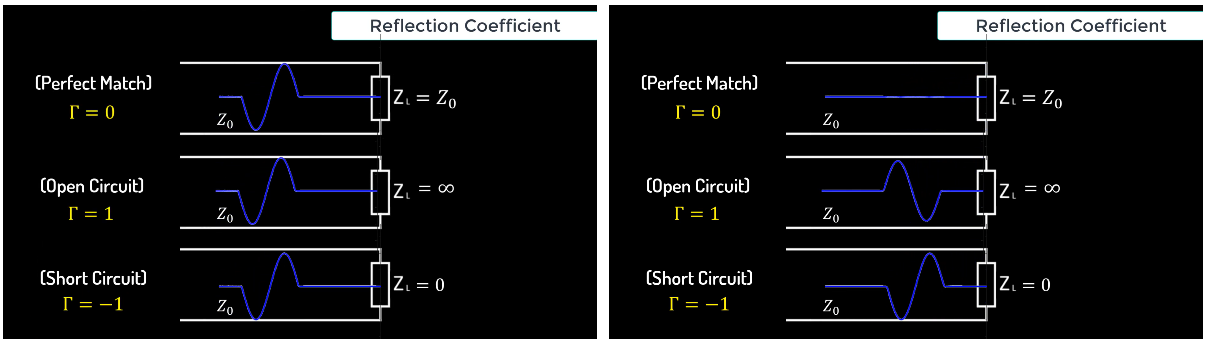
**(b) Terminal short circuit** $Z_L = 0$

When a pulse is transmitted on the transmission line and reaches the short-circuited terminal, the energy of the pulse cannot be absorbed due to the absence of resistance at the terminal.

When two pulses meet at the short circuit, current will flow with zero voltage, so that the subsequent propagation must be **two equal and opposite pulses**, one moving into the short circuit and the other moving out of it back along the line. The effect is **reflection with inversion**.

**(c) Terminal open circuit** $Z_L = \infty$

In this situation, the energy of the pulse cannot be absorbed at the end of the transmission line, so it is completely reflected. At the open circuit, **the current is zero**, but the voltage can be maintained. The reflected voltage signal is **in the same direction** as the incident voltage signal, this kind of reflection phenomenon is called **reflection without inversion**.




(a) Incident wave

(b) Reflected wave

Figure 5: Incident wave and reflected wave

### 2.1.4 Application features and instances

Twin-wire line is most commonly used as twisted pair. The following are the application features and instances of twin-wire lines.

#### (a) Application features

- **Low cost:** The cost of twin-wire lines is relatively low, making them suitable for use in various communication systems.
- **Simple structure:** The structure of twin-wire lines is simple, making them easy to install and maintain.
- **Strong anti-interference ability:** The twisting tends to decrease the crosstalk interference between adjacent pairs in a cable.
- **Short transmission distance:** Twin-wire lines are suitable for short-distance transmission, such as telephone lines.

#### (b) Application instances

- **Telephone lines:** Twin-wire lines are widely used in telephone lines for voice communication.
- **Local area network (LAN):** Twin-wire lines are used in LANs to connect computers and other devices.
- **Cable television (CATV):** Twin-wire lines are used in CATV systems to transmit television signals.
- **Digital subscriber line (DSL):** Twin-wire lines are used in DSL systems to provide high-speed Internet access.

## 2.2 Question 2

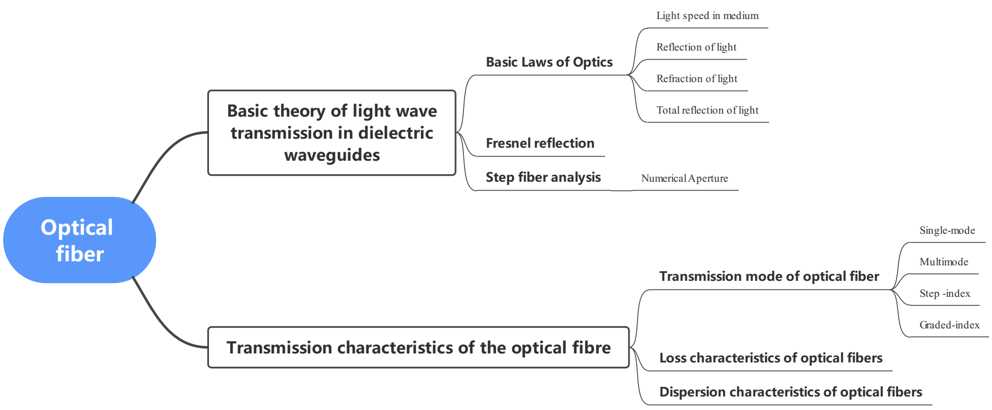



Figure 6: Mind map of optical fiber transmission system

### 2.2.1 Basic theory of light wave transmission in dielectric waveguides

**(a) Basic Laws of Optics**

The law of independent propagation of light states that when light rays from different light sources pass through a point in a medium in different directions, the light rays do not affect each other, as if the other light rays do not exist.

The laws of light's straight propagation, refraction, and reflection state that light travels in straight lines in an isotropic and uniform medium. When light encounters the interface of two different media during propagation, refraction and reflection phenomena occur. As shown in Figure 7, the speed of light in a uniform medium is:

$$v = \frac{c}{n}$$

where $c = 3 \times 10^8 m/s$ is the speed of light in a vacuum, and $n$ is the refractive index of the medium.

