

**King Fahd University of  
Petroleum & Minerals  
Computer Engineering Dept**

---

**COE 543 – Mobile and Wireless  
Networks**

**Term 082**

**Dr. Ashraf S. Hasan Mahmoud**

**Rm 22-148-3**

**Ext. 1724**

**Email: [ashraf@kfupm.edu.sa](mailto:ashraf@kfupm.edu.sa)**

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

1

**Material for This Topic**

---

In addition to the Pahlavan's Chapter of RF propagation, the following paper is a must read:

- B. Skar, "Rayleigh fading channels in mobile digital communication systems .I. Characterization," IEEE Communications Magazine, Vol. 35, Issue 7, pp. 90-100, 1997.

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

2

## **Lecture Contents**

---

1. Free-Space Propagation
2. Two-Ray Model for Mobile Radio Environment
3. Path-Loss Models:
  - a. Path-Loss Models for Macrocellular Areas
  - b. Path-Loss Models for Microcellular Areas
  - c. Path Models for Picocellular Indoor Areas
  - d. Path Models for Femtocellular Areas
4. Multi-path Propagation
  - a. Rayleigh fading
  - b. Doppler
  - c. Delay Spread
  - d. Coherence Bandwidth

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

3

## **Received Signal Strength**

---

- Metric: Received Power / Transmitted Power
- Factors:
  - Distance (Path Loss Model)
  - Slow fading or Shadowing (Obstacles)
  - Fast fading (mobility, scatterers, etc.)
    - Doppler spread
    - Multipath

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

4

## Free-Space Propagation

- For free-space, the ratio of received power,  $P_r$ , to transmitted power,  $P_t$  is given by

$$\frac{P_r}{P_t} = G_t G_r \times \left( \frac{\lambda}{4\pi d} \right)^2$$

- Where:  $G_t$  and  $G_r$  are the transmit and receive antenna gains respectively –  $\lambda$  is the wavelength of the radio signal, while  $d$  is the distance between the transmitter and the receiver
- Define  $P_0$  as the relative signal strength at one meter distance or  $P_0 = P_t G_t G_r (\lambda/4\pi)^2 \rightarrow P_r = P_0 d^2$
- Note that received signal strength is inversely proportional to the square of the distance

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

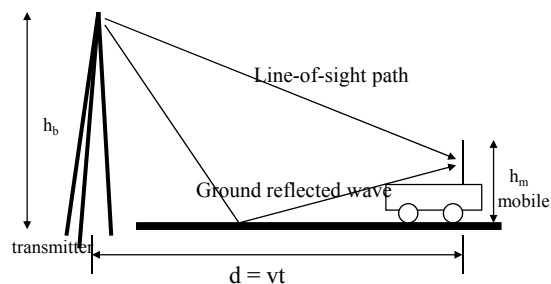
5

## Two-Ray Model for Mobile Radio Environments

- The ratio of received power,  $P_r$ , to transmitted power,  $P_t$  is given by

$$\frac{P_r}{P_t} = G_t G_r \times \left( \frac{h_b h_m}{d^2} \right)^2$$

- Note the received power relative to transmitted power falls 40 dB per decade ( $\propto d^{-4}$ )
- Signal strength increases as antenna heights are increased



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

6

## Distance-Power Gradient Relation

- The ratio of received power,  $P_r$ , to transmitted power,  $P_t$ , is given by

$$P_r = P_t d^{-\alpha}$$

- For free-space  $\alpha = 2$
- For the simplified two-ray model,  $\alpha = 4$
- For indoor and urban radio channels  $\sim$  depending on obstructions and environment:
  - Indoor corridors or open areas  $\alpha < 2$
  - Metallic buildings  $\alpha > 4$  ( $\sim 6$ )

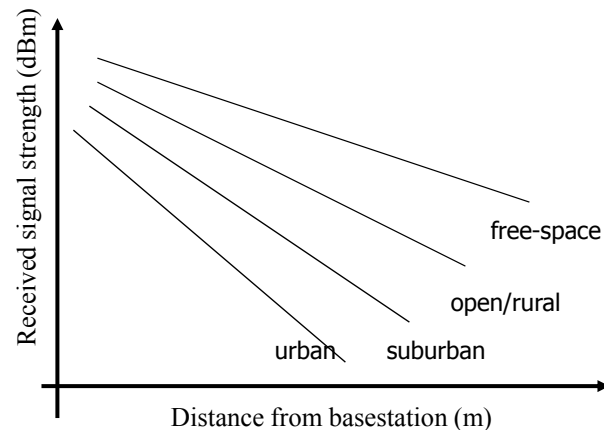
3/8/2009

Dr. Ashraf S. Hasan Mahmoud

7

## Distance-Power Gradient Relation (2)

- Typical outdoor received-signal strength vs. distance curves



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

8

## Distance-Power Gradient Relation (3)

- Writing the previous relation in dBs

$$10\log(P_r) = 10\log(P_0) - 10\alpha \log(d)$$

- The  $10\log(P_0) \sim$  represents the power loss in dB with respect to received power at one meter
- Loss of  $10\alpha$  dB per decade of distance
- Let

$$L_0 = 10\log(P_t) - 10\log(P_0)$$

be the path-loss in dB at a distance of one meter, then the total path-loss,  $L_p$ , at distance  $d$ , is given by

$$L_p = L_0 + 10\alpha \log(d)$$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

