Propagation Channel: Why?

Smart antenna (SA) is a spatial filter matched to the propagation channel.

In order to design a good smart antenna, one has to know the channel.

Thus, good prop. channel understanding is crucial.

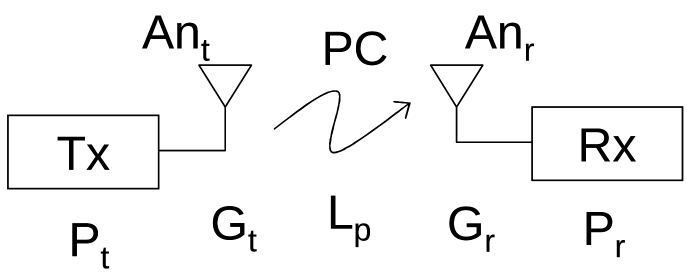
Different channels call for different SAs.

SA good for one channel may be bad for another.

Good news: full wave propagation knowledge is not required. Some basic characteristics are sufficient.

Propagation Channel: Basic Mechanisms

- LOS propagation: consider a link in free space



- Assume for a moment that Tx antenna is isotropic, then power flux density at distance *R* is

$$\Pi_i = \frac{P_t}{4\pi R^2} \tag{2.1}$$

- Since the antenna is not isotropic,

$$\Pi = \frac{P_t G_t}{4\pi R^2} \tag{2.2}$$

- Equivalent isotropic radiated power (EIRP) is

$$P_e = P_t G_t \tag{2.3}$$

- This is the power radiated by isotropic antenna, which produces the same power flux density as our non-isotropic antenna.

Effective Aperture & Received Power: Free Space

- Effective aperture of Rx antenna, S_e:

$$G_R = \frac{4\pi}{\lambda^2} S_e \text{ -> } S_e = \frac{\lambda^2}{4\pi} G_R \qquad (2.4)$$

- Power received by Rx antenna is

$$\mathrm{P}_r = \Pi \cdot S_e = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2 = \frac{G_r P_e}{L_p}; \; L_p = \left(\frac{4\pi R}{\lambda} \right)^2 \qquad (2.5)$$

where L_p is the propagation loss.

- Free space (Friis equation) is valid in far field only:

$$R \geq \frac{2D^2}{\lambda} \text{ \& } \mathrm{R} >> D, \lambda \qquad (2.6)$$

where D is the max. antenna size.

- Usually $D > \lambda$ and only 1st part is important.
- Free space propagation model is simple, but unrealistic. Real environments are more complex.
- However, the free space model provides good starting point for more complex models.

Relation between power flux density and electric field magnitude:

$$\Pi = \frac{E^2}{2W_0}, \quad W_0 = 120\pi \ [\Omega] \approx 377 \ \Omega \qquad (2.7)$$

where W_0 is the free space wave impedance.

- Wavelength and frequency are related:

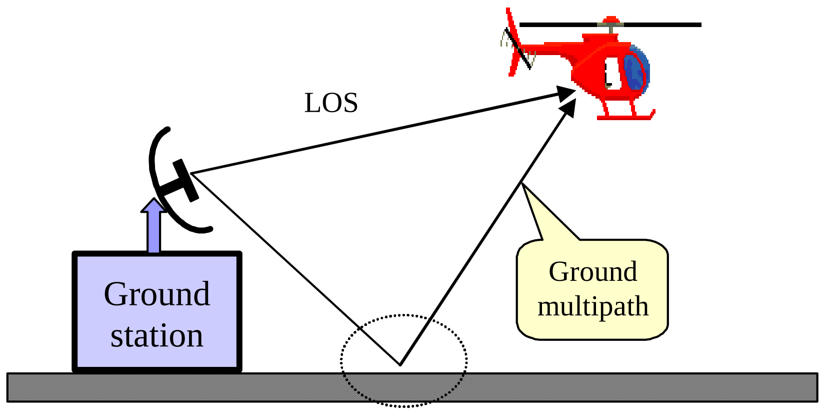
$$\lambda = cT = c / f \qquad (2.8)$$

- where $c=3*10^8$ [m/s] – speed of light, T=1/f – the period.

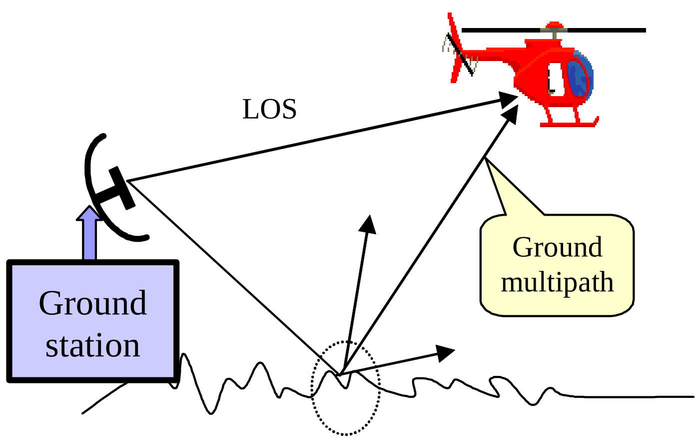
Three Basic Propagation Mechanisms

- Reflection: EM wave impinges on an object of very large size (much greater than λ), like surface of Earth; large buildings, mountains, etc.
- Diffraction: the Tx-Rx path is obstructed by an object or large size (>> λ), maybe with sharp irregularities (i.e. edges). Secondary waves are generated (i.e. bending of waves around the obstacle).
- Scattering: the medium includes objects or irregularities of small size (<<λ). Examples: rough surface, rain drops, foliage, atmospheric irregularities (>10GHz).
- Diffraction: direction of propagation differs from ray optics predictions.
- All three mechanisms are important in general. Individual contributions vary on case by case basis.
- In order to model accurately the PC, one must be able to model all 3 mechanisms.

Propagation Mechanisms: Illustrations



Reflection



Scattering (diffuse reflection)

