



Advanced Topics in Communications

Fall, 2009, By Xiang-Gen Xia

This course covers:

1. Channel Modeling
2. Channel Capacity & Coding
3. Error Correction Codes
 - RS Codes
 - Convolutional codes
4. Trellis Coded Modulation (TCM)
5. Intersymbol Interference Channels

Equalization Methods: ZF, MMSE, DFE
OFDM

6. CDMA systems

CDMA code properties
RAKE Receiver



Introduction

Wireless Systems and Standards

1. First Generation Cellular System (Analog)

Analog FDMA (analog FM technology)

1979, the first analog cellular system from NTT became operational

1981, Ericsson fielded NMT 900 system

1983, AT&T - - - AMPS

2. Second Generation Cellular Systems (Digital)

Late 1992, European GSM (Global System Mobile)

TDMA

1990, North American IS-54 (TDMA)

Later, IS-95 (CDMA)

Qualcomm built system.
rate at the transmission

1.2288 Mcps/s

1991, Japanese Personal Digital Cellular (PDC)

3. Third Generation Cellular System (Wideband CDMA)

CDMA 2000



3GPP (3G Partnership Project) LTE (Longterm Evolution)

Chapter 1. Channel Propagation Modeling

Section 1. Overview

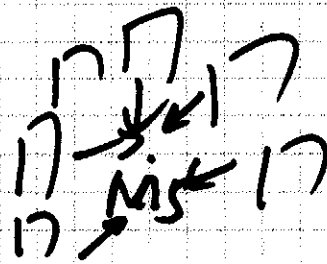
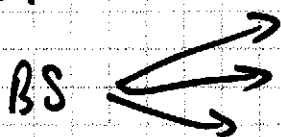
- * The intensity of an EM wave in free space decays with square of the radio path length, d .

The received power is

$$\Omega(d) = P \left(\frac{\lambda_c}{4\pi d} \right)^2$$

Where P is the transmitted power, λ_c is the wavelength
$$\text{wavelength} = \frac{c \text{ (velocity of light)}}{f \text{ (freq. of the wave)}}$$

- * In digital cellular mobile comm. environment (PCS), it is assumed that No direct line-of-sight (LOS) or very short LOS exists between the base station (BS) and mobile station (MS) antennas.

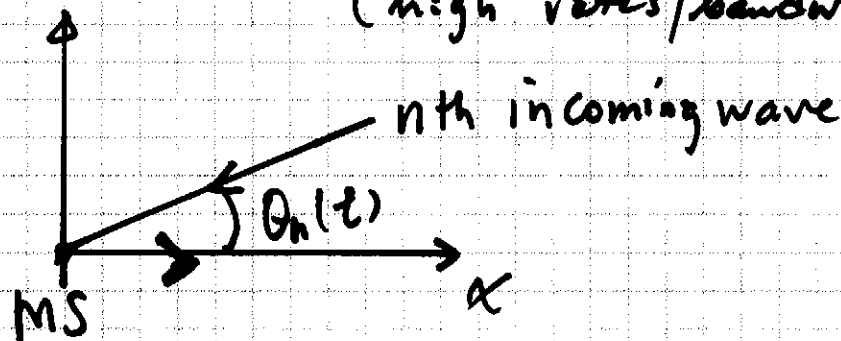




- * Radio propagation includes multipath fading, shadowing, and path loss.

Multipath fading including

- ① frequency-non-selective (flat) multipath fading (low rates/bandwidth)
- ② frequency-selective fading (high rates/bandwidth)



Section 2. Frequency-Non-Selective (Flat) Fading

1. Channel Model.

- * An MS moves along the x -axis with velocity v .
- * In portable and mobile radio application, the transmitted signals are usually vertically polarised, and, therefore, the electric field vector is aligned with the z -axis.



* The n th plane wave arrives at the MS antenna with an angle of incidence $\theta_n(t)$

* The MS movement introduces a Doppler frequency shift given by

$$f_{D,n}(t) = f_m \cos \theta_n(t) \quad \text{Hz}$$

Where $f_m = \frac{v}{\lambda_c} = v f_c / c$, and f_c is the carrier frequency. For example, $f_c = 850 \text{ MHz}$
 $v = 80 \text{ km/hour}$

$$\Rightarrow \lambda_c = \frac{3 \times 10^8}{850 \times 10^6} = 0.35 \text{ m}$$

$$\Rightarrow f_m \approx 63 \text{ Hz}$$

* Consider the transmission of the band-pass signal

$$S(t) = \text{Re} \{ u(t) e^{j2\pi f_c t} \}$$

where $u(t)$ is the complex lowpass signal (baseband),
 Re denotes the real part.

* If the channel is comprised of N paths, then the received bandpass wave form is

$$X(t) = \text{Re} \{ r(t) e^{j2\pi f_c t} \}$$

where the received complex lowpass signal $r(t)$ is

$$r(t) = \sum_{n=1}^N \alpha_n(t) e^{-j2\pi [\underbrace{f_c + f_{D,n}(t)}_{\rightarrow \phi_n(t)} t - \underbrace{f_{D,n}(t) t}_{u(t - \tau_n(t))}]}$$



Where $\alpha_n(t)$ and $\tau_n(t)$ are the amplitude and time delay of the n th path.

$$r(t) = \sum_{n=1}^N \alpha_n(t) e^{-j\phi_n(t)} u(t - \tau_n(t)) \quad (1)$$

and $\phi_n(t)$ is the phase associated with the n th path.

