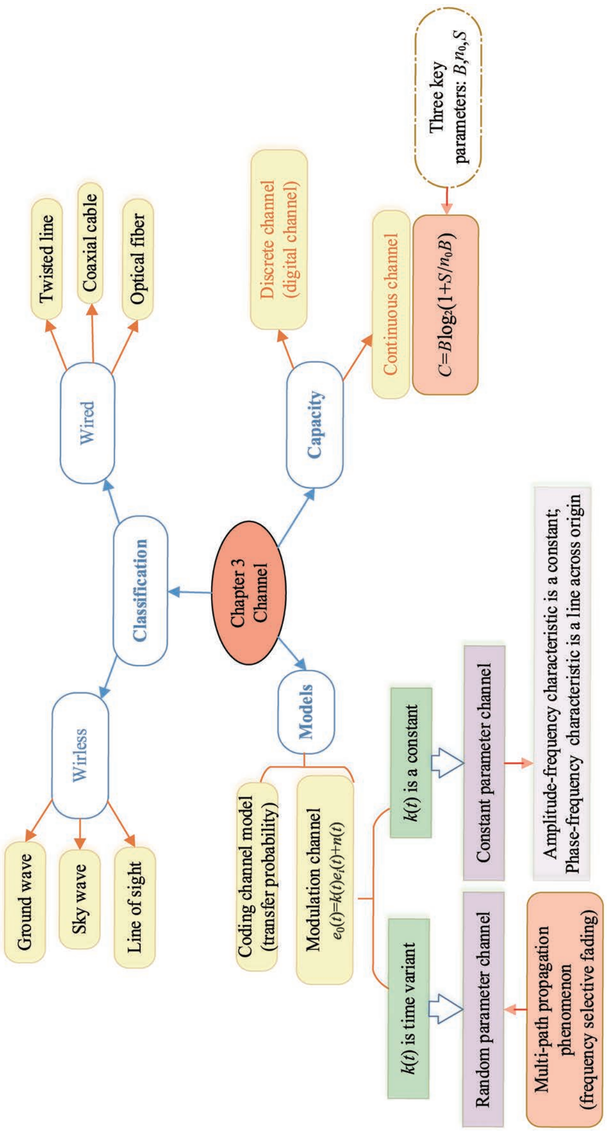
Chapter 3 Channel

Mind map:

Mind map for Chapter 3



In this chapter, the classification of the channel, the channel models, the noise in the channel and the capacity of channel will be introduced and discussed.

3.1 The classification of channels

视频讲解

According to the transmitted media, channels can be classified into two categories: wireless channel and wired channel.

3.1.1 Wireless channels

The transmission of signals in wireless channel is achieved by the propagation of electromagnetic waves in space. In principles, the electromagnetic wave of any frequency can be produced. For effectively transmitting and receiving, the frequency of the magnetic wave used for communications is usually rather high in practical applications.

According to different communication ranges, frequencies and locations, the electromagnetic wave propagation can be classified into three types: the line of sight (LOS: 视线) propagation, the ground wave(地波) and the sky wave(天波)(or called ionosphere reflection wave: 电离层反射波), as shown in Table 3.1.1. The sketch maps of these three propagations are shown in Figure 3.1.1.

Table 3.1.1 The comparison of three propagation modes

Type	Frequency range	Propagation mode	Propagation range
Ground wave	< 2MHz	Along the curved ground surface	Over hundreds to thousands of km
Sky wave	2～30MHz	Many reflections between ground and flayer	More than 10 000km
LOS	>30MHz	Line of sight	$D=\sqrt{50h}$ (km) →Satellite communication