Scattering & Reflection: specular and diffuse

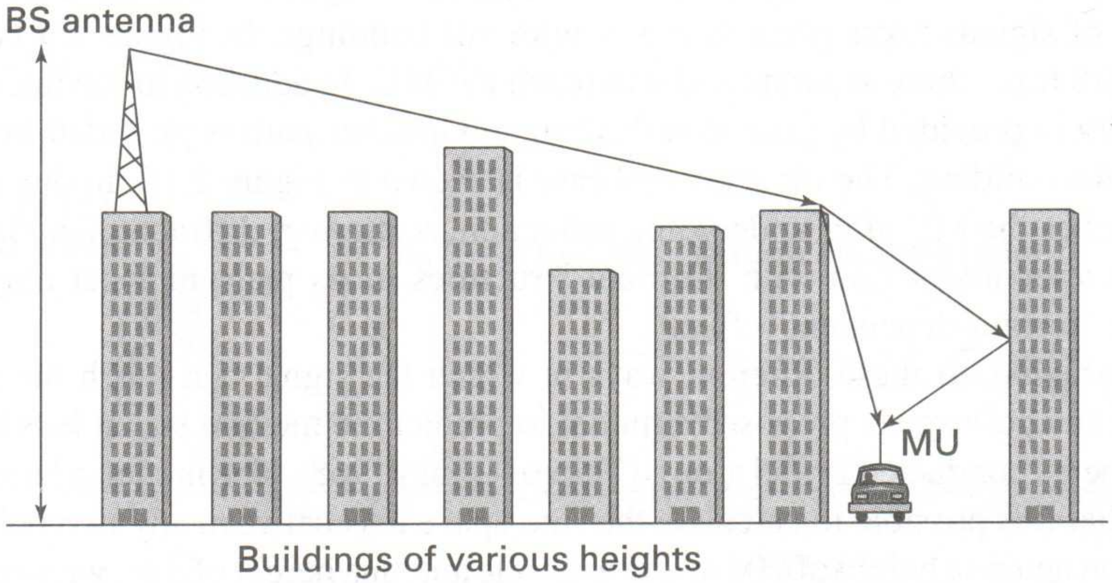


FIGURE 2.8 The signal reaches the receiver through reflection and diffraction.

P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

Propagation Loss Components

- In terms of signal variation in space (i.e. distance) and time, there are 3 main factors as well, in propagation path loss:
- Attenuation: average signal power vs. distance ignoring small-scale variations; keep only large-scale (i.e, over ~(1-10) km) effects, e.g. free space path loss.
- Large-scale fading (shadowing): over ~ 100m (λ), ignoring variations over few wavelengths.
- Small-scale fading (multipath): over fraction of λ to few λ.

$$L_P = L_A L_{LF} L_{SF} \qquad (2.9)$$

Propagation Path Loss Components

$$L_P = L_A L_{LF} L_{SF} \tag{2.9}$$

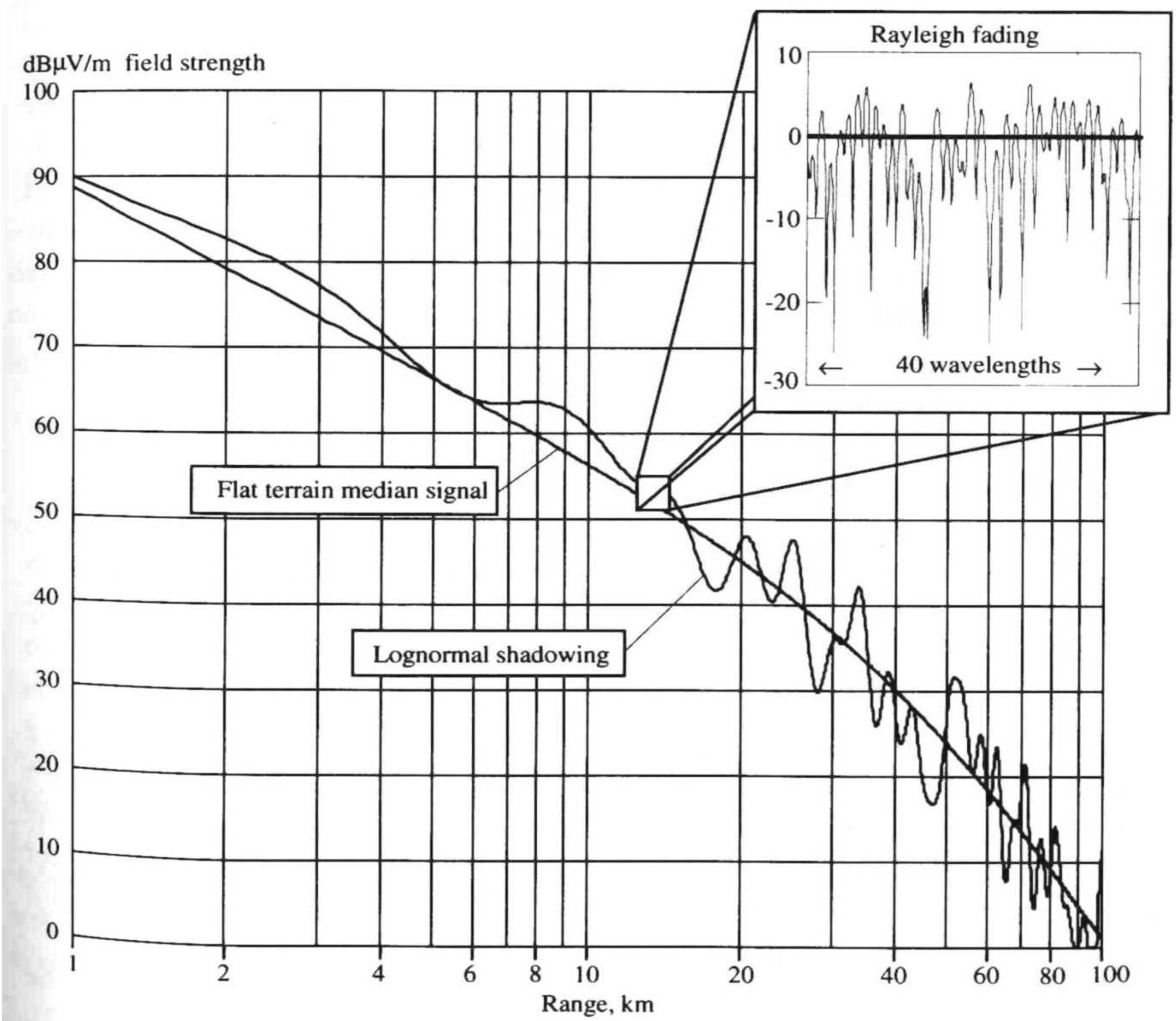


Figure 8.2 Signal behavior in a suburban region showing shadowing and multipath fading. (After: [1].)

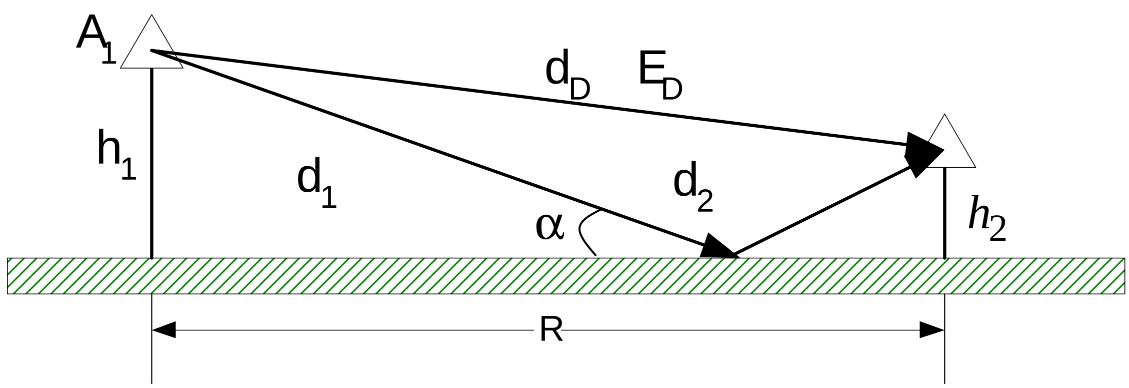
Siwiak, Radiowave Propagation and Antennas for Personal Communications, Artech House, 1998

Attenuation -> similar to free space, but path loss exponent may be different

$$P_r = \frac{a_\nu}{R^\nu};\ \nu = 2...8 \tag{2.10}$$

- free space -> $\nu = 2$; depends on environment; practically, it is derived from measurements
-
- Smart antennas are useful in combating all three factors, but they are most efficient for #3 (small-scale fading).