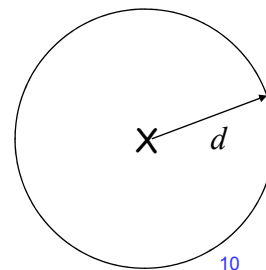
9

## Shadow Fading

- The received signal strength at the same distance  $d$  from transmitted is NOT exactly fixed
  - Due to obstructions (e.g. buildings for outdoor, walls for indoor, etc.)
- The variation is slow (compared to other yet to be introduced variations) – frequency independent (almost)
- Measurements have shown that when the received signal strength is reported in decibels, the variation (or random component) follows the normal distribution
- Modifying the path-loss equation to include this variation, yields

$$L_p = L_0 + 10\alpha \log(d) + X_{dB}$$

Where  $X_{dB}$  follows the normal distribution with mean zero and standard deviation of  $\sigma_{dB}$



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

10

## **Shadow Fading (2)**

- $\sigma_{dB}$  is a function of the propagation environment – typical value  $\sim 8$  dB
- The signal variation on the linear scale – follows the log-normal distribution:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_{dB}x} \exp\left(\frac{-(\ln x - \mu)^2}{2\sigma_{dB}^2}\right)$$

- Note that from the above formula, the distribution of the  $\ln x$  is normal with mean  $\mu$  and standard deviation of  $\sigma_{dB}$
- Fade Margin ( $F_\sigma$ ): When computing signal coverage a margin of power dBs are added to compensate for the slow fading parameter

## **Example: Fade Margin Calculation**

- A mobile system is to provide 95% successful communication at the fringe of coverage with a shadow fading component having a zero mean Gaussian distribution with standard deviation of 8 dBs. What is the required fade margin?

## Example: Fade Margin Calculation

- **Solution:**

Let the local mean =  $M$ ,  
Therefore, the overall signal level,  
 $S = M + X$

where  $X$  is a normal r.v. specifying  
the shadowing process (i.e.  $X \sim N(0, \sigma=8 \text{ dB})$ )

Note that  $\text{Prob}[S < M] = \text{Prob}[S > M] = 0.5$

It is desired to add a fade margin  $F$   
such that

$\text{Prob}[M+X < M+F] = 0.95$ , or

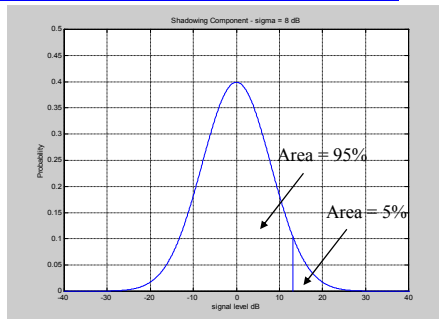
$\text{Prob}[X > F] = 0.05$ , or

$\text{Prob}[X/\sigma > F/\sigma] = 0.05$

$\rightarrow 0.05 = 0.5 \text{erfc}((F/\sigma)/\text{sqrt}(2))$

$\rightarrow F/\sigma = 1.163 \times \text{sqrt}(2)$

$\rightarrow F = 13.16 \text{ dB}$



**Recall:** for a Gaussian variable  $X$  with mean  $m$  and standard deviation of  $\sigma$   
 $\text{Prob}[X > F] = \text{Prob}[(X-m)/\sigma > (F-m)/\sigma] = \text{Prob}[X_\sigma > F_\sigma]$   
where  $X_\sigma$  is the zero-mean Gaussian r.v. with unity standard deviation.

$\text{Pr}[X_\sigma > F_\sigma] = \frac{1}{\sqrt{2\pi}} \int_{F_\sigma}^{\infty} e^{-t^2/2} dt$  which is tabulated as  $Q(F_\sigma)$

One can also use the erfc as well: since erfc is defined as  $\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt$

therefore,  $Q(F_\sigma) = 0.5 \text{erfc}(F_\sigma/\text{sqrt}(2))$ .

## Path-Loss Models for Megacellular Areas

- Span 100s of kilometers
- Served mostly by LEO Satellites
- Model  $\sim$  free space

## **Path-Loss Models for Macrocellular Areas – Okumura-Hata Model**

- Empirical formula calculating the median path-loss for a quasismooth terrain in an urban area

$$L_p = 69.55 + 26.16 \log f_c - 13.83 \log h_b - a(h_m) + [44.9 - 6.55 \log h_m] \log d$$

- Where  $f_c$  in MHz -  $150 < f_c < 1500$  MHz  
 $h_b$  in meters – basestation antenna height -  $30 < h_b < 200$  m  
 $h_m$  in meters – mobile antenna height -  $1 < h_m < 10$  m  
 $d$  in kilometers – distance -  $1 < d < 20$  km

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

15

## **Path-Loss Models for Macrocellular Areas – Okumura-Hata Model (2)**

- The correction factor for the mobile antenna height is given by:

- Small-medium city:

$$a(h_m) = (1.1 \log f_c - 0.7) h_m - (1.56 \log f_c - 0.8)$$

- Large city:

$$a(h_m) = 8.29 (\log 1.54 h_m)^2 - 1.1, \quad f_c \leq 200 \text{ MHz}$$

$$a(h_m) = 3.2 (\log 11.75 h_m)^2 - 4.97, \quad f_c \leq 400 \text{ MHz}$$

- For a suburban area:

$$L_p = L_p(\text{urban}) - \left[ 2 \log \left[ \frac{f_c}{28} \right]^2 - 5.4 \right]$$

- For an open area:

$$L_p = L_p(\text{urban}) - 4.78 (\log f_c)^2 + 18.33 \log f_c - 40.94$$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

16



## Path-Loss Models for Macrocellular Areas – Okumura-Hata Model (3)

- COST-231: For PCS operating at 1,800 – 2,000 MHz, the European Co-operative for Scientific and Technical Research extended the previous model
  - See parameters in Appendix 2C in Pahlavan’s book
- Joint Technical Committee (JTC) of Telecommunication Industry Association (TIA) has models for PCS at 1,800 MHz

A good summary of Hata / COST 231 models can be found at <http://www.comappls.com/tonyt/Applets/Propagation/PropEqns1.doc>

