Chapter 2. Radio transmission channels

2.1-Temporal and frequency behavior of radio channels

Compared to wireline channels, the wireless channels vary over time and frequency depending on the objects surrounding the transmitter, the radiated area and the receiver. The variations of the channel strength can be divided into two classes:

2.1.1-Large-scale fading: coming from the path loss due to the distance between the transmitter and the receiver (typically higher than 100 m) and the shadowing due to the obstacles (typically few meters to 100 m).

2.1.2-Small-scale fading: the transmitted signal could arrive at the receiver through multiple paths, which experience different attenuations, arrive at different time delays and phases. It results in constructive or destructive summation of the transmitted signal and causes rapid variations. As shown in fig.2.1.

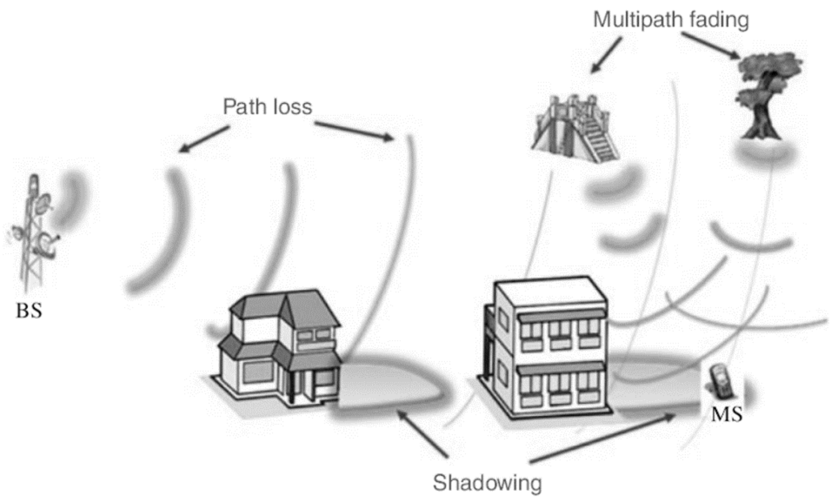

Fig. 2.1 Path loss, shadowing and multiple paths

2.2-Path Loss

We first consider a free space transmission between a fixed transmitter and a receiver situated at a distance *d* from the transmitter as shown in Fig. 2.2.

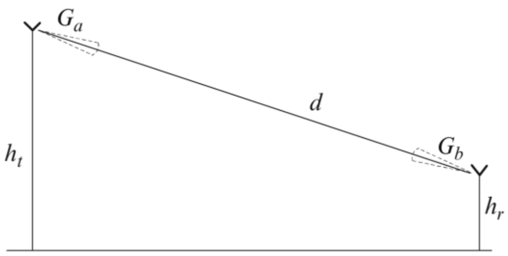

Fig.2.1 Free space model

Let's assume that the transmitted signal is $x(t) = \cos(2\pi f_0 t)$ where f_0 is the carrier frequency. In the far field, the received signal at time *t* is

$$r(t) = \frac{\lambda\sqrt{G_a G_b}}{4\pi d}\cos\left(2\pi f_0\left(t - \frac{d}{c}\right)\right)$$

where G_a and G_b are, respectively, the gain of the transmit and receive antenna in the direction of interest (G_a=1 if the transmit antenna is isotropic),$\lambda = \frac{c}{f_0}$ is the wavelength associated to the carrier frequency f_0 and $c = 3.10^8\ m/s$ is the speed of light.

In the free space, the path loss in dB is given by

$$F_A(d) = 10log_{10}\left(\frac{P_r}{P_t}\right)^{-1}$$

$$= 20\ log_{10}\left(\frac{4\pi d}{\lambda}\right) - 10log_{10}(G_a G_b)$$

$$= 32{,}44 + 20log_{10}f_0 + 20log_{10}d - 10log_{10}(G_a G_b)$$

In mobile radio channel where the pathloss is proportional to *d*, a simple model is given by

$$F_A(d) = -10log_{10}K_A + 10\alpha log_{10}\left(\frac{d}{d_0}\right)$$

Where d_0 is the distance from which the far field assumption is valid (1 < d_0< 10m for indoor systems and 10 <d_0< 100m for outdoor systems). The exponent α range between 1,5 and 6,5. K_A and α can be obtained from measurement campaigns.

