Indoor Propagation Models

Outdoor models are not accurate for indoor scenarios. Examples of indoor scenario: home, shopping mall, office building, factory.

Ceiling structure, walls, furniture and people effect the EM wave propagation. Large/small number of obstacles, material of the walls etc.

Modeling approach: classify various environments into few types and model each type individually. Generic model is very difficult to build.

Key Model

The average path loss is

$$L_A(d) = L_0\left(\frac{d}{d_0}\right)^{\nu} = const \cdot d^{\nu} \sim d^{\nu} \qquad (4.1)$$

or in dB:

$$L_A(d)[dB] = L_0[dB] + 10\nu \lg\left(\frac{d}{d_0}\right)$$

where L_0 is path loss at reference distance d_0.

ITU Indoor Path Loss Model[1]

The model is used to predict propagation path loss inside buildings.

The average path loss in dB is

$$L_A(d)[dB] = 20\lg f + 10\nu \lg d + L_f(n) - 28$$

where: f is the frequency in MHz;
d is the distance in m; $d > 1$ m;
ν is the path loss exponent (found from measurements);
$L_f(n)$ is the floor penetration loss (measurements);
n is the number of floors (penetrated);

Limits:

$$900 MHz \le f \le 5200 MHz$$

$$1 \le n \le 3$$

$$d > 1m$$

[1] Recommendation ITU-R P.1238-8.

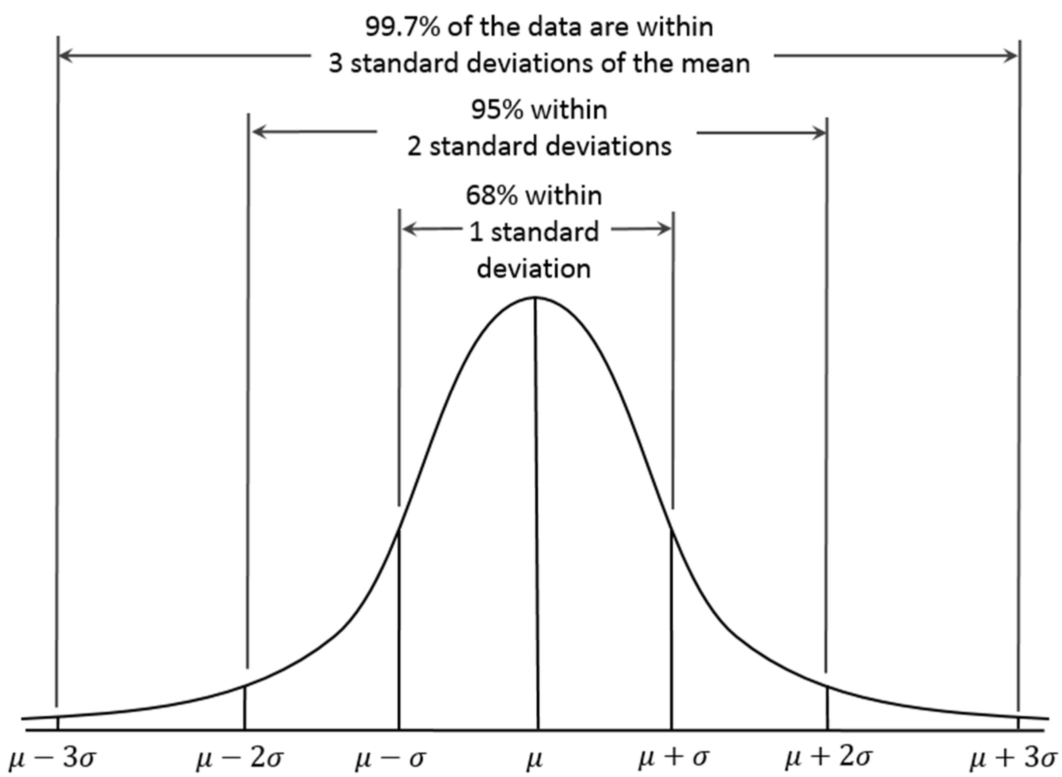
Variations (fading) around the average are accounted for via log-normal distribution:

$$L(d)[dB] = L_A(d)[dB] + X_\sigma \qquad (4.2)$$

where X_σ is a log-normal random variable (in dB) of standard deviation $\sigma[dB]$.

Variations on the order of $(2...3)\sigma[dB]$ should be expected in practice.

(2..3)σ **Rule**



(adopted from "Empirical Rule" by Dan Kernler)

Site-specific models will follow this generic model. Additional factors are included (floors, partitions, indoor-outdoor penetration etc.).

Table 4.7 Path Loss Exponent and Standard Deviation for Various Types of Buildings [Sei92b]

	n	σ (dB)	Number of locations
All Buildings:			
All locations	3.14	16.3	634
Same Floor	2.76	12.9	501
Through One Floor	4.19	5.1	73
Through Two Floors	5.04	6.5	30
Through Three Floors	5.22	6.7	30
Grocery Store	1.81	5.2	89
Retail Store	2.18	8.7	137
Office Building 1:			
Entire Building	3.54	12.8	320
Same Floor	3.27	11.2	238
West Wing 5th Floor	2.68	8.1	104
Central Wing 5th Floor	4.01	4.3	118
West Wing 4th Floor	3.18	4.4	120
Office Building 2:			
Entire Building	4.33	13.3	100
Same Floor	3.25	5.2	37

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Note: $n = \nu$ is the path loss exponent; $f = 914$ MHz.

Table 4.6 Path Loss Exponent and Standard Deviation Measured in Different Buildings [And94]

Building	Frequency (MHz)	*n*	σ (dB)
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile/Chemical	1300	2.0	3.0
Textile/Chemical	4000	2.1	7.0
Paper/Cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			
Indoor Street	900	3.0	7.0
Factory OBS			
Textile/Chemical	4000	2.1	9.7
Metalworking	1300	3.3	6.8