According to the **reflection definition**, the incident Angle of a ray is equal to the reflection Angle, the formula is: $\theta_1 = \theta_1'$.

According to the **refraction definition**, the incident Angle of a ray and the refraction Angle satisfy the Snell's Law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$.

When light travels from a denser medium to a less dense medium, if the angle of incidence is greater than a certain angle, the angle of reflection is 90 degrees. We call this phenomenon total internal reflection. The definition of **total internal reflection** is [3]: when light travels from a denser medium to a less dense medium, if the angle of incidence is greater than the critical angle, there is only reflection and no refraction. The critical angle $\theta_c$ for total internal reflection satisfies: $n_1 \sin \theta_c = n_2 \sin 90° = n_2$, so $\theta_c = \arcsin \frac{n_2}{n_1}$.

The total internal reflection have two features: First, the incident Angle is equal to the reflection Angle. Second, there is no loss of radiated power.

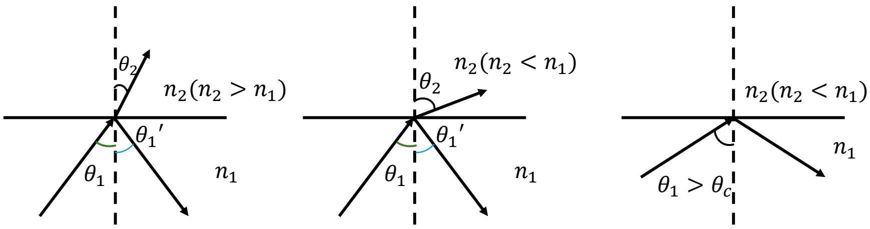



Figure 7: Reflection and refraction of light

**(b) Fresnel reflection**

Fresnel reflection refers to **the reflection phenomenon that occurs when light propagates at the interface of two materials with different refractive indices**. When light enters another medium with a different refractive index from one medium, it will not only refract, but also partially reflect back to the original medium. The intensity of Fresnel reflection depends on the refractive index difference between the two media. **The greater the difference in refractive index, the stronger the reflection**, and thus the greater the power loss.

**(c) Step fiber analysis**

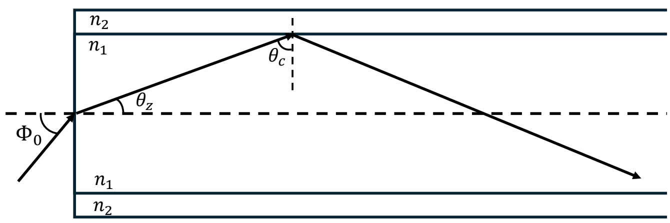



Figure 8: Meridian propagation in optical fiber

Figure 8 shows the case when the fiber within the fiber propagates along the meridian just to reach total reflection.

According to the law of refraction:

$$n_0 \sin \phi_0 = n_1 \sin \theta_z = n_1 \sin (90^\circ - \theta_c) = n_1 \cos \theta_\mathrm{c}$$
$$n_1 \cos \theta_c = n_1 \sqrt{1 - \sin^2 \theta_c} = n_1 \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = n_1 \sqrt{2\Delta} = \sqrt{n_1^2 - n_2^2} \tag{10}$$

where $\Delta = \frac{(n_1^2 - n_2^2)}{2n_1^2}$ is defined as the relative refractive index difference of optical fibers. Therefore, we consider $\Phi_0$ as the maximum incidence angle on the end face of the fiber core, and define the **numerical aperture (NA)** of the optical fiber as:

$$NA = n_0 sin \Phi_0 = n_1 \sqrt{2\Delta} = \sqrt{n_1^2 - n_2^2} \tag{11}$$

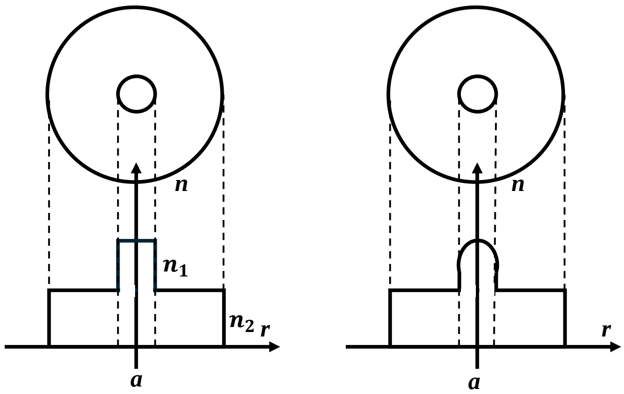
$NA$ characterizes **the ability of the optical fiber to collect light**, and it can be seen that $NA$ is ultimately related to $n_1$ and $n_2$. The larger the difference between $n_1$ and $n_2$, that is, the larger $\Delta$, the larger the numerical aperture of the optical fiber, and the stronger its light-collecting ability. However, **the numerical aperture of optical fibers used for communication is small, so they are called weakly guiding fibers**.

### 2.2.2 Transmission characteristics of the optical fibre

**(a) Transmission mode of optical fiber**

**• Classification by Refractive Index Distribution:**

According to the refractive index of the optical fiber, it can be divided into **graded-index fiber** and **step-index fiber**. The refractive index of graded-index fiber changes continuously along the radius of the fiber, while the refractive index of step-index fiber changes in sections along the radius of the fiber. Figure 9 shows the step-index fiber and graded-index fiber.



