Sri Muthukumaran Institute Of Technology
Department Of Electronics and Communication Engineering
Odd Semester July'23-Dec'23
Question Bank

Sub code: EC3501	Sem/Year: V/III
Sub name: Wireless Communication	Regulation: R2021

UNIT-II-

MOBILERADIOPROPAGATIONPART-A

1. Whatispropagationmodel?
   Propagation models that predict the mean signal strength for an arbitrarytransmitter – receiver separationdistanceareuseful inestimatingtheradiocoverageareaofatransmitter

2. Define largescalepropagationmodel?
   Thepropagationmodelsthatcharacterizethesignalstrengthoverlarge T-Rseparationdistance(severalhundredsorthousandsofmeters).

3. Definefading.
   Fadingisthereductioninradiosignalstrength, normallycausedbyreflectionorabsorptionofthesignal.

4. Whatisfreespacepropagationmodel?
   Thefreespacepropagationmodelisusedtopredictreceivedsignalstrength,whenunobstructedline-of-sightpathbetweentransmitter&receiver.

5. DefineEIRP.
   EIRP of a transmittingsystem in a given directionas the transmitterpower thatwouldbe needed, with an isotropic radiator, to produce the same power density in the givendirectionEIRP=P_tG_t,whereP_t-transmittedpowerinw,G_t-transmittingantennagain.

6. Explainpathloss?
   Thepathlossisdefinedasthedifference(indB)betweentheeffectivetransmittedpower&thereceivedpower,&mayormaynotincludethe effectoftheantennagains.

7. What isintrinsicimpedance&Brewsterangle?
   It is defined by the ratio of electric to magnetic field for a uniform plane wave in theparticular medium. The Brewster angle is the angle at which no reflection occurs intheorigin.

8. What isscattering?
   Whenaradiowaveimpingesonaroughsurface,thereflectedenergyisspreadoutinall

directionsduetoscattering.

9. Explainsmallscale fading?
Small scalefadingis used todescribe the rapid fluctuations of the amplitudes,phases, or multipath delays of a radio signal over a short period of time or traveldistance.

10. Whatarethefactorsinfluencingsmallscalefading?
Factorsinfluencingsmallscalefadingare:
1) Speedofsurroundingobjects.
2) MultipathPropagation.
3) Speedofthemobile.
4) Transmissionbandwidthofthesignal.

11. DefineDopplershift?
Theshiftinreceived signalfrequencyduetomotioniscalledtheDopplershift.

12. Whatflat fading?
If the mobile radio channel has a constant gain & linear phase response over abandwidth which is greater than the bandwidth of the transmitted signal, then thereceivedsignalwillundergoflatfading.

13. Whatisfrequencyselectivefading?
If the channel possesses a constant gain & linear phase response over a bandwidththat issmaller than the bandwidth of the transmitted signal, then the channel creates frequencyselectivefadingonthereceivedsignal.

14. Definefast fadingchannel?
Thechannelimpulseresponsechangesrapidlywithinthesymbolduration.Thistypeofa channeliscalledfastfadingchannel.

15. Defineslowfadingchannel?
Thechannelimpulseresponsechangesataratemuchslower thanthetransmittedbasebandsignal.Thistype ofa channeliscalledslowfadingchannel.

16. DefineDopplershift.
TheshiftinreceivedsignalfrequencyduetomotioniscalledtheDopplershiftanditissimply defined as the movement of the mobile terminal towards or away from the basestation.

17. Whatiscoherence bandwidth?
The coherence bandwidth is a measure of the maximum frequency difference (bandwidth)for which the received signal strongly correlated in amplitude. This bandwidth is inverselyproportionaltothermsvalueoftimedelayspread(σ_τ)

$$B_C \alpha\ 1/\sigma_\tau$$

18. Whatisdiffraction?

Diffraction occurs when the radio path between the transmitter and receiver is obstructed byasurfacethathassharpirregularedged.Thesecondarywavesresultingfromtheobstructingsurface are present throughout the space and even behind the obstacle, giving rise to abending of waves around the obstacle, even when a line-of-sight path does notexistsbetweentransmitterandreceiver.

19. Whatisreflection?
    Reflectionoccurswhenapropagatingelectromagneticwaveimpingesuponanobjectwhichhasverylarge dimensionswhencompared tothewavelengthofthepropagatingwave. Reflectionoccursfromsurfaceoftheearthandfrombuilding andwalls.

20. Whatisscattering?
    Scattering occurswhenthemediumthroughwhichthewave travelsconsistsofobjectswithdimensions smaller than the wavelength and where the number of obstacle per unit volumeislarge.

21. DefineFresnelzone.
    The concentric circles on the plane representing the loci of the origins of secondary waveletswhichpropagatetothereceiversuchthatthetotalpathlengthincreasesby$\lambda/2$forsuccessive circles.These circles are calledFresnelzones.

22. Whatismultipathwave?
    Whenfadingiscausedbyinterferencebetweentwoor moreversionsofthetransmittedsignal which arrives at the receiver at a slightly different time. These waves are calledmultipathwaves.

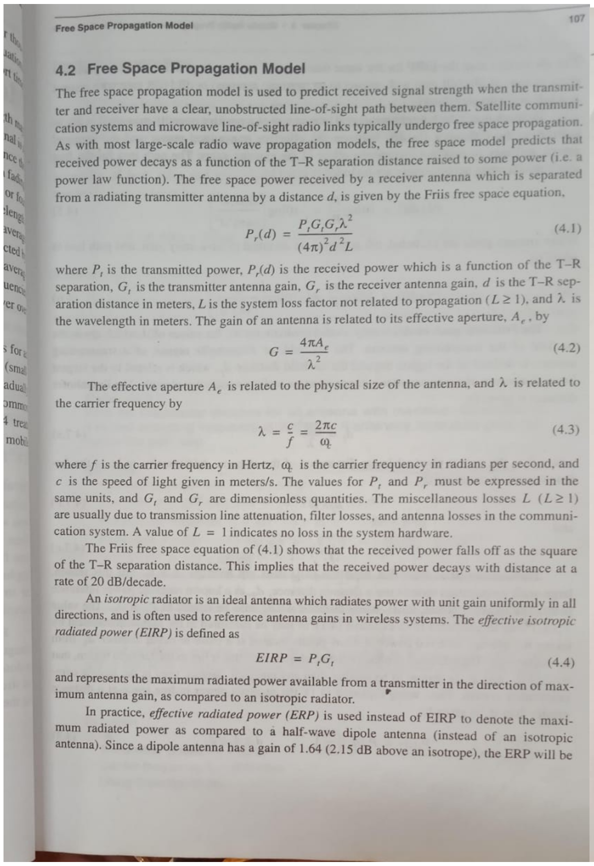
23. Define multipathpropagation.
    In many instances, more version of the transmitted signal takes more than one propagationpathtoreachthereceiverfromthetransmitterataslightlydifferent timesand thissituationiscalledmultipathpropagation.

24. Mentiontheeffectsofsmall-scalefading.
    (i) Rapidchanges insignalstrengthover asmalltraveldistanceortimeinterval.
    (ii) RandomfrequencymodulationduetovaryingDopplershiftsondifferentmultipathsignals.
    (iii) Timedispersion(echoes)causedbymultipathpropagationdelays.

25. DefineLine–of-sight.
    Infreespace, theradiosignalpropagateaslight(independentoftheirfrequency)i.e.,theyfollow a straight line. If such a straight line exists between a sender and receiver then it iscalledasline-of-sight(LOS)path.