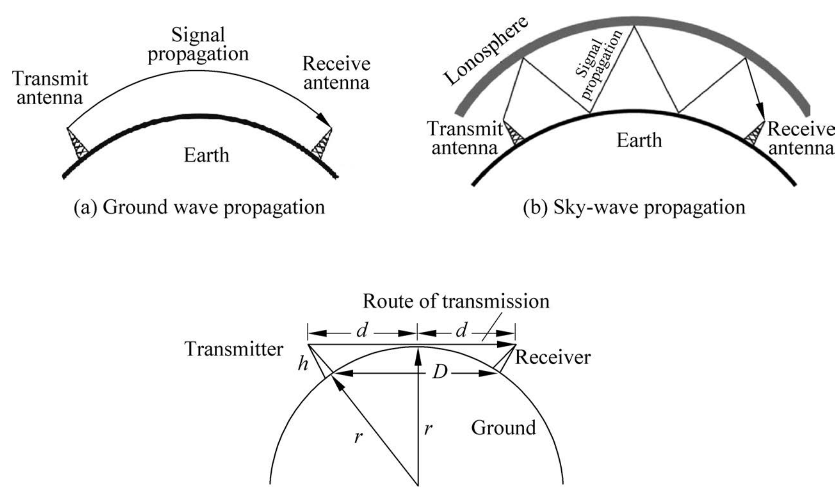


Figure 3.1.1 Sketch of three propagations

The propagation of electromagnetic wave in the atmosphere is influenced by the atmosphere. The relationship between the attenuation characteristics of the atmosphere and the frequency are shown in the following Figure 3.1.2.

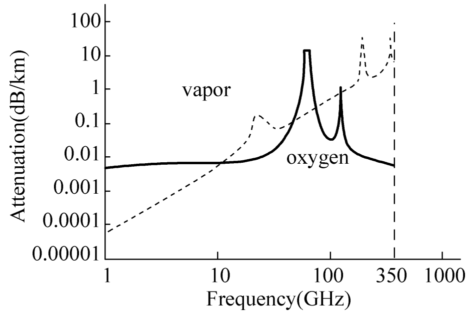


Figure 3.1.2 Attenuation of oxygen（氧气）and vapor（水蒸气）(concentration 7.5g/m^3)

3.1.2 Wire channel

There are three kinds of wired channels: symmetrical cables, coaxial cables and optical fibers.

Symmetrical cables is also called twist wire（双绞线）. The telephone channel is built using twist pairs for signal transmission. A twisted pair consists of two solid copper conductors, each of which is encased in a polyvinylchloride（PVC：聚氯乙烯）sheath. Twisted pairs are usually made up into cables, as in Figure 3.1.3, with each cable consisting of many pairs in close proximity to each other. Twisted pairs are naturally susceptible to electromagnetic interference（EMI：电磁干扰）.

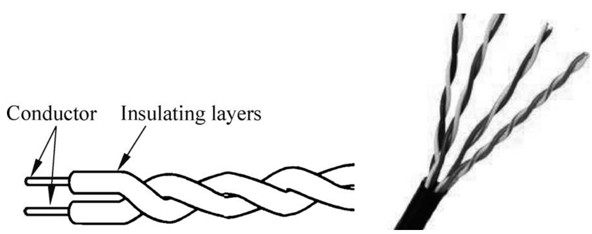


Figure 3.1.3 Twist wire

Typical coaxial cable（同轴电缆）has a characteristic impedance of 50 or 75 ohms. The composition of coaxial cable is shown in Figure 3.1.4. Compared to a twisted-pair cable, a coaxial cable offers a greater degree of immunity to EMI. The standard bite rate is 10Mb/s, which is higher than twisted pairs. The applications of coaxial cables are as the transmission medium for local area networks (LAN) and in cable-television systems.

The optical fiber is widely used for the transmission of light signals from one place to another. It can be classified into two categories: multi-mode and single-mode, as given in Figure 3.1.5.

Optical fibers have unique characteristic that make them highly attractive as a

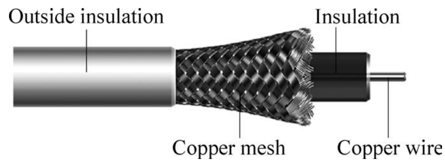


Figure 3.1.4 Coaxial cable

transmission medium. They offer the following unique characteristics:

- Enormous potential bandwidth.
- Low transmission losses.
- Immunity to EMI.
- Small size and weight.
- Ruggedness and flexibility.

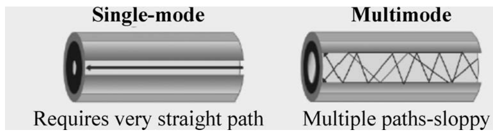


Figure 3.1.5 The structure of single-mode and multimode optical fiber

There are two minimum loss points at 1.31μm and 1.55μm from the following Figure 3.1.6. Therefore, these two wavelengths are widely used.