(a) Step-index fiber (b) Graded-index fiber

Figure 9: Step-index fiber and graded-index fiber

**• Classification by Number of Modes:**

According to the number of modes that can be transmitted, optical fibers can be divided into **single-mode fiber** and **multimode fiber**. Multimode fiber can transmit multiple modes of light, including higher-order modes, lower-order modes, and the fundamental mode. Single-mode fiber, on the other hand, can only transmit one mode of light, specifically the fundamental mode. But multimode optical fibers also have their advantages, ranging from ease of installation, cost, and lightsource compatibility.

Multimode fiber has multiple modes, each with a different transmission path. A signal might consist of waves with various frequencies, and since different frequencies travel at different speeds within the fiber, a phase difference will inevitably occur at the fiber's output. This leads to **pulse broadening (modal dispersion) and timing distortion**.

When the core radius decreases, the angles at which light can reflect within the fiber also decrease. By reducing the core radius to the order of the wavelength, only one angle (one mode) can propagate through the fiber, resulting in single-mode transmission. The core diameter of single-mode fiber is comparable to the wavelength of light. Single-mode fiber can provide superior performance because there is only one propagation path, eliminating the distortion caused by multimode propagation. Therefore, single-mode fiber is commonly used for **long-distance transmission**. But single-mode optical fibers have higher costs and complex installation.

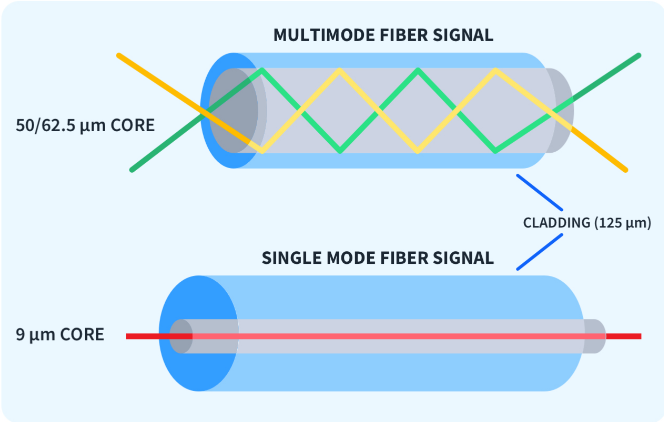



Figure 10: Single-mode fiber and multimode fiber [4]

**• Optical Fiber Transmission Modes**

Based on the above classifications, we can combine them to obtain three types of optical fiber transmission modes: **step-index multimode transmission, single-mode transmission, and graded-index multimode transmission**. Figure 11 shows the 3 transmission modes of optical fibers.

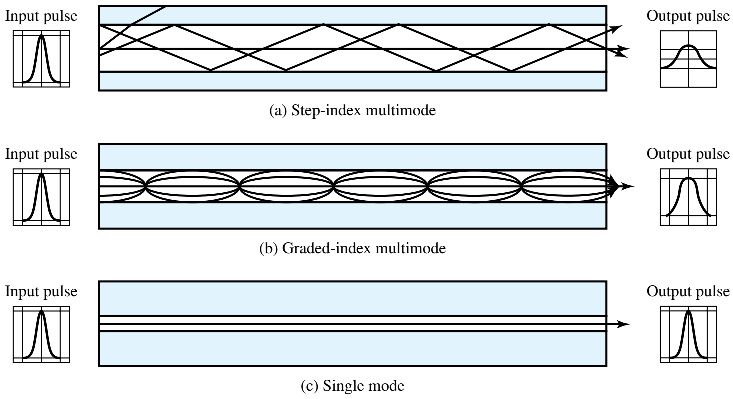



Figure 11: Optical fiber transmission modes [1]

**b) Loss characteristics of optical fibers**

The loss of optical fibers is mainly divided into two categories: **intrinsic loss** and **extrinsic loss**. Intrinsic loss is the transmission loss of the fiber itself, while extrinsic loss refers to the transmission loss caused by fiber use.

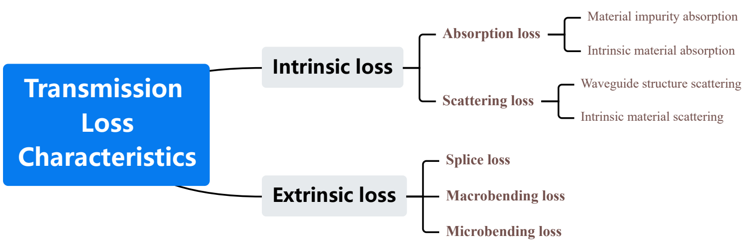



Figure 12: Transmission loss of optical fibers

Figure 12 shows the transmission loss of optical fibers. **Absorption loss** refers to the process where a portion of light energy is absorbed and converted into other forms of energy as light waves pass through optical fiber materials.

**Scattering loss** is the loss caused by the unevenness of the material radiating light energy out of the optical fiber. **Splice loss** refers to the energy loss of light waves due to the reflection and scattering caused by the non-smooth splicing part of the optical fiber when light waves pass through it. **Macro-bending loss** refers to the signal loss caused by light escaping from the fiber core when the optical fiber bends beyond its minimum bending radius. **Micro-bending loss** refers to the loss caused by nanoscale bending of the optical fiber axis.

