A25

Table 3.3 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]
Aluminium 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]
Light textile inventory	3-5	1300 MHz	[Rap91c]
Chain-like fenced in area 20 ft high containing tools, inventory, and people	5-12	1300 MHz	[Rap91c]
Metal blanket — 12 sq ft	4-7	1300 MHz	[Rap91c]
Metallic hoppers which hold scrap metal for recycling - 10 sq ft	3-6	1300 MHz	[Rap91c]
Small metal pole — 6" diameter	3	1300 MHz	[Rap91c]
Metal pulley system used to hoist metal inventory — 4 sq ft	6	1300 MHz	[Rap91c]
Light machinery < 10 sq ft	1-4	1300 MHz	[Rap91c]
General machinery - 10 - 20 sq ft	5-10	1300 MHz	[Rap91c]
Heavy machinery > 20 sq ft	10-12	1300 MHz	[Rap91c]
Metal catwalk/stairs	5	1300 MHz	[Rap91c]
Light textile	3-5	1300 MHz	[Rap91c]
Heavy textile inventory	8-11	1300 MHz	[Rap91c]
Area where workers inspect metal finished products for defects	3-12	1300 MHz	[Rap91c]
Metallic inventory	4-7	1300 MHz	[Rap91c]
Large 1-beam — 16 - 20"	8-10	1300 MHz	[Rap91c]
Metallic inventory racks — 8 sq ft	4-9	1300 MHz	[Rap91c]
Empty cardboard inventory boxes	3-6	1300 MHz	[Rap91c]
Concrete block wall	13-20	1300 MHz	[Rap91c]
Ceiling duct	1-8	1300 MHz	[Rap91c]
2.5 m storage rack with small metal parts (loosely packed)	4-6	1300 MHz	[Rap91c]
4 m metal box storage	10-12	1300 MHz	[Rap91c]
5 m storage rack with paper products (loosely packed)	2-4	1300 MHz	[Rap91c]

Ray Tracing

Freq ↑ ⇒ Attenuation ↑

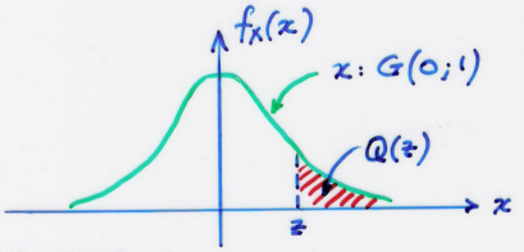
Area under the Gaussian PDF

$x : G(\mu ; \sigma^2)$

$$\text{Prob}(x \geq z) = \frac{1}{\sqrt{2\pi}\,\sigma} \int_z^{\infty} e^{-\frac{(x-\mu)^2}{2\sigma^2}}\,dx \quad \ldots \text{ no closed-form expression}$$

Three tabulated functions

I) $Q(z) \triangleq \dfrac{1}{\sqrt{2\pi}} \displaystyle\int_z^{\infty} e^{-x^2/2}\,dx$

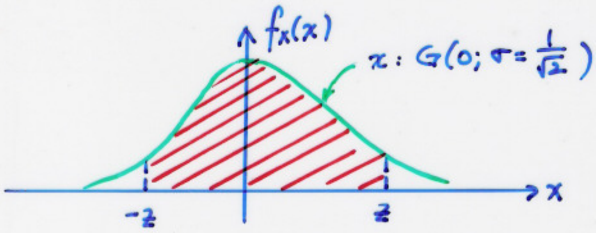


$\lim\limits_{z \to -\infty} Q(z) = 1$ $\qquad Q(0) = \frac{1}{2}$ $\qquad Q(-z) + Q(z) = 1$

$\lim\limits_{z \to \infty} Q(z) = 0$

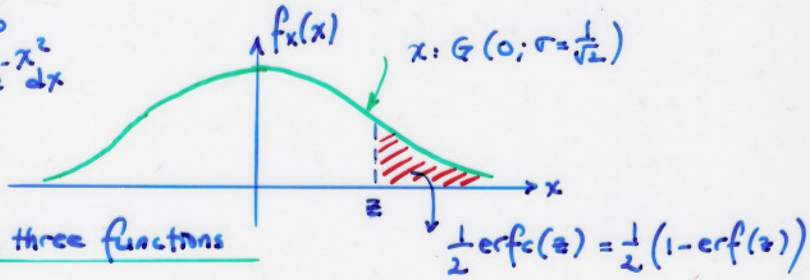
II) $\mathrm{erf}(z) \triangleq \dfrac{2}{\sqrt{\pi}} \displaystyle\int_0^{z} e^{-x^2}\,dx$