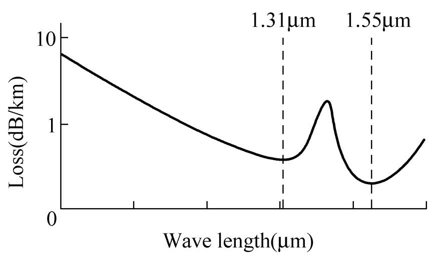


Figure 3.1.6 The relationship between loss and wavelength

3.2 Channel models

视频讲解

We have introduced two types of channels, how to describe the channels in mathematical tool is the content of this part. There are two basic channel models: one is for modulation, another one is for coding.

3.2.1 Modulation channel model（调制解调模型）

The basic modulation channel is defined as

$$e_o(t) = f[e_i(t)] + n(t) \tag{3.2.1}$$

where $e_i(t)$ is the signal voltage at the channel input terminal, $e_o(t)$ is the signal voltage at the channel output, and $n(t)$ is the noise voltage. Noise $n(t)$ always exists in the channel. It is usually called the additive noise because "+". The model is illustrated in Figure 3.2.1.

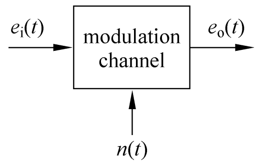


Figure 3.2.1 Modulation channel model

$f(\cdot)$ is the function between $e_i(t)$ and $e_o(t)$. For simplicity, we usually assume $f[e_i(t)] = k(t)e_i(t)$.

$k(t)$ is a complicated function and it reflects the characteristics of the channel.

$$k(t) = \begin{cases} \text{time variant} \Rightarrow \text{random parameter channels(随参信道)} \\ \text{constant} \Rightarrow \text{constant parameter channels(恒参信道)} \end{cases}$$

3.2.2 Coding channel model（编码信道模型）

The input and output signals of the coding channel are digital sequences in Figure 3.2.2.

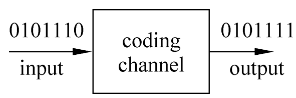


Figure 3.2.2 Coding channel

Error usually happens at the output because of interference. Therefore, the best method to describe this model is the error probability (错误概率). It is also called the transfer probability.

$P(0/0)$	transmitting 0 and receiving 0	Correct transfer probability
$P(1/1)$	transmitting 1 and receiving 1	
$P(1/0)$	transmitting 0 and receiving 1	Error transfer probability
$P(0/1)$	transmitting 1 and receiving 0	

For binary systems:

$$P(0/0) = 1 - P(1/0)$$
$$P(1/1) = 1 - P(0/1)$$

The model in Figure 3.2.3 is the simple binary coding memoryless channel model, in which the occurrence of errors in adjacent symbols is independent.

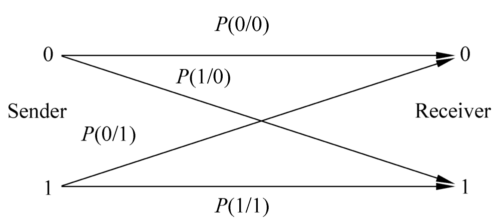


Figure 3.2.3 Binary coding channel model

3.3 Influence of the channel characteristics on transmission (for modulation model)

3.3.1 Influence of constant parameter channel on signal transmission

The main transmission characteristics of the transmission function are usually described by the amplitude-frequency characteristics (幅频特性) and phase-frequency characteristics (相频特性).

In practice, phase-frequency characteristic can also be described by group delay (群延迟).

The amplitude characteristic can be described by insertion loss (插入损耗). Figure 3.3.1 show the ideal amplitude-frequency and phase-frequency characteristics.

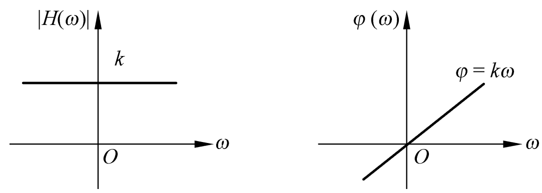


Figure 3.3.1 The ideal amplitude-frequency and phase-frequency characteristics

The definition of group delay is

$$\tau(\omega)=\frac{\mathrm{d}\varphi(\omega)}{\mathrm{d}\omega}$$

The plots of Figure 3.3.2 clearly illustrate the dispersive nature of the telephone channel.