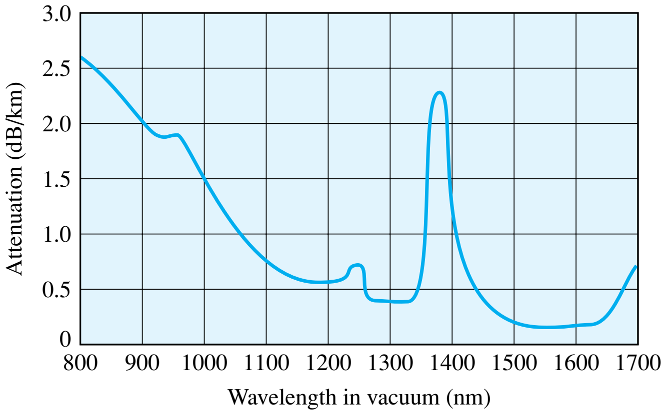



Figure 13: Spectrum curve of optical fiber loss [1]

Figure 13 shows the spectrum curve of optical fiber loss. In certain wavelength intervals, it's noticeable that the loss in fiber transmission is minimal. Therefore, three typical wavelength windows are defined as: **the first window 850nm, the second window 1310nm, and the third window 1550nm**.

#### c) Dispersion characteristics of optical fibers

Optical fiber dispersion refers to the distortion of signals transmitted by the fiber due to the different transmission speeds of different frequency components and different mode components. This dispersion causes the light pulse to broaden, affecting the shape of the signal. Depending on the cause of dispersion, the main types of fiber dispersion are: **mode dispersion, material dispersion, waveguide dispersion, and polarization mode dispersion (PMD) in single-mode fibers**.

**Mode dispersion** only exists in multimode fibers, where light of different modes has different group velocities along the fiber axis, causing pulse broadening upon reaching the terminal.

**Material dispersion** is a phenomenon where the refractive index of the fiber material changes with the wavelength of light, causing light of different wavelengths to have different propagation speeds in the fiber.

**Waveguide dispersion** is due to short-wavelength light mainly propagating in the fiber core, and long-wavelength light mainly propagating in the fiber cladding, causing light of different wavelengths to have different propagation speeds in the fiber, thus causing dispersion.

**Polarization mode dispersion (PMD) in single-mode fibers** is caused by the non-uniformity and stress of the fiber, which changes the refractive index of the fiber with the wavelength of light, causing light of different wavelengths to have different propagation speeds in the fiber, thus causing dispersion.

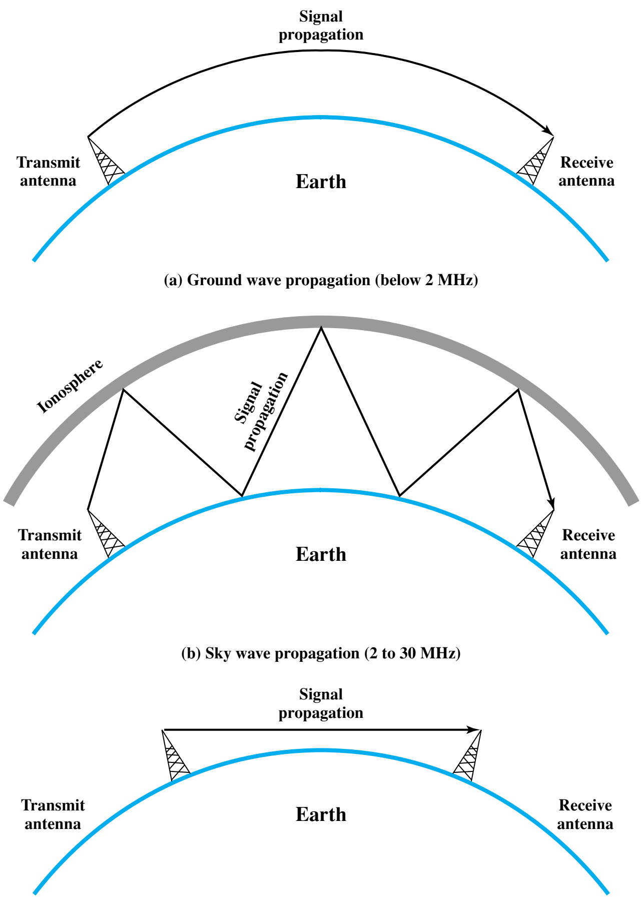
## 2.3 Question 3

A channel is the path for information transmission in communication. It is a general term in communication theory for the quality of information transmission between the transmitter and the receiver. It is an indispensable component of any communication system.

### 2.3.1 Transmission characteristics of the wireless channel

#### (a) Propagation mode of wireless channel

In wireless channels, the transmission of signals is achieved through the propagation of electromagnetic waves in the atmosphere. The electromagnetic waves emitted from the antenna will propagate along one of the following three paths: **ground wave, sky wave, or line of sight (LOS)**. Figure 14 shows the corresponding three propagation modes of wireless channels.



(a) Ground wave propagation (below 2 MHz)
(b) Sky wave propagation (2 to 30 MHz)
(c) Line-of-sight (LOS) propagation (above 30 MHz)

Figure 14: Propagation modes of wireless channels [1]

• **Ground wave propagation (below 2MHz)**

Ground wave propagation more or less follows the contour of the earth and can propagate considerable distances, well over the visual horizon. Electromagnetic waves with frequencies below **2MHz** can propagate along the surface of the earth beyond the visual horizon. This is due to the uneven density of the tropospheric atmosphere, which causes refraction of the electromagnetic waves during propagation.