Different models are available in the literature and standards depending on the context (macrocell, microcell, picocell, urban, rural, indoor, . . .).

2.3-Shadowing

The shadowing effect is due to objects like trees and buildings, obstructing the propagation path between the transmit and the receive antennas. Since the properties of these objects (nature, location, etc.) is not known in advance, we model these properties as a random process. A good approximation of this effect consists in considering that the distribution of the shadow loss is log-normal. The distribution of the logarithm of ψ in dB is Gaussian as follows:

$$p(\psi_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{\psi_{dB}}} exp\left(-\frac{(\psi_{dB})^2}{2\sigma_{\psi_{dB}}^2}\right)$$

where $\sigma_{\psi_{dB}}$ is the standard deviation of ψ_{dB}. generally chosen between 5 and 12 dB.

2.4-Doppler Effect

Let's consider a car equipped with a receive antenna moving in the direction of the transmitter with a speed v as shown in Fig. 2.2.

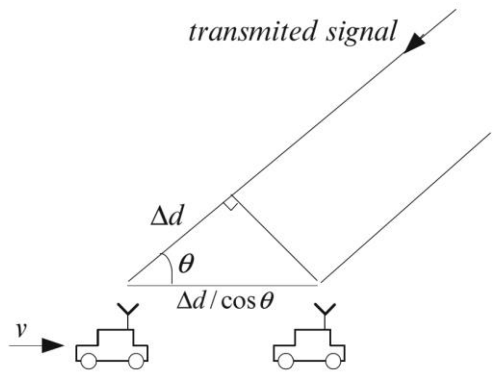

Fig. 2.2 Doppler effect

During Δt, the distance between the transmitter and the receiver decreases by $\Delta d = v\Delta t\ cos\theta$ corresponding to a phase shift of $\Delta\emptyset = \frac{v\Delta t\ cos\theta}{\lambda} 2\pi$

The associated Doppler shift is given by

$$f_D = \frac{vf_o}{c} cos\theta$$

3-Wireless channel models

In wireless communications, multipath fading effect occurs in almost all environment. In urban area where the heights of the mobile antennas are below the height of the surrounding structures there is no line of sight (NLOS) path between the transmitter and the receiver. Thus, the transmitted signal arrives at the receiver through many different paths, reflection, refraction or diffraction over large objects. Multipath fading effects are difficult to predict and consequently they are commonly studied using statistic models. The most general description of the impulse response of the multipath fading channel can written as the sum of *N* elementary responses with amplitude $\alpha_n(t)$, phase $\emptyset_n(t)$ and excess time delay τ_n as

$$h(\tau, t) = \sum_{n=0}^{N-1} \alpha_n(t) e^{-j\emptyset_n(t)} \delta(t - \tau_n)$$

where $\delta(.)$ is the Dirac delta function.

For the 1st path we have: $n = 0 \rightarrow \alpha_0(t) e^{-j\emptyset_0(t)} \delta(t - \tau_0)$

For the 2nd path we have: $n = 1 \rightarrow \alpha_1(t) e^{-j\emptyset_1(t)} \delta(t - \tau_1)$

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For the N-1 path we have: $n = N - 1 \rightarrow \alpha_{N-1}(t) e^{-j\emptyset_{N-1}(t)} \delta(t - \tau_{N-1})$

3.1-Power-delay profile

The power $E(\alpha_n^2)$ and the delay τ_n of each path is determined with the power-delay profile (PDP) which is generally represented as plots of relative received power as a function of the delay spread with respect to time as shown in Fig.2.3.