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

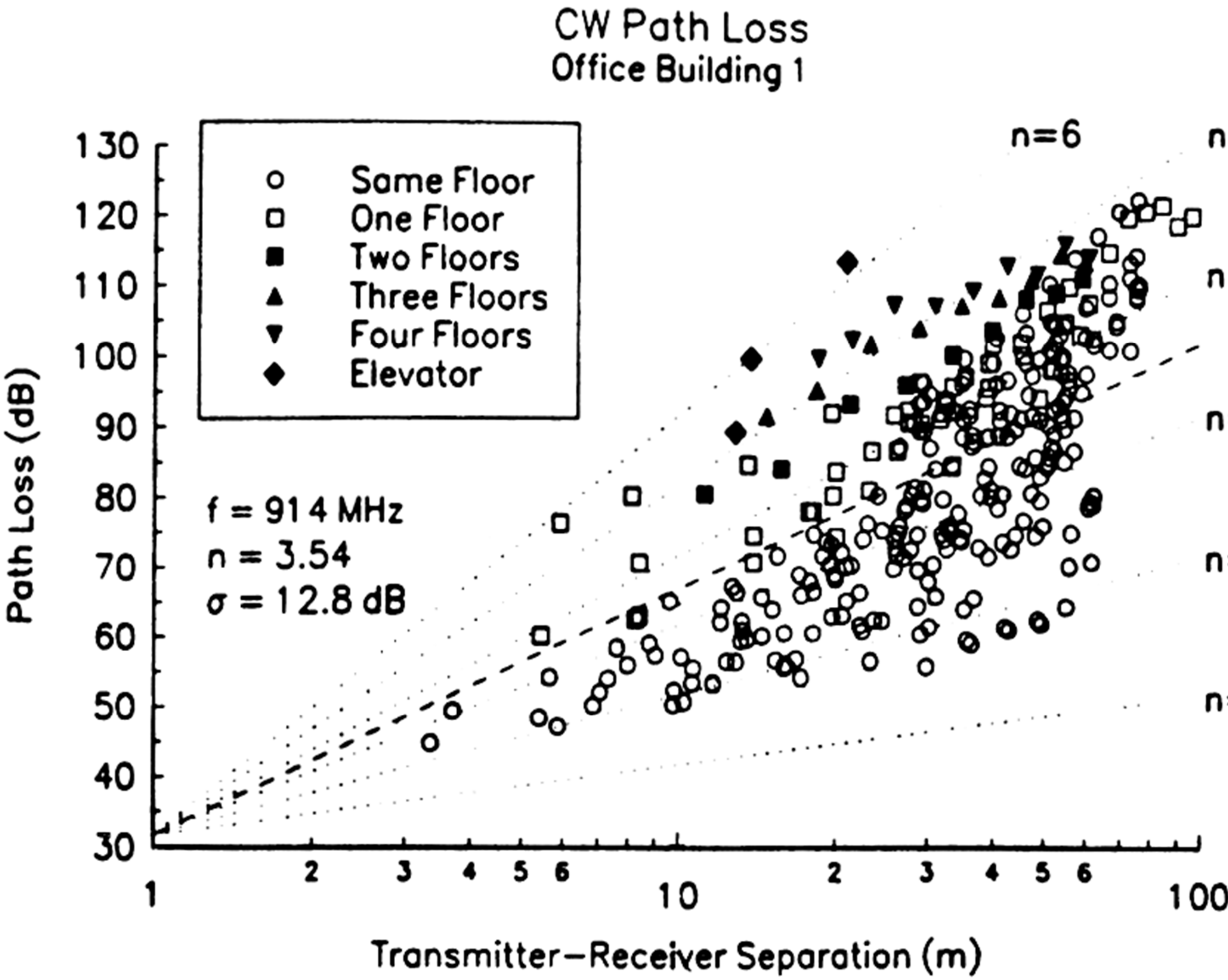


Figure 4.28 Scatter plot of path loss as a function of distance in Office Building 1 [from [Sei92b] © IEEE].

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Table 4.1: path loss exponent factor 10ν in various environments

Frequency band	Residential area	Office area	Commercial area
900 MHz	N/A	33	20
1.2 GHz	N/A	32	22
1.3 GHz	N/A	32	22
1.8 GHz	28	30	22
4 GHz	N/A	28	22
5.2 GHz	N/A	31	N/A
60 GHz	N/A	22	17

Table 4.2: Floor penetration loss $L_f(n)$ in various environments

Frequency band	Number of floors	Residential area	Office area	Commercial area
900 MHz	1	N/A	9	N/A
900 MHz	2	N/A	19	N/A
900 MHz	3	N/A	24	N/A
1.8 GHz	n	4n	15+4(*n*-1)	6 + 3(*n*-1)
2.0 GHz	n	4n	15+4(*n*-1)	6 + 3(*n*-1)
5.2 GHz	1	N/A	16	N/A

Log-normal fading should be added as well,

$$L(d)[dB] = L_A(d)[dB] + X_\sigma \tag{4.2}$$

Table 4.4 Total Floor Attenuation Factor and Standard Deviation σ (dB) for Three Buildings. Each Point Represents the Average Path Loss Over a 20λ Measurement Track [Sei92a]

Building	915 MHz FAF (dB)	σ (dB)	Number of locations	1900 MHz FAF (dB)	σ (dB)	Number of locations
Walnut Creek						
One Floor	33.6	3.2	25	31.3	4.6	110
Two Floors	44.0	4.8	39	38.5	4.0	29
SF PacBell						
One Floor	13.2	9.2	16	26.2	10.5	21
Two Floors	18.1	8.0	10	33.4	9.9	21
Three Floors	24.0	5.6	10	35.2	5.9	20
Four Floors	27.0	6.8	10	38.4	3.4	20
Five Floors	27.1	6.3	10	46.4	3.9	17
San Ramon						
One Floor	29.1	5.8	93	35.4	6.4	74
Two Floors	36.6	6.0	81	35.6	5.9	41
Three Floors	39.6	6.0	70	35.2	3.9	27

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Table 4.3 Average Signal Loss Measurements Reported by Various Researchers for Radio Paths Obstructed by Common Building Material

Material Type	Loss (dB)	Frequency	Reference
All metal	26	815 MHz	[Cox83b]
Aluminum siding	20.4	815 MHz	[Cox83b]
Foil insulation	3.9	815 MHz	[Cox83b]
Concrete block wall	13	1300 MHz	[Rap91c]
Loss from one floor	20-30	1300 MHz	[Rap91c]
Loss from one floor and one wall	40-50	1300 MHz	[Rap91c]
Fade observed when transmitter turned a right angle corner in a corridor	10-15	1300 MHz	[Rap91c]

Material Type	Loss (dB)	Frequency	Reference
5 m storage rack with paper products (loosely packed)	2-4	1300 MHz	[Rap91c]
5 m storage rack with large paper products (tightly packed)	6	1300 MHz	[Rap91c]
5 m storage rack with large metal parts (tightly packed)	20	1300 MHz	[Rap91c]
Typical N/C machine	8-10	1300 MHz	[Rap91c]
Semi-automated assembly line	5-7	1300 MHz	[Rap91c]
0.6 m square reinforced concrete pillar	12-14	1300 MHz	[Rap91c]
Stainless steel piping for cook-cool process	15	1300 MHz	[Rap91c]
Concrete wall	8-15	1300 MHz	[Rap91c]
Concrete floor	10	1300 MHz	[Rap91c]

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Ericsson's Indoor Path Loss Model

(900 MHz)