PART-B

1. Explainindetailaboutthefreespacepropagationmodel.



4.2 Free Space Propagation Model

The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them. Satellite communication systems and microwave line-of-sight radio links typically undergo free space propagation. As with most large-scale radio wave propagation models, the free space model predicts that received power decays as a function of the T–R separation distance raised to some power (i.e. a power law function). The free space power received by a receiver antenna which is separated from a radiating transmitter antenna by a distance *d*, is given by the Friis free space equation,

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \qquad (4.1)$$

where P_t is the transmitted power, $P_r(d)$ is the received power which is a function of the T–R separation, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, d is the T–R separation distance in meters, L is the system loss factor not related to propagation ($L \geq 1$), and λ is the wavelength in meters. The gain of an antenna is related to its effective aperture, A_e, by

$$G = \frac{4\pi A_e}{\lambda^2} \qquad (4.2)$$

The effective aperture A_e is related to the physical size of the antenna, and λ is related to the carrier frequency by

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c} \qquad (4.3)$$

where f is the carrier frequency in Hertz, ω_c is the carrier frequency in radians per second, and c is the speed of light given in meters/s. The values for P_t and P_r must be expressed in the same units, and G_t and G_r are dimensionless quantities. The miscellaneous losses L ($L \geq 1$) are usually due to transmission line attenuation, filter losses, and antenna losses in the communication system. A value of $L = 1$ indicates no loss in the system hardware.

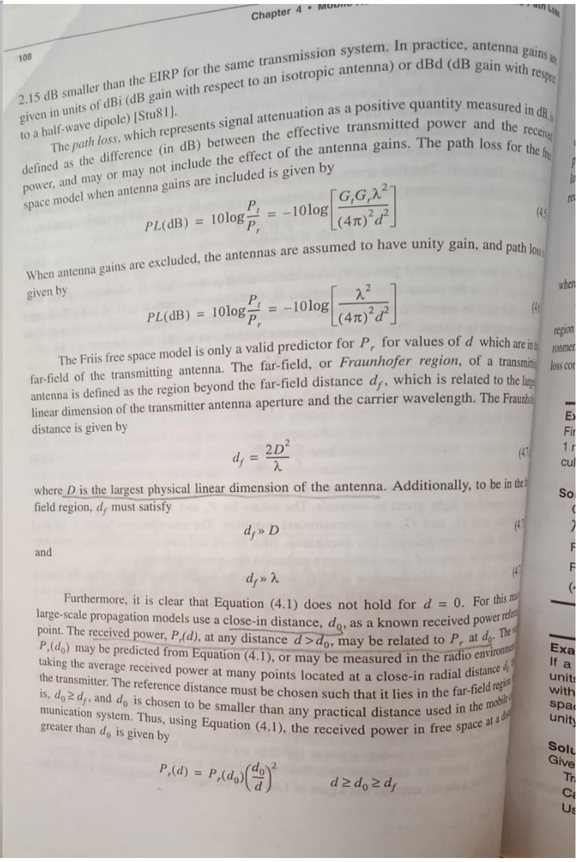
The Friis free space equation of (4.1) shows that the received power falls off as the square of the T–R separation distance. This implies that the received power decays with distance at a rate of 20 dB/decade.

An *isotropic* radiator is an ideal antenna which radiates power with unit gain uniformly in all directions, and is often used to reference antenna gains in wireless systems. The *effective isotropic radiated power (EIRP)* is defined as

$$EIRP = P_t G_t \qquad (4.4)$$

and represents the maximum radiated power available from a transmitter in the direction of maximum antenna gain, as compared to an isotropic radiator.

In practice, *effective radiated power (ERP)* is used instead of EIRP to denote the maximum radiated power as compared to a half-wave dipole antenna (instead of an isotropic antenna). Since a dipole antenna has a gain of 1.64 (2.15 dB above an isotrope), the ERP will be



2.15 dB smaller than the EIRP for the same transmission system. In practice, antenna gains ar given in units of dBi (dB gain with respect to an isotropic antenna) or dBd (dB gain with respe to a half-wave dipole) [Stu81].

The *path loss*, which represents signal attenuation as a positive quantity measured in dB, i defined as the difference (in dB) between the effective transmitted power and the receive power, and may or may not include the effect of the antenna gains. The path loss for the fre space model when antenna gains are included is given by

$$PL(\text{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right] \qquad (4.5$$

When antenna gains are excluded, the antennas are assumed to have unity gain, and path loss given by

$$PL(\text{dB}) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{\lambda^2}{(4\pi)^2 d^2}\right] \qquad (4$$

The Friis free space model is only a valid predictor for P_r for values of d which are in t far-field of the transmitting antenna. The far-field, or *Fraunhofer region*, of a transmitti antenna is defined as the region beyond the far-field distance d_f, which is related to the large linear dimension of the transmitter antenna aperture and the carrier wavelength. The Fraunho distance is given by

$$d_f = \frac{2D^2}{\lambda} \qquad (4.7$$

where D is the largest physical linear dimension of the antenna. Additionally, to be in the f field region, d_f must satisfy

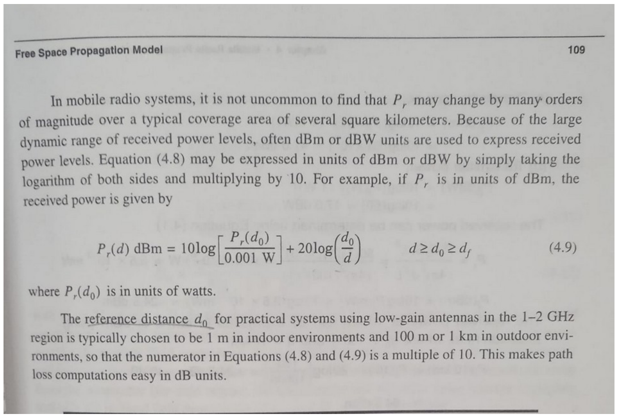
$$d_f \gg D \qquad (4$$

and

$$d_f \gg \lambda \qquad (4$$

Furthermore, it is clear that Equation (4.1) does not hold for $d = 0$. For this rea large-scale propagation models use a close-in distance, d_0, as a known received power refer point. The received power, $P_r(d)$, at any distance $d > d_0$, may be related to P_r at d_0. The v $P_r(d_0)$ may be predicted from Equation (4.1), or may be measured in the radio environme taking the average received power at many points located at a close-in radial distance d_0 f the transmitter. The reference distance must be chosen such that it lies in the far-field region is, $d_0 \geq d_f$, and d_0 is chosen to be smaller than any practical distance used in the mobile munication system. Thus, using Equation (4.1), the received power in free space at a dis greater than d_0 is given by

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0 \geq d_f$$



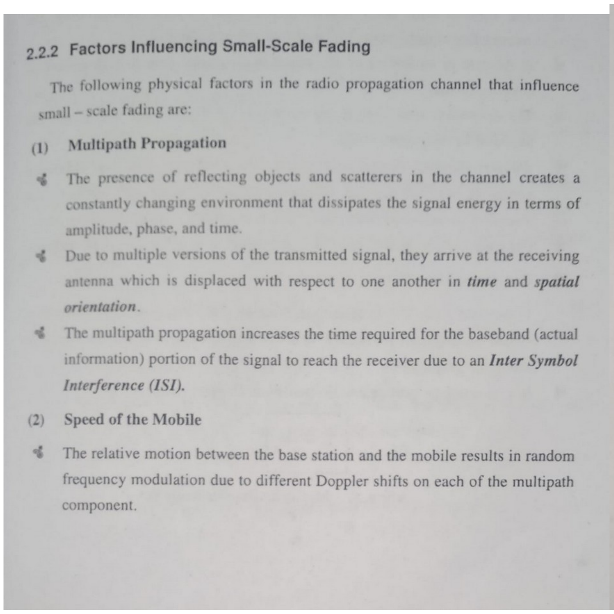
In mobile radio systems, it is not uncommon to find that P_r may change by many orders of magnitude over a typical coverage area of several square kilometers. Because of the large dynamic range of received power levels, often dBm or dBW units are used to express received power levels. Equation (4.8) may be expressed in units of dBm or dBW by simply taking the logarithm of both sides and multiplying by 10. For example, if P_r is in units of dBm, the received power is given by

$$P_r(d)\ \text{dBm} = 10\log\left[\frac{P_r(d_0)}{0.001\ \text{W}}\right] + 20\log\left(\frac{d_0}{d}\right) \qquad d \geq d_0 \geq d_f \qquad (4.9)$$

where $P_r(d_0)$ is in units of watts.