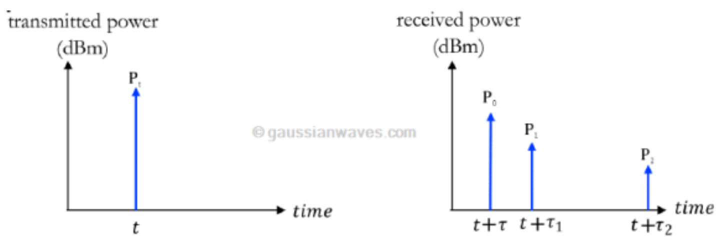

Fig.2.3. Power-delay profile

3.2-Narrowband Model

In this model, we consider that the delay spread is small compared to the symbol period $x(t - \tau_n) \approx x(t)$. Under this hypothesis, the received signal can be approximated as follows:

$$r(t) = \sum_{n=0}^{N-1} \alpha_n(t) e^{-j\emptyset_n(t)} x(t)$$

Where $\emptyset_n(t) = 2\pi f_0 \tau_n + 2\pi f_{Dn} t + \emptyset_0$

As the multipath could arrive at the receiver in the same time delay with different phases, the amplitudes of these paths could add constructively or destructively. When the resulting amplitude is zero or near zero, we refer to it as a deep fade.

$$r(t) = x(t) \sum_{n=0}^{N-1} \alpha_n(t) e^{-j\emptyset_n(t)}$$

$$h(t) = \sum_{n=0}^{N-1} \alpha_n(t) e^{-j\emptyset_n(t)}$$

Example:

For: $N = 2\ paths: a_0 = a_1 = 1, \tau_0 = 0\ and\ \tau_1 = \frac{1}{2f_0}$

$h = \sum_{n=0}^{2-1} a_i e^{-j2\pi f_0 \tau_n} = 1 * e^0 + 1 * e^{-j\pi} = 1 - 1 = 0, \qquad e^{j\theta} = cos\,\theta + j\,sin\,\theta$

$\Rightarrow r(t) = 0 * s(t) = 0 \Rightarrow$ destructive interferences

For: $N = 2\ paths: a_0 = a_1 = 1, \tau_0 = 0\ and\ \tau_1 = \frac{1}{f_0}$

$h = \sum_{n=0}^{2-1} a_n e^{-j2\pi f_0 \tau_n} = 1 * e^0 + 1 * e^{-j2\pi} = 1 + 1 = 2$

$\Rightarrow r(t) = 2s(t) \Rightarrow$ constructive interferences (amplifies the amplitude of the received signal).

h is called the fading channel coefficient. The fading process causes the different variations in the received signal strength, which is an important aspect in wireless communications. (a_n↑→ $r(t)$↑→SNR↑→BER↓).

2.4-Rayleigh Distribution

The phase and the delay of paths can change significantly within a short period of time. Since the number of paths is high, using the central limit theorem, the channel impulse response $h(t)$ can be modelled as a complex Gaussian random process. When there is NLOS, the amplitude of the channel $|h(t)|$ at any time instant is Rayleigh distributed (Fig2.4) and the distribution of the phase is uniform over the interval $[0, 2\pi]$ (Fig.2.5).

The Rayleigh distribution is given by

$$p_R(r) = \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right)$$

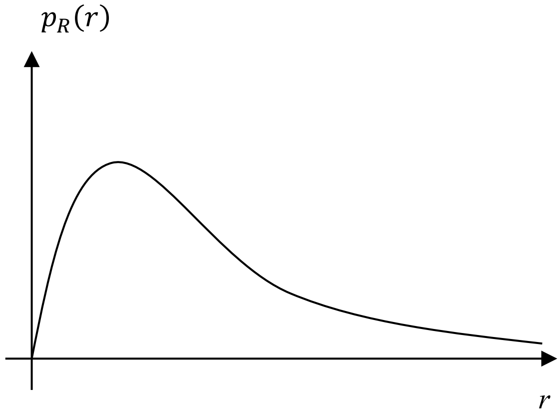

Fig.2.4. Rayleigh distribution

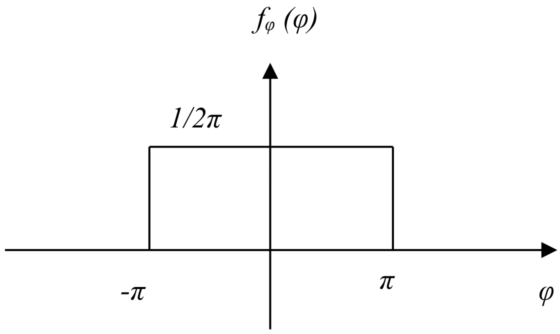

Fig.2.5. Uniform distribution

The square of the amplitude $|h(t)|^2$ is exponentially distributed with density

$$p_s(s) = \frac{1}{\sigma^2} exp\left(-\frac{s}{2\sigma^2}\right)$$

When there is a direct link between the transmit and receive antennas, i.e., when there is a line of sight (LOS). The amplitude of the channel is modelled using Rician distribution and is correspondingly named the Rician fading channel. The Rician distribution is given by

