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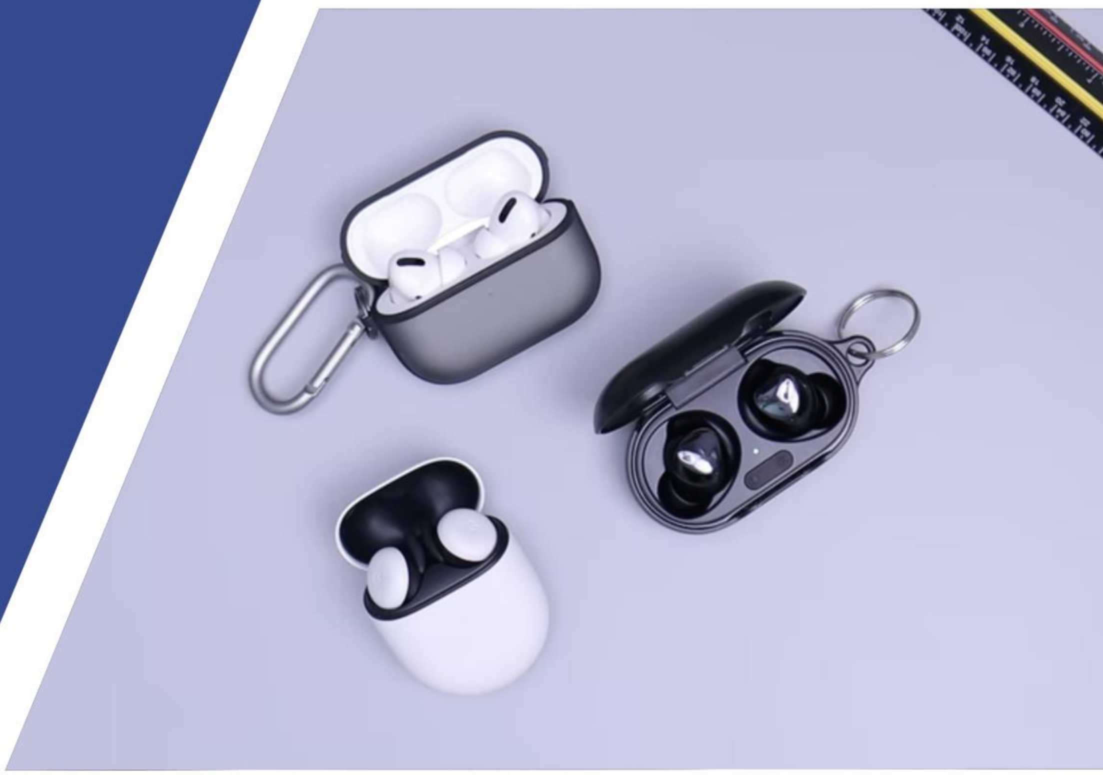

Wireless Communication I

Module 3

CIT 855 Wireless Communications I Module 3

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Unit 1 Small Scale Fading and Multipath

1.0 Introduction

Small scale fading or in simple word fading, is used to describe the rapid fluctuations in amplitudes, phases, or multipath delays of a radio signal over a small period of time or travel distance, so that large-scale path loss effects may be ignored. In wireless communications, fading is deviation or the attenuation that a carrier-modulated telecommunication signal experiences over certain propagation media. The fading may vary with time, geographical position and/or radio frequency, and is often modelled as a random process. A fading channel is a communication channel that experiences fading. In wireless systems, fading may be due to multipath propagation, referred to as multipath induced fading, or due to shadowing from obstacles affecting the wave propagation, sometimes referred to as shadow fading.

2.0 Objectives

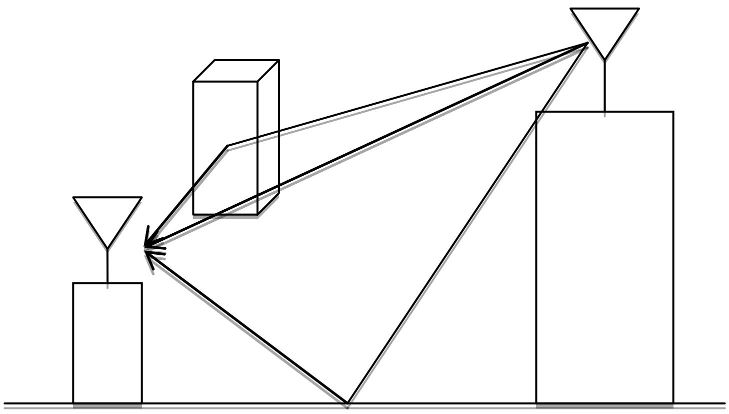
At the end of this unit, you should be able to:

- write concisely on the concept of small scale propagation
- identify the effects of multipath in the radio channel
- discuss the factors affecting small-scale fading
- explain Doppler shift.

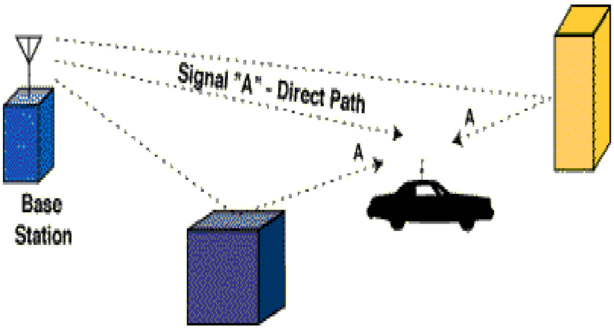
3.0 Main Content

3.1 Small-Scale Multipath Propagation

The objects located around the path of the wireless signal reflect the signal. Some of these reflected waves are also received at the receiver. Since each of these reflected signals takes a different path, it has a different amplitude and phase.



(a)



(b)

Fig.1.1(a &b): Example of Multipath

As a matter of fact, multipath in the radio channel produces small-scale fading effects. The three important effects are:

i. rapid changes in signal strength over a small travel distance or time interval

ii. random frequency modulation due to varying Doppler shifts on different multipath signals

iii.time dispersion (echoes) caused by multipath propagation delays.

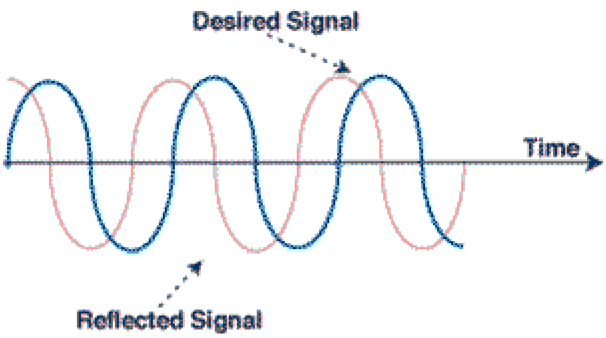


Fig. 1.2: Phase Difference between Original and Reflected Wave

In built-up urban areas, fading occurs since the height of the mobile antennas are well below the height of surrounding structures, hence there is no single line-of-sight path to the base station. Even when a line-of-sight exists, multipath still occurs due to reflections from the ground and surrounding structures. The incoming radio waves arrive from different directions with different propagation delays. The signal received by the mobile at any point in space may consist of a large number of plane waves having randomly distributed amplitudes, phases and angles of arrival. These multipath components combine in a vectorial manner at the receiver antenna and can cause the signal received by the mobile to distort or fade. Even when a mobile receiver is stationary, the received signal may fade because of movement of surrounding objects in the radio channel. If objects in the radio channel are static and motion is considered to be only due to that of the mobile, then fading is purely a spatial phenomenon.

3.1.1 Factors Affecting Small-Scale Fading

The physical factors in the radio propagation channel influencing small-scale fading are:

i. **Multipath Propagation**: The presence of reflecting objects and scattering in the channel creates a constantly changing environment that dissipates the signal energy in amplitude, phase and time. The random phase and amplitudes of different multipath components cause fluctuations in signal strength, thereby inducing small scale fading, signal distortion or both. Multipath propagation often lengthens the time required for the baseband portion of the signal to reach the receiver which can cause signal smearing due to inter-symbol interference.

ii. **Speed of the Mobile:** The relative motion between the base station and the mobile results in random frequency modulation due to different Doppler shifts on each of the multipath component. Doppler shift will be positive or negative depending on whether the mobile receiver is moving toward or away from the base station.