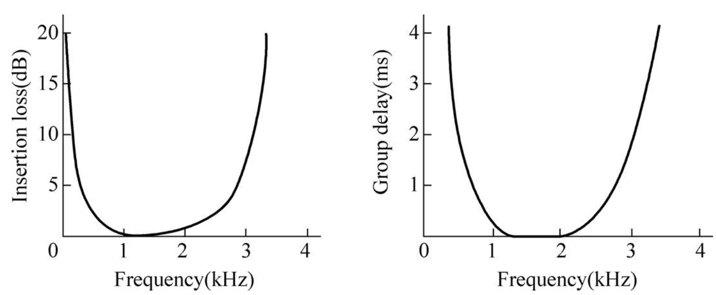


Figure 3.3.2 Characteristic of typical telephone connection

3.3.2 Influence of random parameter channel of signal transmission

There are there common characteristics:

(1) Transmission attenuation of the signal is varying with time;

(2) Transmission delay of the signal varies with time;

(3) Signal arrives at the receiver over several paths, i. e. multi-path propagation

phenomenon exists.

Multi-path will be discussed for its great influence on the quality of the signal transmission, the model of multipath is illustrated in Figure 3.3.3.

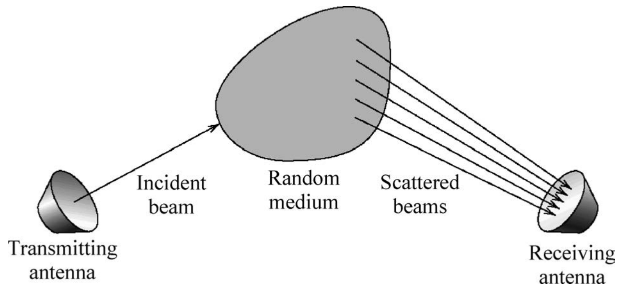


Figure 3.3.3 Model of a multipath channel

Suppose the transmitting signal is $A\cos\omega_0 t$, which is a common signal model in a communication system. When the signal propagates to the receiver over n paths, then the received signal $R(t)$ may be written as:

$$R(t)=\sum_{i=1}^{n}\mu_i(t)\cos\omega_0[t-\tau_i(t)]=\sum_{i=1}^{n}\mu_i(t)\cos[\omega_0 t+\varphi_i(t)] \qquad (3.3.1)$$

where

$$\left.\begin{array}{l}\mu_i(t) \text{ is the attenuation of } i\text{-th path}\\ \tau_i(t) \text{ is the delay of } i\text{-th path}\\ \varphi_i(t)=-\omega_0\tau_i(t)\end{array}\right\} \text{are random varying}$$

Equation (3.3.1) can also be written as:

$$R(t)=\sum_{i=1}^{n}\mu_i(t)\cos\varphi_i(t)\cos\omega_0 t-\sum_{i=1}^{n}\mu_i(t)\sin\varphi_i(t)\sin\omega_0 t \qquad (3.3.2)$$

Let

$$X_c(t)=\sum\mu_i\cos\varphi_i(t)$$

$$X_s(t)=\sum\mu_i\sin\varphi_i(t)$$

Then

$$R(t)=X_c(t)\cos\omega_0 t-X_s(t)\sin\omega_0 t=V(t)\cos[\omega_0 t+\varphi(t)]$$

where

$$V(t)=\sqrt{X_c^2(t)+X_s^2(t)}\text{—envelope}$$

$$\varphi(t)=\arctan\frac{X_s(t)}{X_c(t)}\text{—phase}$$

Comparing this eq. with the narrowband random process yields:

$$X(t)=X_c\cos\omega_c t-X_s\sin\omega_c t=a_x(t)\cos[\omega_c t+\varphi_x(t)]$$

So $R(t)$ can be regarded as a narrowband signal with random varying envelope and phase, as shown in Figure 3.3.4.

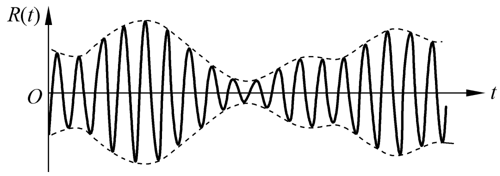


Figure 3.3.4 The narrowband signal

To simplify the problem, here we only discuss two paths of the multi-path propagation with the same attenuation and different delays.

Suppose the transmission signal is $f(t)$, the received signals are $Af(t-\tau_0)$ and $Af(t-\tau_0-\tau)$, respectively, where A is a constant.