• **Sky wave propagation (2MHz $\sim$ 30MHz)**

High-frequency electromagnetic waves (**2MHz $\sim$ 30MHz**) can be reflected once or several times by the **ionosphere**, and the communication distance can reach thousands of kilometers. This propagation method that **utilizes ionospheric reflection is called sky wave propagation**. However, due to the instability of the ionosphere, it is difficult to mathematically derive and model.

• **Line of sight (LOS) propagation (greater than 30MHz)**

When the frequency of the electromagnetic wave exceeds **30MHz**, the electromagnetic wave will propagate in a straight line, and the curvature of the earth will not affect the propagation of the electromagnetic wave. This is called line-of-sight propagation. The transmission distance of line-of-sight propagation is limited by the visual horizon, which is the farthest distance that can be seen by the human eye. The visual horizon is approximately $\mathbf{4.12\sqrt{h}}$ kilometers, where **h** is the height of the antenna in meters.

**(b) Radio wave propagation characteristics**

Different wavelengths correspond to different propagation methods, as previously mentioned and shown in Figure 14. However, they share the following common characteristics.

**1. Rectilinear propagation** The direction of the electromagnetic field is constant, and it continues to spread in the original direction.

**2. Reflection and refraction** When electromagnetic waves encounter obstacles, they will be reflected or refracted. The reflection and refraction of electromagnetic waves are determined by the refractive index of the medium.

**3. Interference of radio waves** When electromagnetic waves from the same source reach the receiving point via different paths, interference occurs. This phenomenon is known as **multipath effect**.

**4. Diffraction phenomenon** When electromagnetic waves encounter obstacles, they will bend around the obstacles and spread to the other side. This phenomenon is called diffraction.

**(c) Wireless Channel propagation loss**

The wireless propagation loss includes **free space loss, atmospheric absorption loss, rain-induced loss, and additional loss caused by refraction, scattering, diffraction, circuit layer scintillation, and multipath effects**. Among them, the most significant is the **free space propagation loss**, as electromagnetic waves in wireless communication mainly propagate in the free space of the atmosphere.

**• Free space loss**

Free space loss refers to the power attenuation of an electromagnetic wave as it travels through free space. This loss is primarily due to the divergence of the wave, resulting in a decrease in its power density as the distance increases.

**• Loss caused by natural phenomena**

This type of loss includes **atmospheric absorption loss**, **scattering loss caused by rain and fog**, **loss caused by atmospheric refraction**, and **loss caused by ionospheric and tropospheric scintillation**.

Only electromagnetic waves with very high frequencies (greater than $12GHz$) will be significantly affected by atmospheric absorption loss. Rain fade is caused by the scattering and absorption of electromagnetic waves by raindrops and fog, therefore, the communication system should reserve about $2dB$ of transmission power margin.

**• Loss caused by multipath propagation**

This loss is mentioned in previous paragraph, which name is **interference of radio waves**.

**(d) Wireless Channel Noise and fading**

**• Channel noise**

Based on its source, noise can be classified into man-made noise, natural noise, and internal noise. Based on its nature, noise can be categorized into single-frequency noise, pulse noise, and fluctuating noise. Fluctuating noise includes thermal noise, which, as mentioned in Section 1.2.3, should be the primary consideration when discussing the impact of noise on transmission systems.

**• Fading**

Fading refers to the phenomenon where the received signal strength fluctuates due to the interference of multiple signals. Fading can be divided into two types: **slow fading** and **fast fading**.

**Slow fading** It is also known as shadow fading, is caused by changes in the environment between the transmitter and receiver. This type of fading occurs over a period measured in seconds and tends to form and dissipate gradually.

**Fast fading** It is also known as multipath fading, is caused by the interference of multiple signals arriving at the receiver through different paths. This type of fading occurs over a period measured in milliseconds and tends to form and dissipate rapidly.

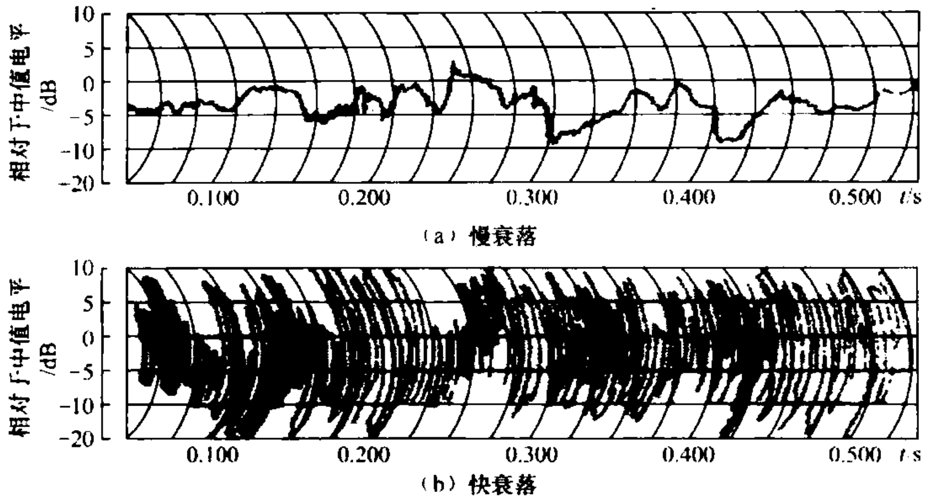



Figure 15: Fading diagram [2]

Figure 15 shows the fast fading and slow fading. It can be observed that the fast fading is more severe than the slow fading, and the fast fading is more likely to cause signal distortion and even signal loss.

