Wireless Communications

Principles and Practice

2nd Edition

T.S. Rappaport

Chapter 4: Mobile Radio Propagation: Large-Scale Path Loss

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Multiple knife-edge diffraction

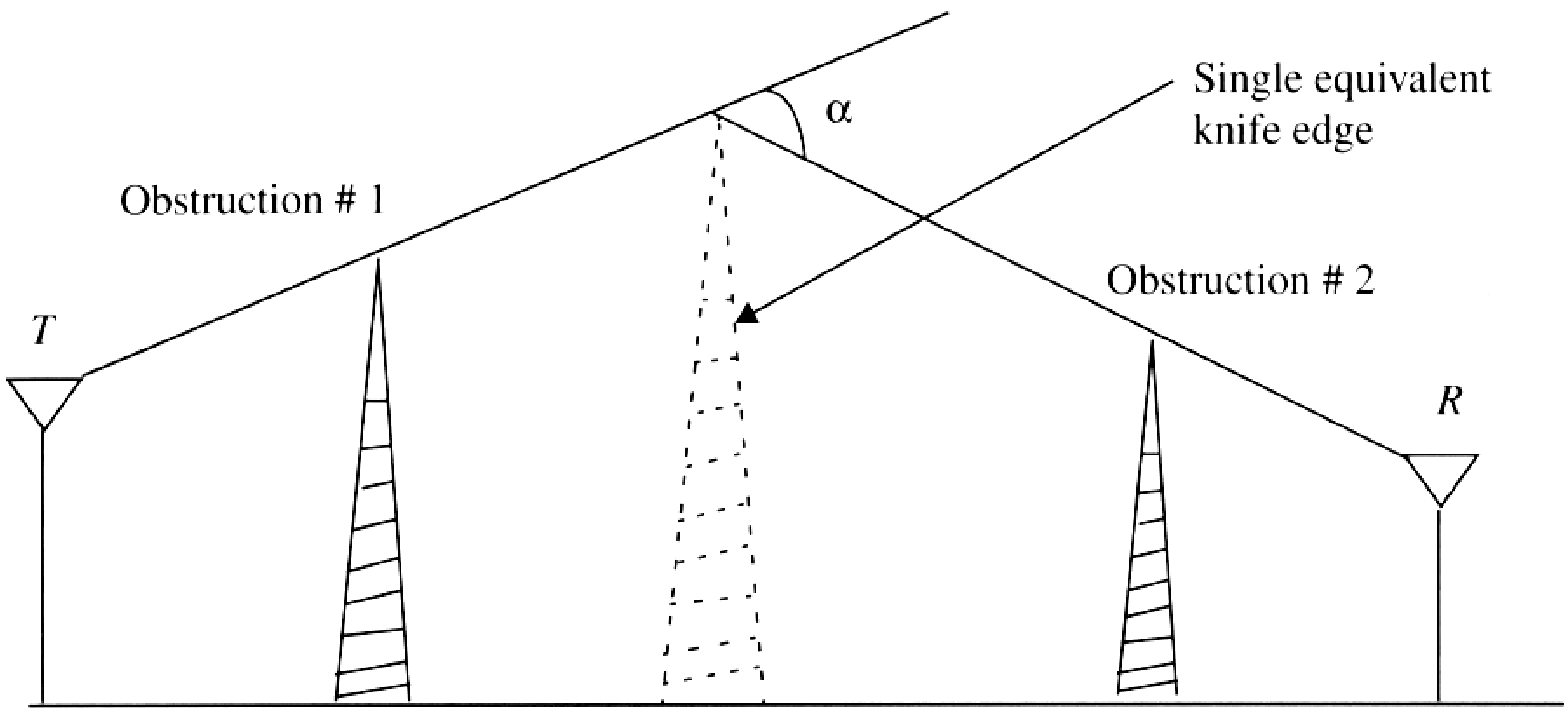

Figure 4.15 Bullington's construction of an equivalent knife edge [from [Bul47] © IEEE].