Their corresponding Fourier transforms are

Input:

$$f(t) \Leftrightarrow F(\omega)$$
$$Af(t-\tau_0) \Leftrightarrow AF(\omega)\mathrm{e}^{-\mathrm{j}\omega\tau_0}$$
$$Af(t-\tau_0-\tau) \Leftrightarrow AF(\omega)\mathrm{e}^{-\mathrm{j}\omega(\tau_0+\tau)}$$

Output:

$$Af(t-\tau_0)+Af(t-\tau_0-\tau) \Leftrightarrow AF(\omega)\mathrm{e}^{-\mathrm{j}\omega\tau_0}(1+\mathrm{e}^{-\mathrm{j}\omega\tau})$$

Therefore, the transfer function of the two paths channel is

$$H(\omega)=A\mathrm{e}^{-\mathrm{j}\omega\tau_0}(1+\mathrm{e}^{-\mathrm{j}\omega\tau})$$
$$\begin{aligned}|H(\omega)| &= |A\mathrm{e}^{-\mathrm{j}\omega\tau_0}(1+\mathrm{e}^{-\mathrm{j}\omega\tau})| \\ &= A\,|1+\mathrm{e}^{-\mathrm{j}\omega\tau}| \\ &= A\,|1+\cos\omega\tau-\mathrm{j}\sin\omega\tau| = A\sqrt{(1+\cos\omega\tau)^2+\sin^2\omega\tau} = 2A\left|\cos\frac{\omega\tau}{2}\right|\end{aligned}$$

The curve drawn according to the above equation is shown in Figure 3.3.5.

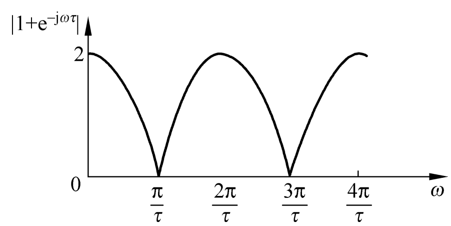


Figure 3.3.5 Multipath effect

From the above curve, we consider that fading is related to the frequency, it is called **frequency selective fading** (频率选择性衰落).

Figure 3.3.6 illustrates the effect of Rayleigh fading on the waveform of the received signal, whose amplitude and phase components vary randomly with time.

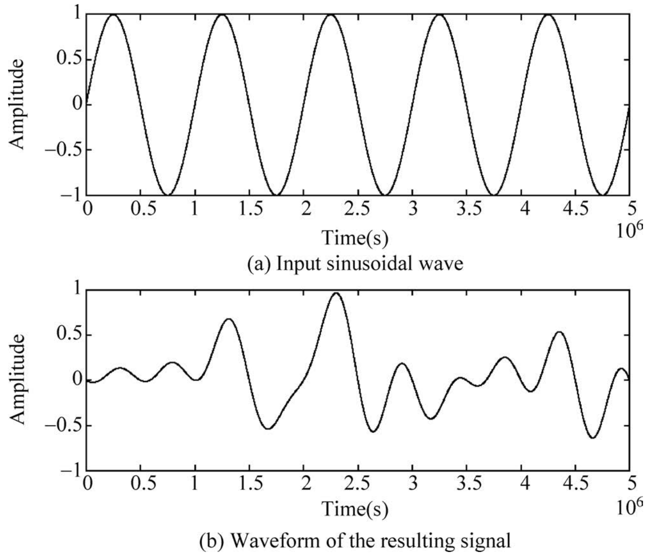


Figure 3.3.6 Effect of Rayleigh fading on a sinusoidal wave

视频讲解

3.4 Channel capacity（continuous channel）

The information capacity of a continuous channel of bandwidth BHz, with the addictive white Gaussian noise of PSD $\frac{n_0}{2}$ and limited in B, is given by

$$C_t = B\log_2\left(1+\frac{S}{n_0 B}\right)\text{(b/s)} \tag{3.4.1}$$

where S is the average transmitted power.

There are three key system parameters: channel bandwidth (B), average transmitted power (S) and the noise power spectral density ($n_0/2$).

(1) When S increases or n_0 decreases, C increases.

(2) When $B \to \infty$, C_t approaches to the following limit:

$$\begin{aligned}\lim_{B\to\infty} C_t &= \lim_{x\to 0}\frac{S}{n_0}\frac{Bn_0}{S}\log_2\left(1+\frac{S}{n_0 B}\right)\\ &= \lim_{x\to 0}\frac{S}{n_0}\log_2(1+x)^{1/x} = \frac{S}{n_0}\log_2 \mathrm{e} \approx 1.44\frac{S}{n_0}\end{aligned}$$

The channel capacity approaches 1.44 times of signal power to noise PSD ratio.