error function



III) $\mathrm{erfc}(z) \triangleq 1 - \mathrm{erf}(z) = \dfrac{2}{\sqrt{\pi}} \displaystyle\int_z^{\infty} e^{-x^2}\,dx$

complementary error function



Transformations between the three functions

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{-\frac{x^2}{2}}\,dx$$

let $\dfrac{x}{\sqrt{2}} = u \;\rightarrow\; Q(z) = \dfrac{1}{\cancel{\sqrt{2}}\sqrt{\pi}} \displaystyle\int_{z/\sqrt{2}}^{\infty} e^{-u^2} \cancel{\sqrt{2}}\,du = \frac{1}{2}\mathrm{erfc}\left(\frac{z}{\sqrt{2}}\right) = \frac{1}{2}\left(1 - \mathrm{erf}\left(\frac{z}{\sqrt{2}}\right)\right)$

$$\rightarrow \mathrm{erfc}(z) = 2Q(\sqrt{2}\,z)$$
$$\mathrm{erf}(z) = 1 - 2Q(\sqrt{2}\,z)$$

$x : G(\mu;\sigma^2)$ $\qquad$ $\text{Prob}(x \geq z) = ?$

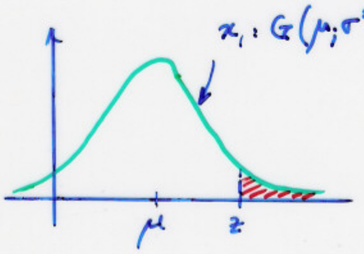
a) First soln:

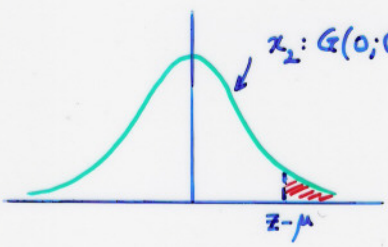
$$\text{Prob}(x \geq z) = \frac{1}{\sqrt{2\pi}\,\sigma} \int_z^{\infty} e^{-\frac{(x-\mu)^2}{2\sigma^2}}\,dx$$

let $\frac{x-\mu}{\cancel{\sigma}} = u \rightarrow \text{Prob}(x \geq z) = \frac{1}{\sqrt{2\pi}\,\cancel{\sigma}} \int_{\frac{z-\mu}{\sigma}}^{\infty} e^{-u^2/2}\,\cancel{\sigma}\,du$

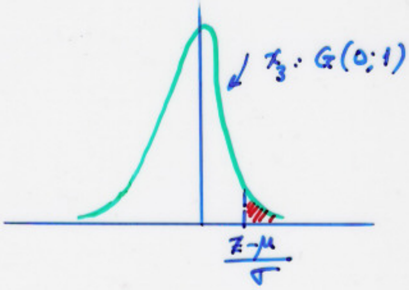
$$= Q\left(\frac{z-\mu}{\sigma}\right)$$

b) Second soln:





$x_2 = x_1 - \mu$



$x_3 = \frac{x_2}{\sigma} = \frac{x_1-\mu}{\sigma}$

$$P(x_1 : G(\mu;\sigma^2) \geq z)$$

$$= P(x_2 : G(0;\sigma^2) \geq z-\mu)$$

$$= P\left(x_3 : G(0;1) \geq \frac{z-\mu}{\sigma}\right) = Q\left(\frac{z-\mu}{\sigma}\right)$$