### 2.3.2 Key factors of free space loss

In section 2.3.1 we have mentioned the free space loss, which is the most significant loss in wireless communication. Figure 16 shows the free space loss model.

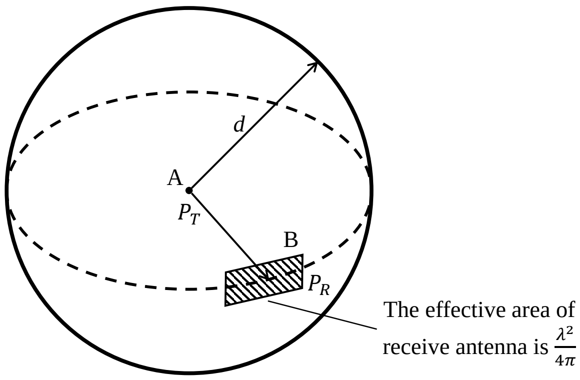



Figure 16: Free space loss model

Assume that the transmit power of point A (isotropic antenna) is $P_T$, the receive power of point B is $P_R$, the distance between point A and point B is $d$. The average power of the radio waves per unit area at the receiving point B is:

$$W_s = \frac{P_T}{4\pi d^2}$$

According to the antenna theory [5], the effective area of the isotropic antenna is $A = \frac{\lambda^2}{4\pi}$, where $\lambda$ is the wavelength of the radio wave. The power received by the receiving point B is:

$$P_R = W_s \cdot A = \frac{P_T}{4\pi d^2} \cdot \frac{\lambda^2}{4\pi}$$

The definition pf free space loss is:

$$
\begin{aligned}
[L_{\mathrm{P}}] &= 10\lg\frac{P_{\mathrm{T}}}{P_{\mathrm{R}}} = 10\lg\left(\frac{4\pi df}{c}\right)^2 (\mathrm{dB}) \\
&= 32.45 + 20\lg d(\mathrm{km}) + 20\lg f(\mathrm{MHz})
\end{aligned}
\tag{12}
$$

From equation 12, it can be seen that the key factors of free space loss are **the distance between the transmitter and receiver** and **the frequency of the radio wave**. The free space loss increases with the distance between the transmitter and receiver, and the frequency of the radio wave.

# 3 Conclusions

## 3.1 Basic concept of Telecommunication transmission

### 1. Definition of telecommunication

The definition of telecommunication is the transmission of signals over long distance, such as by telegraph, radio, or television. There are 4 basic types of medium: wire pair, coaxial cable, optical fiber, and radio wave.

### 2. A communication model

The communication model consists of source, transmitter, transmission medium, receiver, and destination. As shown in figure 1, the source generates the message, the transmitter encodes the message into signals, the transmission medium carries the signals, the receiver decodes the signals, and the destination receives the message.

### 3. Difference between transmission and propagation

Transmission refers to the process of sending and receiving signals, while propagation refers to the process of signal transmission in the medium. The transmission medium can be divided into guided media and unguided media.

### 4. Topology of the transmission system

The **star topology** and the **full-mesh topology** are the most common network structures. The star topology has a hierarchical concept with a central node being more important, while the full-mesh topology lacks a hierarchical concept. In layered networks, these two topologies are often used together. However, there is a current trend towards reducing the number of network layers, promoting a shift from hierarchical to flatter network architectures.

### 5. The decibel

The decibel(dB) is a measurement unit widely used in transmission systems. Gain is:

$$G(dB) = 10\lg\frac{P_2}{P_1}$$

The loss is:

$$L(dB) = 10\lg\frac{P_1}{P_2}$$

where $P_1$ is the input power, and $P_2$ is the output power. When calculating the gain, loss, and power level of a **series network**, you can directly add or subtract the gain of each node in the series network. When calculating a **parallel network**, convert the decibel value to a power value, add the power values, and then convert back to a decibel value.

### 6. Basic derived decibel units

The **dBm** is a unit of power measurement that represents the power level relative to 1 milliwatt. The **dBW** is a unit of power measurement that represents the power level relative to 1 watt, the dBW is used extensively in microwave applications.

$$P(dBm) = 10\lg\frac{P(mW)}{1mW}, \quad P(dBW) = 10\lg\frac{P(W)}{1W}$$

**7. The Neper**

$$N_p = \frac{1}{2}\ln\frac{P_2}{P_1}, \quad 1N_p = 8.686dB$$

## 3.2 Data Transmission in Telecommunication

### 3.2.1 Transmission Terminology

**Channel (Transmission media)** Channel can be classified as **wired and wireless**, the corresponding transmission media are **guided media and unguided media**. In both cases, communication is in the form of electromagnetic waves. The guided media includes twisted pair, coaxial cable, and optical fiber, while the unguided media includes radio waves and microwaves.

**Direct link** Direct link means the transmission path between two devices in which signals propagate directly from transmitter to receiver with no intermediate devices, other than amplifiers or repeaters used to increase signal strength.

**Simplex, half-duplex, and full-duplex** Duplexing is a description of the degree of sharing of the media.

**Frequency, Spectrum, and Bandwidth** The spectrum of a signal refers to the range of frequencies it contains. The **absolute bandwidth** of a signal is the width of its spectrum, which is the difference between the upper and lower frequency limits. Some signals have infinite bandwidth, but the majority of the signal's energy is concentrated within a relatively narrow frequency band, known as the **effective bandwidth**.