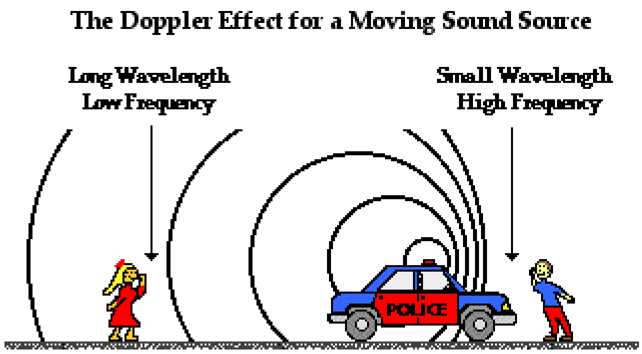


Fig.1.3: The Doppler Effect for a Moving Sound

Source: Spring 07- CS 527 – Lecture 3

iii. **Speed of Surrounding Objects:** If objects in the radio channel are in motion, they induce a time varying Doppler shift on multipath components. If the surrounding object moves at a greater rate than the mobile, then this effect dominates the small scale fading. Otherwise, motion of surrounding objects may be ignored, and only the speed of the mobile need be considered.

iv. **The Transmission Bandwidth of the signal:** If the transmitted radio signal bandwidth is greater than the "bandwidth" of the multipath channel, the received signal will be distorted, but the received signal strength will not fade much over a local area (i.e. the small scale fading will not be significant). If the transmitted signal has a narrow bandwidth as compared with the channel, the amplitude of the signal will change rapidly, but the signal will not be distorted in time. Thus, the statistics of small-scale signal strength and the likelihood of signal smearing over small-scale distance are very related to the specific amplitudes and delays of the multipath channel, as well as the bandwidth of the transmitted signal.

3.1.2 Multi-Path Fading Channel Models

- The received signal

$$r(t) = \sum_{n=1}^{N(t)} \alpha_n(t) e^{-j2\pi f c \tau n(t)} x(t - \tau_n(t))$$

$\alpha_n(t)$ represents the amplitude fluctuation introduced to the transmitted signal by the nth scatterer at time t

f_c is the carrier frequency

$\tau_n(t)$ is the associated propagation delay

$\delta(t)$ denotes the Dirac delta function

$N(t)$ denotes the number of scatterers at time t

- The channel output $r(t)$ (Time variant Channel)

$$r(t) = c(t) \times x(t) = \int_{-\infty}^{+\infty} c(\tau, t) x(t - \tau) d\tau$$

- Impulse response of a multi-path model

$$c(\tau, t) = \sum_{n=1}^{N(t)} \alpha_n(t) e^{-j2\pi f c \tau n(t)} \delta(\tau - \tau_n(t))$$

Source: NUS- Statistical Modeling and characterisation of Fading Channel

3.1.3 Concept of Doppler

Just as a train whistles or car horn appears to have a different pitch, depending on whether it is moving toward or away from one's location, radio waves demonstrate the same phenomenon. If a receiver is moving toward the source, then the zero crossings of the signal appear faster, and consequently, the received frequency is higher. The opposite effect occurs if the receiver is moving away from the source. The resulting change in frequency is known as the Doppler shift.

Let the *n*-th reflected wave with amplitude c_n and phase ϕ_n arrive from an angle α_n relative to the direction of the motion of the antenna.

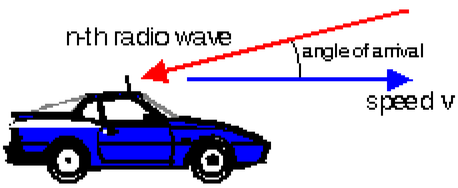


Fig.1.4: Doppler Shift

The Doppler shift of this wave is

$$f_n = f_D = -\frac{f_0}{c} v\cos\alpha$$

where f_0 is the carrier transmission frequency, *v* is the speed of the antenna

Self-Assessment Exercise

An aircraft is headed toward an airport control tower with a speed of 500km/h at an elevation of 20^0. Safety communications between the aircraft tower and the plane occur at frequency of approximately 128MHz. What is the expected Doppler shift of the received signal?

Solution

The velocity of the aircraft in the direction away from the tower is

v = -500km/hr x cos 200 = -130m/s

Speed of light = 3 x 10^8

The corresponding Doppler shift is

$$f_D = -\frac{f_0}{c} v\cos\alpha = -\frac{128\times10^6}{3\times10^8}\times(-130) = 55Hz$$

If the plane banks suddenly and heads in the other direction, the Doppler shift will change from 55Hz to -55Hz. This rapid change in frequency, df_D/dt, is sometimes referred to as frequency slewing. A good mobile receiver must be capable of tracking the frequency slew rates that can be generated by the receiving motion.

Self-Assessment Exercise

Given a transmitter which radiates a sinusoidal carrier frequency of 1850 MHz. For a vehicle moving at 60mph, calculate the received carrier frequency if the mobile is moving (i) directly toward the transmitter, (ii) directly away from the transmitter, and (iii) in a direction which is perpendicular to the direction of arrival of the transmitted signal.

Solution

Given that Carrier frequency f_c = 1850MHz

Hence,

$$\text{wavelength } \lambda = \frac{c}{f_c} = \frac{3\times10^8}{1850\times10^6} = 0.162m$$

Vehicle speed v =60mph = 26.82m/s

i. The vehicle is moving directly towards the transmitter.

The Doppler shift in this case will be positive and the received frequency will be given by

$$f = f_c + f_d = 1850\times10^6 + \frac{3\times10^8}{1850\times10^6}$$
$$f = 1850.00016MHz$$

ii. The vehicle is moving directly away from the transmitter.

The Doppler shift in this case will be negative and therefore, the received frequency will be given by

$$f = f_c - f_d = 1850\times10^6 - \frac{3\times10^8}{1850\times10^6}$$
$$f = 1849.999834MHz$$

iii. The vehicle is moving perpendicular to the angle of arrival of the transmitted signal. In this case, $\theta = 90^0$, cos θ = 0, and hence, there is no Doppler shift. Thus, in this case, the received signal frequency will remain same as the transmitted frequency of 1850MHz.

Self-Assessment Exercise

Explain four factors affecting small-scale fading

4.0 Conclusion

In wireless communications, fading is deviation or the attenuation that a carrier-modulated telecommunication signal experiences over certain propagation media. The fading may vary with time, geographical position and/or radio frequency, and is often modeled as a random process. Fading may be due to multipath propagation, referred to as multipath induced fading, or due to shadowing from obstacles affecting the wave propagation, sometimes referred to as shadow fading.

5.0 Summary

The main points in this unit are:

- multipath in the radio channel produces three important fading effects which are:
  (i) Rapid changes in signal strength over a small travel distance or time interval
  (ii) Random frequency modulation due to varying Doppler shifts on different multipath signals (iii) Time dispersion (echoes) caused by multipath propagation delays.

- even when mobile is stationary, the received signals may fade due to movement of surrounding objects.

- the physical factors in the radio propagation channel influencing small-scale fading are: Multipath propagation, speed of the mobile, speed of surrounding objects, the transmission bandwidth of the signal.

- the Doppler shift can be expressed as

$$f_n = f_D = -\frac{f_0}{c} v\cos\alpha$$

where f_0 is the carrier transmission frequency, v is the speed of the antenna.

6.0 Self-Assessment Exercise

i. What is Doppler Effect? Explain

ii. What do you understand by small scale fading

iii. Identify the three important effects of multipath in the radio channel

7.0 References/Further Reading

Linnartz's, J. M. G. (1996). *Wireless Communication*. Baitzer Science Publishers.

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Unit 2 Types of Small Scale Fading

1.0 Introduction

The presence of reflectors in the environment surrounding a transmitter and receiver create multiple paths that a transmitted signal can traverse.

As a result, the receiver sees the superposition of multiple copies of the transmitted signal, each traversing a different path. Each signal copy will experience differences in attenuation, delay and phase shift while traveling from the source to the receiver. This can result in either constructive or destructive interference, amplifying or attenuating the signal power seen at the receiver. Strong destructive interference is frequently referred to as a deep fade and may result in temporary failure of communication due to a severe drop in the channel signal-to-noise ratio.

A common example of multipath fading is the experience of stopping at a traffic light and hearing an FM broadcast degenerate into static, while the signal is re-acquired if the vehicle moves only a fraction of a meter.

The loss of the broadcast is caused by the vehicle stopping at a point where the signal experienced severe destructive interference. Cellular phones can also exhibit similar momentary fades.

Fading channel models are often used to model the effects of electromagnetic transmission of information over the air in cellular networks and broadcast communication. Fading channel models are also used in underwater acoustic communications to model the distortion caused by the water. Mathematically, fading is usually modeled as a time-varying random change in the amplitude and phase of the transmitted signal.

2.0 Objectives

At the end of this unit, you should be able to:

- Mention two types of small scale fading
- Explain fading effects due to Doppler spread
- Discuss fading effect due to multipath time delay spread.