Determination of Percentage of Coverage Area

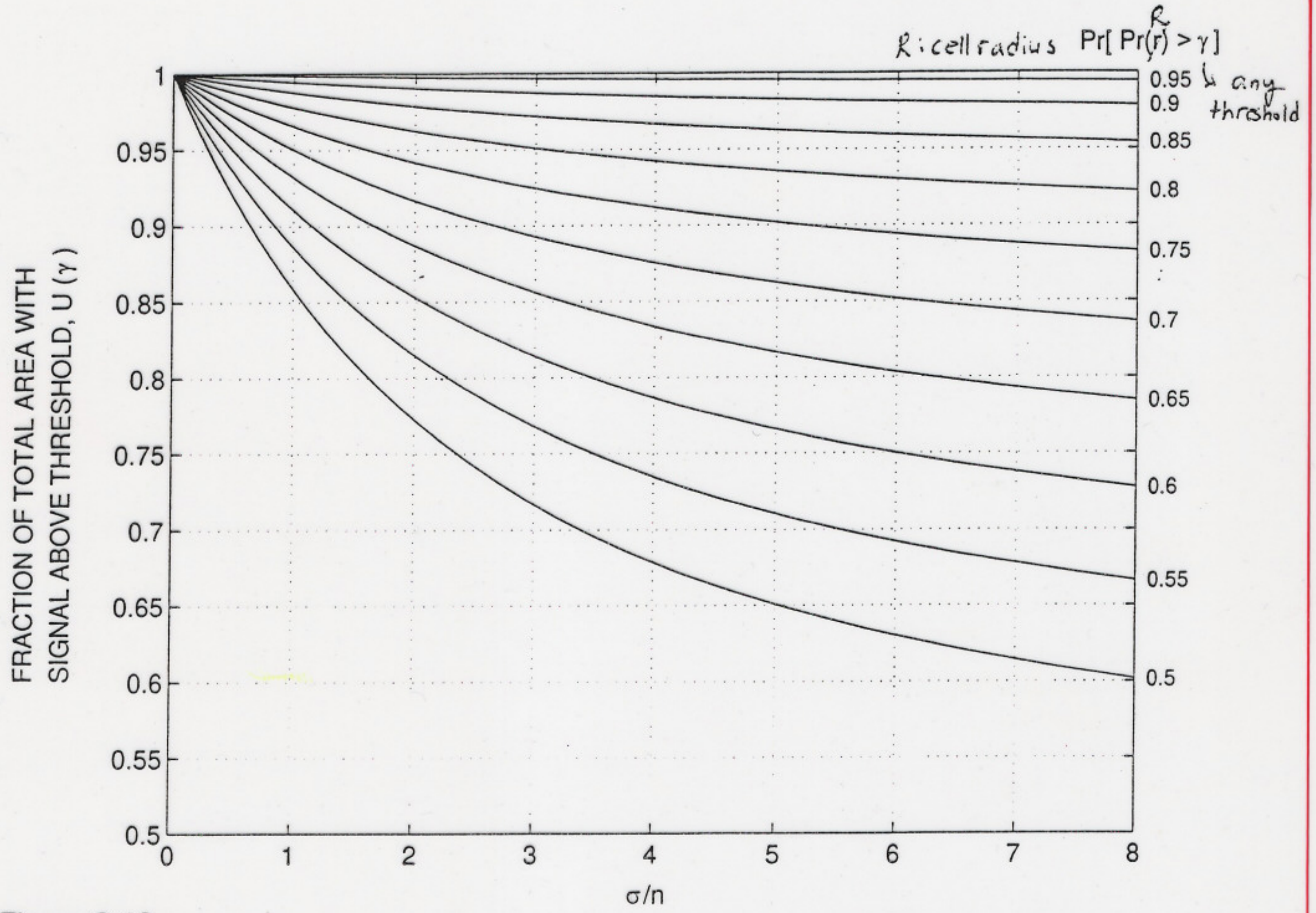


Figure 3.18
Family of curves relating fraction of total area with signal above threshold, $U(\gamma)$ as a function of probability of signal above threshold on the cell boundary.

Example 4.9 (Rappaport, 2nd ed., p. 143)

Four received power measurements were taken at distances of 100 m, 200 m, 1 km, and 3 km from a transmitter. These measured values are given in the following table. It is assumed that the path loss for these measurements follow the model in Eq. 4.69a, where $d_0 = 100$ m:

(a) Find the minimum mean square error (MMSE) estimate for the path loss exponent, n.

(b) Calculate the standard deviation about the mean value.

(c) Estimate the received power at $d = 2$ km using the resulting model.

(d) Predict the likelihood that the received signal level at 2 km will be greater than −60 dBm.

(e) Predict the % of area within a 2 km radius cell that receives signals greater than −60 dBm, given the results in (d).

Solution

i	$d(i)$ [m]	actual received power $P_{R,a}(d_i)$ [dBm]	Mean estimate power $\bar{P}_R(d_i;n)$ [dBm]
1	100	0	
2	200	-20	
3	1000	-35	
4	3000	-70	

(a) $$\bar{P}_R(d_i;n) = \overbrace{P_T G_T G_R \left(\frac{4\pi\lambda}{d_0}\right)^2}^{\bar{P}_R(d_0)} \left(\frac{d_0}{d_i}\right)^n, \qquad d_i \geq d_0$$

$$\bar{P}_R(d_i;n)\,[\text{dBm}] = \underbrace{10\log_{10}\left(P_T G_T G_R \left(\frac{4\pi\lambda}{d_0}\right)^2\right)}_{\text{dBm, because}} + \underbrace{10n\log_{10}\left(\frac{d_0}{d_i}\right)}_{\text{unitless} \to \text{dB}}$$

meter

meter

meter

mW unitless

after cancellation: $10\log_{10}(\text{mW})$: dBm