The reference distance d_0 for practical systems using low-gain antennas in the 1–2 GHz region is typically chosen to be 1 m in indoor environments and 100 m or 1 km in outdoor environments, so that the numerator in Equations (4.8) and (4.9) is a multiple of 10. This makes path loss computations easy in dB units.

2. Explainindetailaboutthefactorsinfluencingthesmallscalefading.



2.2.2 Factors Influencing Small-Scale Fading

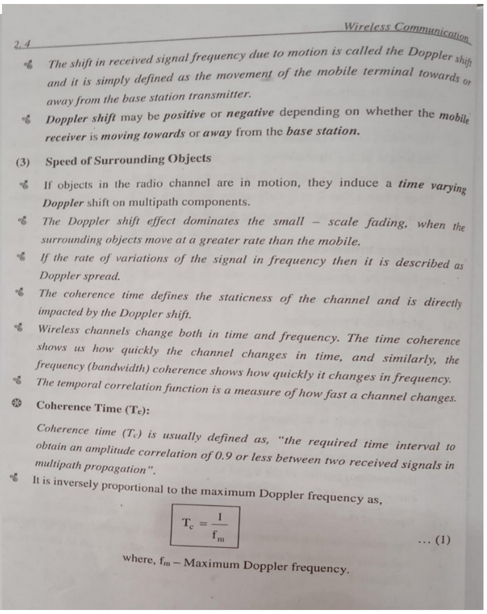
The following physical factors in the radio propagation channel that influence small – scale fading are:

(1) Multipath Propagation

- The presence of reflecting objects and scatterers in the channel creates a constantly changing environment that dissipates the signal energy in terms of amplitude, phase, and time.
- Due to multiple versions of the transmitted signal, they arrive at the receiving antenna which is displaced with respect to one another in ***time*** and ***spatial orientation***.
- The multipath propagation increases the time required for the baseband (actual information) portion of the signal to reach the receiver due to an ***Inter Symbol Interference (ISI).***

(2) 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.



- *The shift in received signal frequency due to motion is called the Doppler shift and it is simply defined as the movement of the mobile terminal towards or away from the base station transmitter.*
- ***Doppler shift*** may be ***positive*** or ***negative*** depending on whether the ***mobile receiver*** is ***moving towards*** or ***away*** from the ***base station.***

(3) Speed of Surrounding Objects

- If objects in the radio channel are in motion, they induce a ***time varying Doppler*** shift on multipath components.
- *The Doppler shift effect dominates the small – scale fading, when the surrounding objects move at a greater rate than the mobile.*
- *If the rate of variations of the signal in frequency then it is described as Doppler spread.*
- *The coherence time defines the staticness of the channel and is directly impacted by the Doppler shift.*
- *Wireless channels change both in time and frequency. The time coherence shows us how quickly the channel changes in time, and similarly, the frequency (bandwidth) coherence shows how quickly it changes in frequency.*
- *The temporal correlation function is a measure of how fast a channel changes.*

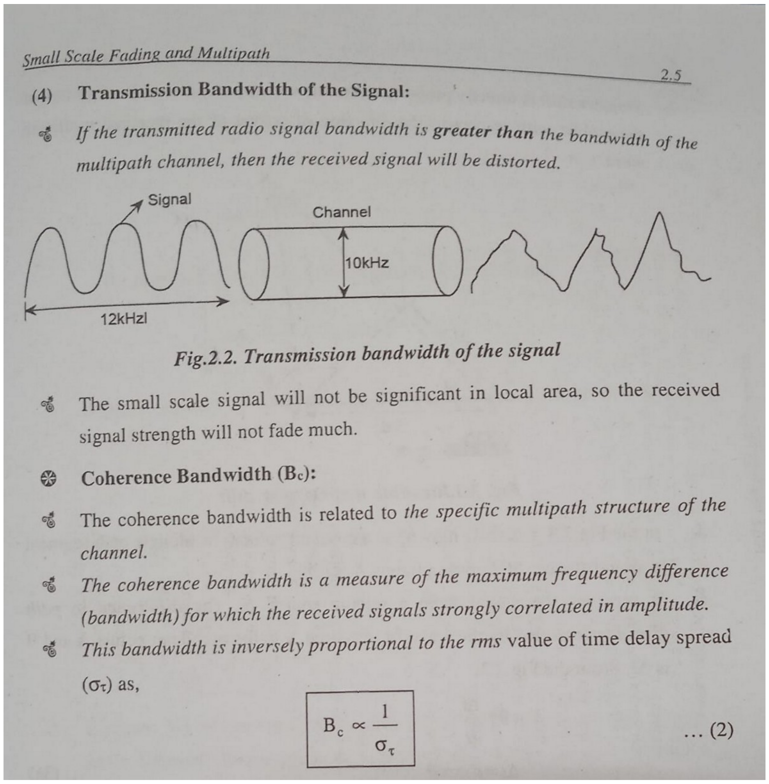
Coherence Time (T_c):

Coherence time (T_c) is usually defined as, "the required time interval to obtain an amplitude correlation of 0.9 or less between two received signals in multipath propagation".

- It is inversely proportional to the maximum Doppler frequency as,

$$\boxed{T_c = \frac{1}{f_m}} \qquad \dots (1)$$

where, f_m – Maximum Doppler frequency.



(4) Transmission Bandwidth of the Signal:

- *If the transmitted radio signal bandwidth is* **greater than** *the bandwidth of the multipath channel, then the received signal will be distorted.*

Fig.2.2. Transmission bandwidth of the signal

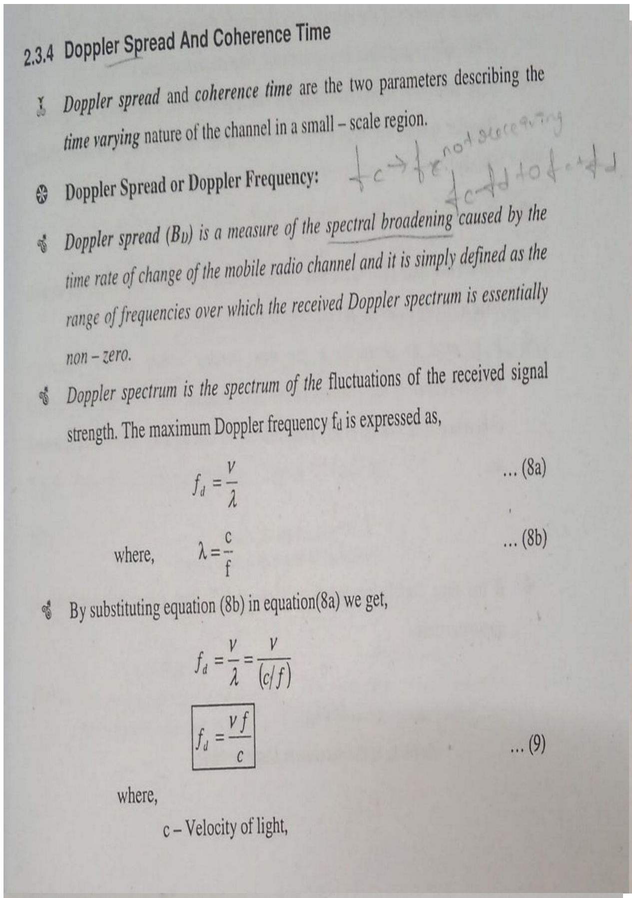
- The small scale signal will not be significant in local area, so the received signal strength will not fade much.

Coherence Bandwidth (B_c):

- The coherence bandwidth is related to *the specific multipath structure of the channel.*
- *The coherence bandwidth is a measure of the maximum frequency difference (bandwidth) for which the received signals strongly correlated in amplitude.*
- *This bandwidth is inversely proportional to the rms* value of time delay spread (σ_τ) as,

$$\boxed{B_c \propto \frac{1}{\sigma_\tau}} \qquad \dots (2)$$

3. GiveadetailednoteonDoppler spreadandcoherencetime.



2.3.4 Doppler Spread And Coherence Time

- ***Doppler spread*** and ***coherence time*** are the two parameters describing the *time varying* nature of the channel in a small – scale region.