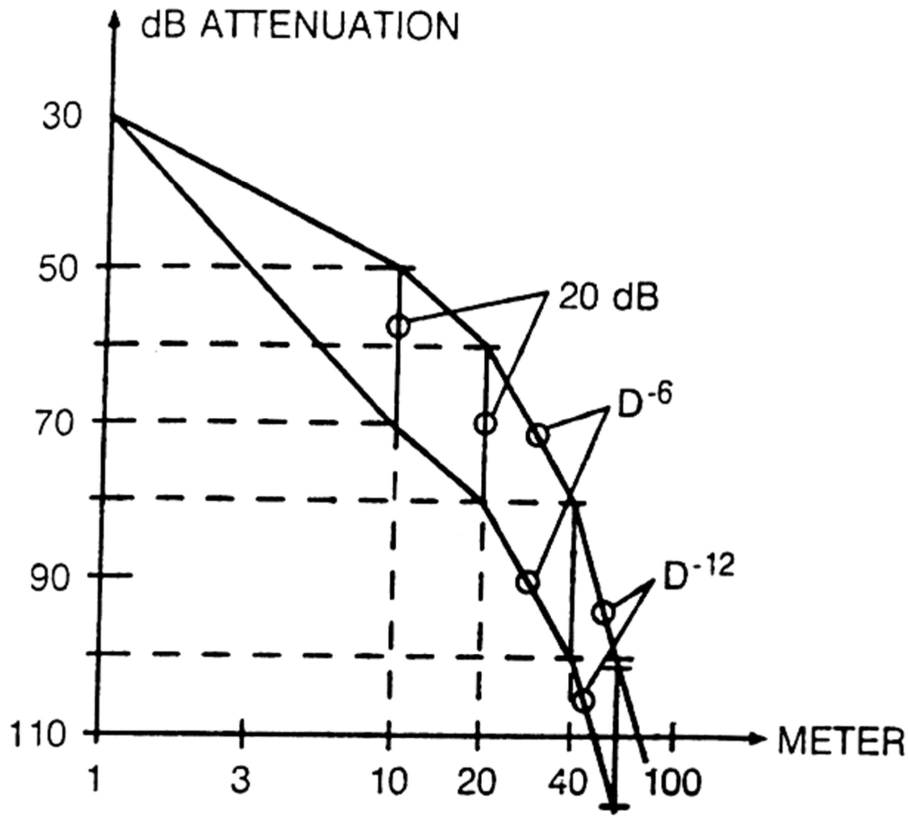


Figure 4.27 Ericsson in-building path loss model [from [Ake88] © IEEE].

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Log-Normal Fading (Shadowing)

Reminder: 3 factors in the total path loss,

$$L_P = L_A L_{LF} L_{SF} \tag{2.5}$$

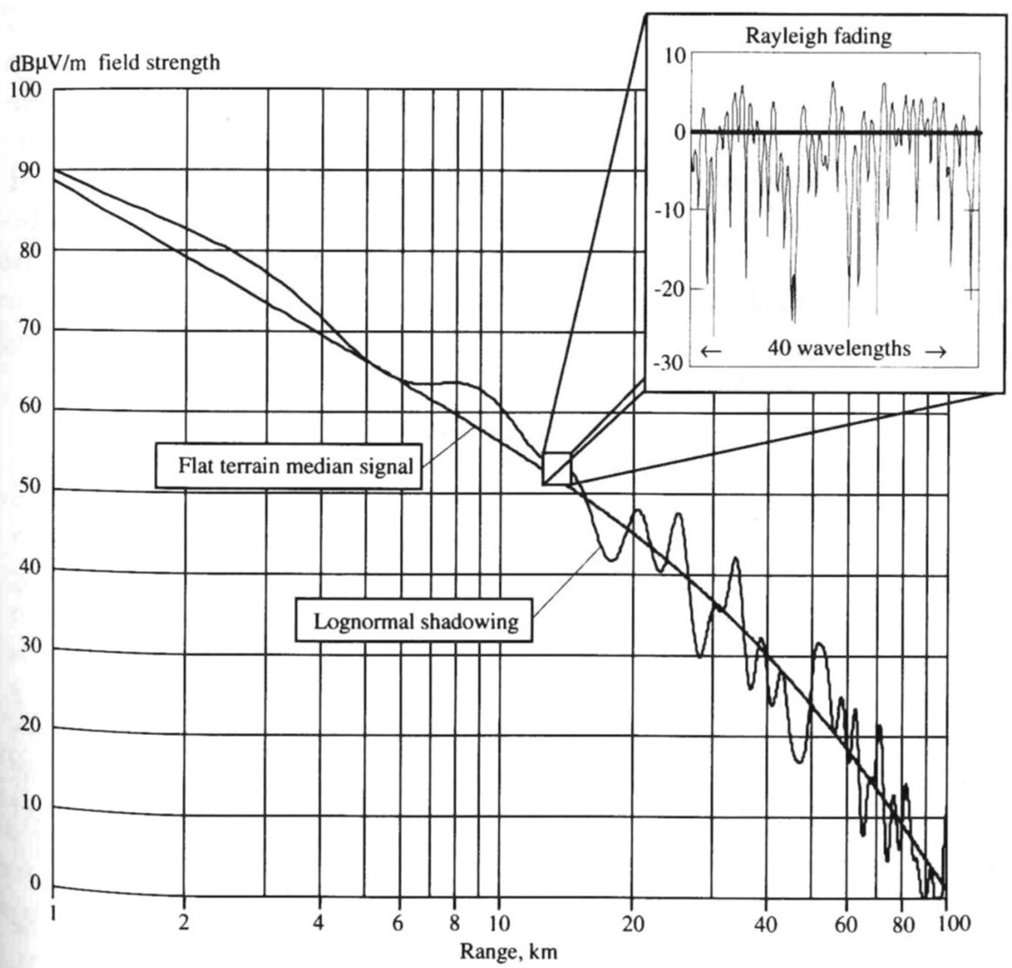


Figure 8.2 Signal behavior in a suburban region showing shadowing and multipath fading. (After: [1].)

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

Log-Normal Fading (shadowing): this is a long-term (or large-scale) fading since characteristic distance is a few hundreds wavelengths.

Due to various terrain effects, the actual path loss varies about the average value predicted by the models above,

$$L_p = \overline{L_p} + \Delta L \quad [\mathrm{dB}] \tag{4.5}$$

where $\overline{L_p}$ is the average path loss , ΔL - its variation, which can be described by log-normal distribution.

Overall, L_p becomes a log-normal RV,

$$\rho\left(L_p\right) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{\left(L_p - \overline{L_p}\right)^2}{2\sigma^2}} \tag{4.6}$$

where L_p and $\overline{L_p}$ are in dB, and σ is the standard deviation (in dB as well).