Example 3.4.1: A frame of black and white TV image is composed of 300 thousand pixels, each pixel has 10 levels of brightness and these 10 levels occur at equal probabilities. If the image is transmitted at a rate of 25 frames per second, the image signal to noise ratio is required to reach 30dB, find the required transmission bandwidth.

Answer: Since each pixel takes 10 possible levels with equal probability, the information content of each pixel I_p is

$$I_p = \log_2 10 = 3.32(\mathrm{b/pixel})$$

The information content I_f of each image frame is

$$I_f = 30\,000 \times 3.32 = 9.96 \times 10^5(\mathrm{b/frame})$$

Since there are 25 frames of image per second, the required information transmission rate is

$$I_f \times 25 = 9.96 \times 25 \times 10^5 = 24.9 \times 10^6(\mathrm{b/s})$$

According to the formula

$$C = B\log_2(1 + S/N)$$

$$24.9 \times 10^6 = B\log_2(1 + 10^3) = 9.96B$$

The bandwidth is:

$$B = 24.9 \times 10^6/9.96 = 2.5(\mathrm{MHz})$$

Summary and discussion

Channel plays a very important role in the communication system, which also is the basis of the following chapters. The classification of the channel is given in this chapter. Three main wireless channels are the line of sight (LOS: 视线) propagation, the ground wave(地波) and the sky-wave(天波). There are also three main kinds of wired channels: symmetrical cables, coaxial cables and optical fibers. Nowadays, these channels are widely used, and they have affected our daily lives, due to their wide range of applications.

It is important to understand two mathematics models of channel. Modulation channel model is usually regarded as analog channel. The multiplicative noise and additive noise are used to reflect the channel effect. Multiplicative noise $k(t)$ can cause signal distortion, including linear distortion, non-linear distortion, time delay and attenuation. Depending on the $k(t)$ being a constant or time varying, constant parameter channel and random parameter channel are distinguished. The influence of random parameter channel on signal is multipath effect, which can cause the frequency selective fading of the signal. Additive noise always exists in communication systems. Thermal noise is usually called white noise. We mainly discuss the influence of the white noise, especially the Gaussian white noise in this book.

Coding channel model is usually viewed as digital channel. Both additive noise and multiplicative noise influence the coding channel. Error probability is used to describe this kind of channels, which is also called the transfer probability.

There is a Shannon-Hartley theorem (香农定理) about continuous channel capacity:

$$C_t = B\log_2\left(1 + \frac{S}{n_0 B}\right)(\mathrm{b/s})$$

C_t represents maximal information rate which can be transmitted by the channel, and its unit is b/s. The bandwidth and SNR can be traded off. If the bandwidth is increased then the SNR decreases and the capacity remains unchanged. This trade-off relationship has very steering significance in the design of communication systems. This trade off cannot be naturally achieved. It required that the signal is modulated or encoded to increase its occupied bandwidth, and then it is sent to the channel for transmission corresponding to demodulation for decoding at the receiver.

Homework

3.1 Assume a wireless link uses line-of-sight propagation for communication, and the heights of the transmitting antenna and the receiving antenna are both 80m. Find the maximum communication distance.

3.2 A voice-grade channel of the telephone network has a bandwidth of 3.4kHz.

(1) Calculate the information capacity of the telephone channel for a signal-to-noise ratio of 30dB.

(2) Calculate the minimum SNR required to support information transmission through the telephone channel at the rate of 9600b/s.

Vocabulary and terminologies

attenuation	衰减	coaxial cable	同轴电缆
copper	铜	constant parameter channel	恒参信道
channel	信道	EMI	电磁干扰
electromagnetic	电磁的	frequency selective fading	频率选择性衰落
fiber	光纤	ground wave	地波
interference	干扰	group delay	群延时
oxygen	氧气	insert loss	插入损耗
propagation	传播	multipath effect	多径效应
surface	表面	random parameter channel	随参信道
terminal	终端	sky wave	天波
vapor	水蒸气	transfer probability	转移概率
wireless	无线	twist wire	双绞线
channel capacity	信道容量		