Doppler Spread or Doppler Frequency:

$f_c \to f_r$ not receiving

$f_c - f_d$ to $f_c + f_d$

- *Doppler spread (B_D) is a measure of the spectral broadening caused by the time rate of change of the mobile radio channel and it is simply defined as the range of frequencies over which the received Doppler spectrum is essentially non – zero.*
- *Doppler spectrum is the spectrum of the* fluctuations of the received signal strength. The maximum Doppler frequency f_d is expressed as,

$$f_d = \frac{v}{\lambda} \qquad \text{... (8a)}$$

where, $$\lambda = \frac{c}{f} \qquad \text{... (8b)}$$

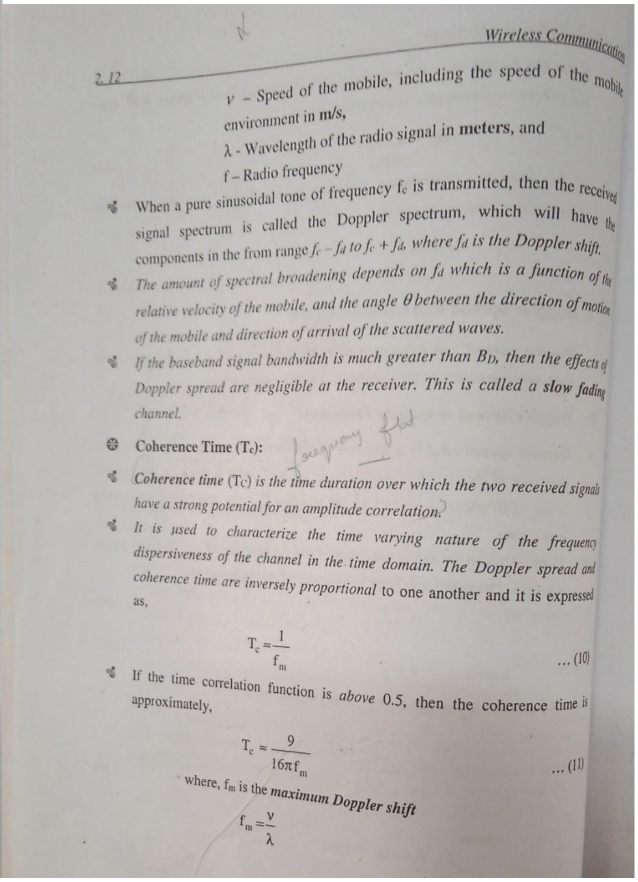
- By substituting equation (8b) in equation(8a) we get,

$$f_d = \frac{v}{\lambda} = \frac{v}{(c/f)}$$

$$\boxed{f_d = \frac{vf}{c}} \qquad \text{... (9)}$$

where,

c – Velocity of light,



v – Speed of the mobile, including the speed of the mobile environment in **m/s,**

λ - Wavelength of the radio signal in **meters,** and

f – Radio frequency

- When a pure sinusoidal tone of frequency f_c is transmitted, then the received signal spectrum is called the Doppler spectrum, which will have the components in the from range *$f_c - f_d$ to $f_c + f_d$, where f_d is the Doppler shift.*
- *The amount of spectral broadening depends on f_d which is a function of the relative velocity of the mobile, and the angle θ between the direction of motion of the mobile and direction of arrival of the scattered waves.*
- *If the baseband signal bandwidth is much greater than B_D, then the effects of Doppler spread are negligible at the receiver. This is called a* ***slow fading*** *channel.*

Coherence Time (T_c):

frequency flat

- *Coherence time* (T_C) *is the time duration over which the two received signals have a strong potential for an amplitude correlation.*
- *It is used to characterize the time varying nature of the frequency dispersiveness of the channel in the time domain. The Doppler spread and coherence time are inversely proportional* to one another and it is expressed as,

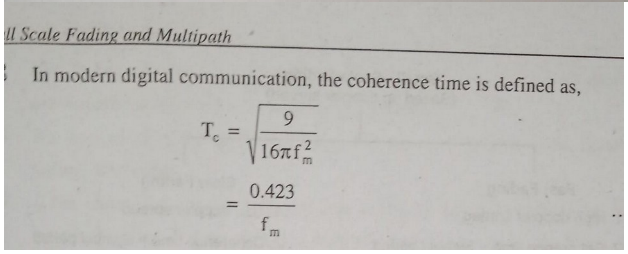
$$T_c \approx \frac{1}{f_m} \qquad \text{... (10)}$$

- If the time correlation function is *above* 0.5, then the coherence time is approximately,

$$T_c \approx \frac{9}{16\pi f_m} \qquad \text{... (11)}$$

where, f_m is the ***maximum Doppler shift***

$$f_m = \frac{v}{\lambda}$$



In modern digital communication, the coherence time is defined as,

$$T_c = \sqrt{\frac{9}{16\pi f_m^2}}$$

$$= \frac{0.423}{f_m}$$

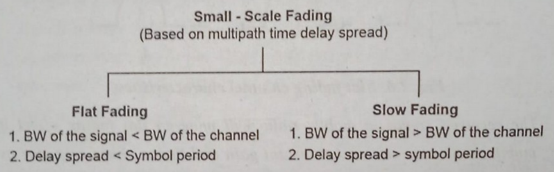
4. Explainindetailaboutthetypesofsmallscalefadingwith neatsketches.

2.4 TYPES OF SMALL – SCALE FADING

2.4.1 Introduction

- The type of fading experienced by a signal propagating through a mobile radio channel depends on the ***nature*** of the ***transmitted signal*** with respect to the ***characteristics*** of the channel.
- Depending on the relation between the ***signal parameters*** (such as ***bandwidth***, ***symbol period,*** etc) and the ***channel parameters*** (*namely*, ***rms delay spreac*** and ***Doppler spread***), different transmitted signals will undergo a differen types of fading.
- Multipath delay spread leads to ***time dispersion*** and ***frequency selectiv fading***. The Doppler spread leads to ***frequency dispersion*** and ***time selectiv fading***.

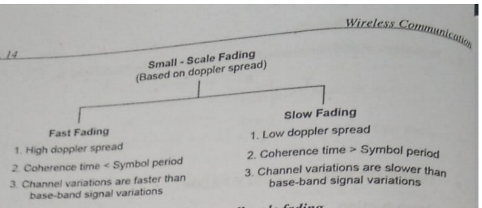
2.4.2 Tree Of The Four Different Types Of Fading



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

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

Slow Fading
1. BW of the signal > BW of the 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 are faster than base-band signal variations

Slow Fading
1. Low doppler spread
2. Coherence time > Symbol period
3. Channel variations are slower than base-band signal variations

Fig. 2.5.Types of small scale fading

2.4.3 Fading Effects Due To Multipath Time Delay Spread

Time dispersion due to multipath causes the transmitted signal to undergo either ***a flat*** or ***frequency selective fading***.

Flat Fading:

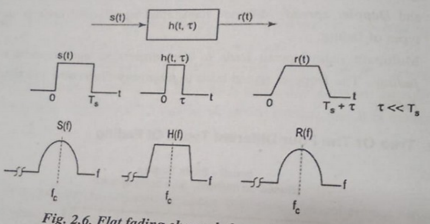


Fig. 2.6. Flat fading channel characteristics.

- *The received signal in mobile radio will undergo* ***flat fading effect*** *if the mobile radio channel has a* ***constant gain*** *and* ***linear phase response*** *over a bandwidth which is* ***greater than the bandwidth of the transmitted signal.***
- In flat fading, the *strength of the received signal changes with time, due to the fluctuations in the gain of the channel caused by multipath.*

- *Flat fading channels are also known as an amplitude varying channels and are sometimes referred to as narrowband channels.*
- *The bandwidth of the applied signal is narrow as compared to the channel flat fading bandwidth.*
- *If the channel gain changes overtime, a change of amplitude occurs in the received signal. Over a time, the received signal r(t), varies in gain, but the spectrum of the transmission is preserved.*
- *The condition for flat fading is,*

BW of the signal << BW of the channel.