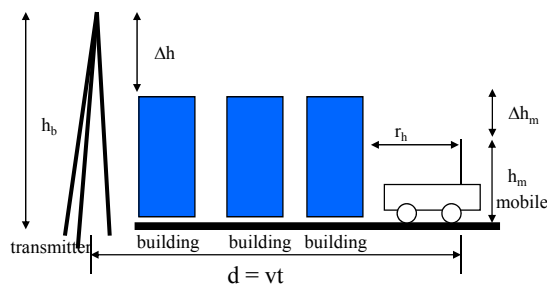
3/8/2009

Dr. Ashraf S. Hasan Mahmoud

17

## Path-Loss Models for Microcellular Areas

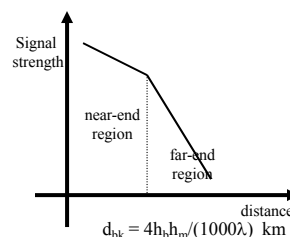
- Spanning: 100 m ~ few kilometers
- Basestation height ~ roof tops or lampposts
- See Table 2.2 (of Pahlavan’s book) for detailed model



Typical microcellular environment

3/8/2009

Dr. Ashraf S. Hasan Mahmoud



Typical path-loss model

18

## **Path-Loss Models for Picocellular Indoor Areas**

- Covering buildings or parts of buildings
- Spanning: 30 ~ 100 m
- Applications: WLANs, wireless PBX, PCS
- Multifloor Attenuation Model

$$L_p = L_0 + nF + 10\alpha \log(d)$$

Where

- F is signal attenuation per floor
- $L_0$  is the path-loss at first meter
- d is distance in meters
- n is number of floors

- Typical values for F = 10 dB and 16 dB for measurements at 900 MHz and 1.7 GHz, respectively
- Furniture objects cause shadowing  $\sim \sigma_{dB} = 4$  dB

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

19

## **Path-Loss Models for Picocellular Indoor Areas – JTC Model (@ 1.8 GHz)**

- The previous formula modified to

$$L_p = L_0 + L_f(n) + 10\alpha \log(d) + X$$

Where

- $L_f$  is power loss due to floors
- $L_0$  is the path-loss at first meter
- d is distance in meters
- $\alpha$  is the path-loss exponent
- n is number of floors
- X is log-normally distributed ( $\sigma_{dB}$ )

Environment	Residential	Office	Commercial
$L_0$	38	38	38
$10\alpha$	28	30	22
$L_f(n)$	4n	15+4(n-1)	6+3(n-1)
$\sigma_{dB}$	8	10	10

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

20

## **Path-Loss Models for Picocellular Indoor Areas – Partition Dependent Model**

- Fixed path-loss exponent  $\alpha = 2$ ; introduces loss for each partition encountered by a straight line connecting the transmitter and receiver

$$L_p = L_0 + 20 \log(d) + \sum m_{type} w_{type}$$

Where  $m_{type}$  refers to # of partition of that type  
 $w_{type}$  the loss in dBs for that type  
 $d$  is distance in meters

- Partitions: Soft  $\sim 1.4$  dB –  
Hard  $\sim 2.4$  dB
- Walls: dry plywood  $\sim 1$  dB –  
concrete  $\sim 20$  dB

	<b>Signal Attenuation of 2.4 GHz through</b>	<b>dB</b>
	Window in brick wall	2
	Metal frame, glass wall into building	6
	Office wall	6
	Metal door in office wall	6
	Cinder wall	4
	Metal door in brick wall	12.4
	Brick wall next to metal door	3

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

21

## **Path-Loss Models for Femtocellular**

- Span: 2  $\sim$  10s of meters
- Individual residences
- Applications: bluetooth, home RF
- Previous JTC model may apply at 1.8 GHz
- For operation at 2.4 GHz and 5 GHz (unlicensed bands)

$$L_p = L_0 + 10\alpha \log(d)$$

Where  $L_0$  is the path-loss at first meter  
 $d$  is distance in meters  
 $\alpha$  is the path-loss exponent

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

22

## **Path-Loss Models for Femtocellular – Model Parameters**

$f_c$ (GHz)	Environment	Scenario	Path Loss at $d = 1$ m (dB)	Path Loss Gradient $\alpha$
2.4	Indoor office	LOS	41.5	1.9
		NLOS	37.7	3.3
5.1	Meeting room	LOS	46.6	2.22
		NLOS	61.6	2.22
5.2	Suburban residences	LOS and same floor	47	2 to 3
		NLOS and same floor		4 to 5
		NLOS and room in the higher floor directly above Tx		4 to 6
		NLOS and room in the higher floor not directly above the Tx		6 to 7

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

23

## **Multi-path Characteristic of a Radio Wave**

- Radio waves arrive at the receiver from different directions with different delays
- At the receiver antenna they combine via vector addition



- Received signal level varies (10s of dBs):
  - Short-term (rapid) variations
  - Long-term (slow) variations

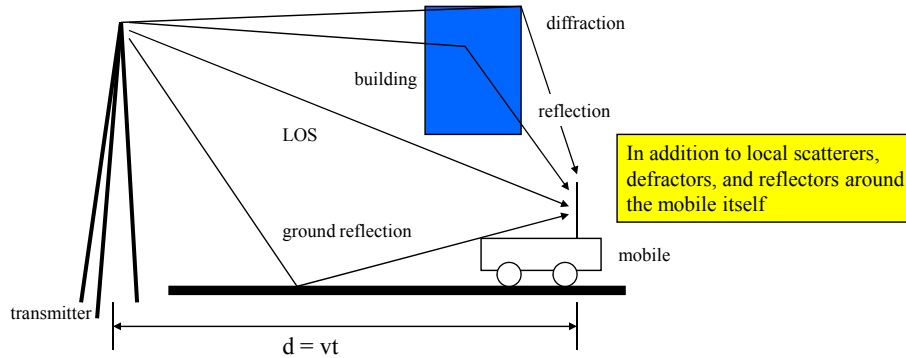
3/8/2009

Dr. Ashraf S. Hasan Mahmoud

24

## Statistical Propagation Model

- Random number of paths, each with
  - Random amplitude and phase
  - Random Doppler
  - Random delay