$$p_R(r) = \frac{r}{\sigma^2} exp\left(-\frac{r^2 + s^2}{2\sigma^2}\right) I_0\left(\frac{r.s}{\sigma^2}\right)$$

where I_0 is the modified Bessel function of the first kind with order zero and s is the amplitude of the LOS. The Rician distribution is often described with the fading parameter $K = \frac{s^2}{2\sigma^2}$.

Note :

In the case NLOS, the component s tends to 0 and the Rician distribution tends to Rayleigh distribution.

-Error probability of Rayleigh fading channel

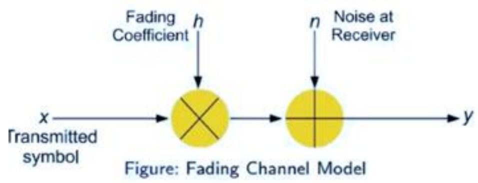

Figure: Fading Channel Model

$$y = hx + n$$

Where h is the fading coefficient:

and n is the noise (AWGN with 0 mean and σ_0^2 variance)

In this case the receiver power is: $|h|^2 p$; $h = ae^{-j\varphi} \rightarrow |h| = a$

$|h|^2 p = a^2 p$

$SNR_F = \frac{a^2 p}{\sigma_0^2} = a^2 SNR$

For B-PSK signals, the BER is:

$BER = p_B = Q\left(\sqrt{SNR_F}\right) = Q\left(\sqrt{a^2 SNR}\right)$

We have a is random quantity, so, BER is also random quantity. To find the average BER, we average with respect to the distribution of a:

We have

$$p_a(a) = \frac{a}{\sigma^2} exp\left(-\frac{a^2}{2\sigma^2}\right)$$

For the average power $2\sigma^2 = 1$:

$$p_a(a) = 2a\, e^{-a^2}$$

The average BER is:

$$BER = \int_{0}^{+\infty} Q\left(\sqrt{a^2 SNR}\right) p_a(a)\, da$$

$$BER = \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{2 + SNR}}\right)$$

Example:

Compute the BER of a wireless Rayleigh fading channel for $SNR_{dB} = 20$

$$SNR_{dB} = 10log_{10}(SNR) = 20$$

$$SNR = 100$$

$$BER = \frac{1}{2}\left(1 - \sqrt{\frac{100}{2 + 100}}\right) = 4.92 \times 10^{-3}$$

-Error probability of Rician fading channel

Using the same steps as the BER of Rayleigh fading channel, the BER of Rician fading channel is given as:

$$BER = \frac{1}{2} erfc\left(1 - \sqrt{\frac{K\, SNR}{K + SNR}}\right)$$

Where

$$erfc(x) = \int_{0}^{x} \frac{2}{\sqrt{\pi}} e^{-x^2} dx$$

Where $K = \frac{s^2}{2\sigma^2}$ is the fading parameter.

2.5-Delay Spread and Coherence Bandwidth

From the delay profile, we can compute the maximum delay spread τ_{max} , the mean delay τ_m and the root mean square (RMS) delay spread τ_{rms} as

$$\tau_m = \frac{\sum_{n=1}^{M-1} g_n \tau_n}{\sum_{n=0}^{M-1} g_n}$$

$$\tau_{rms} = \sqrt{\frac{\sum_{n=0}^{M-1} g_n (\tau_n - \tau_m)^2}{\sum_{n=0}^{M-1} g_n}}$$

Also, τ_{rms} can calculated as:

$$\tau_{rms} = \sqrt{\overline{\tau^2} - (\tau_m{}^2)}$$

Where $\overline{\tau^2}$ is the second moment.