$(B_s << B_C)$ and

Symbol period >> Delay spread

$(T_s >> \sigma_\tau)$

where, T_s – Symbol period (reciprocal bandwidth),
B_s – Signal bandwidth,
σ_τ - RMS delay spread, and
B_C – Coherence bandwidth.

Frequency Selective Fading (Time Delay Spread):

- *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.*
- *Frequency selective fading varies propagation distance of the reflected signals which causes time variations in the reflected signal.*
- *In other words, the frequency selective fading is due to time dispersion of the transmitted symbols within the channel. Thus, the channel induces Inter Symbol Interference (ISI).*
- *Frequency selective fading channels are also known as wideband channels because the bandwidth of the signal is wider than the bandwidth of the channel impulse response.*
- *Frequency selective fading channels* are much more difficult to model.

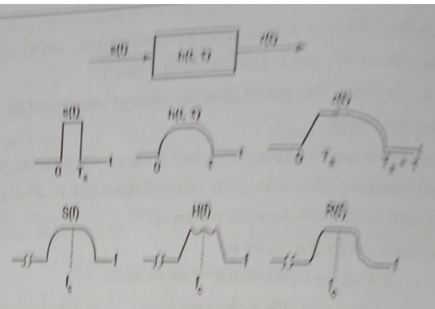


Fig.2.7. Frequency selective fading channel characteristics

- A signal undergoes frequency selective fading if

BW of the signal > BW of the channel.

$(B_s > B_c)$ and

Symbol period < Delay period

$(T_s < \sigma_\tau)$

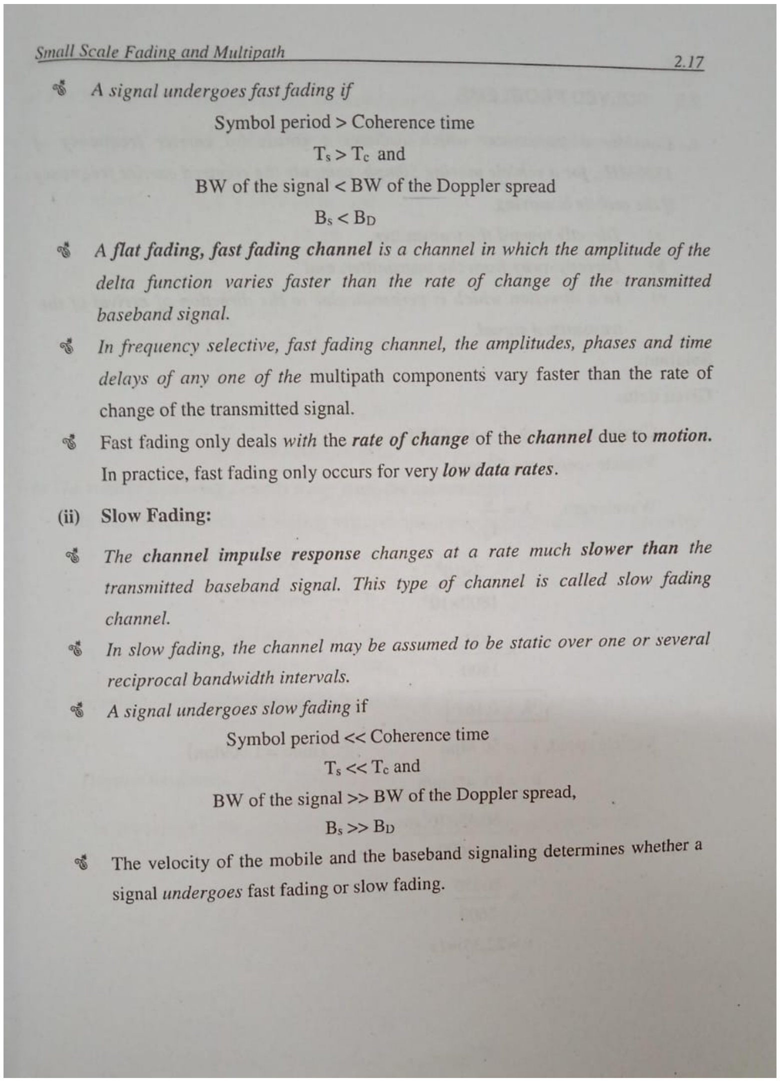
2.4.4 Fading Effects Due to Doppler Spread

Based on Doppler spread, a channel may be classified into two types

(i) Fast fading, and
(ii) Slow fading.

(i) Fast Fading Channel:

- *The* ***channel impulse response*** *changes rapidly within the symbol duration. This type of channel is called fast fading channel.*
- *The coherence time of the channel is smaller than the symbol period of the transmitted signal.*
- *Signal distortion due to fast fading increases with increasing in the Doppler spread relative to the bandwidth of the transmitted signal.*



Small Scale Fading and Multipath 2.17

- *A signal undergoes fast fading if*

Symbol period > Coherence time

$T_s > T_c$ and

BW of the signal < BW of the Doppler spread

$B_s < B_D$

- *A* ***flat fading, fast fading channel*** *is a channel in which the amplitude of the delta function varies faster than the rate of change of the transmitted baseband signal.*
- *In frequency selective, fast fading channel, the amplitudes, phases and time delays of any one of the* multipath components vary faster than the rate of change of the transmitted signal.
- Fast fading only deals *with* the ***rate of change*** of the ***channel*** due to ***motion.*** In practice, fast fading only occurs for very ***low data rates***.

(ii) Slow Fading:

- *The* ***channel impulse response*** *changes at a rate much* ***slower than*** *the transmitted baseband signal. This type of channel is called slow fading channel.*
- *In slow fading, the channel may be assumed to be static over one or several reciprocal bandwidth intervals.*
- *A signal undergoes slow fading* if

Symbol period << Coherence time

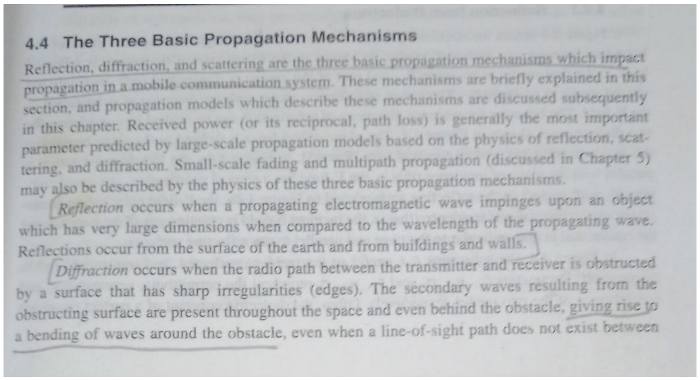
$T_s << T_c$ and

BW of the signal >> BW of the Doppler spread,

$B_s >> B_D$

- The velocity of the mobile and the baseband signaling determines whether a signal *undergoes* fast fading or slow fading.

5. Whatarethethreebasicpropagationmechanisms? Explain.

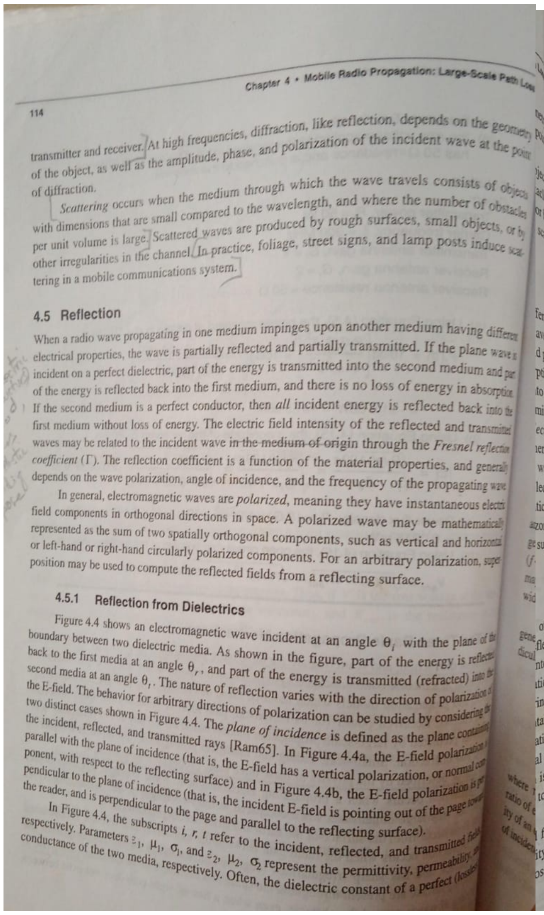


4.4 The Three Basic Propagation Mechanisms

Reflection, diffraction, and scattering are the three basic propagation mechanisms which impact propagation in a mobile communication system. These mechanisms are briefly explained in this section, and propagation models which describe these mechanisms are discussed subsequently in this chapter. Received power (or its reciprocal, path loss) is generally the most important parameter predicted by large-scale propagation models based on the physics of reflection, scattering, and diffraction. Small-scale fading and multipath propagation (discussed in Chapter 5) may also be described by the physics of these three basic propagation mechanisms.

Reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength of the propagating wave. Reflections occur from the surface of the earth and from buildings and walls.

Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities (edges). The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of waves around the obstacle, even when a line-of-sight path does not exist between



transmitter and receiver. At high frequencies, diffraction, like reflection, depends on the geometry of the object, as well as the amplitude, phase, and polarization of the incident wave at the point of diffraction.

Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel. In practice, foliage, street signs, and lamp posts induce scattering in a mobile communications system.

4.5 Reflection

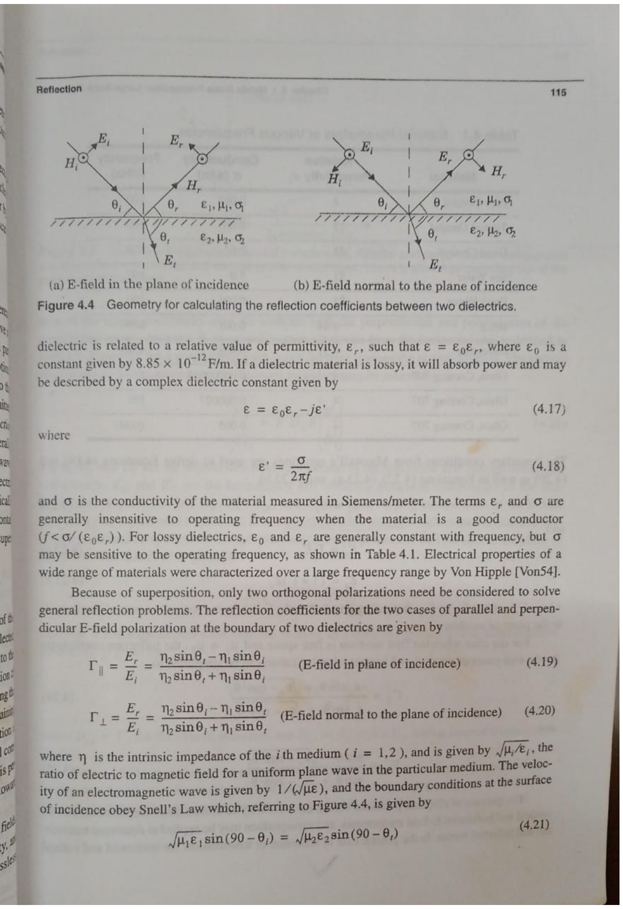
When a radio wave propagating in one medium impinges upon another medium having different electrical properties, the wave is partially reflected and partially transmitted. If the plane wave is incident on a perfect dielectric, part of the energy is transmitted into the second medium and part of the energy is reflected back into the first medium, and there is no loss of energy in absorption. If the second medium is a perfect conductor, then *all* incident energy is reflected back into the first medium without loss of energy. The electric field intensity of the reflected and transmitted waves may be related to the incident wave ~~in the medium of origin~~ through the *Fresnel reflection coefficient* (Γ). The reflection coefficient is a function of the material properties, and generally depends on the wave polarization, angle of incidence, and the frequency of the propagating wave.

In general, electromagnetic waves are *polarized*, meaning they have instantaneous electric field components in orthogonal directions in space. A polarized wave may be mathematically represented as the sum of two spatially orthogonal components, such as vertical and horizontal, or left-hand or right-hand circularly polarized components. For an arbitrary polarization, superposition may be used to compute the reflected fields from a reflecting surface.

4.5.1 Reflection from Dielectrics

Figure 4.4 shows an electromagnetic wave incident at an angle θ_i with the plane of the boundary between two dielectric media. As shown in the figure, part of the energy is reflected back to the first media at an angle θ_r, and part of the energy is transmitted (refracted) into the second media at an angle θ_t. The nature of reflection varies with the direction of polarization of the E-field. The behavior for arbitrary directions of polarization can be studied by considering the two distinct cases shown in Figure 4.4. The *plane of incidence* is defined as the plane containing the incident, reflected, and transmitted rays [Ram65]. In Figure 4.4a, the E-field polarization is parallel with the plane of incidence (that is, the E-field has a vertical polarization, or normal component, with respect to the reflecting surface) and in Figure 4.4b, the E-field polarization is perpendicular to the plane of incidence (that is, the incident E-field is pointing out of the page towards the reader, and is perpendicular to the page and parallel to the reflecting surface).

In Figure 4.4, the subscripts *i, r, t* refer to the incident, reflected, and transmitted fields respectively. Parameters ε_1, μ_1, σ_1, and ε_2, μ_2, σ_2 represent the permittivity, permeability, and conductance of the two media, respectively. Often, the dielectric constant of a perfect (lossless)



(a) E-field in the plane of incidence (b) E-field normal to the plane of incidence

Figure 4.4 Geometry for calculating the reflection coefficients between two dielectrics.

dielectric is related to a relative value of permittivity, ε_r, such that $\varepsilon = \varepsilon_0\varepsilon_r$, where ε_0 is a constant given by 8.85×10^{-12} F/m. If a dielectric material is lossy, it will absorb power and may be described by a complex dielectric constant given by

$$\varepsilon = \varepsilon_0\varepsilon_r - j\varepsilon' \tag{4.17}$$

where

$$\varepsilon' = \frac{\sigma}{2\pi f} \tag{4.18}$$

and σ is the conductivity of the material measured in Siemens/meter. The terms ε_r and σ are generally insensitive to operating frequency when the material is a good conductor ($f < \sigma/(\varepsilon_0\varepsilon_r)$). For lossy dielectrics, ε_0 and ε_r are generally constant with frequency, but σ may be sensitive to the operating frequency, as shown in Table 4.1. Electrical properties of a wide range of materials were characterized over a large frequency range by Von Hipple [Von54].

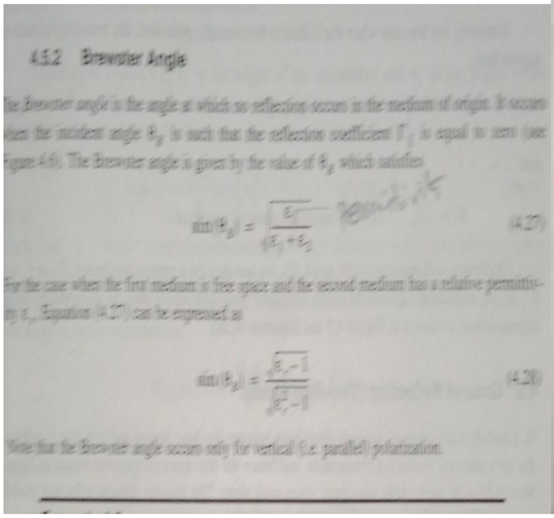
Because of superposition, only two orthogonal polarizations need be considered to solve general reflection problems. The reflection coefficients for the two cases of parallel and perpendicular E-field polarization at the boundary of two dielectrics are given by

$$\Gamma_{\|} = \frac{E_r}{E_i} = \frac{\eta_2\sin\theta_t - \eta_1\sin\theta_i}{\eta_2\sin\theta_t + \eta_1\sin\theta_i} \quad \text{(E-field in plane of incidence)} \tag{4.19}$$

$$\Gamma_{\perp} = \frac{E_r}{E_i} = \frac{\eta_2\sin\theta_i - \eta_1\sin\theta_t}{\eta_2\sin\theta_i + \eta_1\sin\theta_t} \quad \text{(E-field normal to the plane of incidence)} \tag{4.20}$$

where η is the intrinsic impedance of the ith medium ($i = 1,2$), and is given by $\sqrt{\mu_i/\varepsilon_i}$, the ratio of electric to magnetic field for a uniform plane wave in the particular medium. The velocity of an electromagnetic wave is given by $1/(\sqrt{\mu\varepsilon})$, and the boundary conditions at the surface of incidence obey Snell's Law which, referring to Figure 4.4, is given by

$$\sqrt{\mu_1\varepsilon_1}\sin(90-\theta_i) = \sqrt{\mu_2\varepsilon_2}\sin(90-\theta_t) \tag{4.21}$$