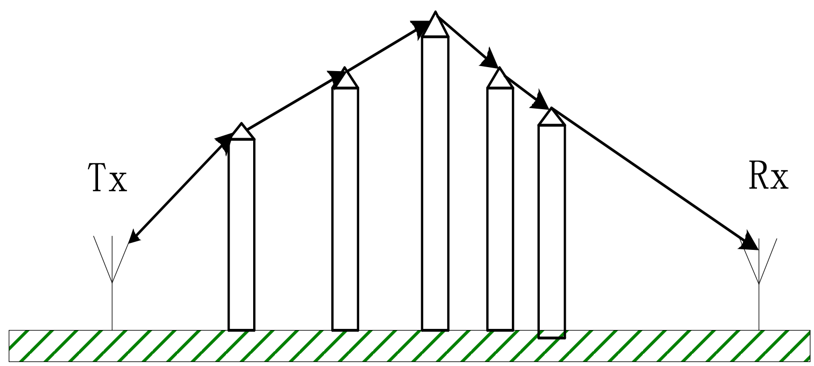
Physical explanation: multiple diffractions + the central limit theorem (in dB).

Shadowing: due to the obstruction of LOS path.

The semi-empirical models above can be used together with the log-normal distribution.

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

Log-Normal Fading: Derivation



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

$$E_t = E_0 \prod_{i=1}^{N} \Gamma_i, \quad |\Gamma_i| \leq 1 \tag{4.7}$$

Total Rx power:

$$P_t \sim |E_t|^2 = |E_0|^2 \prod_{i=1}^{N} |\Gamma_i|^2 \quad or \quad P_t = P_0 \prod_{i=1}^{N} |\Gamma_i|^2$$

$$P_{dB} = P_{0,dB} + 20 \sum_{i=1}^{N} \lg |\Gamma_i| \tag{4.8}$$

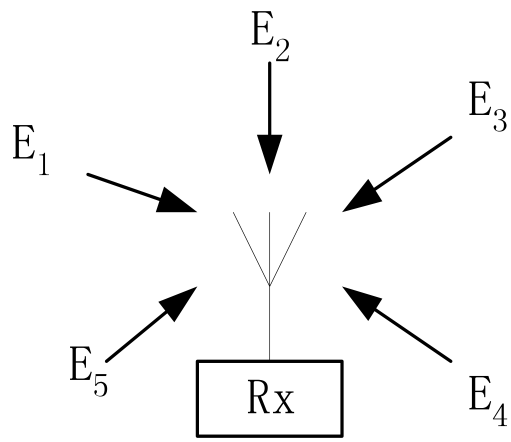
If $|\Gamma_i|$ are i.i.d., then $P_{dB} \sim \mathbb{N}(P_{0,dB}, \sigma_{dB})$

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

In practice: $\sigma_{dB} = 5...10$ dB (can take 8 dB as an average).

System design: allow for $2\sigma_{dB}$ margin (for about 95% reliability).

Small-Scale (multipath) Fading Model



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

$$
\begin{aligned}
E_t(t) &= \sum_{i=1}^{N} E_i \cos(\omega t + \varphi_i) \\
&= \sum_{i=1}^{N} E_i \cos\varphi_i \cos\omega t - \sum_{i=1}^{N} E_i \sin\varphi_i \sin\omega t
\end{aligned}
\qquad (4.9)
$$

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

$$
\begin{aligned}
&E_t(t) = E_x \cos\omega t - E_y \sin\omega t = E\cos(\omega t + \varphi) \\
&where \qquad E = \sqrt{E_x^2 + E_y^2} \rightarrow envelope \\
&I:\ E_x = \sum_{i=1}^{N} E_i \cos\varphi_i,\ \text{Q: } E_y = \sum_{i=1}^{N} E_i \sin\varphi_i
\end{aligned}
\qquad (4.10)
$$

Assume that E_i are i.i.d., and that $\varphi_i \in [0, 2\pi]$ are i.i.d.

By central limit theorem, $E_x, E_y \sim \mathbb{N}(0,\sigma^2)$

E is Rayleigh distributed with pdf

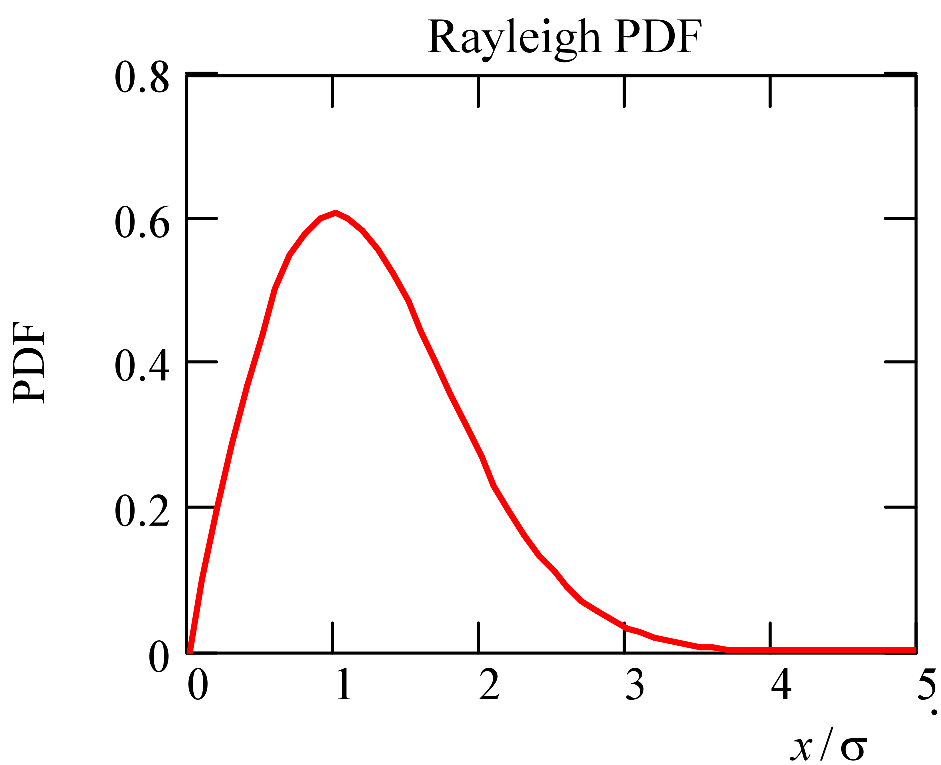
$$\rho(x) = \frac{x}{\sigma^2}\exp\left(-\frac{x^2}{2\sigma^2}\right), \qquad x \geq 0 \qquad (4.11)$$

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

$$\sigma^2 = \left\langle E_x^2 \right\rangle = \frac{1}{2}\sum_{i=1}^{N}\left\langle E_i^2 \right\rangle \qquad (4.12)$$

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 and CDF

Importance of the CDF in wireless system design.

Rx operates well if $E \geq E_{th} \rightarrow$ the threshold effect.
If $E < E_{th}$, the link is lost --> this is an outage.