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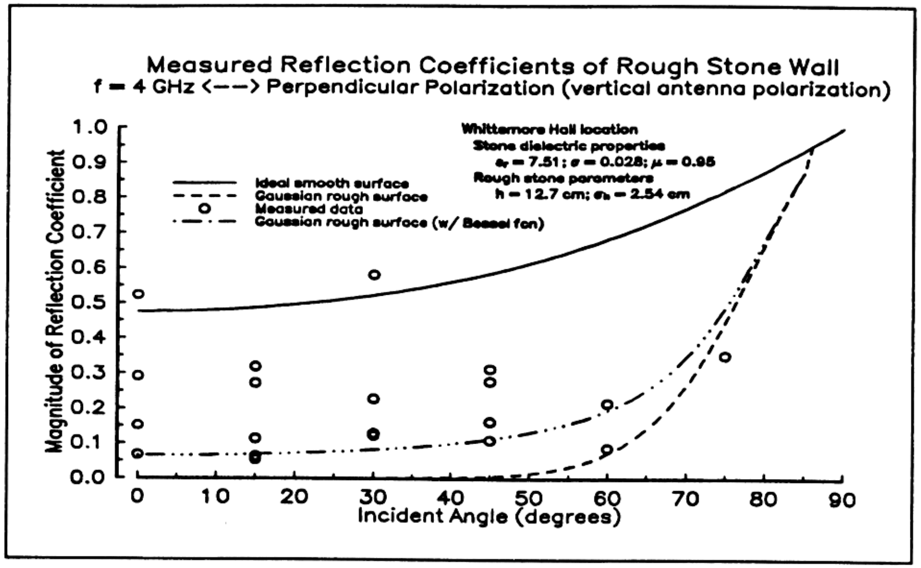
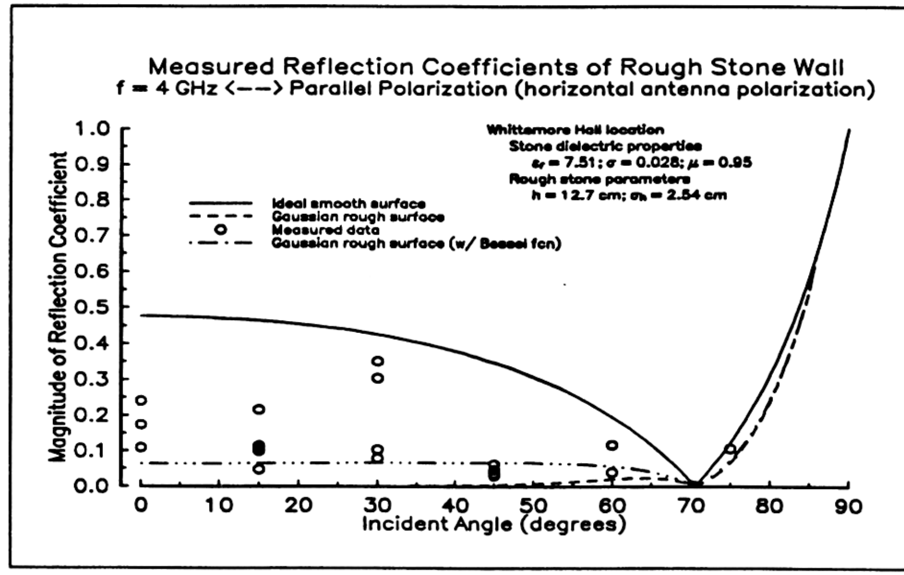
Measured results



(a) E-field in the plane of incidence (parallel polarization).



(b) E-field normal to plane of incidence (perpendicular polarization).

Figure 4.16 Measured reflection coefficients versus incident angle at a rough stone wall site. In these graphs, incident angle is measured with respect to the normal, instead of with respect to the surface boundary as defined in Figure 4.4. These graphs agree with Figure 4.6 [Lan96].