3.0 Main Content

3.1 Types of Small-Scale Fading

The type of fading experienced by signal propagating through a mobile radio channel depends upon the nature of the transmitted signal with respect to the characteristics of the channel. Depending on the relation between the signal parameters and the channel parameters, different transmitted signals will undergo different types of fading.

- Fading Effects due to Multipath Time Delay Spread

- Fading Effects due to Doppler Spread

Small-Scale Fading
(Based on multipath time delay spread)

Flat Fading
1. BW of signal < BW of channel
2. Delay spread < Symbol period

Frequency Selective Fading
1. BW of signal > BW of channel
2. Delay spread > Symbol period

Small-Scale Fading
(Based on Doppler spread)

Fast Fading
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than baseband signal variations

Slow Fading
1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

Fig. 2.1: Illustration of Types of Small-Scale Fading

3.1.1 Fading Effects Due to Multipath Time Delay Spread

As the carrier frequency of a signal is varied, the magnitude of the change in amplitude will vary. The coherence bandwidth measures the separation in frequency after which two signals will experience uncorrelated fading. Time Dispersion because of Multipath cause the transmitted signal to experience either flat or frequency selective fading

i. Flat Fading

In flat fading, the coherence bandwidth of the channel is larger than the bandwidth of the signal. Therefore, all frequency components of the signal will experience the same magnitude of fading. That is if the mobile radio channel exhibits a constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal, then the received signal will experience flat fading. In flat fading, the multipath structure of the channel is such that the spectral characteristics of the transmitted signal are preserved at the receiver. However, the strength of the signal changes with time, because of fluctuations in the gain of the channel created by multipath. Flat fading channels are also referred to as amplitude varying channel or narrowband channel.

ii. Frequency Selective Fading

In frequency-selective fading, the coherence bandwidth of the channel is smaller than the bandwidth of the signal. Different frequency components of the signal therefore experience decorrelated fading. That is if the channel possesses a constant-gain and linear phase response over a bandwidth that is smaller than the bandwidth of transmitted signal, then the channel creates frequency selective fading on the received signal. Under such conditions, the channel impulse response has a multipath delay spread which is greater than the reciprocal bandwidth of the transmitted message waveform. When this occurs, the received signal includes multiple versions of the transmitted waveform which are attenuated (faded) and delayed in time, and hence the received signal is distorted. Frequency selective fading is due to time dispersion of the transmitted symbols within the channel.

Since different frequency components of the signal are affected independently, it is highly unlikely that all parts of the signal will be simultaneously affected by a deep fade. Certain modulation schemes such as OFDM and CDMA are well-suited to employing frequency diversity to provide robustness to fading. OFDM divides the wideband signal into many slowly modulated narrowband subcarriers, each exposed to flat fading rather than frequency selective fading. This can be combated by means of error coding, simple equalization or adaptive bit loading. Inter-symbol interference is avoided by introducing a guard interval between the symbols. CDMA uses the Rake receiver to deal with each echo separately.

Frequency-selective fading channels are also *dispersive*, in that the signal energy associated with each symbol is spread out in time. This causes transmitted symbols that are adjacent in time to interfere with each other. Equalisers are often deployed in such channels to compensate for the effects of the inter symbol interference.

The echoes may also be exposed to Doppler shift, resulting in a time varying channel model.

3.1.2 Fading Effects Due to Doppler Spread

Depending on how rapidly the transmitted baseband signal changes as compared to the rate of change of the channel, a channel may be classified either as a fast fading or slow fading channel. The terms slow and fast fading refer to the rate at which the magnitude and phase change imposed by the channel on the signal changes. The coherence time is a measure of the minimum time required for the magnitude change of the channel to become decorrelated from its previous value.

- **Slow Fading:** In Slow fading channel, the impulse response changes at a rate much slower than the transmitted baseband signal. In this case, the channel may be assumed to be static over one or several reciprocal bandwidth interval. In frequency domain, this implies that the Doppler spread of the channel is much less than the bandwidth of the baseband signals.

Slow fading arises when the coherence time of the channel is large relative to the delay constraint of the channel. In this regime, the amplitude and phase change imposed by the channel can be considered roughly constant over the period of use. Slow fading can be caused by events such as shadowing, where a large obstruction such as a hill or large building obscures the main signal path between the transmitter and the receiver. The amplitude change caused by shadowing is often modeled using a log-normal distribution with a standard deviation according to the log-distance path loss model.

- **Fast Fading:** In fast fading channel, the channel response changes rapidly within the symbol duration. That is the coherence time of the channel is smaller than the symbol period of the transmitted signal. This causes frequency dispersion (also called time selective fading) due to Doppler spreading, which leads to signal distortion. When viewed in the frequency domain, signal distortion due to fast fading increases with increasing Doppler spread relative to the bandwidth of transmitted signal.

In a fast-fading channel, the transmitter may take advantage of the variations in the channel conditions using time diversity to help increase robustness of the communication to a temporary deep fade. Although a deep fade may temporarily erase some of the information transmitted, use of an error-correcting code coupled with successfully transmitted bits during other time instances (interleaving) can allow for the erased bits to be recovered. In a slow-fading channel, it is not possible to use time diversity because the transmitter sees only a single realisation of the channel within its delay constraint. A deep fade therefore lasts the entire duration of transmission and cannot be mitigated using coding.

The coherence time of the channel is related to a quantity known as the Doppler spread of the channel. When a user (or reflectors in its environment) is moving, the user's velocity causes a shift in the frequency of the signal transmitted along each signal path. This phenomenon is known as the Doppler shift. Signals traveling along different paths can have different Doppler shifts, corresponding to different rates of change in phase. The difference in Doppler shifts between different signal components contributing to a single fading channel tap is known as the Doppler spread. Channels with a large Doppler spread have signal components that are each changing independently in phase over time. Since fading depends on whether signal components add constructively or destructively, such channels have a very short coherence time.

In general, coherence time is inversely related to Doppler spread, typically expressed as:

$$T_c = \frac{k}{D_s}$$

where T_c is the coherence time, D_s is the Doppler spread, and k is a constant taking on values in the range of 0.25 to 0.5.

3.2 Mitigation

Fading can cause poor performance in a communication system because it can result in a loss of signal power without reducing the power of the noise. This signal loss can be over some or all of the signal bandwidth.

Fading can also be a problem as it changes over time: communication systems are often designed to adapt to such impairments, but the fading can change faster than when adaptations are made. In such cases, the probability of experiencing a fade (and associated bit errors as the signal-to-noise ratio drops) on the channel becomes the limiting factor in the link's performance.

RF multipath problems can be mitigated in a number of ways.

(i) Radio system design: redundant paths for each receiver, if at all possible.

(ii) Antenna system design: dual diversity antennas used at each receiver, as a minimum.

(iii) Signal/waveform design: spread spectrum radio design with the highest feasible chip rate.

(iv) Building/environment design: not much can be done in this area, unless new "RF Friendly" buildings are constructed.

The effects of fading can be combated by using diversity to transmit the signal over multiple channels that experience independent fading and coherently combining them at the receiver. The probability of experiencing a fade in this composite channel is then proportional to the probability that all the component channels simultaneously experience a fade, a much more unlikely event.

Diversity can be achieved in time, frequency, or space. Common techniques used to overcome signal fading include:

- Diversity reception and transmission
- OFDM (orthogonal frequency division multiplexing)
- Rake receivers
- Space–time codes
- MIMO (multiple-input multiple-output)

Self-Assessment Exercise

Mention two types of small scale fading.

4.0 Conclusion

In this unit, we have discussed the two types of small scale fading. They are: fading effects due to multipath time delay spread and fading effects due to Doppler spread.

5.0 Summary

In this unit you have learnt that:

- fading channel models are often used to model the effects of electromagnetic transmission of information over the air in cellular networks and broadcast communication.
- the two types of small scale fading are fading effect due to multipath time delay spread and fading effect due to Doppler spread
- fading effect due to multipath time delay spread causes the signal to experience either flat or frequency selective fading
- in flat fading, the coherence bandwidth of the channel is larger than the bandwidth of the signal.
- in frequency-selective fading, the coherence bandwidth of the channel is smaller than the bandwidth of the signal.
- fading effect due to Doppler spread may be classified either as a fast fading or slow fading channel
- in Slow fading channel, the impulse response changes at a rate much slower than the transmitted baseband signal.
- in fast fading channel, the channel response changes rapidly within the symbol duration.

6.0 Self-Assessment Exercise

i. Explain briefly slow and fast fading

ii. Write short note on fading effects due to multipath time delay spread.