Example of Reflection: Two-Ray ground reflection model



- Total received field is

$$E_t = E_D + E_R e^{j\Delta\varphi}$$

$$E_D = \frac{A}{d_D}; \qquad E_R = \frac{A \cdot \Gamma}{d_1 + d_2} \qquad (2.11)$$

$$\left|E_t\right| = \frac{A}{d_D}\left|1 + \Gamma \frac{d_D}{d_1 + d_2} e^{j\Delta\varphi}\right|$$

- ED - direct LOS component,
- ER - reflected component,
- $\Delta\varphi$ - phase difference
- Γ - complex reflection coefficient

Reflection results in a fading channel.

- The phase difference is

$$\Delta\varphi = \frac{2\pi}{\lambda}(d_1 + d_2 - d_D) = \frac{2\pi}{\lambda}\Delta d \qquad (2.12)$$

- In many cases,

$$d_1 + d_2, d_D \gg \lambda;\ d_1, d_2, d_D \gg h_1, h_2 \text{ and } \frac{d_D}{d_1 + d_2} \approx 1 \qquad (2.13)$$

- For small α $(\alpha \ll 1) \Rightarrow \Gamma \approx -1$
- Under these approximations, the total received field becomes:

$$|E_t| \approx \frac{A}{d_D}\left|1 - e^{j\Delta\varphi}\right| \approx \frac{4\pi h_1 h_2 A}{\lambda R^2},\quad R > \frac{20 h_1 h_2}{\lambda} \qquad (2.14)$$

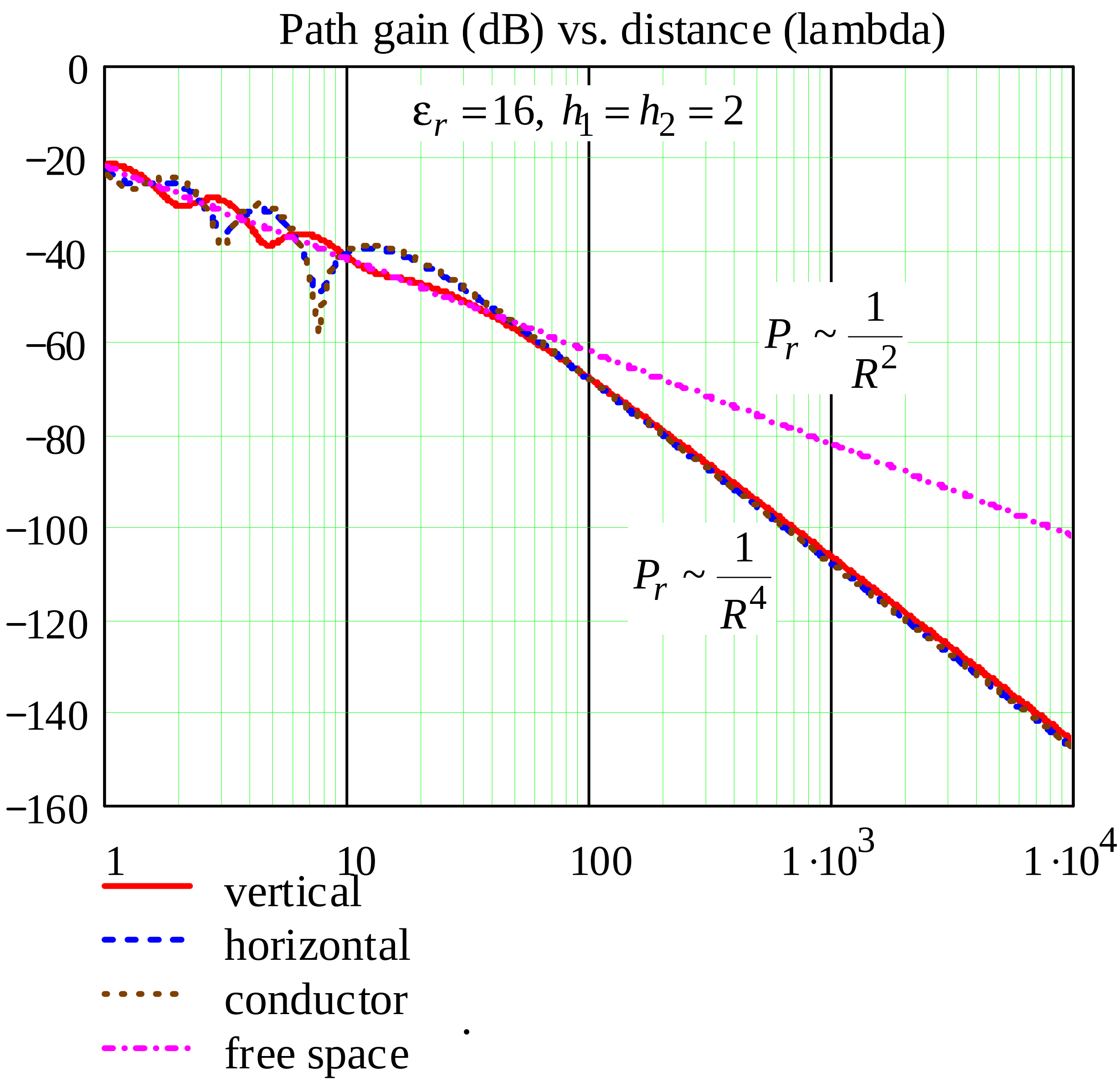
- Note that total receive power $P_r \sim |E_t|^2 \sim \frac{1}{R^4}$
- The path loss is

$$\boxed{L_p = \frac{R^4}{h_t^2 h_r^2}} \qquad (2.15)$$

- Compare with free space: $P_r \sim 1/R^2$

- Conclusion: multipath can significantly affect the path loss!

Example of Two-Ray Path Loss



Diffraction

Diffraction: responsible for large-scale fading due to shadowing.

Line-of-sight (LOS) is blocked (NLOS) –> results in large additional path loss -> SNR is low.

For physical modeling - see Rapport's book.