Outage probability = CDF is

$$F(x) = \int_0^x \rho(t)dt = \Pr(E < x) \tag{4.13}$$

Rayleigh Fading

For Rayleigh distribution, the outage probability is

$$F(x) = \Pr(E < x) = \int_0^x \rho(t)dt = 1 - \exp\left(-\frac{x^2}{2\sigma^2}\right) \qquad (4.14)$$

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

$$\begin{aligned} P_{out} &= \Pr\{\text{SNR} < \gamma\} \\ &= 1 - \exp\left(-\frac{\gamma}{\overline{\gamma}}\right) = 1 - \exp\left(-\frac{P}{\overline{P}}\right) = F(P), \end{aligned} \qquad (4.15)$$

so that normalized SNR ($\gamma / \overline{\gamma}$) or power ($P / \overline{P}$) PDF and CDF:

$$f(x) = e^{-x}, \;\; F(x) = 1 - e^{-x} \qquad (4.15a)$$

and asymptotically,

$$P \ll \overline{P} \quad \Rightarrow \quad P_{out} = F(P) \approx \frac{P}{\overline{P}} = \frac{\gamma}{\overline{\gamma}} \qquad (4.16)$$

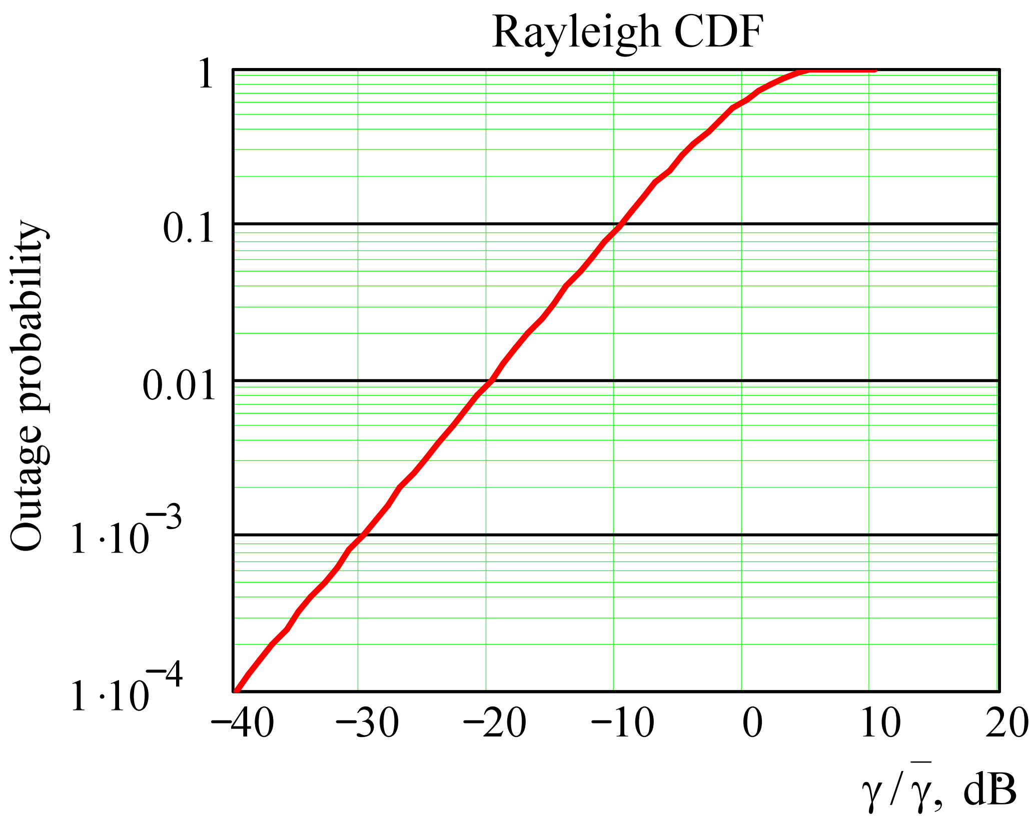
Note that $\frac{P}{\overline{P}} = \frac{\gamma}{\overline{\gamma}}$, where γ is the SNR.

Note in (4.16) the 10db/decade law.

Example:

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

i.e. if $P_{out} = 10^{-3}$ is desired, the Rx threshold is 30dB below one without fading (the average).



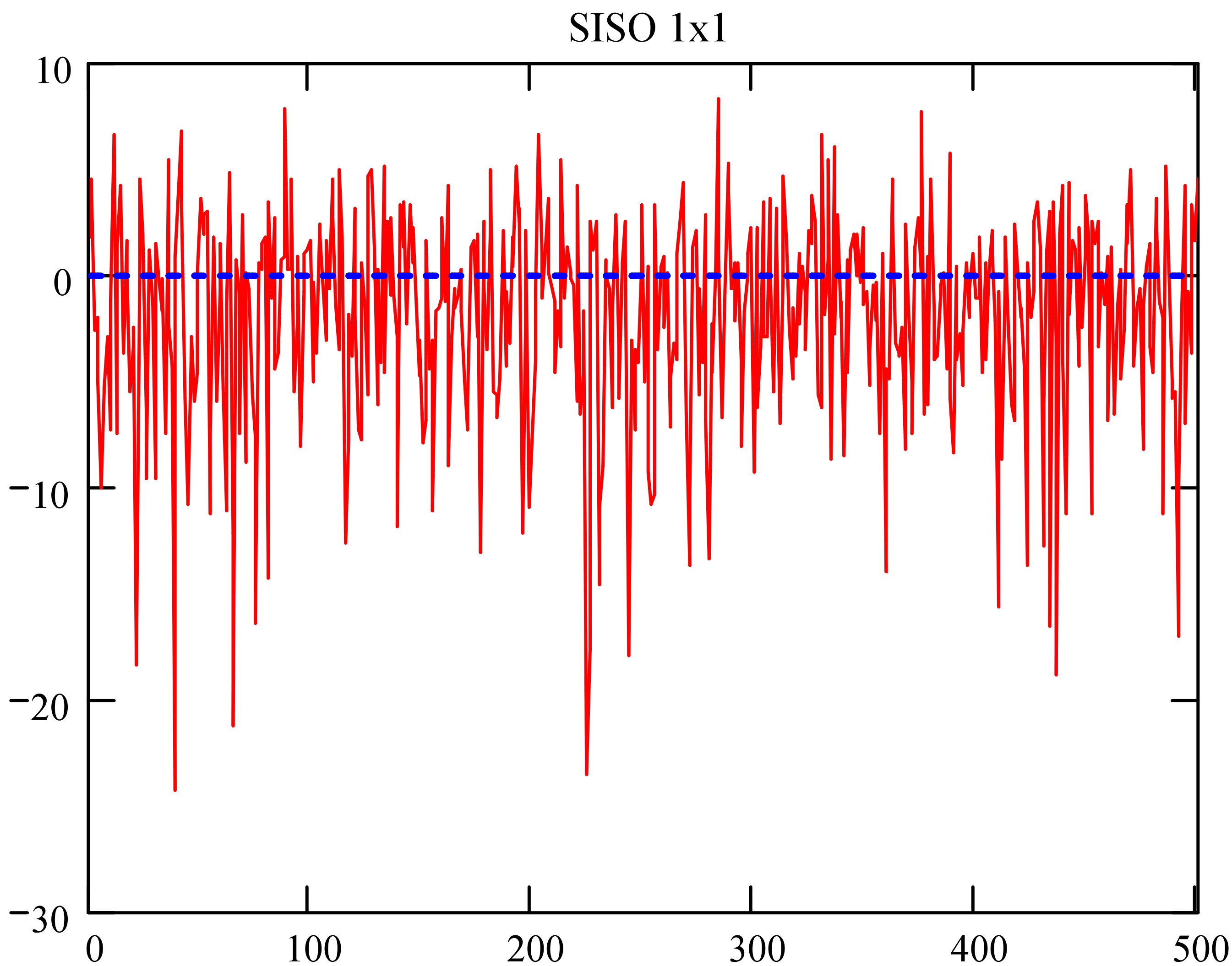
Complex-valued model:

$$E_t(t) = \sum_{i=1}^{N} E_i e^{j\varphi_i} e^{j\omega t} \qquad (4.17)$$

results in complex Gaussian variables.

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

Rayleigh Fading Channel



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

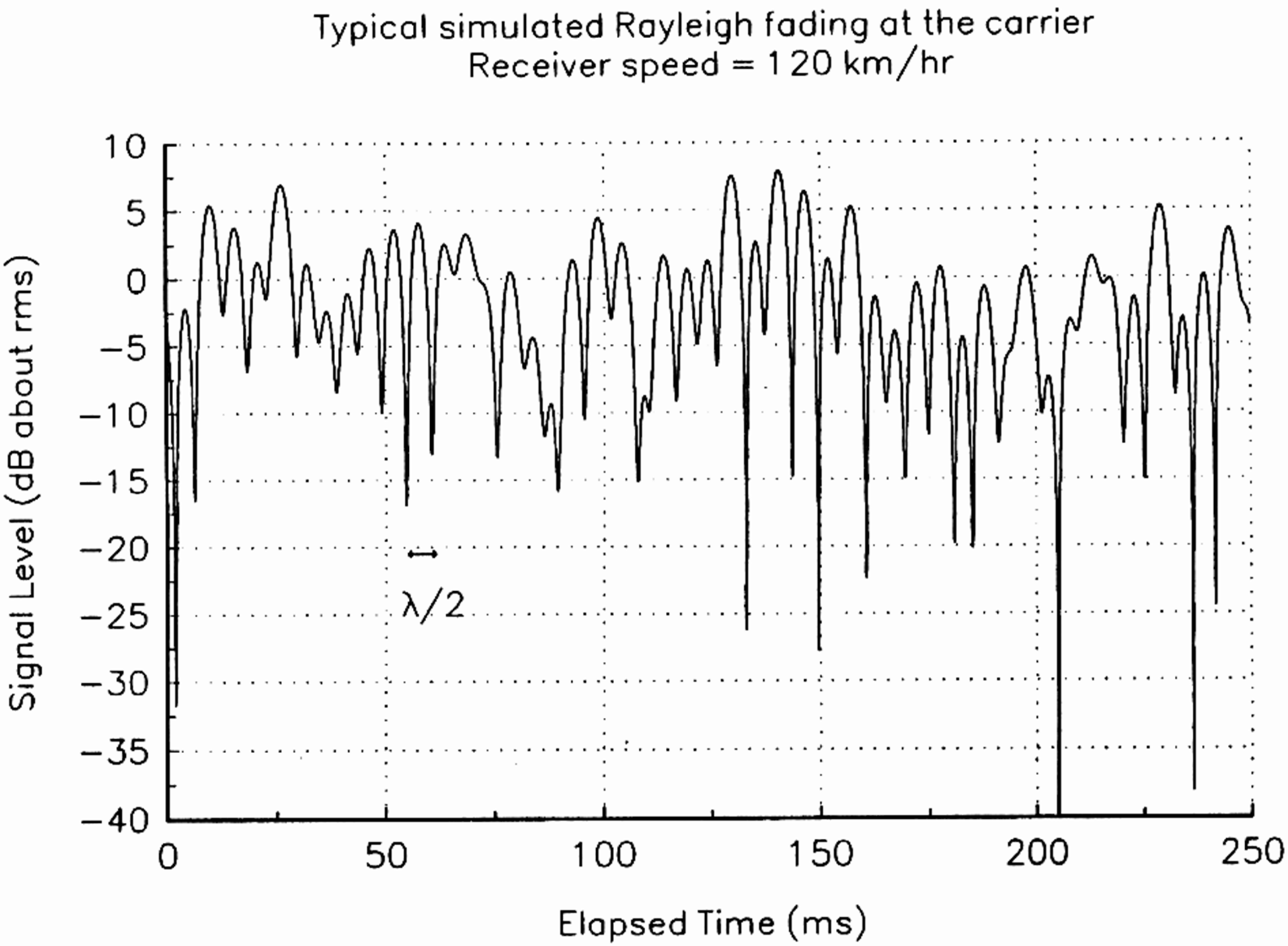


Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002

Measured Fading Channels

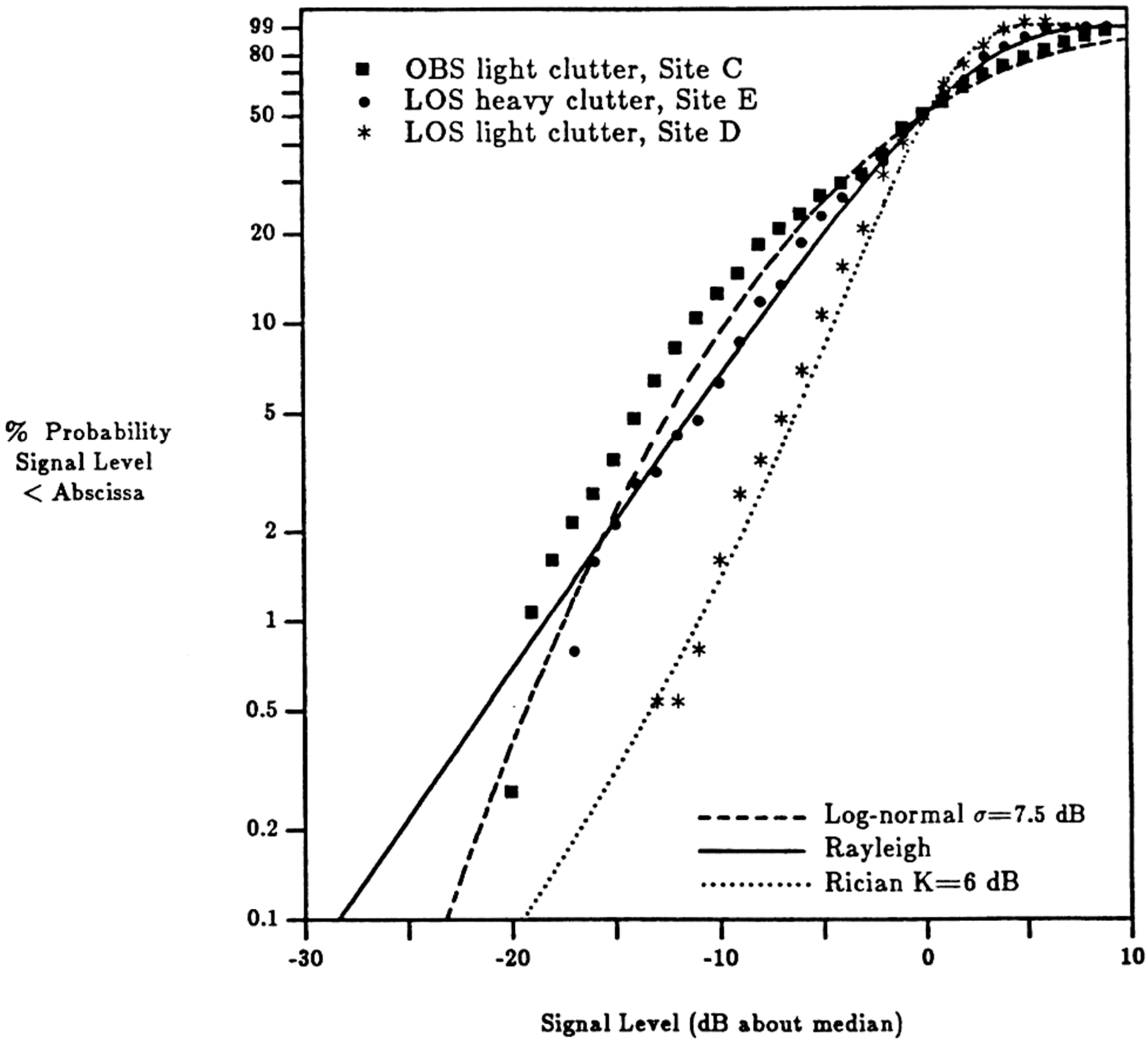


Figure 5.17 Cumulative distribution for three small-scale fading measurements and their fit to Rayleigh, Ricean, and log-normal distributions [from [Rap89] © IEEE].

T.S. Rappaport, Wireless Communications, Prentice Hall, 2002.

LOS and Ricean Model

Motivation: a LOS component. The distribution of in-phase and quadrature components is still Gaussian, but non-zero mean:

$$E_t(t) = \sum_{i=1}^{N} E_i \cos(\omega t + \varphi_i) + E_0 \cos(\omega t + \varphi_0) \quad (4.18)$$

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

$$E_t(t) = (E_x + E_{x0})\cos\omega t - (E_y + E_{y0})\sin\omega t$$
$$\langle E_x \rangle = \langle E_y \rangle = 0, and \qquad E = \sqrt{(E_x + E_{x0})^2 + (E_y + E_{y0})^2} \quad (4.19)$$

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

$$\rho(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2 + x_0^2}{2\sigma^2}\right) I_0\left(\frac{x x_0}{\sigma^2}\right), \quad (4.20)$$

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

Introduce <u>K-factor:</u>

$$K = x_0^2 / (2\sigma^2) \quad (4.21)$$

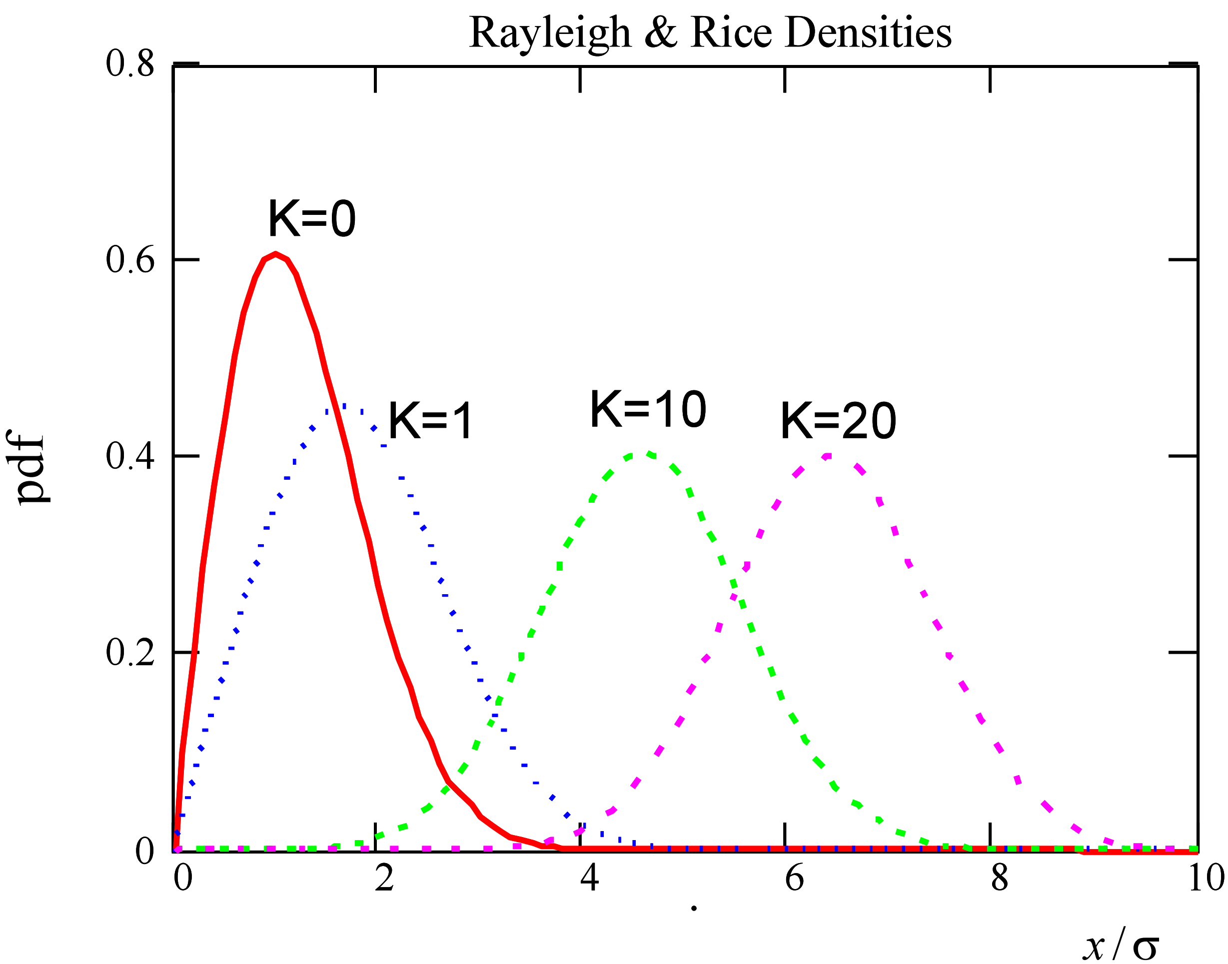
where $x_0^2 / 2$ is the LOS power, it is called LOS ("steady" or "specular") component, σ^2 is the scattered (multipath or diffused) power, it is called diffused component.