7.0 References/Further Reading

Molisch, A. F. (2005). *Wireless Communications*. Wiley and Associate.

Rappaport, T. S. (2005). *Wireless Communication: Principle and Practice.* (2nd ed.). India: Prentice Hall.

Sharma, S. (2007). *Wireless and Cellular Communication*. New Delhi: S. K. Kataria & Sons.

Unit 3 Small Scale Fading - Rician, Rayleigh and Nakagami

1.0 Introduction

Small scale fading results from the fact that the propagation channel consists of several obstacles and reflectors.

2.0 Objectives

At the end of this unit, you should be able to:

- discuss on the small scale fading models
- list examples of fading models
- differentiate between the fading models.

3.0 Main Content

3.1 Fading Models/Local Propagation Effects with Mobile Radio

Most mobile communication systems are used in and around centers of population. The major difficulties are caused by the fact that the mobile antenna is well below the surrounding buildings. Thus, most communication is via scattering of electromagnetic waves from surfaces or diffraction over and around buildings. These multiple propagation paths or multipath have both slow and fast aspects:

i. slow-fading arises from the fact that most of the large reflectors and diffracting objects along the transmission path are distant from the terminal. The motion of the terminal relative to these distant objects is small. Consequently, the corresponding propagation changes are slow. These factors contribute to the median path losses between a fixed transmitter and a fixed receiver. The slow fading also referred to as shadowing or log-normal fading.

ii. fast fading is the rapid variation of signal levels when the user terminal moves short distances. Fast fading is due to reflection of local objects and the motion of terminal relative to those objects. That is, the received signal is the sum of a number of signals reflected from local surfaces, and these signals sum in a signals constructive and destructive manner depending on their relative phase relationships.

Examples of fading models for the distribution of the attenuation are:

- Rician fading
- Rayleigh fading
- Nakagami fading
- Log-normal shadow fading

- Weibull fading: is a simple statistical model of fading used in wireless communications and based on the Weibull distribution. It is an effective model in both indoor and outdoor environments
- Dispersive fading models, with several echoes, each exposed to different delay, gain and phase shift, often constant. This results in frequency selective fading and inter-symbol interference. The gains may be Rayleigh or Rician distributed. The echoes may also be exposed to Doppler shift, resulting in a time varying channel model.

3.1.1 Rician Fading

Rician fading is a stochastic model for radio propagation anomaly caused by partial cancellation of a radio signal by itself , the signal arrives at the receiver by two different paths and at least one of the paths is changing (lengthening or shortening). Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others. In Rician fading, the amplitude gain is characterized by a Rician distribution.

The model behind Rician fading is similar to that of Rayleigh fading, except that in Rician fading a strong dominant component is present.

This dominant component can for instance be the line-of-sight wave. Refined Rician models also consider that:

- the dominant wave can be a phasor sum of two or more dominant signals, e.g. the line-of-sight, plus a ground reflection. This combined signal is then mostly treated as a deterministic (fully predictable) process, and that
- the dominant wave can also be subject to shadow attenuation. This is a popular assumption in the modeling of satellite channels.

Besides the dominant component, the mobile antenna receives a large number of reflected and scattered waves.

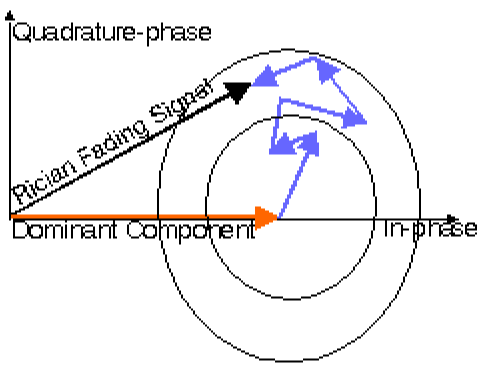

Fig. 3.1: Phasor Diagram of Rician Fading

Rician fading happens when:

- there is a dominant signal component such as LOS.
- random components arriving at different angles are superimposed on a stationary signal i.e. a component is essentially added to the multipath.

Signal Model

A narrowband propagation channel can be model by considering a sinusoidal transmitted carrier: $s(t) = \cos w_c t$

This signal received over a Rician multipath channel can be expressed as $v(t) = C \cos w_t t + S_{n=1}^{N} r_n \cos(w_c t + f_n)$

where

C is the amplitude of the line-of-sight component

rn is the amplitude of the n-th reflected wave

fn is the phase of the n-th reflected wave

$n = 1 .. N$ identify the reflected, scattered waves.

Rayleigh fading is recovered for $C = 0$

The Rician *K*-factor is defined as the ratio of signal power in dominant component over the (local-mean) scattered power.

$$K = \frac{C^2/2}{\sigma^2} = \frac{direct\ power}{scattered\ power}$$

In the expression for the received signal, the power in the line-of-sight equals $C^2/2$. In indoor channels with an unobstructed line-of-sight between transmitting and receiving antennas the *K*-factor is between, say, 4 and 12 dB. Rayleigh fading is recovered for $K = 0$ (-infinity dB).

Rician Channels

Examples of Rician fading are found in

- Microcellular channels
- Vehicle to Vehicle communication, e.g., for AVCS
- Indoor propagation
- Satellite channels

3.1.2 Rayleigh Fading

Rayleigh fading is a statistical model for the effect of a propagation environment on a radio signal. It is a specialised model for stochastic fading when there is no line of sight signal, and is sometimes considered as a special case of the more generalised concept of Rician fading. In Rayleigh fading, the amplitude gain is characterised by a Rayleigh distribution. Rayleigh fading models assume that the magnitude of a signal that passed through a communications channel will vary randomly, or fade, according to a Rayleigh distribution (i.e. the radial component of the sum of two uncorrelated Gaussian random variables).

Rayleigh fading is most applicable when there is no dominant propagation along a line of sight between the transmitter and receiver. If there is a dominant line of sight, Rician fading may be more applicable.

Rayleigh fading is caused by multipath reception. The mobile antenna receives a large number, say N, reflected and scattered waves. As a result of wave cancellation effects, the instantaneous received power seen by a moving antenna becomes a random variable, dependent on the location of the antenna.

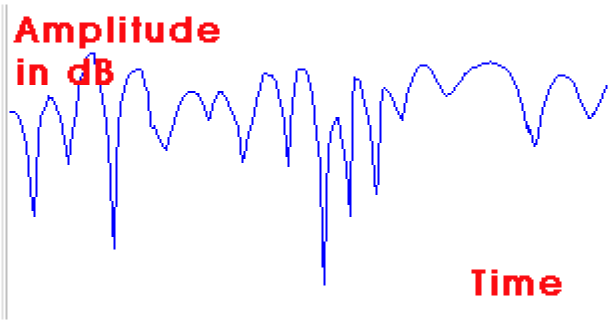

Fig. 3.2: A Sample of a Rayleigh Fading Signal

Signal amplitude (in dB) versus time for an antenna moving at constant velocity.

Deep fades occur occasionally but it have the tendency to occur approximately every half a wavelength of motion. Also, if the antenna speed is set to zero, channel fluctuations will no longer occur. Fading is due to motion of the antenna but an exception occurs if reflecting objects move. In a vehicular cellular phone system, the user is likely to move out of a fade, but in a Wireless LAN, a terminal may by accident be placed permanently in a fade where no reliable coverage is available.

Rayleigh fading happens when:

- flat fading or narrowband mobile radio channel bandwidth of applied signal is narrow compared to channel bandwidth.
- either transmitter or receiver is immersed in cluttered surrounding so that there is no LOS component.

The Model

Rayleigh fading is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver. The central limit theorem holds that, if there is sufficiently much scatter, the channel impulse response will be well-modeled as a Gaussian process irrespective of the distribution of the individual components. If there is no dominant component to the scatter, then such a process will have zero mean and phase evenly distributed between 0 and 2π radians. The envelope of the channel response will therefore be Rayleigh distributed.

It is called random variable R; it will have a probability density function:

$$P_R(r) = \frac{2r}{\Omega} e^{-r^2/\Omega}, \quad r \geq 0$$

where $\Omega = E(R^2)$.

3.1.2.1 Rayleigh Fading Simulator

Narrowband Rayleigh fading is modeled often as a random process that multiplies the radio signal by a complex-valued Gaussian random function. The spectrum of this random function is determined by the Doppler spread of the channel. Thus one can generate two appropriately filtered Gaussian noise signals and use these to modulate the signal and a 90 degree phase shifted version of the signal.