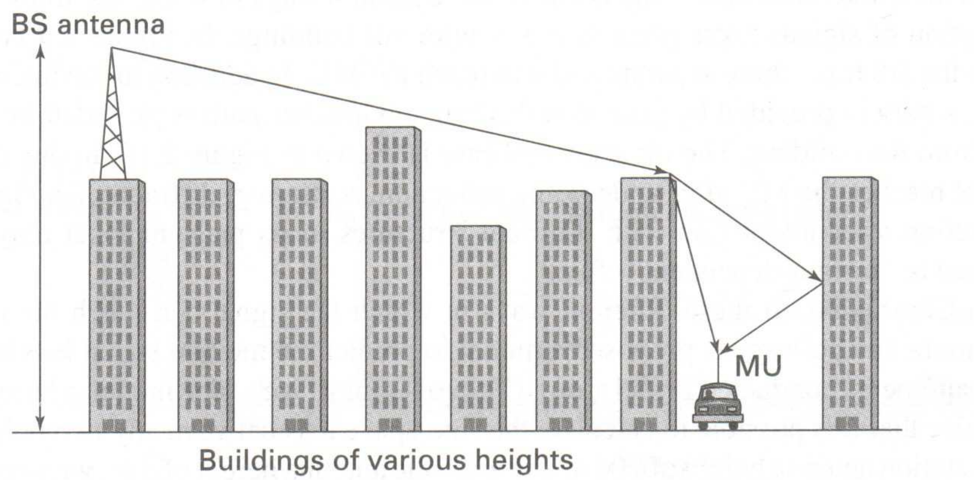
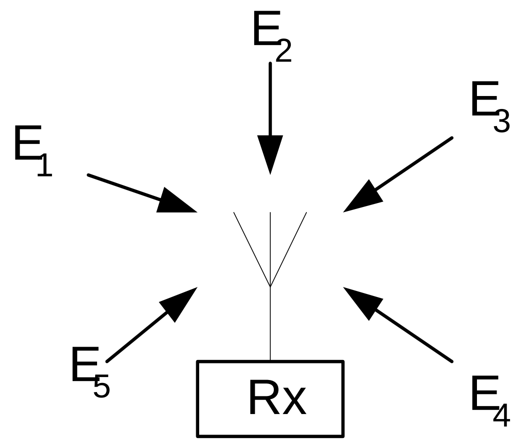


FIGURE 2.8 The signal reaches the receiver through reflection and diffraction.

Small-Scale (multipath) Fading Model



Many multipath components (plane waves) arriving at Rx at different angles,

$$\begin{aligned} E_t(t) &= \sum_{i=1}^{N} E_i \cos(\omega t + \varphi_i) \\ &= \sum_{i=1}^{N} E_i \cos\varphi_i \cos\omega t - \sum_{i=1}^{N} E_i \sin\varphi_i \sin\omega t \end{aligned} \tag{2.16}$$

This is in-phase (I) and quadrature (Q) representation

$$\begin{aligned} & E_t(t) = E_x \cos\omega t - E_y \sin\omega t = E\cos(\omega t + \varphi) \\ & \textit{where} \qquad E = \sqrt{E_x^2 + E_y^2} \to \textit{envelope} \\ & I:\ E_x = \sum_{i=1}^{N} E_i \cos\varphi_i,\ \text{Q: } E_y = \sum_{i=1}^{N} E_i \sin\varphi_i \end{aligned} \tag{2.17}$$

Assume that E_i are i.i.d., and that $\varphi_i \in [0, 2\pi]$ are i.i.d. (no LOS). By the central limit theorem, $E_x, E_y \sim \mathbb{N}(0, \sigma^2)$.

E is Rayleigh distributed with pdf

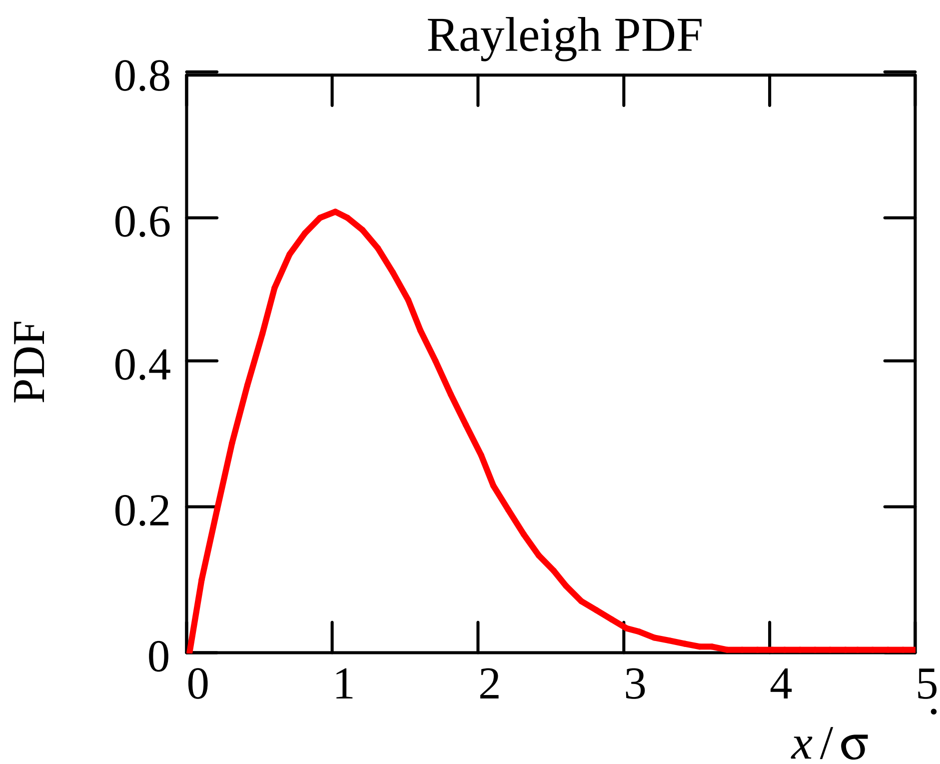
$$\rho(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right), \qquad x \geq 0 \tag{2.18}$$

where σ^2 is the variance of E_x (or E_y),

$$\sigma^2 = \left\langle E_x^2 \right\rangle = \frac{1}{2} \sum_{i=1}^{N} \left\langle E_i^2 \right\rangle \tag{2.19}$$

which is the total received power (for isotropic antennas).

For this result to hold, N must be "large" ($N \geq 5 \sim 10$).



Outage probability (or cdf) is

$$F(x) = \int_0^x \rho(t)dt = \Pr(E < x) \qquad (2.20)$$

Rx operates well if $E \geq E_{th} \rightarrow$ threshold effect.

If $E < E_{th}$, the link is lost -> this is an outage.