K tells us how strong the LOS is.

Total average power = $x_0^2 / 2 + \sigma^2 = \sigma^2 (1 + K)$

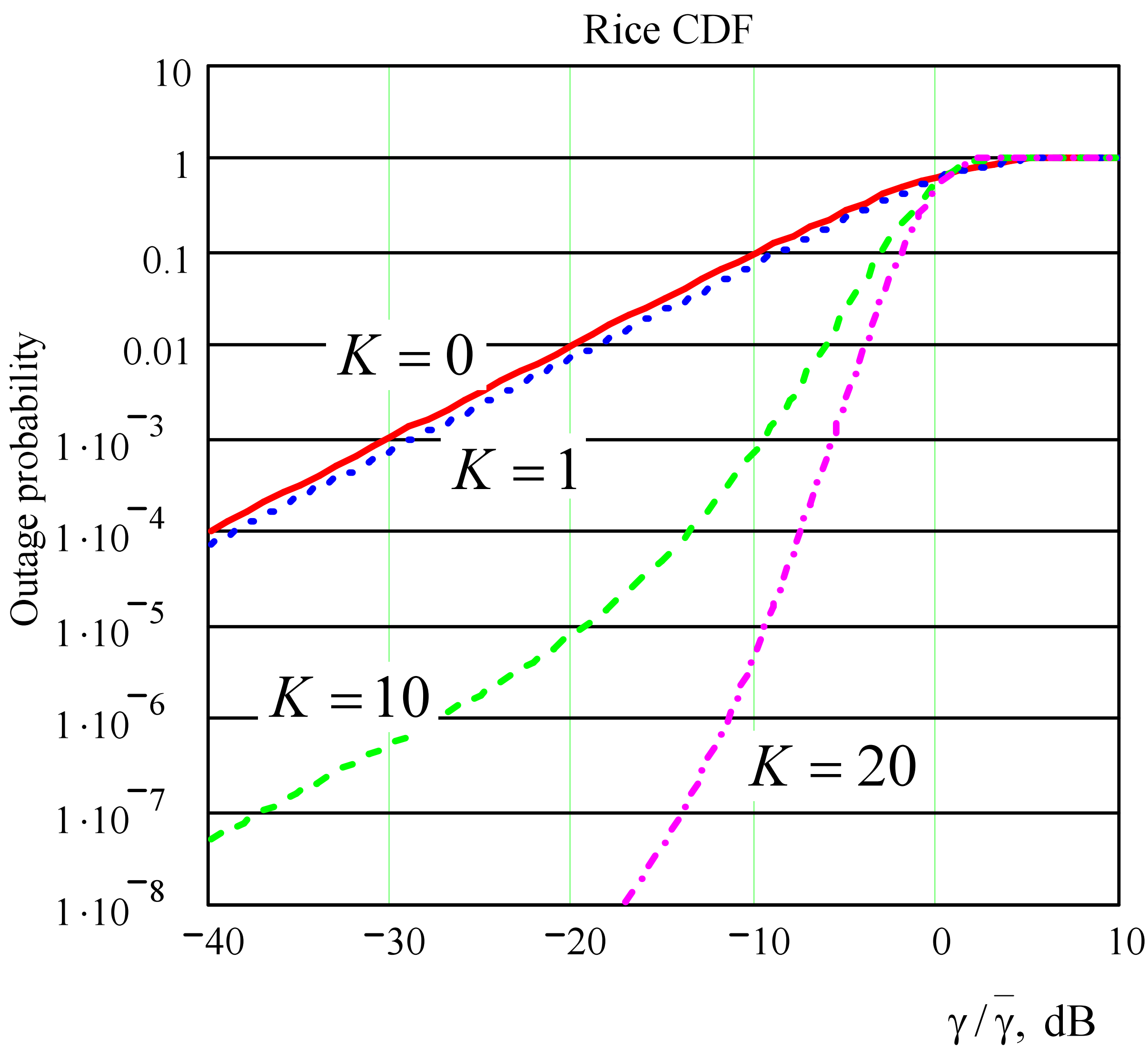
PDF of E becomes

$$\rho(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2} - K \right) I_0\left(\sqrt{2K} \frac{x}{\sigma} \right) \quad (4.22)$$



Note: normalized to the multipath power only.

Q: do the same graph if normalized to the total average power.



Q.: find the CDF of Ricean distribution as a function of K and total (LOS + multipath) average power or SNR.

Applications of Outage Probability

1) Fade margin evaluation for the link budget:

$$P_{out}(\gamma_{th}/\gamma_0) = \varepsilon \rightarrow F = \gamma_0/\gamma_{th} = 1/P_{out}^{-1}(\varepsilon)$$

2) Average outage time:

$$T_{out} = P_{out}T$$

2) Average # of users in outage:

$$N_{out} = P_{out}N$$

To be discussed later on:

- level crossing rates (# of fades per unit time)
- average fade duration

Monte-Carlo Method

It is a powerful simulation technique to solve many statistical problems numerically in a very efficient way. You should be familiar with it. Detailed description of the method and many examples can be found in numerous references, including the following:

[1] M.C. Jeruchim, P. Balaban, K.S. Shanmugan, Simulation of Communication Systems, Kluwer, New York, 2000.
[2] W.H. Tranter et al, Principles of Communication System Simulation with Wireless Applications, Prentice Hall, Upper Saddle River, 2004.
[3] J.G. Proakis, M. Salehi, Contemporary Communication Systems Using MATLAB, Brooks/Cole, 2000.

This is used in labs extensively.

Summary

- Indoor propagation path loss models.
- Log-normal shadowing.
- Small-scale fading.
- Rayleigh & Rice distributions.
- Physical mechanisms.

Reading:

o Rappaport, Ch. 4.

References:

o S. Salous, Radio Propagation Measurement and Channel Modelling, Wiley, 2013. (available online)

o J.S. Seybold, Introduction to RF propagation, Wiley, 2005.

o https://en.wikipedia.org/wiki/ITU_model_for_indoor_attenuation

o Other books (see the reference list).

Note: Do not forget to do end-of-chapter problems. Remember the learning efficiency pyramid!