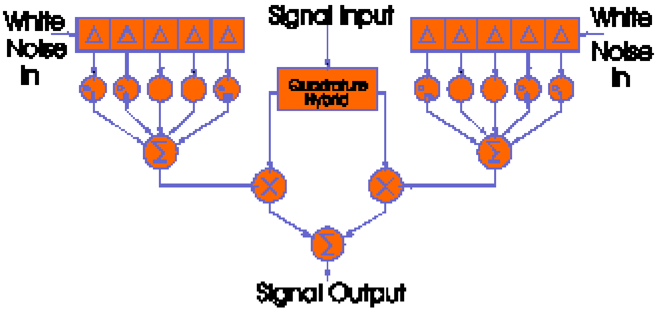

Fig. 3.4: Block Diagram of a Narrowband Rayleigh Fading Simulator (in baseband)

***Source:* Linnartz J. (2009)**

3.1.2.2 Jakes' Simulator

It is common practice to generate two filtered noise components by adding a set of six or more sinusoidal signals. Their frequencies are chosen as to approximate the typical U-shaped Doppler spectrum.

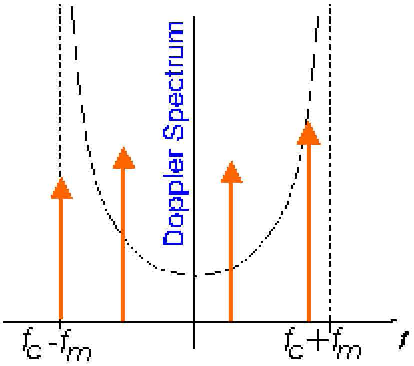

Fig.3.5: Crude Approximation (Orange) of the Theoretical Doppler Spectr1m (Black) used in Animation taking only 4 Components (*N*=3)

Source: Linnartz J. (2009)

N frequency components are taken as

$$f_i = f_m \cos\frac{2\pi}{2(2N+1)} \quad with\ i = 1,2,\ldots, N$$

This specific set of frequencies is chosen to approximate the U-shaped Doppler spectrum. All amplitudes are taken equal to unity. One component at the maximum Doppler shift is also added, but at amplitude of $1/\sqrt{2}$,i.e., at about 0.707 . Jakes suggests using 8 sinusoidal signals.

3.1.2.3 Frequency Domain Simulator

Many channel simulation models follow the narrowband model. Wideband channels are often simulated by extending the model assuming multiple time-delayed resolvable paths. This allows the simulation of the channel impulse response, including its stochastic behavior. To determine the performance of a multicarrier, OFDM or MC-CDMA system, another approach can be to model a set of fading sub channels. Considering a single subcarrier, the channel may be modeled as a narrowband fading channel, for instance with Rician or Rayleigh amplitude distributions. The collection of multiple subcarriers can be modeled as a set of mutually dependent fading channels.

3.1.3 Nakagami Fading

Besides Rayleigh and Rician fading, refined models for the probability density function (pdf) of signal amplitude exposed to mobile fading is Nakagami fading.

Nakagami Math

The distribution of the amplitude and signal power can be used to find probabilities on signal outages.

- If the envelope is Nakagami distributed, the corresponding instantaneous power is gamma distributed.
- The parameter m is called the 'shape factor' of the Nakagami or the gamma distribution.
- In the special case m = 1, Rayleigh fading is recovered, with an exponentially distributed instantaneous power
- For m > 1, the fluctuations of the signal strength reduce compared to Rayleigh fading.

The Nakagami fading model was initially proposed because it matched empirical results for short wave ionospheric propagation. In current wireless communication, the main role of the Nakagami model can be summarised as follows

When does Nakagami Fading occur?

- It describes the amplitude of received signal after maximum ratio diversity combining. After *k*-branch maximum ratio combining (MRC) with Rayleigh-fading signals, the resulting signal is Nakagami with $m = k$. MRC combining of *m*-Nakagami fading signals in *k* branches gives a Nakagami signal with shape factor *mk*.
- The sum of multiple independent and identically distributed (i.i.d.) Rayleigh-fading signals have a Nakagami distributed signal amplitude. This is particularly relevant to model interference from multiple sources in a cellular system.
- The Nakagami distribution matches some empirical data better than other models
- Nakagami fading occurs for multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves.
- The Rician and the Nakagami model behave approximately equivalently near their mean value.

Self-Assessment Exercise

Discuss briefly Rician and Rayleigh fading.

4.0 Conclusion

In this unit, we have discussed on the Rician fading, Rayleigh fading and Nakagami fading.

5.0 Summary

In this unit you have learnt that:

- Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others
- the model behind Rician fading is similar to that of Rayleigh fading, except that in Rician fading a strong dominant component is present. This dominant component can for instance be the line -of-sight wave
- Rayleigh fading is caused by multipath reception
- Rayleigh fading is most applicable when there is no dominant propagation along a line of sight between the transmitter and receiver
- Nakagami fading occurs for multipath scattering with relatively large delay-time spreads, with different clusters of reflected waves.

6.0 Self-Assessment Exercise

i. Mention five examples of fading models.

ii. Differentiate between Rician and Nakagami fading.

iii. When does Rician fading occur?

7.0 References/Further Reading

Awad. M., Wong, K. T. & Li Z. (2008). 'An Integrative Overview of the Open Literature's Empirical Data on the Indoor Radiowave Channel's Temporal Properties, IEEE Transactions on Antennas & Propagation'. 56, 5, 1451-1468.

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Unit 4 Small-Scale Fading-Threshold Crossing, Fade Duration and Scatter Function

1.0 Introduction

In this unit, you will learn what threshold crossing rate, fade duration, average fade duration and scatter function are.

2.0 Objectives

At the end of this unit, you should be able to:

- explain the concept threshold crossing rate
- discuss briefly on average fade duration
- discuss concisely on scatter function.

3.0 Main Content

3.1 Fading

3.1.1 Threshold Crossing Rate

The average number of times per second that a fading signal crosses a certain threshold is called the threshold crossing rate. Let us enlarge the following (orange) signal path, at the (yellow) instant when it crosses the (purple) threshold.

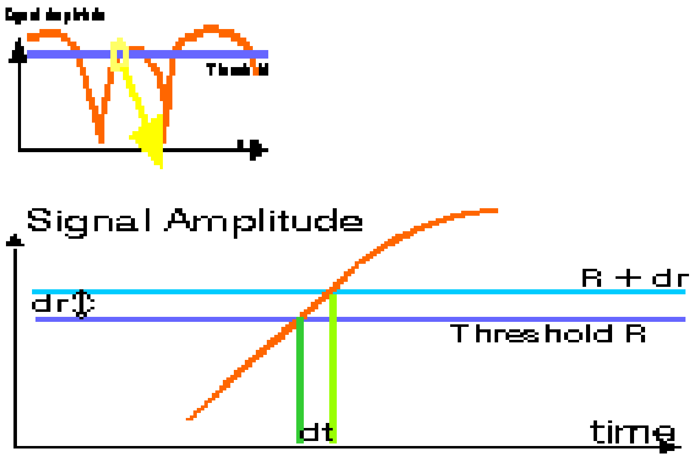

Fig. 4.1: Threshold Crossing Threshold *R* is Crossed with derivative *dr/dt*.

The above crossing of the threshold R with width *dr* lasts for *dt* seconds. The derivative of the signal amplitude, with respect to time, is *dr/dt*.

If the signal always crosses the threshold with the same derivative, then:

Average number of crossings per second * *dt* = Probability that the amplitude is in the interval [*R*, *R* + *dr*].

The probability that the signal amplitude is within the window [R, R + dr] is known from the probability density of the signal amplitude, which can for instance be Rayleigh, Rician or Nakagami. Moreover, the joint pdf of signal amplitude and its derivative can be found for a Rayleigh-fading signal.

- The amplitude is Rayleigh, with mean equal to the local-mean power
- The derivative is zero-mean Gaussian with variance
- var = 2 * (π)^2 * (Doppler spread)^2 * local-mean power

The expected number of crossings per second is found by integrating over all possible derivatives.

$$TRC = \frac{\sqrt{2\pi}\, f_D}{\sqrt{M}} \exp^{(-1/M)}$$

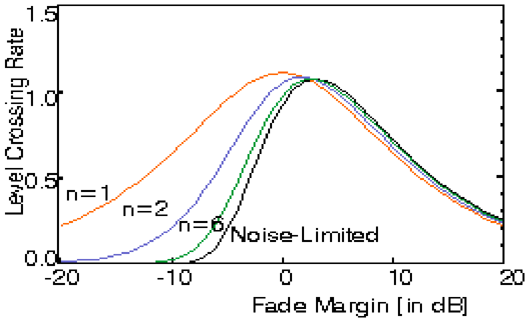

Fig. 4.2: Threshold Crossing Rate in Rayleigh-fading Channel versus fade Duration for *n* = 1, 2, and 6 Rayleigh-Fading Interfering Signals and for a Constant Noise Floor. Normalized to the Doppler Spread.