Rayleigh Fading (no LOS)

For Rayleigh distribution, the outage probability is

$$F(x) = \int_0^x \rho(t)dt = 1 - \exp\left(\frac{x^2}{2\sigma^2}\right) \qquad (2.21)$$

Introduce the instantaneous signal power

$P = x^2/2, \quad \langle P \rangle = \overline{P} = \sigma^2 =$ the average power, then

$$F(P) = 1 - \exp\left(-\frac{P}{\overline{P}}\right) = 1 - \exp\left(-\frac{\gamma}{\overline{\gamma}}\right), \qquad (2.22)$$

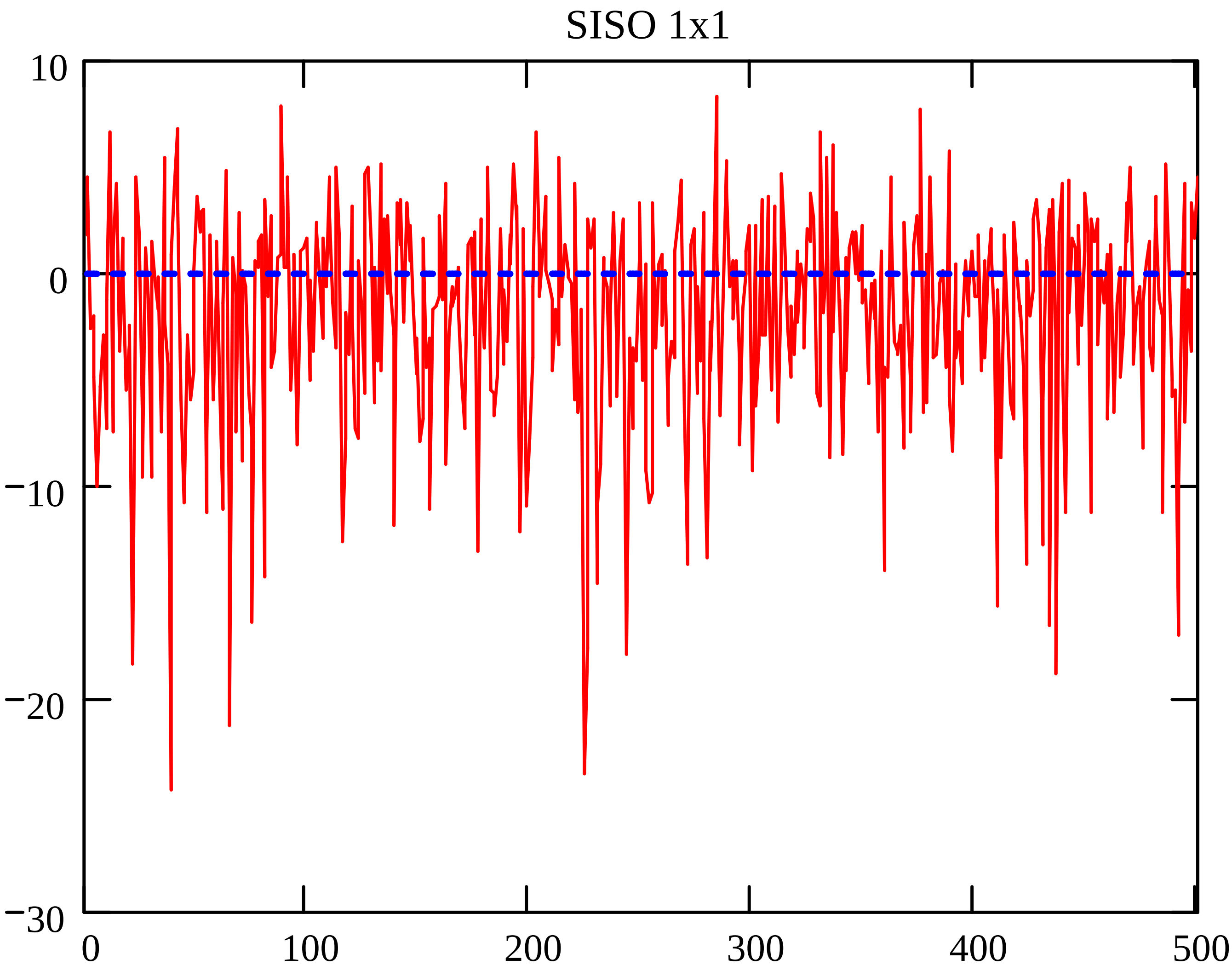
and asymptotically,

$$P \ll \overline{P} \Rightarrow F(P) \approx \frac{P}{\overline{P}} \approx \frac{\gamma}{\overline{\gamma}} \qquad (2.23)$$

Note the 10db/decade law.

Note: $\frac{P}{\overline{P}} = \frac{\gamma}{\overline{\gamma}}$, where γ is SNR.

Rayleigh Fading Channel



Received power (SNR) norm. to the average [dB] vs distance (location, time)

Example:

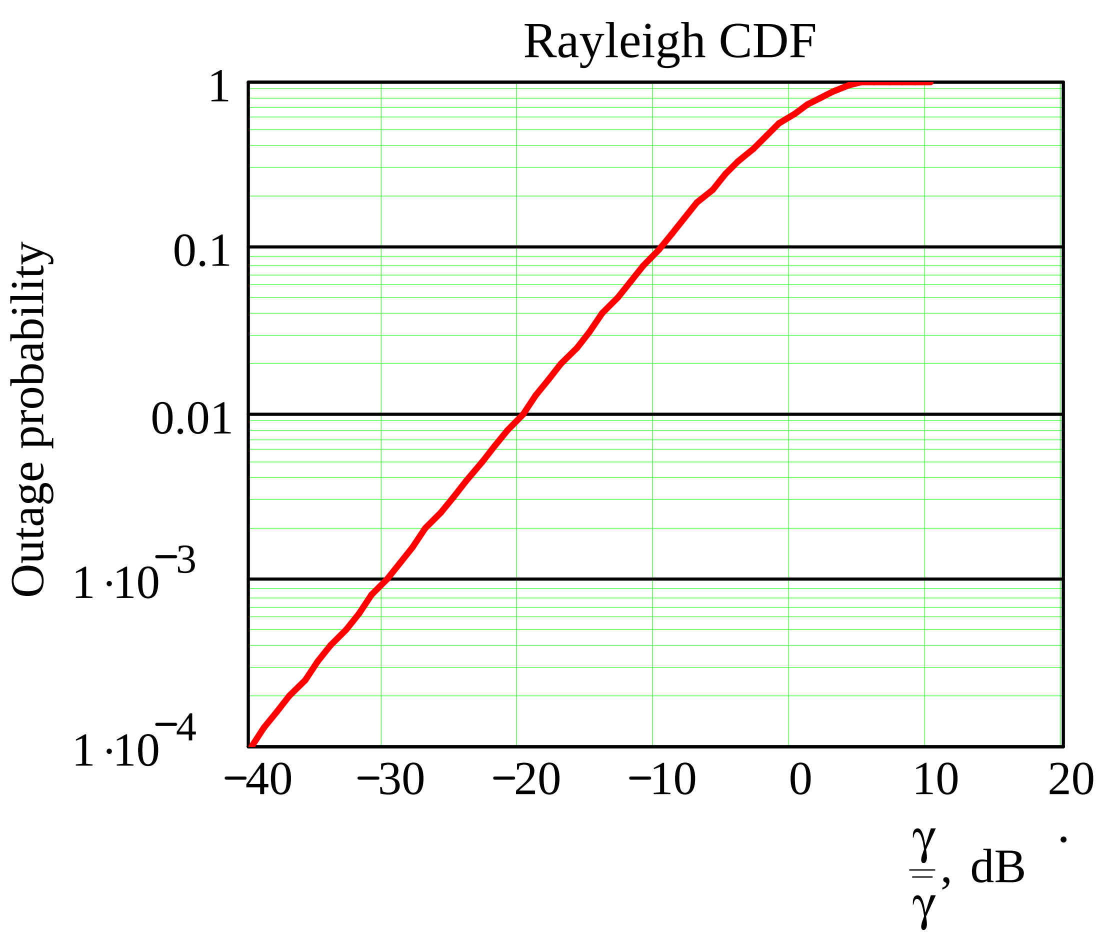
$P_{out} = 10^{-3} \to P = 10^{-3}\bar{P}, or -30dB$ w.r.t. $\bar{P}$

Complex-valued model

$$E_t(t) = \sum_{i=1}^{N} E_i e^{j\varphi_i} e^{j\omega t} \tag{2.24}$$

results in complex Gaussian variables.