The coherence bandwidth B_{coh} can be defined as the range of frequencies over which the amplitude of the spectral components of the channel response are correlated

$$B_{coh} = \frac{1}{\tau_{rms}}$$

Depending on the delay spread and the symbol transmission time T_s and the transmitted signal bandwidth $B_s = \frac{1}{T_s}$ the channels can be categorized as flat fading channel or frequency selective fading channel.

Flat fading channel: When the signal bandwidth is much less than the channel coherence bandwidth $B_s \ll B_{coh};\ (\tau_{rms} \ll T_s)$ the channel is flat fading or non-frequency-selective.

Frequency selective fading channel: When the bandwidth of constant amplitude and linear phase response of the channel is significantly less than the transmitted signal bandwidth $B_{coh} \ll B_s$; $(T_s \ll \tau_{rms})$ the channel is frequency selective. In this case, the channel applies different gains or attenuations to different frequency components of the transmitted signal, causing spectral distortion in the signal. In the time domain, the frequency selective fading channel creates intersymbol interference (ISI).

2.6-Doppler Spread and Coherence Time

The Doppler spread B_d is the difference between the largest and the smallest frequency shift of multiple paths, $B_d = 2f_{Dmax}, f_{Dmax} = \frac{vf_0}{c}$. From B_d the coherence time T_{coh} is defined as

$$T_{coh} = \frac{1}{B_d}$$

By using this coherence time, the multipath fading channels can be categorized into the fast fading channel or slow fading channel.

Slow fading channel: When $T_s \ll T_{coh}$; ($B_s \gg B_d$), the channel is slow fading and the channel is unchanged while the symbol is transmitted.

Fast fading channel: When $T_s \gg T_{coh}$; $B_s \ll B_d$ the channel is said to be fast fading and the fading characteristics of the channel change while transmitting the symbol.

2.7-Channels classification summary

The Fig.2.6 summarizes the channel classification according to the previous section. The Fig.2.7 and Fig.2.8 show examples for slow fading and fast fading channels respectively.