4.5.2 Brewster Angle

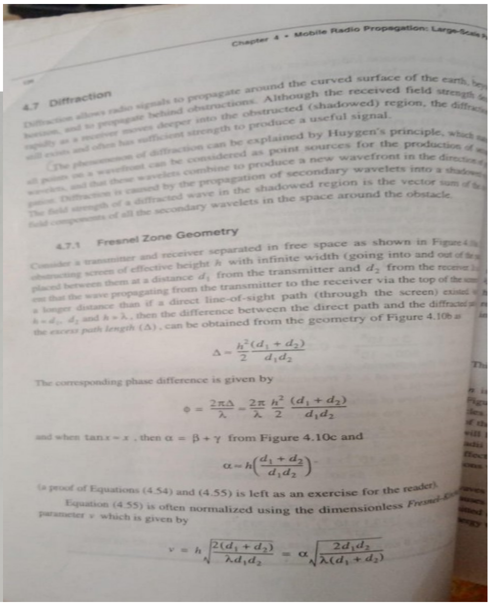
The Brewster angle is the angle at which no reflection occurs in the medium of origin. It occurs when the incident angle θ_B is such that the reflection coefficient $\Gamma_{\|}$ is equal to zero (see Figure 4.6). The Brewster angle is given by the value of θ_B which satisfies

$$\sin(\theta_B) = \sqrt{\frac{\varepsilon_1}{\varepsilon_1+\varepsilon_2}} \tag{4.22}$$

For the case when the first medium is free space and the second medium has a relative permittivity ε_r, Equation (4.22) can be expressed as

$$\sin(\theta_B) = \frac{\sqrt{\varepsilon_r-1}}{\sqrt{\varepsilon_r^2-1}} \tag{4.23}$$

Note that the Brewster angle occurs only for vertical (i.e. parallel) polarization.



4.7 Diffraction

Diffraction allows radio signals to propagate around the curved surface of the earth, beyond the horizon, and to propagate behind obstructions. Although the received field strength decreases rapidly as a receiver moves deeper into the obstructed (shadowed) region, the diffraction field still exists and often has sufficient strength to produce a useful signal.

The phenomenon of diffraction can be explained by Huygen's principle, which states that all points on a wavefront can be considered as point sources for the production of secondary wavelets, and that these wavelets combine to produce a new wavefront in the direction of propagation. Diffraction is caused by the propagation of secondary wavelets into a shadowed region. The field strength of a diffracted wave in the shadowed region is the vector sum of the electric field components of all the secondary wavelets in the space around the obstacle.

4.7.1 Fresnel Zone Geometry

Consider a transmitter and receiver separated in free space as shown in Figure 4.10a. Let an obstructing screen of effective height h with infinite width (going into and out of the paper) be placed between them at a distance d_1 from the transmitter and d_2 from the receiver. It is apparent that the wave propagating from the transmitter to the receiver via the top of the screen travels a longer distance than if a direct line-of-sight path (through the screen) existed. Assuming $h \ll d_1, d_2$ and $h \gg \lambda$, then the difference between the direct path and the diffracted path, called the *excess path length* (Δ), can be obtained from the geometry of Figure 4.10b as

$$\Delta \approx \frac{h^2}{2}\frac{(d_1+d_2)}{d_1d_2}$$

The corresponding phase difference is given by

$$\phi = \frac{2\pi\Delta}{\lambda} \approx \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{(d_1+d_2)}{d_1d_2}$$

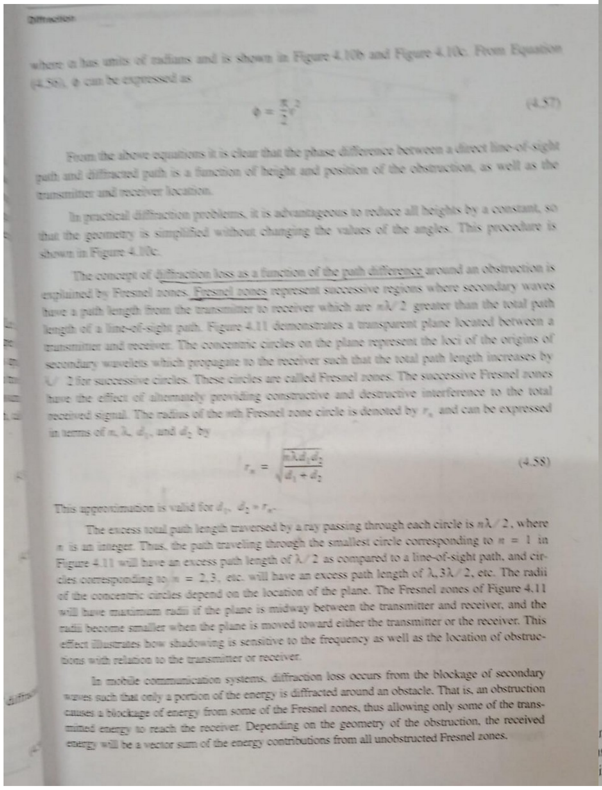
and when $\tan x \approx x$, then $\alpha = \beta + \gamma$ from Figure 4.10c and

$$\alpha \approx h\left(\frac{d_1+d_2}{d_1d_2}\right)$$

(a proof of Equations (4.54) and (4.55) is left as an exercise for the reader).

Equation (4.55) is often normalized using the dimensionless *Fresnel-Ki* parameter v which is given by

$$v = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1d_2}} = \alpha\sqrt{\frac{2d_1d_2}{\lambda(d_1+d_2)}}$$



where α has units of radians and is shown in Figure 4.10b and Figure 4.10c. From Equation (4.56), φ can be expressed as

$$\phi = \frac{\pi}{2}v^2 \tag{4.57}$$

From the above equations it is clear that the phase difference between a direct line-of-sight path and diffracted path is a function of height and position of the obstruction, as well as the transmitter and receiver location.

In practical diffraction problems, it is advantageous to reduce all heights by a constant, so that the geometry is simplified without changing the values of the angles. This procedure is shown in Figure 4.10c.

The concept of diffraction loss as a function of the path difference around an obstruction is explained by Fresnel zones. Fresnel zones represent successive regions where secondary waves have a path length from the transmitter to receiver which are $n\lambda/2$ greater than the total path length of a line-of-sight path. Figure 4.11 demonstrates a transparent plane located between a transmitter and receiver. The concentric circles on the plane represent the loci of the origins of secondary wavelets which propagate to the receiver such that the total path length increases by $\lambda/2$ for successive circles. These circles are called Fresnel zones. The successive Fresnel zones have the effect of alternately providing constructive and destructive interference to the total received signal. The radius of the nth Fresnel zone circle is denoted by r_n and can be expressed in terms of n, λ, d_1, and d_2 by

$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \tag{4.58}$$

This approximation is valid for $d_1, d_2 \gg r_n$.