Propagation channel gain – simply normalized received signal, has the same distribution.



LOS and Rician Model

There is a LOS component -> the distribution of in-phase and quadrature components is still Gaussian , but non-zero mean

$$E_t(t) = \sum_{i=1}^{N} E_i \cos(\omega t + \varphi_i) + E_0 \cos(\omega t + \varphi_0) \qquad (2.25)$$

Both E_0 and φ_0 are fixed (non-random constants).

$$E_t(t) = (E_x + E_{x0})\cos\omega t - (E_y + E_{y0})\sin\omega t$$
$$\langle E_x \rangle = \langle E_y \rangle = 0, and \qquad E = \sqrt{(E_x + E_{x0})^2 + (E_y + E_{y0})^2} \qquad (2.26)$$

Pdf of E has a Rice distribution$(x = E, x_0 = E_0)$:

$$\rho(x) = \frac{x}{\sigma^2}\exp\left(-\frac{x^2 + x_0^2}{2\sigma^2}\right) I_0\left(\frac{x x_0}{\sigma^2}\right), \qquad (2.27)$$

Note that if $x_0 = 0$, it reduces to the Rayleigh pdf.

Introduce K-factor:

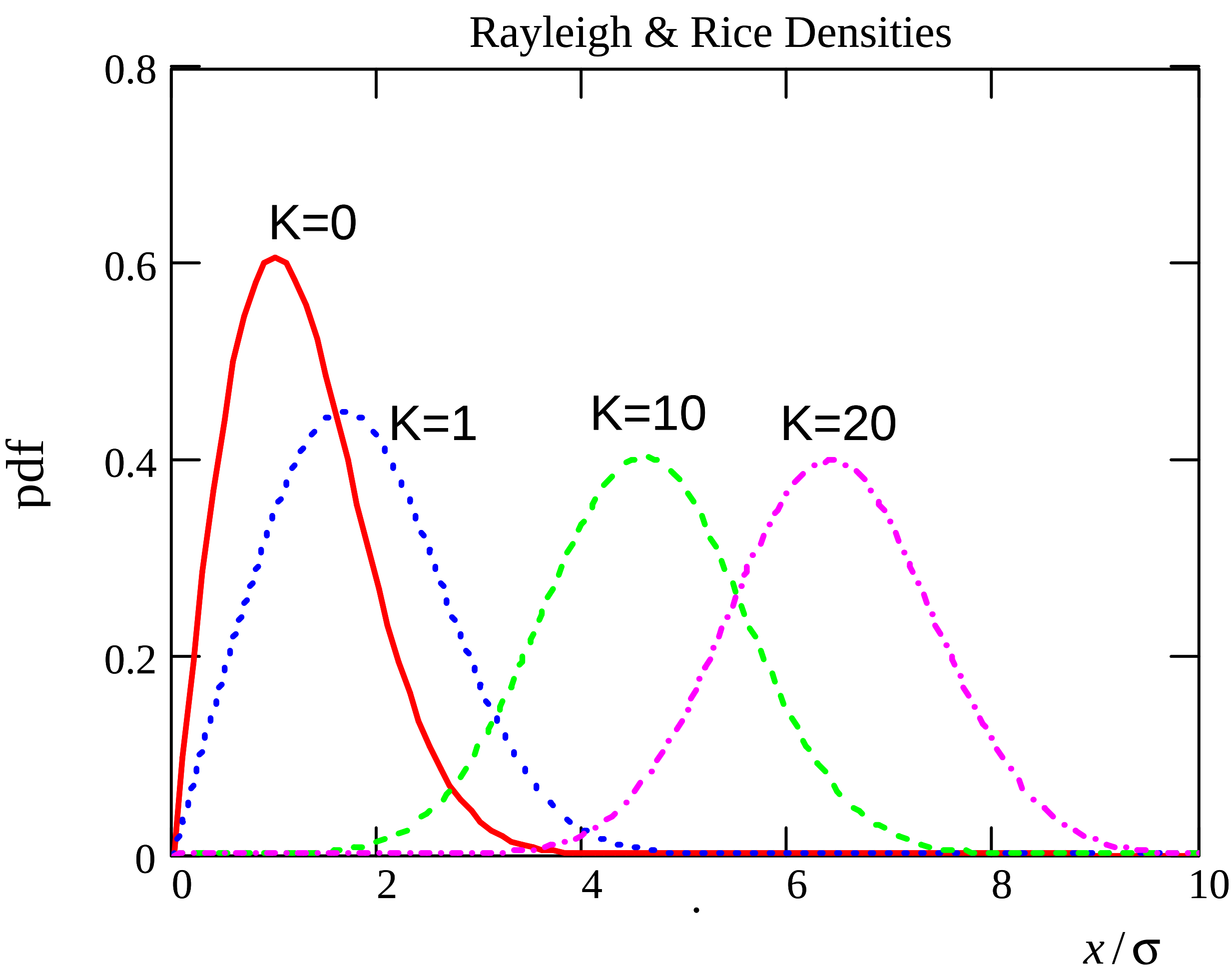
$$K = x_0^2 / 2\sigma^2 \qquad (2.28)$$

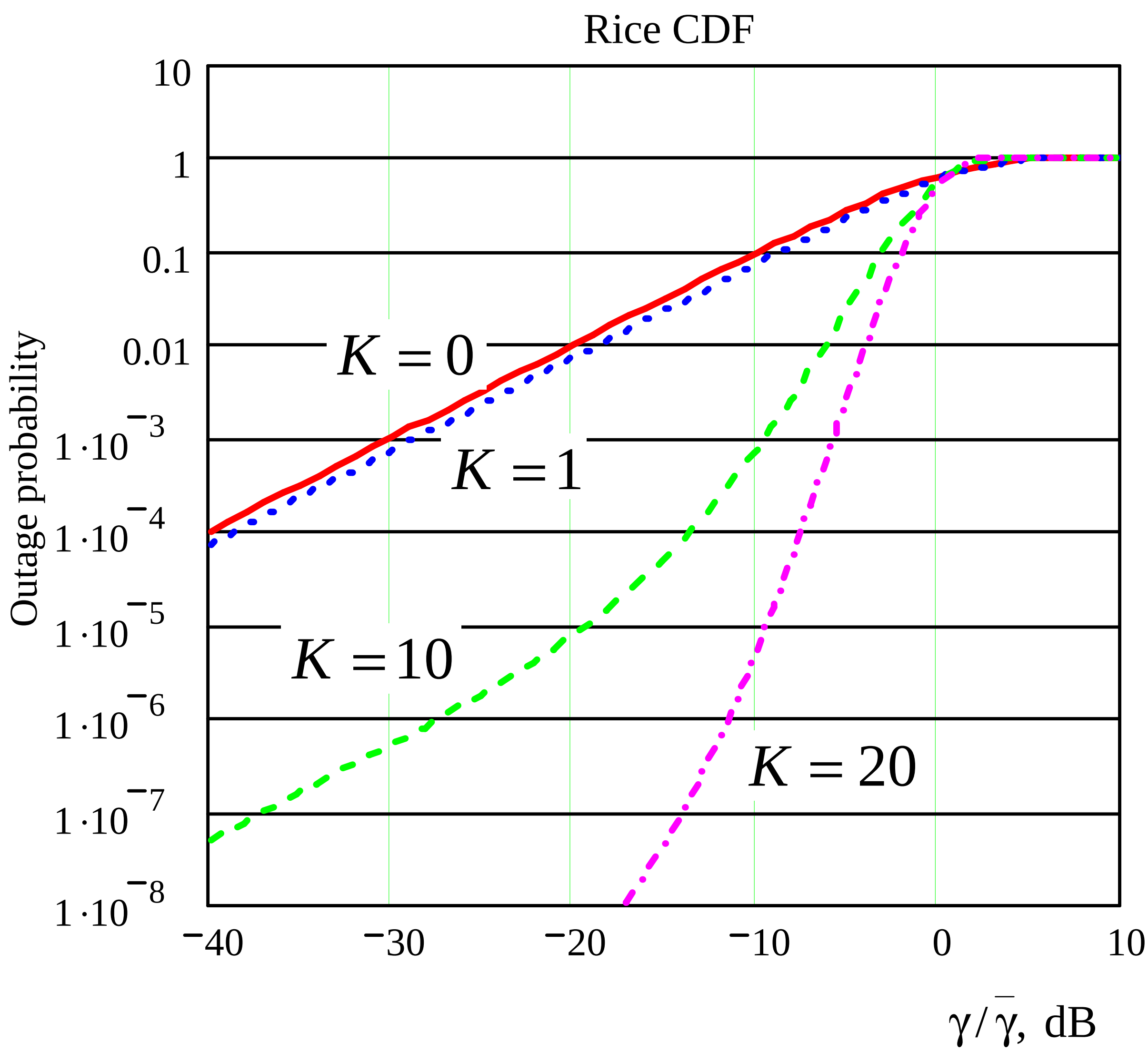
where $x_0^2 / 2$ is the LOS power, it is called LOS ("steady") component, σ^2 is the scattered (multipath) power, it is called diffused component.

K tells us how strong the LOS is.

Pdf of E becomes

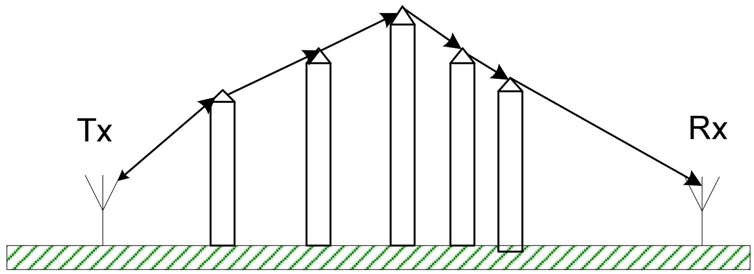
$$\rho(x) = \frac{x}{\sigma^2}\exp\left(-\frac{x^2}{2\sigma^2} - K\right) I_0\left(\sqrt{2K}\,\frac{x}{\sigma}\right) \quad (2.29)$$




Rice CDF
Outage probability
10
1
0.1
0.01
1·10−3
1·10−4
1·10−5
1·10−6
1·10−7
1·10−8
−40
−30
−20
−10
0
10
γ/γ̄, dB
K = 0
K = 1
K = 10
K = 20

Large-Scale Fading (shadowing) Model

Consider multiple reflections/scattering/diffraction (no LOS)