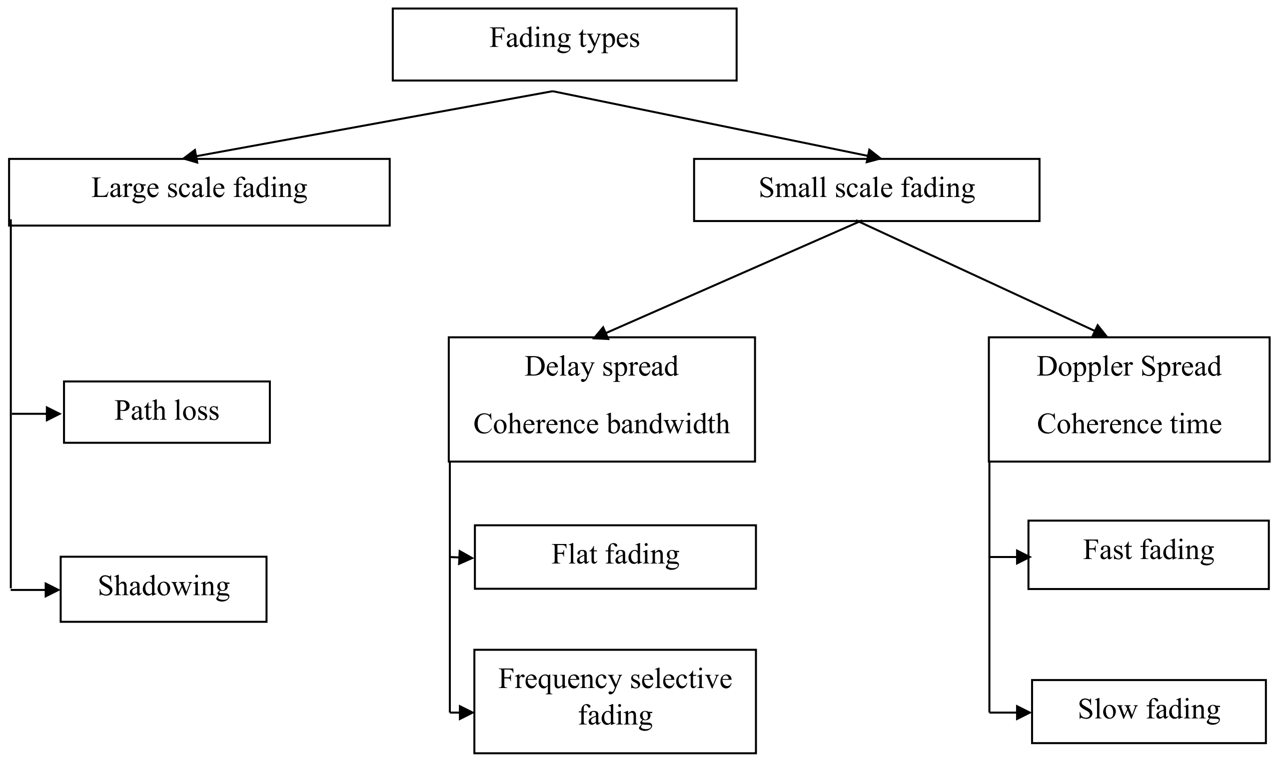

Fig.2.6 channel classification

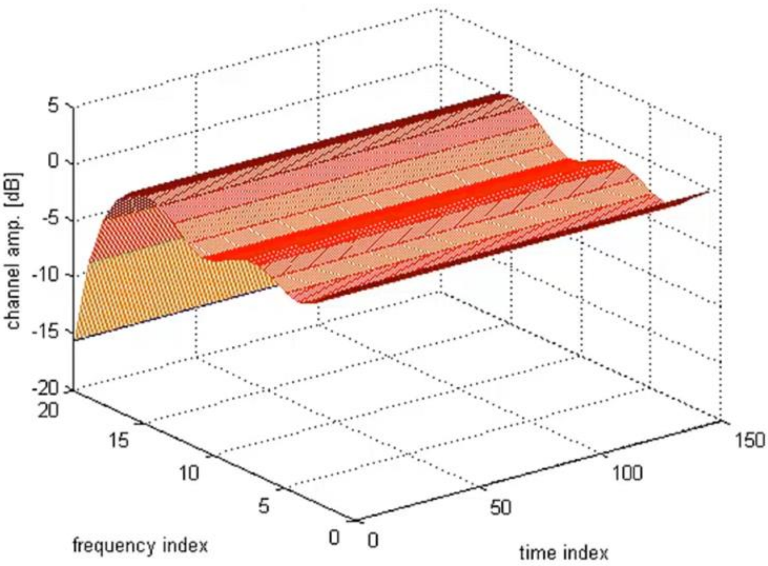

Fig.2.6 Slow fading channel

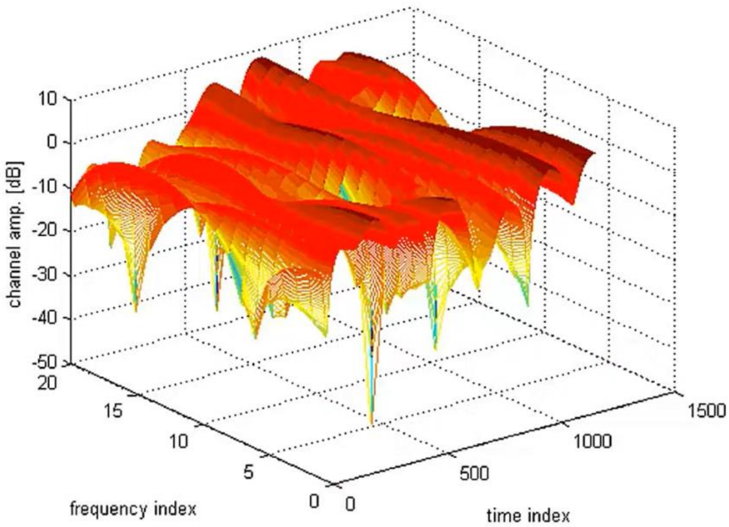

Fig.2.7 Fast fading channel