3/8/2009

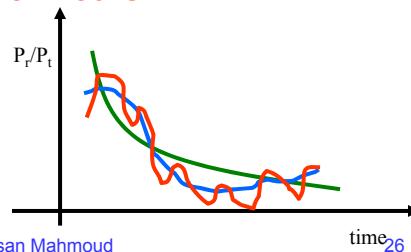
Dr. Ashraf S. Hasan Mahmoud

25

## Short-Term Fading

- Three contributors to final signal level:
  - Path loss (function of distance and path loss exponent – covered earlier)
  - Long-term or slow fading – function of obstructions and environment (covered earlier too)
  - Short-term or fast fading – function of scattering environment and speed of mobile

Received power relative to transmitted power as the mobile moves away from transmitter – Of course the net or observed level is the red one



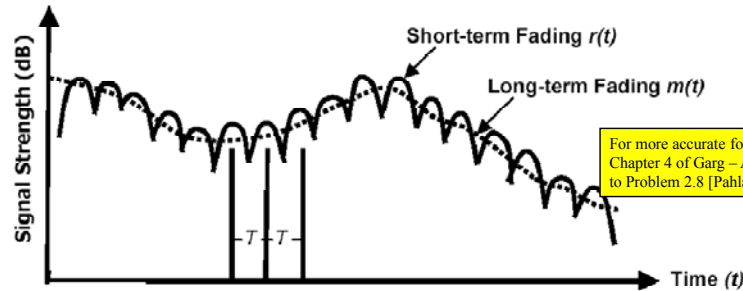
3/8/2009

Dr. Ashraf S. Hasan Mahmoud

time<sub>26</sub>

## Short-Term Fading (2)

- Signal Strength at a given *fixed* distance from transmitter



- Level crossing rate  $N(R) \approx \sqrt{2\pi} \frac{v}{\lambda} \rho$ ;  $\rho = R / R_{RMS}$
- Average fade duration  $\tau(R) \approx \frac{\lambda}{v} \frac{\rho}{\sqrt{2\pi}}$ ;  $\rho = R / R_{RMS}$

Function of Doppler

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

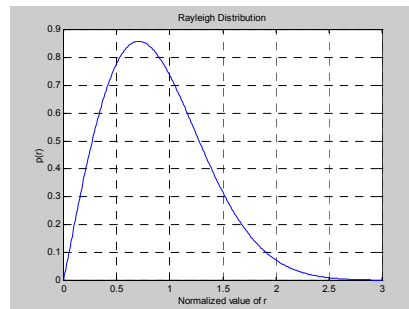
27

## Modeling of Multipath Fading

- Let
  - $2P_0$  is the mean power received at the mobile,
  - $r$  is the received signal *envelope* (random variable)
- Then the distribution of  $r$  is given by

$$f(r) = \frac{r}{P_0} \exp\left(\frac{-r^2}{2P_0}\right)$$

- This is referred to as Rayleigh Distribution
- $E[r] = \sqrt{P_0(\pi/2)}$ ,  $E[r^2] = 2P_0$
- This analysis assumes the received signal envelope has zero mean (i.e. no line of sight)



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

Normalization:  $2P_0 = 1$

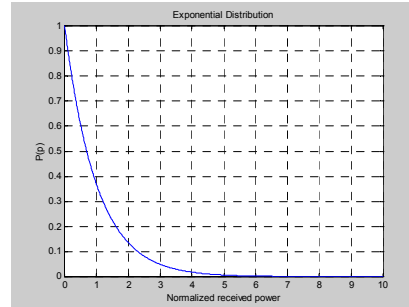
28

## Modeling of Multipath Fading (2)

- What is the instantaneous power?
- Instantaneous power =  $r^2$
- The distribution of the instantaneous power is exponential, as in

$$f(p) = \frac{1}{2P_0} \exp\left(\frac{-p}{2P_0}\right)$$

- You can note that the mean received power is  $2P_0$



Normalization:  $2P_0 = 1$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

29

## What if There is a Line-of-Sight Component?

- When there is a LOS component, the signal envelope follows the Rician distribution:

$$f(r) = \frac{r}{P_0} \exp\left(\frac{-(r^2 + K)}{2P_0}\right) I_0\left(\frac{Kr}{P_0}\right) \quad r \geq 0; K \geq 0$$

- **Exercise:**
  1. Derive the Rician probability distribution for the case where the LOS component is not equal to 0?
  2. Show that this reduces to the Rayleigh distribution when the line-of-sight component is set to zero.