Source: Linnartz J. (1996)

The TCR curve has a maximum if the local-mean-power is as large as the threshold noise or interference power. If the signal is on average much stronger than the threshold, the number of threshold crossings (i.e., deep fades) is relatively small. Also, if the signal is much weaker than the threshold, the number of crossings is small because signals "up-fades" are unlikely.

3.1.2 Fade Duration

The mobile Rayleigh or Rician radio channel is characterized by rapidly changing channel characteristics. As the amplitude of a signal received over such a channel also fluctuates, the receiver will experience periods during which the signal cannot be recovered reliably. If a certain minimum (threshold) signal level is needed for acceptable communication performance, the received signal will experience periods of

- sufficient signal strength or "non-fade intervals"", during which the receiver can work reliably and at low bit error rate

- insufficient signal strength or “"fades”, during which the bit error rate inevitably is close to one half (randomly guessing ones and zeros) and the receiver may even fall out of lock.

This two-state simplification of the wireless channel behaviour is called a Gilbert-Elliot model.

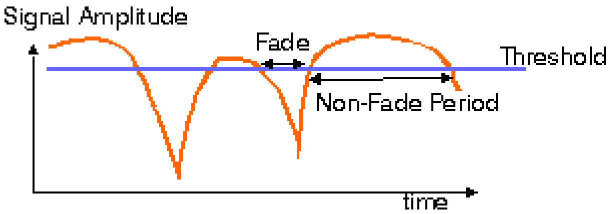

Fig. 4.3: Fade and non-fade Periods for a Sample of a Fading Signal

It is of critical importance to the performance of digital mobile networks that the block length or packet duration is chosen taking into account the expected duration of fades and non-fade intervals. One of two approaches can make:

- the block length at least an order of magnitude longer than the average fade / non-fade period, and rely on error correction to cope with burst errors. This approach can be used for mobile reception of digital broadcast signals (e.g. DAB), particularly if the effect of fading is mitigated through using a wide transmission bandwidth and appropriate signal processing. This approach would be impractical in indoor office communication (wireless LANs) with high bit rates and extremely small Doppler spreads, i.e., with very long fade / non-fade periods.
- the block length shorter than the average fade / non-fade period and retransmit lost data. This approach works best in full duplex mobile data systems and random access data systems. The effective throughput depends on two aspects: (1) the probability that a block runs into a fade and (2) the overhead bits required in block headers.

If the data block length is larger than the average non-fade period, almost all blocks will experience a signal fade and a corresponding burst of bit errors. This may result in an excessive packet dropping rate, unless powerful error correction codes are used. If the system supports a feedback signal with acknowledgments of received blocks, it is mostly advantageous to use only limited error correction coding, but to rely on retransmission of lost blocks. To minimise the number of retransmissions, one should choose the block length shorter than the average fade and non-fade period.

3.1.2.1 Average Fade Duration

The average fade duration quantifies how long the signal spends below the threshold.

Outage Probability = Average number of fades per second * Average fade duration where the average number of fades per second is called the threshold crossing rate.

Expressions for Average (Non-) Fade Duration

In a Rayleigh fading channel with fade margin *M*, the average nonfade duration (ANFD) is

$$ANFD = \frac{\sqrt{M}}{\sqrt{2\pi}\, f_D}$$

where f_D is the Doppler spread, M is the ratio of the local-mean signal power and the minimum (threshold) power needed for reliable communication.

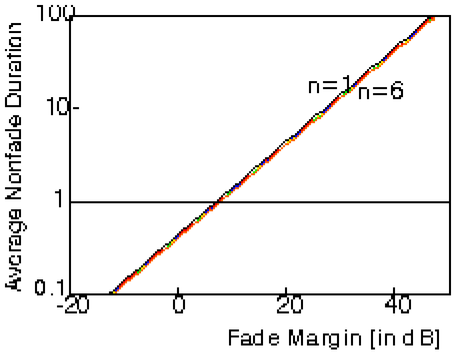

Fig. 4.4: Average non-fade duration in Rayleigh-fading channel versus fade margin for *n* = 1, 2, 3, 4, 5 and 6 Rayleigh-fading interfering signals. Normalized by dividing by the Doppler Spread.

Source: Linnartz J. (1996).

The curve for $n = 6$ closely resembles the curve of ANFD in an interference-free but noise-limited channel.

Thus,

- The ANFD is inversely proportional to the speed of the mobile user. Channel fading occurs mainly because the user moves. If the user is stationary almost no time variations of the channel occur (except if reflecting elements in the environment move)
- The ANFD increases proportional with the square root of the fade margin.
- The non-fade duration is not so sensitive to whether the signal experiences fades below a constant noise-floor or a fading interfering signal.

Calculation of the distribution of non-fade periods is tedious, but has been elaborated by Rice. Because of the shape of the Doppler spectrum, fade durations that coincide with a motion of about half a wavelength are relatively frequent.

The average fade duration (AFD) is

$$AFD = \frac{\sqrt{(M)}}{\sqrt{2\pi}\, f_D}\left(\exp^{(1/M)} - 1\right)$$

Thus

- The AFD is inversely proportional to the speed of the mobile user.
- The fade durations rapidly reduce with increasing fade margin, but the time between fades increases much slower.

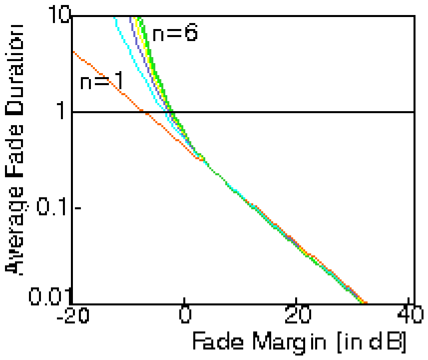

Fig. 4.5: Average fade duration in Rayleigh-fading channel versus fade margin for *n* = 1, 2, 3, 4, 5 and 6 Rayleigh-fading interfering signals. Normalised by dividing by the Doppler Spread

Source: Linnartz J. (1996).

Experiments revealed that at large fade margins, the fade durations are approximately exponentially distributed around their mean value.

For deep fades, Rice showed that for Rayleigh fading, the probability that a fade duration ☐ lasts longer than *T* seconds tends to

$$P(\tau > T) = 2\frac{AFD}{T} I_1\left[\frac{2AFD^2}{\pi T^2}\right]\exp\left[\frac{2AFD^2}{\pi T^2}\right]$$

where I_1 is the modified Bessel function of the first kind. For small z, $I_1(z)$ approximates *z*/2.

3.1.3 Scatter Function

Multipath fading and user mobility lead to a time and frequency dependent channel. The Transfer function of a particular sample channel does not necessarily provide enough details about the stochastic behavior of the radio channel. Such stochastic properties are captured in the scatter function. The scatter function combines information about

- Doppler spread (which relates to angles of arrival) and
- Path delays.

The scatter function provides a statistical model for the channel.

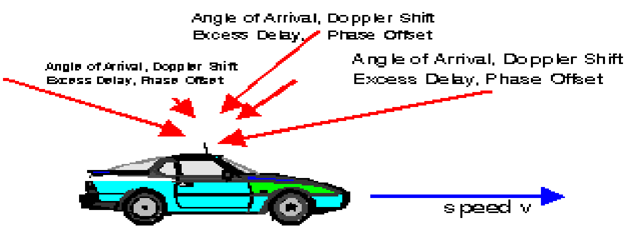

Fig. 4.6: The Basic Idea behind the Scatter Function is that it Plots the Expected Power per Doppler Shift and per Excess Delay bin. Sometimes, angle of Incidence (bearing) is plotted instead of the Doppler shift.

Each path can be described by its

- Angle of arrival or Doppler shift
- Excess delay

A Practical Example

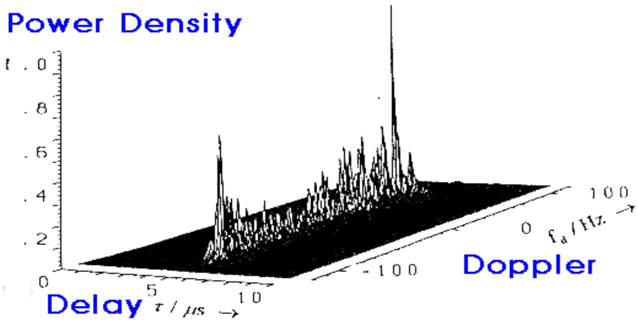

Fig.4.7: Measured Scatter Plot for DCS 1800 MHz System

Doppler spread = 60.3 Hz; Coherence time = 5.9 msec.