Assume signal at Rx is a result of many scattering/diffractions:

$$E_t = E_0 \prod_{i=1}^{N} \Gamma_i, \qquad |\Gamma_i| \le 1 \tag{2.30}$$

Total Rx power

$$P_t \sim |E_t|^2 = |E_0|^2 \prod_{i=1}^{N} |\Gamma_i|^2 \tag{2.31}$$

$$or \qquad P_t = P_0 \prod_{i=1}^{N} |\Gamma_i|^2 \tag{2.32}$$

$$P_{dB} = P_{0,dB} + 20 \sum_{i=1}^{N} \lg |\Gamma_i| \tag{2.33}$$

P_0 = LOS power

If $\left|\Gamma_i\right|$ are i.i.d , then

$$P_{dB} \sim \mathbb{N}(P_{0,dB}, \sigma_{dB}) \tag{2.34}$$

$$\rho(P_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{dB}} \exp\left\{-\frac{(P_{dB} - P_{0,dB})^2}{2\sigma_{dB}^2}\right\} \tag{2.35}$$

$$P_{0,dB} = 10\lg(P_0) \tag{2.36}$$

$$\sigma_{dB}^2 = \left\langle (P_{dB} - P_{0,dB})^2 \right\rangle \tag{2.37}$$

Log-normal distribution: works well for i.i.d multiple diffractions /scatterings ($N \geq 3...5$) and is used in practice to model large-scale fading (shadowing).

Reasonable physical assumptions result in statistical models for PC. This approach is very popular and extensively used.

Other distributions/models are used (Nakagami, Suzuki).

Important System Effects of the Propagation Channel

Fluctuation of received power is not the only effect of fading channel.

Pulse shape may also be distorted.

Important effects of multipath channels:

- Signal strength fluctuation
- Delay spread
- Doppler spread (Doppler effect)

Delay spread and inter-symbol interference (ISI) are modeled using the impulse response of the channel.

Example: Impulse Response of Wireless Channel

One impulse at Tx -> many impulses at Rx (why?)