($\alpha_0(t)$ is the direct path ($\alpha_0(t) \gg \alpha_n(t)$)

From (1), the channel can be modeled by a time-variant linear filter having the complex low-pass impulse response

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

Observations:

- ① Since $f_c + f_{D,n}(t)$ is very large, a small change in the path delay $\tau_n(t)$ causes a large change in the phase $\phi_n(t)$. At any time t , these random phases may result in the constructive or destructive addition of the components.



- ② The amplitude $\alpha_n(t)$ depends on the cross sectional area of the n th scatter or the length of the n th diffracting surface.
- ③ The above quantities do not change significantly over small spatial distances
- ④ Fading is primarily due to time variations in the random phases $\phi_n(t)$ that are caused by the Doppler shifts $f_{D,n}(t)$.

2. Received Signal Correlation and Spectrum (at MS)

(rough idea about the received signal)

Purpose: for simulation and detection.

* Since usually the signal bandwidth is very small compared to the carrier frequency, we consider the transmission of an unmodulated carrier (i.e., assume $u(t)=1$ for all t). In this case,

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

and $x(t) = r_I(t) \cos 2\pi f_c t - r_Q(t) \sin 2\pi f_c t$
(received signal before de-carrier)



where $r_I(t) = \sum_{n=1}^N \alpha_n(t) \cos \phi_n(t)$: In phase component of $r(t)$

$r_Q(t) = \sum_{n=1}^N \alpha_n(t) \sin \phi_n(t)$: Quadrature component of $r(t)$.

$$r(t) = r_I(t) + j r_Q(t)$$

* For large N , by the central limit theorem,

$r_I(t)$ and $r_Q(t)$ can be treated as independent (i.i.d.) Gaussian random processes with mean zero.

Assuming that these random processes are wide sense stationary, we have the autocorrelation of $x(t)$:

$$\phi_{xx}(\tau) = E(x(t) x(t+\tau))$$

$$= \phi_{r_I r_I}(\tau) \cos 2\pi f_c \tau - \phi_{r_Q r_I}(\tau) \sin 2\pi f_c \tau$$

By noting that $\phi_{r_I r_I}(\tau) = \phi_{r_Q r_Q}(\tau)$

$$\phi_{r_I r_Q}(\tau) = -\phi_{r_Q r_I}(\tau),$$

Assume that the phases $\phi_n(t)$ and $\phi_m(t)$ are independent for $m \neq n$ and uniformly distributed



in $[-\pi, \pi]$. Then, one can calculate

$$\phi_{r_z r_z}(\tau) = \frac{\Omega_P}{2} E_Q [\cos(2\pi f_m \tau \cos(\theta))],$$

where θ is the arrival angle,

$$\begin{aligned} \frac{\Omega_P}{2} &= E x^2(t) = E [r_z^2(t)] = E [r_\theta^2(t)] \\ &= \frac{1}{2} \sum_{n=1}^N E |\alpha_n|^2 \end{aligned}$$

is the total average power from all multipath components.

Cross correlation of $r_z(t)$ and $r_a(t)$ is similarly,

$$\phi_{r_z r_a}(\tau) = \frac{\Omega_P}{2} E_Q [\sin(2\pi f_m \tau \cos(\theta))]$$

where f_m is the Doppler spread $f_m = \frac{v}{\lambda_c} = \frac{v f_c}{c}$.

To further evaluate these two correlations functions, we need to know the probability density functions of the random variable θ . For macrocellular application, it is reasonable to assume that the plane waves arrive at the MS antenna from all directions in the (x, y) plane with equal probability, i.e., θ is uniformly distributed over $[-\pi, \pi]$.



(known as Clarke's two-dimensional isotropic scattering model). Thus,

$$\begin{aligned}\phi_{r_2 r_2}(\tau) &= \frac{\Omega_P}{2} \frac{1}{2\pi} \int_{-\pi}^{\pi} \cos(2\pi f_m \tau \cos \theta) d\theta \\ &= \frac{\Omega_P}{2} \frac{1}{\pi} \int_0^{\pi} \cos(2\pi f_m \tau \sin \theta) d\theta \\ &= \frac{\Omega_P}{2} J_0(2\pi f_m \tau)\end{aligned}$$

where $J_0(x)$ is the zero-order Bessel function of the first kind. And

$$\phi_{r_2 r_0}(\tau) = \frac{\pi}{2} \frac{1}{2\pi} \int_{-\pi}^{\pi} \sin(2\pi f_m \tau \cos \theta) d\theta = 0.$$