Delay Spread = 1.2 msec; coherence BW = 1.3 MHz

Source: Research group of Prof. Paul Walter Baier, U. of Kaiserslautern, Germany.

Theoretical Example

Let us consider a

- U-shaped Doppler spectrum, as it occurs with uniformly distributed angles of arrival of reflected waves. The maximum shift is f_m.
- an exponential delay spread with mean T_{rms}

Moreover, we assume that the delay spread and Doppler spread are separable. Then the amount of scatter power per frequency and time bin can be expressed as

$$P(f,t) = \frac{P_{local-mean}}{4\pi f_m} \frac{1}{\sqrt{\left(1 - \frac{(f-f_c)^2}{f_m^2}\right)}} \frac{1}{T_{rms}} \exp\left(-\frac{t}{T_{rms}}\right)$$

The integral over *p(f,t)* gives total received local mean power $P_{local\text{-}mean}$.

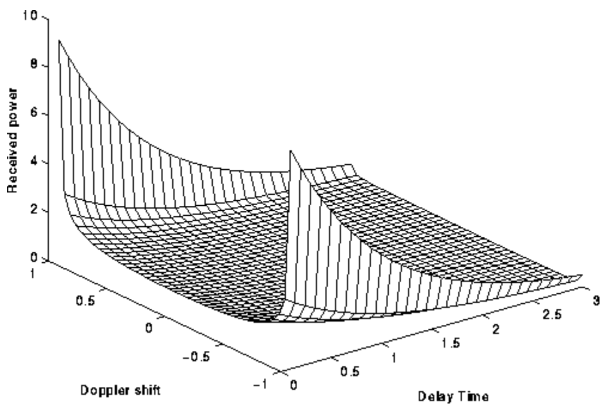

Fig.4.8(a): Scatter function. Received power per unit of frequency shift and per unit of excess time delay. Frequency shift normalised to the maximum Doppler shift.Delay time normalised to the delay spread.

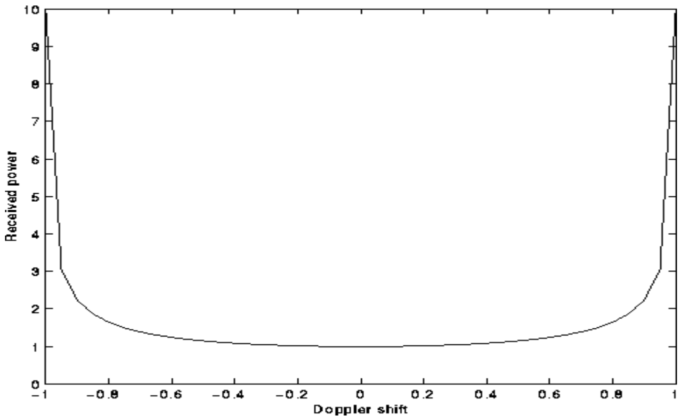

Fig. 4.8(b): Scatter function projected to frequency axis. This gives the Doppler spread. Received power per unit of frequency shift. Frequency shift normalised to the maximum Doppler shift.

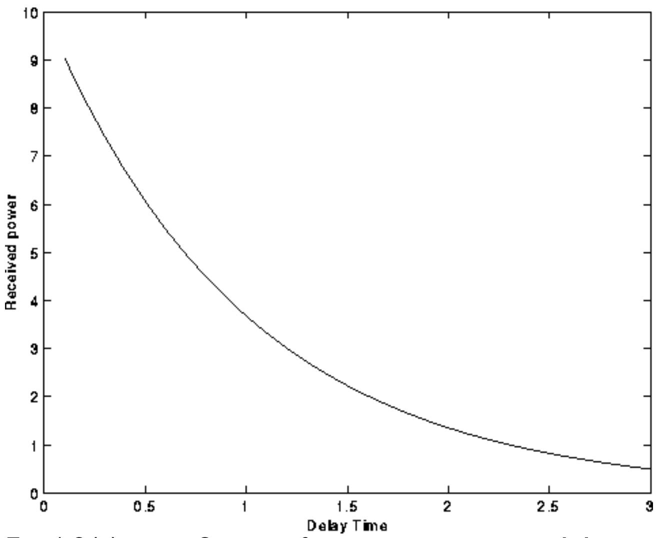

Fig.4.8(c): Scatter function project to delay time axis: This gives the delay profile. Received power per unit. of excess time delay. Delay time normalised to the delay spread.

Source: Channel simulations based on this theoretical model have been contributed by Ralph Haas (2009).

Self-Assessment Exercise

Write a short note on threshold crossing rate.

4.0 Conclusion

In this unit, you studied the concepts of threshold crossing rate, average fade duration and scatter function.

5.0 Summary

In this unit, you have learnt that:

- threshold crossing rate is average number of times per second that a fading signal crosses a certain threshold.
- the expected number of crossings per second is found by integrating over all possible derivatives

$$TRC = \frac{\sqrt{2\pi}\, f_D}{\sqrt{M}} \exp^{(-1/M)}$$

- the average fade duration quantifies how long the signal spends below the threshold.
- the average fade duration is inversely proportional to the speed of the mobile user.
- the average fade duration (AFD) is

$$AFD = \frac{\sqrt{(M)}}{\sqrt{2\pi}\, f_D}\left(\exp^{(1/M)} - 1\right)$$

- the average nonfade duration (ANFD) can be expressed as

$$ANFD = \frac{\sqrt{M}}{\sqrt{2\pi}\, f_D}$$

where f_D is the Doppler spread, M is the ratio of the local-mean signal power and the minimum (threshold) power needed for reliable communication

- the scatter function combines information about the Doppler spread (which relates to angles of arrival) and Path delays.

6.0 Tutor-Marked Assignment

What is meant by Average fade duration and scatter function.

7.0 Reference/Further Reading

Linnartzs, J. M. G. (1996). *Wireless Communication*. Baitzer Science Publisher.

Unit 5 Channel Classification

1.0 Introduction

In previous units, we investigated the effect which various propagation phenomena have on the received electric field. From observations, we can categorise these as large scale propagation effects and small scale propagation effects.

Large scale effects are due to the general terrain and the density and height of buildings and vegetation. Large-scale effects are important for predicting the coverage and availability of a particular service.

Small scale effects are due to the local environment, nearby trees, buildings etc. and the movement of the radio terminal through that environment. Small-scale effects are important for the design of the modulation format and for general transmitter and receiver design.

2.0 Objectives

At the end of this unit, you should be able to:

- define a channel
- explain different classifications of channel

3.0 Main Content

3.1 Channel Classification

Channel, in communications (sometimes called communications channel), refers to the medium used to convey information from a sender (or transmitter) to a receiver. Channel can be classified as follows: time-selective channels, frequency selective channels, general channels, WSSUS channels, coherence time channels, power-delay profile channels, coherence bandwidth channels, stationary and non-stationary channels.

3.1.1 Time-Selective Channels

A channel is said to be Time selective, if the channel is better at selected times than at other times.

Time variations of the channel due to a relative motion between transmitter and receiver lead to a broadening of the signal spectrum.

This frequency dispersion can be characterized by the U-shaped power spectrum of isotropic scattering.

$$S_C(f) = \begin{cases} \frac{2}{\pi B_D} \frac{1}{\sqrt{1-4\frac{f^2}{B_D^2}}} & |f| < \frac{B_D}{2} \\ 0 & |f| \geq \frac{B_D}{2} \end{cases}$$

The spectral line of a pure sine wave will have a power spectrum as shown in figure 5.1 after transmission over the channel. The frequency range, where the power spectrum is nonzero defines the Doppler spread B_D. The reciprocal of B_D approximates the coherence time T_c of the channel. If we represent the channel influence as an attenuation of the signal amplitude, T_c denotes the minimum time interval between two decorrelated attenuation factors.