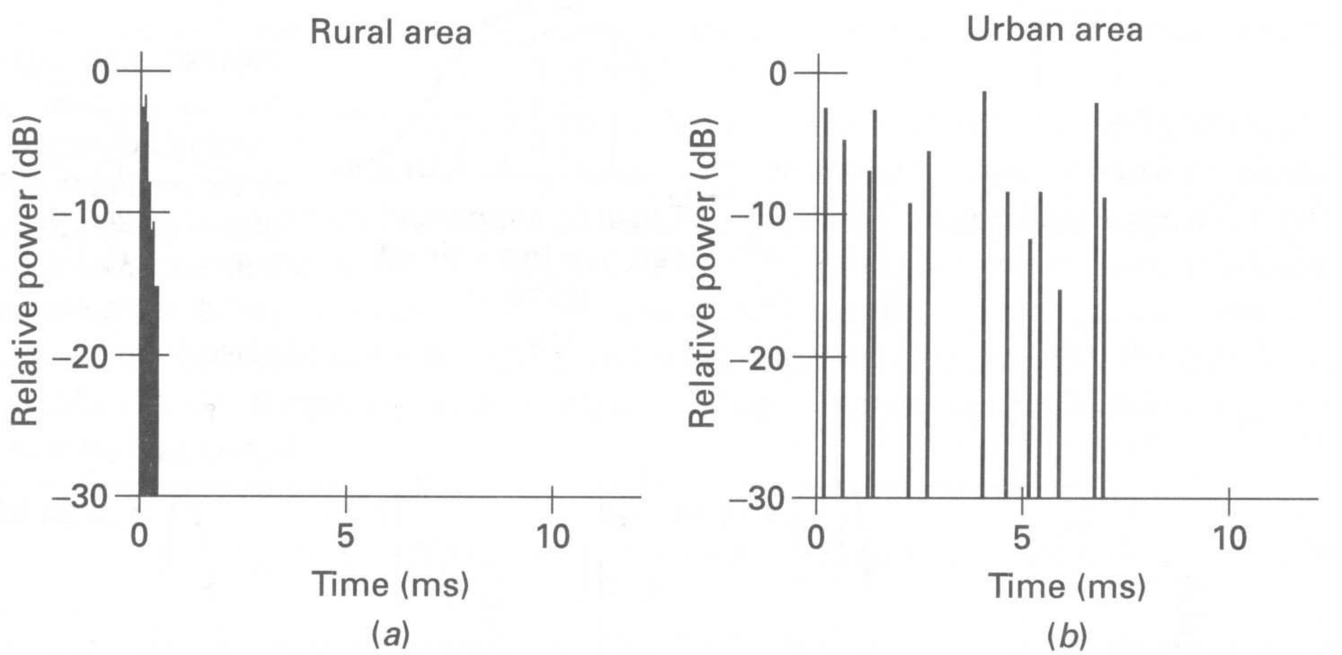


FIGURE 2.22 Impulse responses of two channels. (*a*) A typical rural area. (*b*) An urban area.

Overview of System-Level Propagation Effects

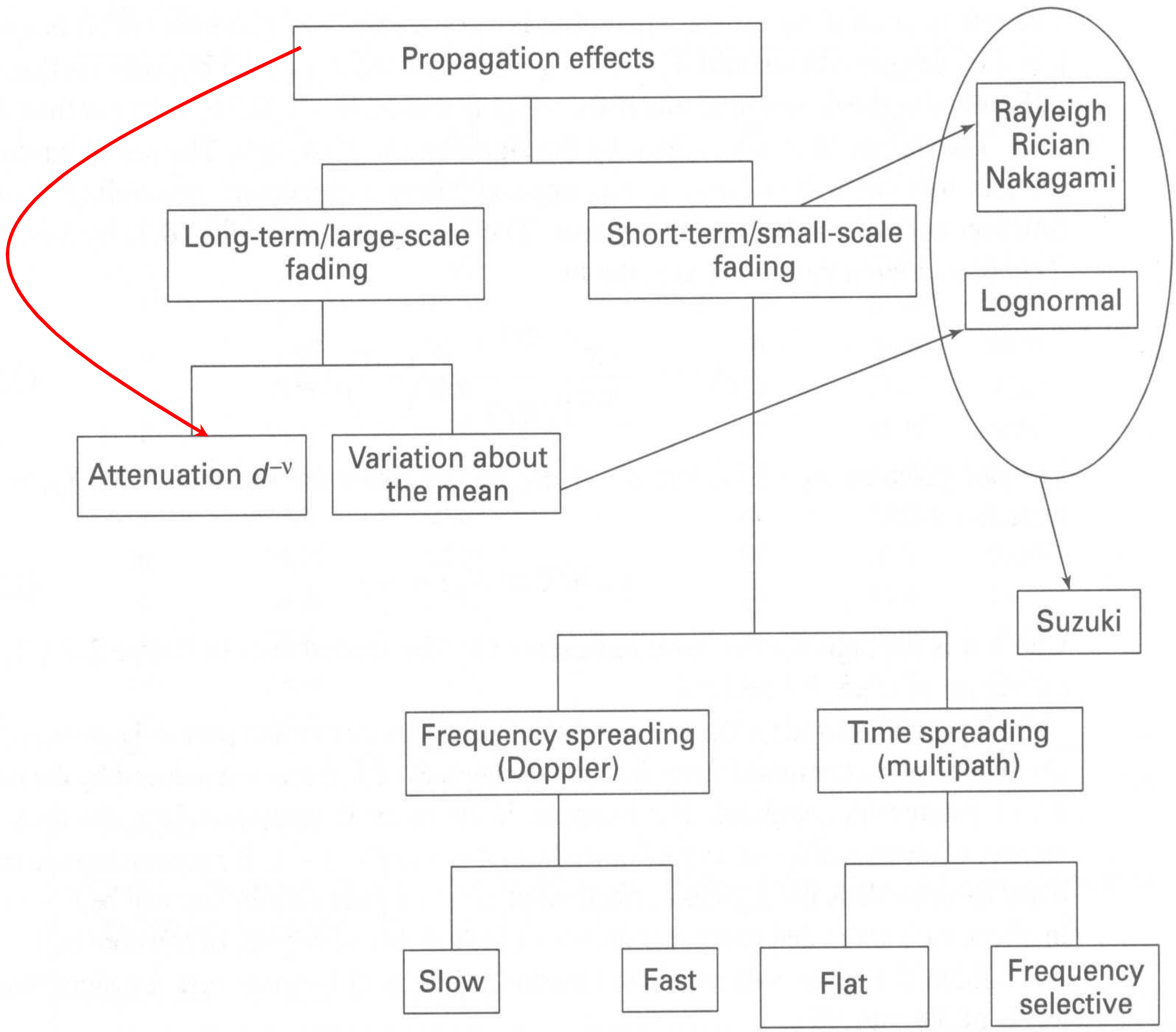


FIGURE 2.38 Overview of attenuation and fading. All forms of fading are shown along with their origins and relationships.

P.M. Shankar, Introduction to Wireless Systems, Wiley, 2002.

Summary

Propagation channel is important for smart antennas (which is a spatial filter, matched to the channel).

Three basic propagation mechanisms: reflection, diffraction and scattering.

Free-space propagation and Friis equation (path loss).

Two-ray ground multipath model.

Large-scale and small-scale fading. Rayleigh and Rice models.

Diffraction and shadowing. Log-normal distribution.

Other system-level effects.

Interference, channel fading and large path loss are the major obstacles to reliable wireless communications!

All can be combated by smart antennas (to a certain extent).

References:

1. T.S. Rappaport, Wireless Communications: Principles and Practice, Prentice Hall, New Jersey, 2002.
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