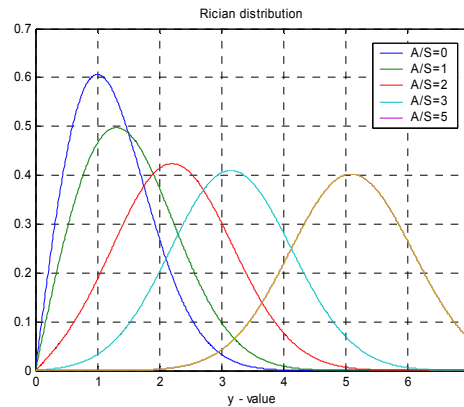
3/8/2009

Dr. Ashraf S. Hasan Mahmoud

30

## Rician Distribution

- Distribution for the normalized r.v  $r/\sqrt{\sigma}$ 
  - When  $A/\sigma = 0 \rightarrow$  Rayleigh distribution



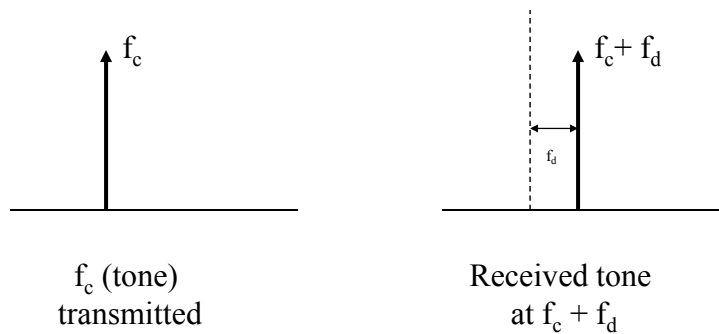
3/8/2009

Dr. Ashraf S. Hasan Mahmoud

31

## Doppler Shift

- Due to relative motion between transmitter and receiver – the received signal is not at the same transmitted frequency!



3/8/2009

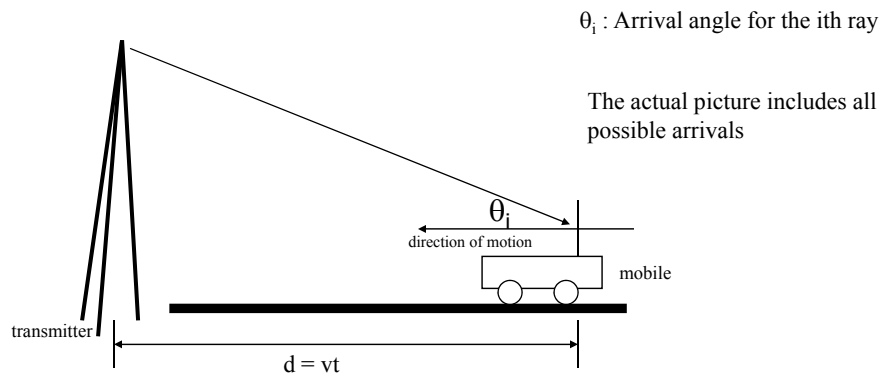
Dr. Ashraf S. Hasan Mahmoud

32



## Doppler Shift (2)

- Due to relative motion between transmitter and receiver – the received signal is not at the same transmitted frequency!



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

33

## Doppler Shift (3)

- Speed of light,  $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 3 \times 10^8$   
Where  $\mu_0$  and  $\epsilon_0$  are the free-space magnetic permeability ( $4\pi \times 10^{-7}$  H/m), and the free-space electric permittivity ( $8.854 \times 10^{-12}$  F/m)

- For a vehicle moving in a direction with a constant velocity,  $v$ , the received carrier is Doppler shifted by

$$f_d = f_m \times \cos(\theta) = \frac{v \cos(\theta)}{\lambda} = \frac{v_{eff}}{\lambda} = \frac{v_{eff} \times f_c}{c}$$

Where  $f_m = v/\lambda =$  maximum value of Doppler

$v_{eff}$  is the effective velocity

$f_c$  is the carrier frequency

$\theta$  is the path angle

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

34

## ***Example:***

---

- A vehicle is traveling at speed of 100 km/h receiving a signal at a carrier frequency of 880 MHz → maximum Doppler shift,  $f_m = v/\lambda = 100 \times (1000/3600) \times 880 \times 10^6 / 3 \times 10^8 = 81.5 \text{ Hz}$

## ***Is Doppler Shift Bad?***

---

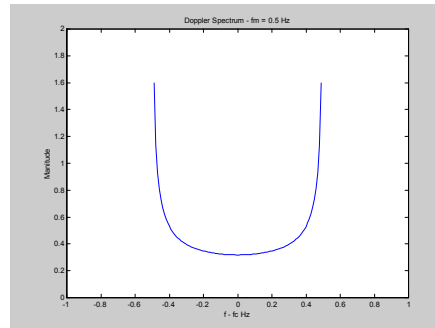
- It is not so much the frequency shift that is harmful, but rather the fact that a large number of rays with different amplitudes and phases add vector-wise to form the resultant signals
- This resultant signal varies greatly in amplitude and phase
- The GREATER the Doppler shift the greater this variation
- Verify the above statement by comparing the expression for the level crossing rate with the Doppler shift expression

## Doppler Spectrum

- The Doppler spectrum for a Rayleigh fading channel is modeled by

$$D(f) = \frac{1}{2\pi f_m} \times \frac{1}{\sqrt{1 - \left(\frac{f - f_c}{f_m}\right)^2}}$$

- The uniform model is also used for indoor channels (see problem 2.10 [Pahlavan])



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

37

## How Do Systems Overcome the Doppler Effect?

- Analog Technology:
  - Use low carrier frequency  $\rightarrow f_m$  is low
- GSM
  - Channel bit rate well above Doppler spread
  - TDMA during each bit / burst transmission the channel is fairly constant.
  - Receiver training/updating during each transmission burst
  - Feedback frequency correction
- IS-95
  - Downlink: Pilot signal for synchronization and channel estimation
  - Uplink: Continuous tracking of each signal

Source: [http://www.wireless\\_per.nl:202/multimed/cdrom97/doppler.htm](http://www.wireless_per.nl:202/multimed/cdrom97/doppler.htm)

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

38

## Delay Spread

- Due to multipath, a transmitted narrow pulse arrives as multiple added copies with different strengths and different delays
- Wideband channel impulse response

$$h(t) = \sum_{i=0}^L \alpha_i \delta(t - \tau_i) \exp(j\phi_i)$$

- Where:  $\alpha_i \sim$  Rayleigh distributed amplitude  
 $\phi_i \sim$  uniform r.v.  $(0, 2\pi)$   
 $\tau_i \sim$  multipath arrival time
- $E[\alpha_i^2] = 2\sigma_i^2$  – power associated with the  $i^{\text{th}}$  path
- Intersymbol Interference (ISI) → irreducible errors