Any transmission system can only accommodate a limited range of frequencies, and this bandwidth limits the data transmission rate (bit rate).

### 3.2.2 Analog and digital data transmission

**Analog and Digital Signals** In communication systems, data is propagated from one point to another in the form of electromagnetic signals. The principal advantages of digital signaling are that it is generally cheaper than analog signaling and is less susceptible to noise interference. The principal disadvantage is that digital signals suffer more from attenuation than do analog signals.

The standard spectrum for a voice channel is $\boldsymbol{300Hz \sim 3400Hz}$, and the sampling frequency is $8000Hz$.

**Analog and Digital Transmission** For analog data, such as voice, quite a bit of distortion can be tolerated and the data remain intelligible. However, for digital data, cascaded amplifiers will introduce errors.

### 3.2.3 Transmission Impairments

The significant impairments in data transmission are **attenuation, distortion, and noise**. Section 1.2 has discussed the causes and effects of these impairments.

**Channel Capacity**

**Nyquist Bandwidth** With multilevel signaling, the Nyquist formulation becomes: $C = 2B\log_2 M$, where $M$ is the number of signal levels.

**Shannon Capacity** The Shannon capacity is: $C = B\log_2(1 + S/N)$, where $S/N$ is the signal-to-noise ratio.

## 3.3 Transmission Media(Guided Media)

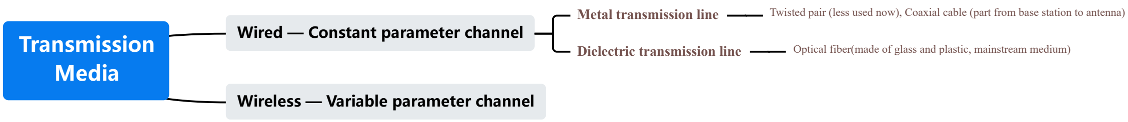
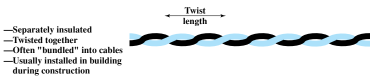
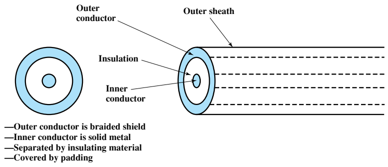


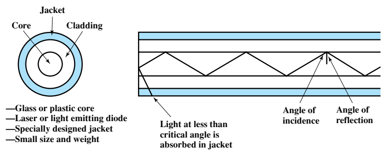

Figure 17: Transmission media




(a) Twisted pair




(b) Coaxial cable




(c) Optical fiber

Figure 18: Guided transmission media [1]

### 1. Twisted Pair

As shown in figure 18a, a twisted pair consists of two insulated copper wires arranged in a regular spiral pattern. **The twisting tends to decrease the crosstalk interference between adjacent pairs in a cable**.

Compared to other commonly used guided transmission media, twisted pair is limited in distance, bandwidth, and data rate. Twisted pair comes in two varieties: **unshielded and shielded**. Unshielded twisted pair (UTP) is the most commonly used type of twisted pair.

### 2. Coaxial Cable

Coaxial cable consists of a hollow outer cylindrical conductor that surrounds a single inner wire conductor. The application of coaxial cable are: Television distribution, Long-distance telephone transmission, Short-run computer system links and Local area networks.

### 3. Optical Fiber

Optical fiber is a transmission medium that uses light to carry information. The corresponding characteristics of optical fiber have been discussed in section 2.2.2.

## 3.4 Multiplexing Technologies

### 1. FDM

The two common forms of multiplexing are frequency division multiplexing (FDM) and time division multiplexing (TDM).

Frequency division multiplexing can be used with analog signals. A number of signals are carried simultaneously on the same medium by allocating to each signal a different frequency band.

### 2. Synchronous time division multiplexing

Synchronous Time Division Multiplexing is a method of transmitting multiple data streams simultaneously over the same communication medium. This is achieved by allocating a time slot to each data stream (user), whether or not there is data to transmit in that slot at a given moment. These time slots are combined into a frame for transmission. The effect is to interleave bits of data from the various sources.

**3. Statistical time division multiplexing (Asynchronous TDM)**

In Statistical Time Division Multiplexing (StatTDM), time slots are not pre-assigned to specific data sources. Instead, user data is buffered and transmitted as quickly as possible when there are available time slots. This allows for more efficient use of bandwidth, as time slots are only used when there is data to send, thereby reducing the waste of time slots.

## 3.5 Metal Transmission Line Theory and Applications

The propagation speed and wavelength of a wave in different media can change, but the frequency does not. The definition of **the driving point is**: the point at which useful signals are coupled into the transmission channel. The reference starting point can also be the starting point for research.