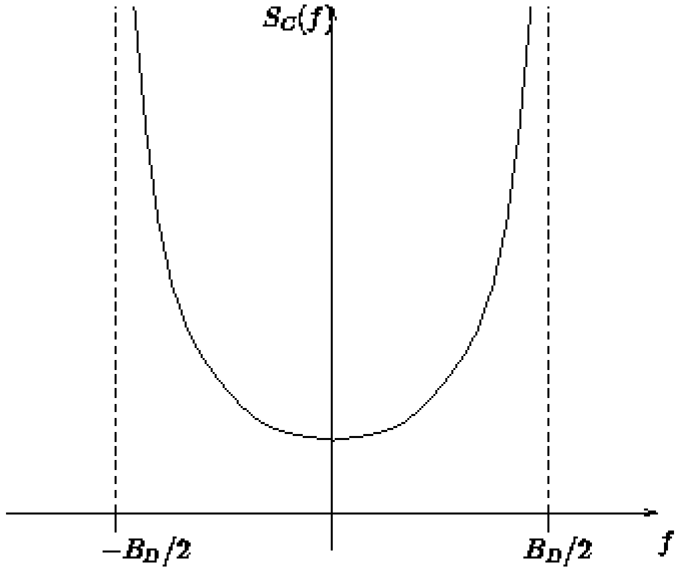

Fig. 5.1: Power density Spectrum of a sine Wave suffering from a Doppler Spread

3.1.2 Frequency Selective Channels

With large-scale effects, the signal may arrive at the receiver via paths with different path lengths. As a result, in complex phasor notation, a model for this large-scale effect is

$$\tilde{x}(t) = \sum_{i=1}^{L} \tilde{\alpha}_l \tilde{s}(t - \tau_l)$$

where τ_l relative delay associated with the l[th] path and, for the moment, the complex gains $\{\tilde{\alpha}_l\}$ are assumed constant (due to the transmitter and receiver being physically stationary). With this channel impulse response can be represented as

$$\tilde{h}(t,\tau) = \sum_{i=1}^{L} \tilde{\alpha}_l \delta(\tau - \tau_l)$$

This channel is time-invariant but it does show a frequency-dependent response.

The multipath delay spread T_m represents the time interval for which the impulse response of the channel is considerably greater than zero.

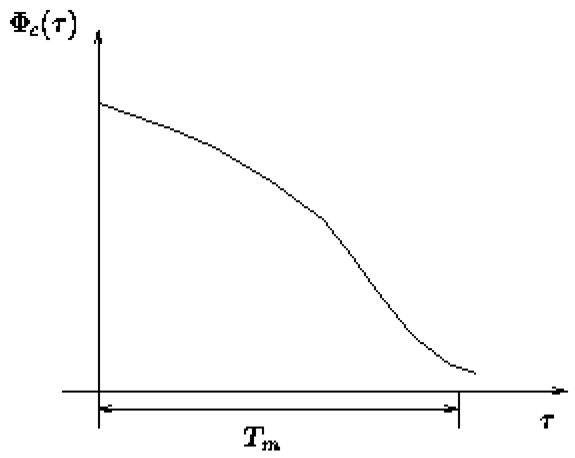

Fig. 5.2: Delay Profile Expected Received Power as a Function of Excess Delay Time

The coherence bandwidth B_c of the channel is proportional to the reciprocal of T_m. B_c denotes the maximum frequency separation of two sinusoidal signals, for which the channel affects these waves still in a highly correlated manner. This implies that a signal with a bandwidth larger than B_c will suffer from intersymbol interference. If its bandwidth is considerably smaller than B_c the channel can be considered as frequency-nonselective or "flat" fading.

3.1.3 General Channels

In a situation where the channel is neither time varying nor frequency varying, such a channel is referred to as flat-flat, since the response is flat in both the time and frequency domains

3.1.4 WSSUS Channels

The mobile channel introduces delay spread into the received signal.

That is, the received signal has a longer duration than that of the transmitted signal, due to the different delays of the signal paths. This is referred to as **Time Dispersion**.

The mobile channel introduces Doppler spread into the received signal.

That is, the received signal has a larger bandwidth than that of the transmitted signal, due to the different Doppler shifts introduced by the components of the multipath. This is referred to as **Frequency Dispersion.**

Both time dispersion and frequency dispersion introduce distortion into the received signal. The amount of degradation caused by this distortion depends on how the signal is designed. Doppler spreading or frequency dispersion causes variations of the received signal in the time domain.

Of interest for the design of data transmission systems is the maximum duration for which the channel can be assumed to be approximately constant. A transmitted data symbol that has duration less than this time should suffer little distortion from the effects of frequency dispersion.

However, it will still suffer the effects of reduced signal levels.

Just as fading does in the time domain, time dispersion causes slow variations in the received signal in the frequency domain. Of interest in the design of digital transmissions systems is the maximum transmission bandwidth over which there is little variation. A signal contained within that bandwidth should suffer little distortion from the effects of time dispersion.

A random process is wide-sense stationary if it has a mean that is time independent and a correlation function. It is also assumed that, in multipath channels, the gain and phase shift at one delay are uncorrelated with the gain and phase shift at another delay. This type of behaviour is referred to as uncorrelated scattering (US). The combination of a wide-sense stationary signal and uncorrelated scattering is referred to as a wide-sense stationary uncorrelated scattering (WSSUS) channel. The wide sense stationary uncorrelated scattering (WSSUS) model is commonly used for multipath fading channels. WSSUS channel assumes that the channel correlation function is invariant over time, and that the scattering with different path delays are uncorrelated

3.1.5 Coherence Time

The coherence time is defined as the period over which there is a strong correlation of the channel time response. It is a measure of the length of time for which the channel can be assumed to be approximately constant in the time domain. Coherence time is the time over which a propagating wave may be considered coherent. In other words, it is the time interval within which its phase is, on average, predictable. In long-distance transmission systems, the coherence time may be reduced by propagation factors such as dispersion, scattering, and diffraction.

Coherence Time can be expressed as $T_{coherence \cong} \cong \frac{1}{2 f_D}$

That is, coherence time of the channel is approximately the inverse of the Doppler spread of the channel

3.1.6 Power-Delay Profile

The power delay profile (PDP) gives the intensity of a signal received through a multipath channel as a function of time delay. The time delay is the difference in travel time between multipath arrivals. The abscissa is in units of time and the ordinate is usually in decibels. It is easily measured empirically and can be used to extract certain channel's parameters such as the delay spread.

3.1.7 Coherence Bandwidth

Coherence bandwidth is a statistical measurement of the range of frequencies over which the channel can be considered “flat”, or in other words the approximate maximum bandwidth or frequency interval over which two frequencies of a signal are likely to experience comparable or correlated amplitude fading. Coherence bandwidth is a measure of the approximate bandwidth within which the channel can be assumed to be nearly constant. Coherence bandwidth of a channel is related to the autocorrelation function of the time-varying frequency response. As a result of the inverse relationship between the time and frequency domains, we have the relationship

$$BW_{coh} \cong \frac{1}{T_M}$$

That is, the coherence bandwidth is inversely proportional to the multipath spread of the channel. The coherence bandwidth of the channel is the bandwidth over which the frequency response is strongly correlated, that is, relatively flat. If the coherence bandwidth is small with respect to the bandwidth of the transmitted signal, then the channel is said to be frequency selective. When the coherence bandwidth is large with respect to the bandwidth of the transmitted signal, then the channel is said to be frequency non selective or frequency-flat.

3.1.8 Stationary and Non-stationary Channels

The key feature of wide-sense stationary uncorrelated-scattering (WSSUS) channel is that correlation of the channel response depends only on the time difference and not on the absolute time. These stationary models for channel characteristics are convenient for analysis, but often, except for short time intervals, they are not an accurate description of reality. For example, terrestrial mobile channels are usually highly non-stationary, for the following reasons, among others:

i. the propagation often consists of several discontinuities, such as buildings, that can cause significant changes in the propagation characteristics

ii.the environment itself is physically nonstationary. There may be moving trucks, moving people, or other elements of the environment that can significantly affect propagation

iii.the interference caused by other users sharing the same frequency channel will vary dynamically as these other users come onto and leave the system. All of these factors contribute to the non-stationary of the link

Self-Assessment Exercise

What is meant by a channel?

4.0 Conclusion

In this unit, you have learned about channel and classifications of wireless channel. A channel is said to be time selective, if the channel is better at selected times than at other times. The coherence time is defined as the period over which there is a strong correlation of the channel time response.

5.0 Summary

In this unit you learnt that:

- channel refers to the medium used to convey information from a sender (or transmitter) to a receiver

- channels are classified on the basic of the properties of the time-varying impulse response. The effects of noise are not considered in classifying channels
- channel can be classified as follows: time-selective channels, frequency selective channels, general channels, WSSUS channels, coherence time channels, power-delay profile channels, coherence bandwidth channels, stationary and non-stationary channels.

6.0 Tutor-Marked Assignment

Briefly explain any five classes of channels.

7.0 Reference/Further Reading

Sharma, S. (2006). *Wireless & Cellular Communication.* New Delhi: S. K. Kataria & Sons.