See tutorial at: [http://users.ece.gatech.edu/~mai/tutorial\\_multipath.htm](http://users.ece.gatech.edu/~mai/tutorial_multipath.htm)

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

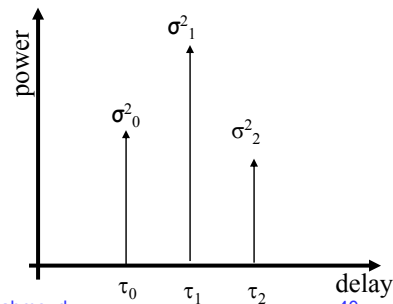
39

## RMS Delay Spread

- For a discrete wideband channel impulse response as the one depicted, the rms delay spread parameter is computed by

$$\tau_{rms} = \sqrt{\frac{\sum_{k=0}^N \tau_k^2 \sigma_k^2}{\sum_{k=0}^N \sigma_k^2} - \left( \frac{\sum_{k=0}^N \tau_k \sigma_k^2}{\sum_{k=0}^N \sigma_k^2} \right)^2}$$

- Delay spread limits the maximum data rate supported by the channel – successive symbols interfere with each other (ISI) and can not be detected properly – refer to coherence bandwidth slides



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

40

## Typical Delay Spread Figures

- Indoor: @910 MHz: 50~250 ns; @2.4GHz: 10~40 ns
- Urban areas
  - RMS delay spread: 2  $\mu$ sec
  - Min 1  $\mu$ sec to max 3  $\mu$ sec
- Suburban areas
  - RMS delay: 0.25  $\mu$ sec to 2  $\mu$ sec
- Rural areas
  - RMS delay: up to 12  $\mu$ sec
- GSM example
  - Bit period 3.69  $\mu$ sec
  - Uses adaptive equalization to tolerate up to 15  $\mu$ sec of delay spread (26-bit Viterbi equalizer training sequence)

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

41

## Coherence Bandwidth

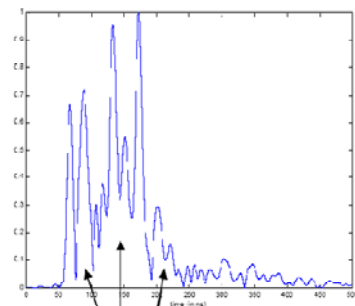
- Coherence Bandwidth of a Channel,  $B_c$ : The range of frequencies that experience the same (flat) fading
- $B_c \sim 1/(5\tau_{rms})$
- Signals with bandwidth less than  $B_c$  are said to experience *flat* fading
- Signals with bandwidth greater than  $B_c$  are said to experience *selective* fading
- Transmission rate,  $R$  is typically equal to  $B_c$  (without resorting to advanced transmission techniques)
  - Example: For indoor areas  $\tau_{rms} \sim 30$ ns to about 300 ns  $\rightarrow$  Maximum data rate  $\sim 6.7$  Mb/s to about 0.67 Mb/s at most
  - Example: For outdoor urban  $\tau_{rms} \sim 4\mu$ s  $\rightarrow$  Maximum data rate  $\sim 50$  kb/s

3/8/2009

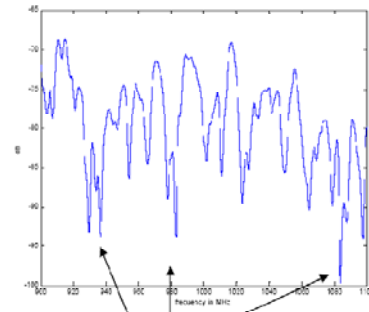
Dr. Ashraf S. Hasan Mahmoud

42

## ***Frequency Selective Fading***



(a) Multipath arrival



(b) Frequency selective fading

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

43

## ***Mitigation Methods***

<b>Issue</b>	<b>Performance Affected</b>	<b>Mitigation Techniques</b>
Shadow fading	Received signal strength	Fade margin – Increase transmit power or decrease cell size
Fast fading	Bit error rate	Error control coding
	Packet error rate	Interleaving, Frequency hopping, Diversity
Multipath delay spread	ISI and irreducible error rates	Equalization, DS-spread spectrum, OFDM, Directional antennas

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

44

## References

- Chapter 2: "Principles of Wireless Networks – A Unified Approach," Kaveh Pahlavan and Prashant Krishnamurthy
- Chapter 4: "Wireless and Personal Communications Systems," Vijay Garg and Joseph Wilkes
- Chapters 3 and 4 "Probability and Random Processes for Electrical Engineering," Alberto Leon-Garcia Addison Wesley, 1989 (TK153.L425 1989)

A necessary background info for the course

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

45

## Example 1:

- **Problem 2.8 [Pahlavan]:** The modulation technique used in the existing AMPS is analog FM. The transmission bandwidth is 30 kHz per channel and the maximum transmitted power from a mobile user is 3 W. The acceptable quality of the input SNR is 18 dB, and the background noise in the bandwidth of the system is -120 dBm (120 dB below the 1mW reference power). In the cellular operation we may assume the strength of the signal drops 30 dB for the first meter of distance from the transmitter antenna and 40 dB per decade of distance for distances beyond 1 meter.
  - a. What is the maximum distance between the mobile station and the base station at which we have an acceptable quality of signal?
  - b. Repeat (a) for digital cellular systems for which the acceptable SNR is 14 dB

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

46

## Example 1: cont'd

### • Solution:

(a) Maximum distance for an SNR of 18 dB.