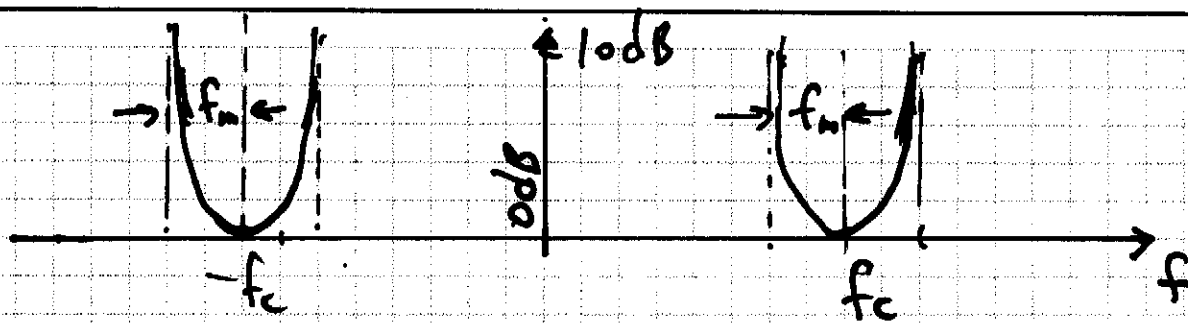
$\Rightarrow$ The autocorrelation function of the received signal $x(t)$ is

$$\phi_{xx}(\tau) = \frac{\Omega_P}{2} J_0(2\pi f_m \tau) \cos 2\pi f_c \tau$$

The power density spectrum (psd) of $x(t)$ is

$$S_{xx}(f) = \frac{1}{2} [S_{r_2 r_2}(f - f_c) + S_{r_2 r_2}(-f - f_c)]$$

$$\text{where } S_{r_2 r_2}(f) = \mathcal{F}[\phi_{r_2 r_2}(\tau)] = \begin{cases} \frac{\Omega_P}{4\pi f_m} \frac{1}{\sqrt{1 - (\frac{f}{f_m})^2}}, & |f| \leq f_m, \\ 0, & \text{otherwise.} \end{cases}$$



When an LOS or a specular component at the angle θ_0 presents in the received signal,

$$S_{xx}(f) = \begin{cases} \frac{1}{K+1} \frac{3\Omega_p}{4\pi f_m} \frac{1}{\sqrt{1 - \frac{|f-f_c|^2}{f_m^2}}} \\ + \frac{K}{K+1} \frac{3\Omega_p}{4} \delta(f - f_c - f_m \cos \theta_0), & |f - f_c| \leq f_m, \\ 0, & \text{otherwise} \end{cases}$$

K is called the Rice factor and is defined as the ratio of the power in the specular and scatter components of the received signal

* Other distribution of the multipath arriving angle θ may be used.

3. Received Envelope and phase Distribution (Macro-cellular)

§3.1 Rayleigh Fading

When there are a large number of plane waves



in the received signal, $r(t) = r_I(t) + j r_Q(t)$ can be modeled as a complex Gaussian random process. In the absence of an LOS or specular component, $r_I(t)$ and $r_Q(t)$ have zero-mean. Thus, the complex envelope $z(t) = |r(t)|$ has a Rayleigh distribution at any time, t ,

$$p_z(x) = \frac{x}{\sigma^2} \exp\left\{-\frac{x^2}{2\sigma^2}\right\}$$

where $\sigma^2 = \frac{J_p}{2}$ is the average power.

This type of fading is called Rayleigh fading, and applied to any scenario where there is no LOS path between the transmitter & receiver antennas.

§3.2. Ricean Fading (micro-cellular applications)

With a n LOS component, In this case, $r_I(t)$ and $r_Q(t)$ have non-zero mean and the complex envelope has a Ricean distribution at any time t , i.e.,



$$p_g(x) = \frac{x}{\sigma^2} \exp\left\{-\frac{x^2 + s^2}{2\sigma^2}\right\} I_0\left(\frac{xs}{\sigma^2}\right), x \geq 0$$

where $s^2 = \alpha_0^2 \cos^2 \theta_0 + \alpha_0^2 \sin^2 \theta_0 = \alpha_0^2$ is the non-centrality parameter.

α_0 is the power of LOS, θ_0 is the angle of LOS.

The Rice Factor $K = \frac{s^2}{2\sigma^2}$

When $K=0$, the channel $\rightarrow$ Rayleigh fading.

$K=\infty$, No fading

$$\Omega_p = s^2 + 2\sigma^2 \text{ and } s^2 = \frac{K\Omega_p}{K+1}$$

3.3. Nakagami Fading (Rapid fading in long distance H₁ channels)

$$Z(t) = |r(t)|$$

The Nakagami distribution describes $Z(t)$ by a central Chi-square distribution with m degree of freedom, i.e,

$$p_g(x) = \frac{2m^m x^{2m-1}}{\Gamma(m) \Omega_p^m} \exp\left\{-\frac{mx^2}{\Omega_p}\right\}, m \geq \frac{1}{2}$$

$m=1$, the Nakagami distribution is the Rayleigh distribution



$m = \frac{1}{2}$, it becomes a one-sided Gaussian distribution

$m = \infty$, it becomes an impulse (no fading).

One can similarly discuss the correlation and power density spectrum for the received envelope.