### 3.5.1 Twin-wire Transmission line

The definition of "long line": $L \geq \frac{\lambda_{min}}{100}$

**1. A Travelling Sinusoidal Wave on a Loss-Free Line**

The input voltage is

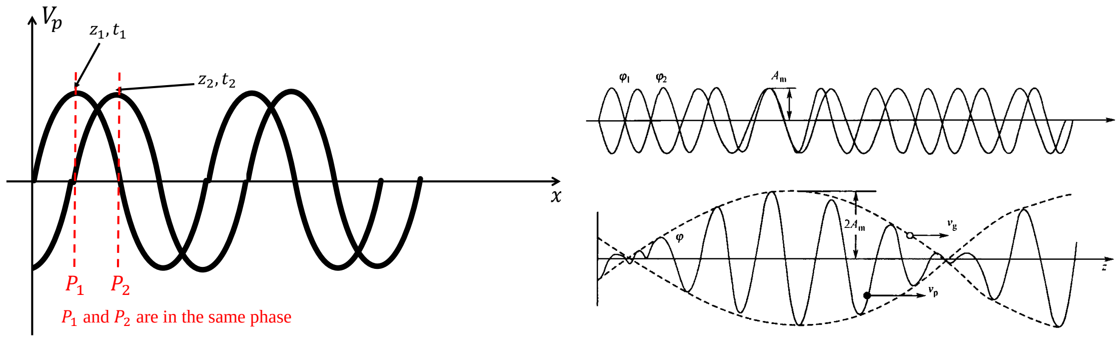
$$v = V sin(\omega t)$$

The voltage at a point on the transmission line is:

$$v = V sin(\omega t - \beta x)$$

where$\beta$ is called the phase change coefficient.

**2. Phase velocity and Group velocity**




(a) Phase velocity

(b) Group velocity

Figure 19: Phase velocity and Group velocity

Figure 19a shows the phase velocity. The phase velocity is the speed at which the phase of a single-frequency signal propagates in a certain direction, such as the phase movement speed of traveling wave voltage, current, etc., denoted as $v_p$.

$$v_p = \frac{\omega}{\beta} = \frac{2\pi f}{\beta} = \frac{\lambda}{T} = f\lambda$$

Figure 19b shows the group velocity. The group velocity is the speed at which the envelope of a modulated signal propagates in a certain direction, denoted as $v_g$.

$$v_g = \frac{d\omega}{d\beta} = \frac{d(2\pi f)}{d\beta} = \frac{d(\frac{c}{\lambda})}{d\beta} = \frac{c}{\lambda^2} = \frac{c}{f}$$

**3. A Travelling Sinusoidal Wave on a Practice Line**

$$v = Ve^{-\alpha x} sin(\omega t - \beta x)$$

where $\alpha$ is the attenuation coefficient, and $\beta$ is the phase change coefficient. This equation shows that the amplitude and phase of a single frequency wave will change during its propagation.

**4. Skin effect**

The skin effect refers to a phenomenon where the current distribution within a conductor is uneven when there is alternating current or an alternating electromagnetic field in the conductor. As the frequency of the electromagnetic wave increases, the charges will gather on the edges of the cross-section of the wire, leading to a hollowing effect in the center. Figure 20 shows the charge distribution in the conductor when the skin effect occurs.

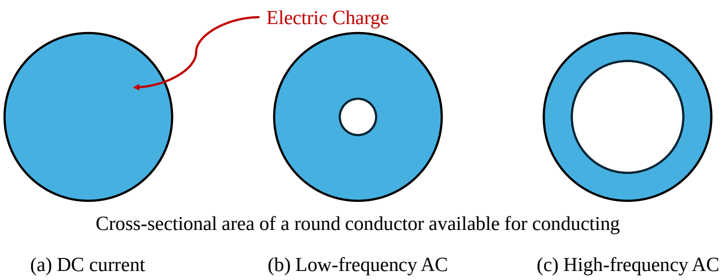



Figure 20: Skin effect

### 3.5.2 Basic theory of transmission line

The **characteristic impedance** is:

$$Z_0 = \frac{V_x}{I_x} = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

The **propagation constant** is:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

The other theory in detail are shown in section 2.1.1, section 2.1.2 and section 2.1.3.

## 3.6 Optical Transmission Line Theory and Applications

### 3.6.1 Structure and classification of optical fiber

As shown in figure 18c, optical fiber is consisted of **core, cladding, and jacket**. Core has a higher refractive index than cladding, and the light is confined to the core by total internal reflection. The jacket protects the fiber from mechanical and environmental damage.

**Classification by refractive index distribution** It can be divided into **graded-index fiber** and **step-index fiber**, the corresponding structure is shown in figure 9. Let $\Delta$ is the relative refractive index difference of optical fibers, for step-index fiber, $\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$, and for graded-index fiber, $\Delta = \frac{n^2(0) - n_2^2}{2n^2(0)}$.

**Classification by number of modes** It can be divided into **single-mode fiber** and **multimode fiber**. The core diameter of single-mode fiber is comparable to the wavelength of light, and the core diameter of multimode fiber is larger than the wavelength of light. Figure 10 shows the difference between single-mode fiber and multimode fiber.

**Light source** Two different types of light source are used in fiber optic systems: the **light-emitting diode (LED)** and the **injection laser diode (ILD)**.

### 3.6.2 Basic theory of optical fiber transmission

The basic parameters of an optical fiber can be considered to be: **light acceptance, light loss, bandwidth**.

**1.Refractive index**

$$n = \frac{\text{velocity of light in a vacuum}}{\text{velocity of light in the medium}}$$

**2. numerical aperture (NA)**

$$NA = n_1 \sin \Phi_0 = n_1 \sqrt{2\Delta} = \sqrt{n_1^2 - n_2^2}$$

**3. Loss characteristics of optical fibers**

The loss of optical fibers is mainly divided into two categories: **intrinsic loss** and **extrinsic loss**. The more detail is shown in section 2.2.2.

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