- The transmitter power is  $P_t = 10 \log(3 \text{ W} / 1 \text{ mW}) = 34.8 \text{ dBm}$
- The minimum acceptable received power is  $P_{rmin} = -120 \text{ dBm} + 18 \text{ dB} = -102 \text{ dBm}$
- The maximum allowable path loss is  $L_{pmax} = P_t - P_{rmin} = 34.8 \text{ dBm} - (-102 \text{ dBm}) = 136.8 \text{ dB}$
- The path loss model based on 30 dB in the first meter and 40 dB per decade of distance is

$$L_p = 30 + 40 \log(d) \quad \text{so that} \quad d = 10^{\frac{L_p - 30}{40}} \quad \text{and}$$

$$d_{max} = 10^{\frac{L_{pmax} - 30}{40}} = 10^{\frac{136.8 - 30}{40}} = 468 \text{ m}$$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

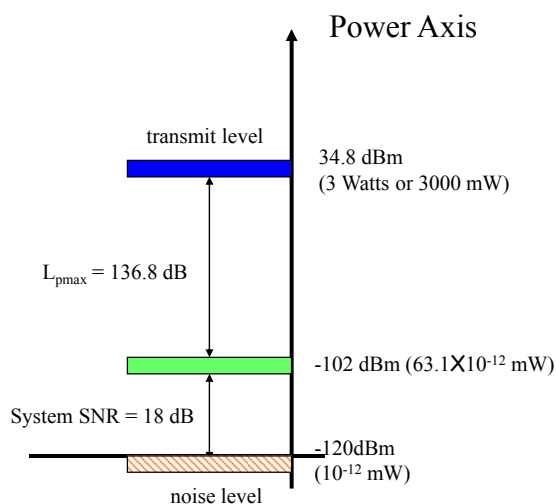
47

## Example 1: cont'd

### • Solution: (a)

If received power falls in this region  
i.e.  $\text{SNR} \geq 18 \text{ dB} \rightarrow$  acceptable link  
quality

If received power falls in this region  
i.e.  $\text{SNR} < 18 \text{ dB} \rightarrow$  unacceptable link  
quality



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

48



## Example 1: cont'd

### • Solution:

(b) Maximum distance for an SNR of 14 dB.

- The transmitter power is  $P_t = 10 \log(3 \text{ W} / 1 \text{ mW}) = 34.8 \text{ dBm}$
- The minimum acceptable received power is  $P_{rmin} = -120 \text{ dBm} + 14 \text{ dB} = -106 \text{ dBm}$
- The maximum allowable path loss is  $L_{pmax} = P_t - P_{rmin} = 34.8 \text{ dBm} - (-106 \text{ dBm}) = 140.8 \text{ dB}$
- The path loss model based on 30 dB in the first meter and 40 dB per decade of distance is

$$L_p = 30 + 40 \log(d) \quad \text{so that} \quad d = 10^{\frac{L_p - 30}{40}} \quad \text{and}$$

$$d_{max} = 10^{\frac{L_{pmax} - 30}{40}} = 10^{\frac{140.8 - 30}{40}} = 589 \text{ m}$$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

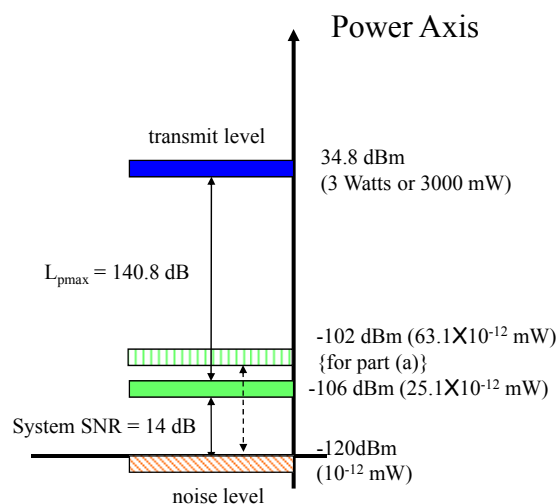
49

## Example 1: cont'd

### • Solution: (b)

If received power falls in this region  
i.e.  $\text{SNR} \geq 14 \text{ dB} \rightarrow$  acceptable link  
quality

If received power falls in this region  
i.e.  $\text{SNR} < 14 \text{ dB} \rightarrow$  unacceptable link  
quality



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

50

## **Example 1: cont'd**

---

- **Solution:**
- A reduced SNR requirement at the mobile receiver translates to greater coverage distance
- Digital modulation and advance communication techniques (equalization, diversity, CDMA, etc) allow the reduction of minimum acceptable SNR

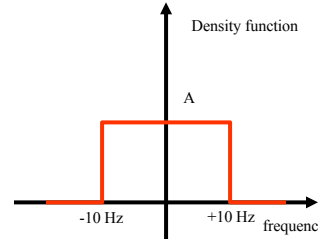
## **Example 2:**

---

- **Problem 2.10 [Pahlavan]:** The Doppler spectrum of the indoor radio is often assumed to have uniform distribution with a maximum Doppler shift of 10 Hz
  - a. Determine the rms Doppler spread of the channel
  - b. Determine the average number of fades per second and the average fade duration, assuming that the threshold for fading is chosen 10 dB below the average rms value of the signal

## Example 2:

- **Solution:** (a)
- The maximum Doppler frequency is  $\pm 10$  Hz, and for a uniform distribution the area should be equal to 1, so that  $A [10 - (-10)] = 20 A = 1$ , or  $A = 0.05 \rightarrow$   
 $D(\lambda) = 0.05 [U(\lambda + 10 \text{ Hz}) - U(\lambda - 10 \text{ Hz})]$