The excess total path length traversed by a ray passing through each circle is $n\lambda/2$, where n is an integer. Thus, the path traveling through the smallest circle corresponding to $n = 1$ in Figure 4.11 will have an excess path length of $\lambda/2$ as compared to a line-of-sight path, and circles corresponding to $n = 2, 3$, etc. will have an excess path length of $\lambda, 3\lambda/2$, etc. The radii of the concentric circles depend on the location of the plane. The Fresnel zones of Figure 4.11 will have maximum radii if the plane is midway between the transmitter and receiver, and the radii become smaller when the plane is moved toward either the transmitter or the receiver. This effect illustrates how shadowing is sensitive to the frequency as well as the location of obstructions with relation to the transmitter or receiver.

In mobile communication systems, diffraction loss occurs from the blockage of secondary waves such that only a portion of the energy is diffracted around an obstacle. That is, an obstruction causes a blockage of energy from some of the Fresnel zones, thus allowing only some of the transmitted energy to reach the receiver. Depending on the geometry of the obstruction, the received energy will be a vector sum of the energy contributions from all unobstructed Fresnel zones.

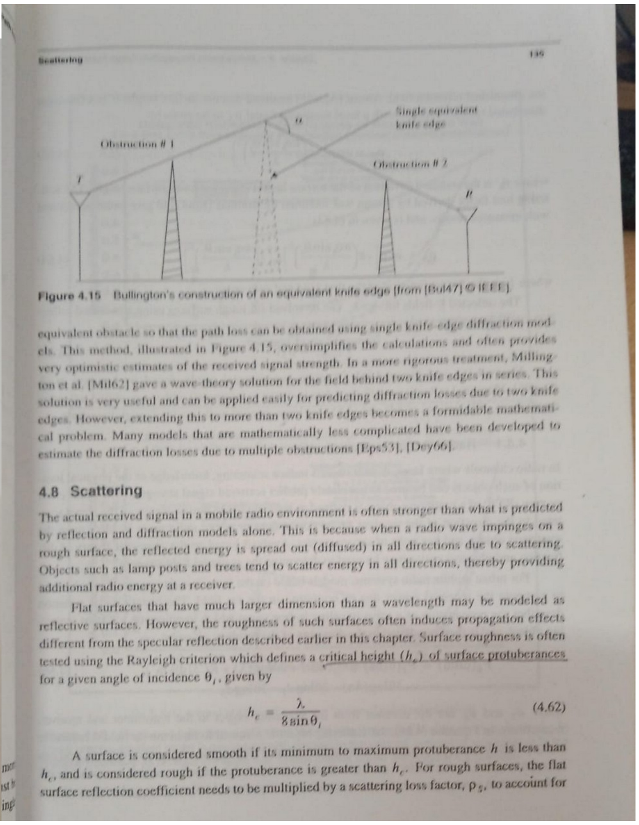


Figure 4.15 Bullington's construction of an equivalent knife edge [from [Bul47] © IEEE].

equivalent obstacle so that the path loss can be obtained using single knife-edge diffraction models. This method, illustrated in Figure 4.15, oversimplifies the calculations and often provides very optimistic estimates of the received signal strength. In a more rigorous treatment, Millington et al. [Mil62] gave a wave-theory solution for the field behind two knife edges in series. This solution is very useful and can be applied easily for predicting diffraction losses due to two knife edges. However, extending this to more than two knife edges becomes a formidable mathematical problem. Many models that are mathematically less complicated have been developed to estimate the diffraction losses due to multiple obstructions [Eps53], [Dey66].

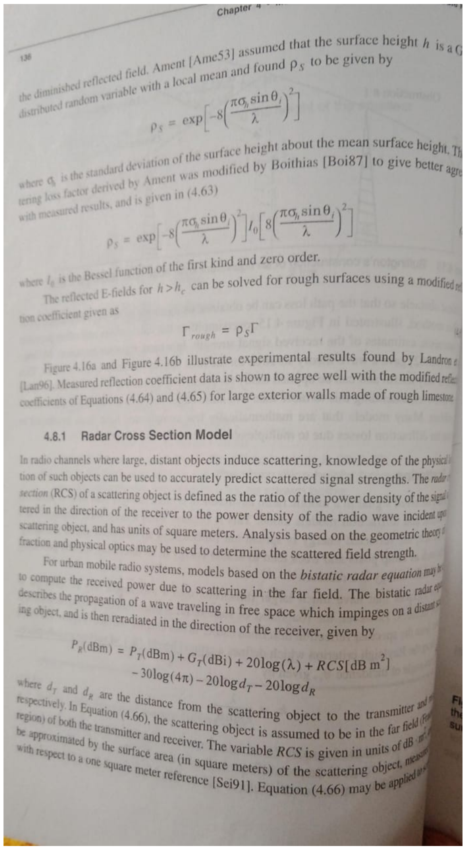
4.8 Scattering

The actual received signal in a mobile radio environment is often stronger than what is predicted by reflection and diffraction models alone. This is because when a radio wave impinges on a rough surface, the reflected energy is spread out (diffused) in all directions due to scattering. Objects such as lamp posts and trees tend to scatter energy in all directions, thereby providing additional radio energy at a receiver.

Flat surfaces that have much larger dimension than a wavelength may be modeled as reflective surfaces. However, the roughness of such surfaces often induces propagation effects different from the specular reflection described earlier in this chapter. Surface roughness is often tested using the Rayleigh criterion which defines a critical height (h_c) of surface protuberances for a given angle of incidence θ_i, given by

$$h_c = \frac{\lambda}{8\sin\theta_i} \tag{4.62}$$

A surface is considered smooth if its minimum to maximum protuberance h is less than h_c, and is considered rough if the protuberance is greater than h_c. For rough surfaces, the flat surface reflection coefficient needs to be multiplied by a scattering loss factor, ρ_S, to account for



the diminished reflected field. Ament [Ame53] assumed that the surface height h is a G
distributed random variable with a local mean and found ρ_S to be given by

$$\rho_S = \exp\left[-8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right]$$

where σ_h is the standard deviation of the surface height about the mean surface height. Th
tering loss factor derived by Ament was modified by Boithias [Boi87] to give better agre
with measured results, and is given in (4.63)

$$\rho_S = \exp\left[-8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right] I_0\left[8\left(\frac{\pi\sigma_h \sin\theta_i}{\lambda}\right)^2\right]$$

where I_0 is the Bessel function of the first kind and zero order.

The reflected E-fields for $h > h_c$ can be solved for rough surfaces using a modified re
tion coefficient given as

$$\Gamma_{rough} = \rho_S \Gamma$$

Figure 4.16a and Figure 4.16b illustrate experimental results found by Landron e
[Lan96]. Measured reflection coefficient data is shown to agree well with the modified refle
coefficients of Equations (4.64) and (4.65) for large exterior walls made of rough limestone

4.8.1 Radar Cross Section Model

In radio channels where large, distant objects induce scattering, knowledge of the physical
tion of such objects can be used to accurately predict scattered signal strengths. The *radar*
section (RCS) of a scattering object is defined as the ratio of the power density of the signal
tered in the direction of the receiver to the power density of the radio wave incident upo
scattering object, and has units of square meters. Analysis based on the geometric theory
fraction and physical optics may be used to determine the scattered field strength.

For urban mobile radio systems, models based on the *bistatic radar equation* may b
to compute the received power due to scattering in the far field. The bistatic radar eq
describes the propagation of a wave traveling in free space which impinges on a distant s
ing object, and is then reradiated in the direction of the receiver, given by

$$\begin{aligned} P_R(\text{dBm}) = {} & P_T(\text{dBm}) + G_T(\text{dBi}) + 20\log(\lambda) + RCS[\text{dB m}^2] \\ & - 30\log(4\pi) - 20\log d_T - 20\log d_R \end{aligned}$$

where d_T and d_R are the distance from the scattering object to the transmitter and
respectively. In Equation (4.66), the scattering object is assumed to be in the far field (Fr
region) of both the transmitter and receiver. The variable RCS is given in units of dB · m²,
be approximated by the surface area (in square meters) of the scattering object, meas
with respect to a one square meter reference [Sei91]. Equation (4.66) may be applied to