- The RMS Doppler spread is given by  $\lambda_{rms} = \sqrt{\lambda^2 - (\bar{\lambda})^2}$ , but

$$\bar{\lambda} = \int_{-\infty}^{\infty} \lambda D(\lambda) d\lambda = \int_{-10}^{10} 0.05 \lambda d\lambda = 0.05 \left[ \frac{\lambda^2}{2} \right]_{-10}^{10} = 0 \text{ Hz, and}$$

$$\bar{\lambda}^2 = \int_{-\infty}^{\infty} \lambda^2 D(\lambda) d\lambda = \int_{-10}^{10} 0.05 \lambda^2 d\lambda = 0.05 \left[ \frac{\lambda^3}{3} \right]_{-10}^{10} = 33.33 \text{ Hz}^2, \text{ therefore}$$

$$\lambda_{rms} = \sqrt{\lambda^2 - \bar{\lambda}^2} = \sqrt{33.33 - (0)^2} = 5.77 \text{ Hz}$$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

53

## Example 2:

- **Solution:** (b)
- For a Rayleigh fading envelope distribution, the average number of downward crossings of a level  $A$  per second,  $N$ , is given by:

$$N(\rho) = \sqrt{2\pi} B_{D-rms} \rho e^{-\rho^2}$$

where  $\rho = A/A_{rms}$  is the ratio of the threshold level to the RMS amplitude of the fading envelope, and  $B_{D-rms}$  is the RMS Doppler shift of the signal.

The average fade duration for a given threshold  $\rho$  is given by

$$\tau(\rho) = \frac{\text{Prob}[\alpha < \rho]}{N(\rho)} = \frac{e^{-\rho^2} - 1}{\sqrt{2\pi} B_{D-rms} \rho}$$

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

54

## Example 2: cont'd

- **Solution:** (b)

In our case,  $\rho = -10$  dB or 0.316 (This is an amplitude so use  $20\log(x)$ ), and  $B_{D-rms} = 5.77$  Hz

and

$$N(\rho) = \sqrt{2\pi} B_{D-rms} \rho e^{-\rho^2} = \sqrt{2\pi} (5.77 \text{ Hz}) 0.316 e^{-0.316^2} = 4.14 \text{ fades / sec}$$

$$\text{The average fade duration } \tau(\rho) = \frac{e^{\rho^2} - 1}{\sqrt{2\pi} B_{D-rms} \rho} = \frac{e^{0.316^2} - 1}{\sqrt{2\pi} 5.77 \text{ Hz} 0.316} = 23 \text{ msec}$$

## Example 3:

- **Problem 2.14 [Pahlavan]:** Use a software tool like Matlab™ or Mathcad to generate 1000 impulse responses of the JTC indoor residential radio channel (for case A). Determine the RMS multi-path delay spread for each sample and plot the cumulative distribution function

## Example 3: cont'd

### • Solution: (code)

```

##### Chapter 2, Problem 2.14 #####
% dependents: ftrms.m
% Generate 1000 circs of JTC indoor residential
% RMS delay spread for each sample
% CDF of the RMS delay spread
#####
close all;
clear;
clc;
akA_db = [0 -13.8]; % avg tap power in db
tkA = [0 100]; % relative delay in ns

%-----
ak_square = 10.^(akA_db/10); % avg tap amplitude linear
tk = 1e-9*tkA; % relative delay in seconds
Ntaps = length(tk);
for i=1:1000
    for j=1:Ntaps
        x_nor_1 = randn(1);
        x_nor_2 = randn(1);
        x_rayleigh = sqrt(x_nor_1^2 + x_nor_2^2);
        ak_square_rayleigh(j) = ak_square(j) +
            x_rayleigh^2;
    end;
    trmsA(i) = ftrms(ak_square_rayleigh, tk);
end;
%-----
[FA x] = hist(trmsA * 1e9, [0:2:300]);
pA = FA./sum(FA);
cdfA = cumsum(pA);
sFA = 1 - cdfA;
figure(1)
plot(x, sFA)
title('JTC indoor residential wideband models - Model
A')
xlabel('RMS delay spread (ns)')
ylabel('probability signal level > abscissa')

```

↑ channel definition

↑ creating random channel samples

↑ calculating the survivor function and plotting the results

3/8/2009 asan Mahmood 57

## Example 3: cont'd

### • Solution: (code)

```

function y=ftrms(sig,tau);
% function y =ftrms(sig,tau) to calculate the RMS delay
spread
% sig is the local mean strengths of the discrete
multipath components
% tau is the relative delays
% Note you should supply sig = E(alpha^2)
den = sum(sig);
tbar=sum(sig.*tau)./den;
tbar2=sum(sig.*tau.^2)./den;
y=sqrt(tbar2-tbar^2);

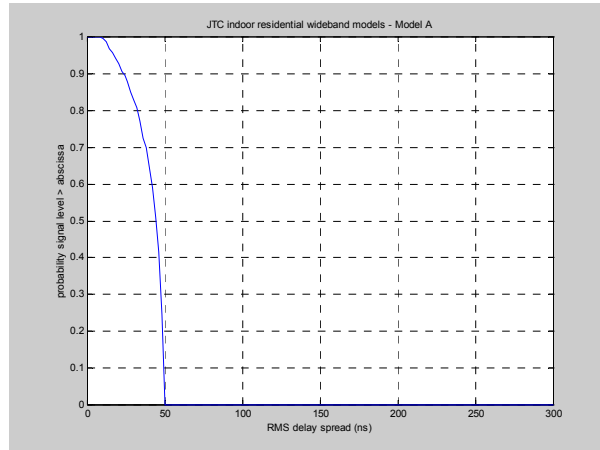
```

↑ Function to calculate  $\tau_{rms}$

## Example 3: cont'd

---

- **Solution:**



3/8/2009

Dr. Ashraf S. Hasan Mahmoud

59

## Problems

---

3/8/2009

Dr. Ashraf S. Hasan Mahmoud

60