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Typical large-scale path loss

Table 4.2 Path Loss Exponents for Different Environments

Environment	**Path Loss Exponent, *n***
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

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Measured large-scale path loss

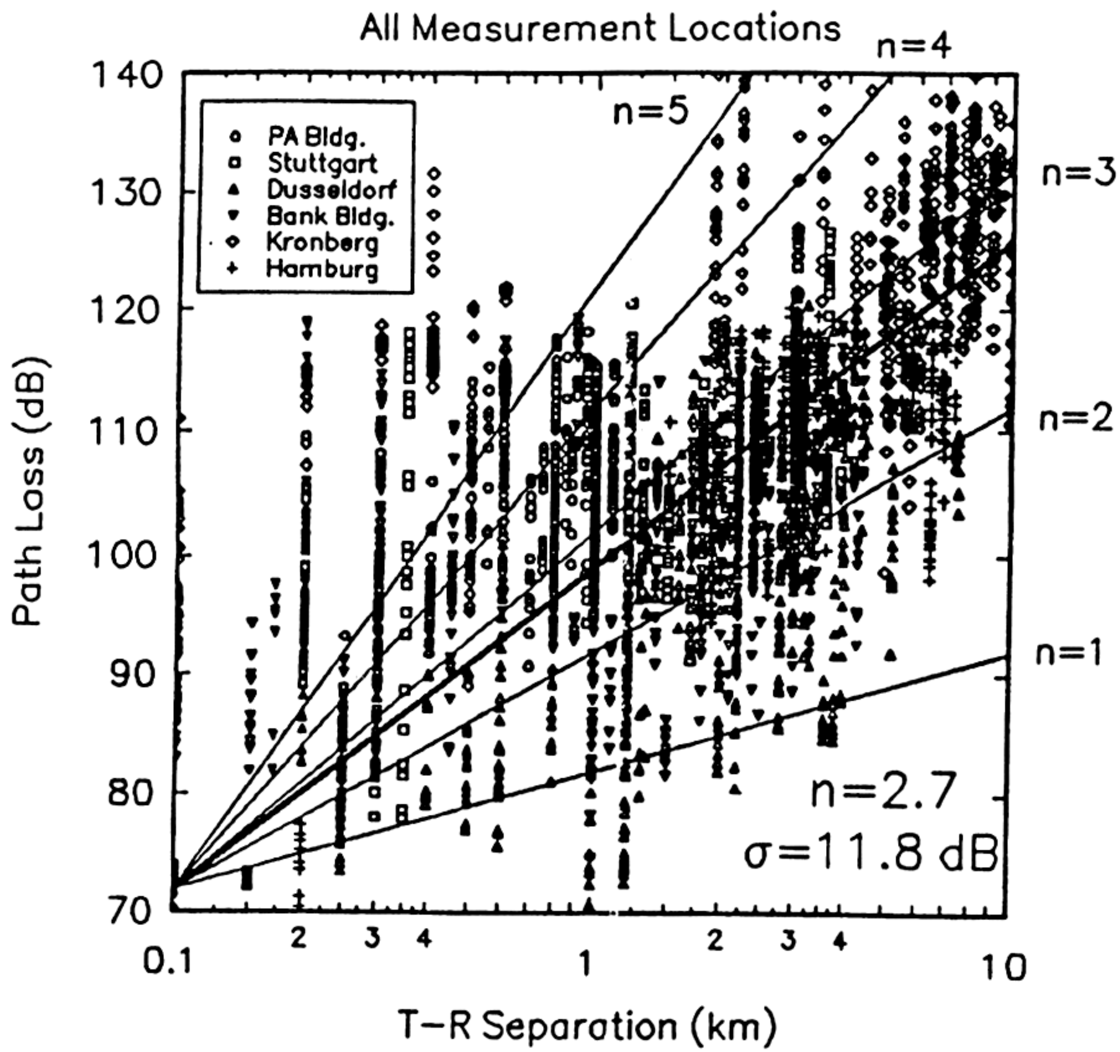

Figure 4.17 Scatter plot of measured data and corresponding MMSE path loss model for many cities in Germany. For this data, $n = 2.7$ and $\sigma = 11.8$ dB [from [Sei91] © IEEE].

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Area versus Distance coverage model with shadowing model

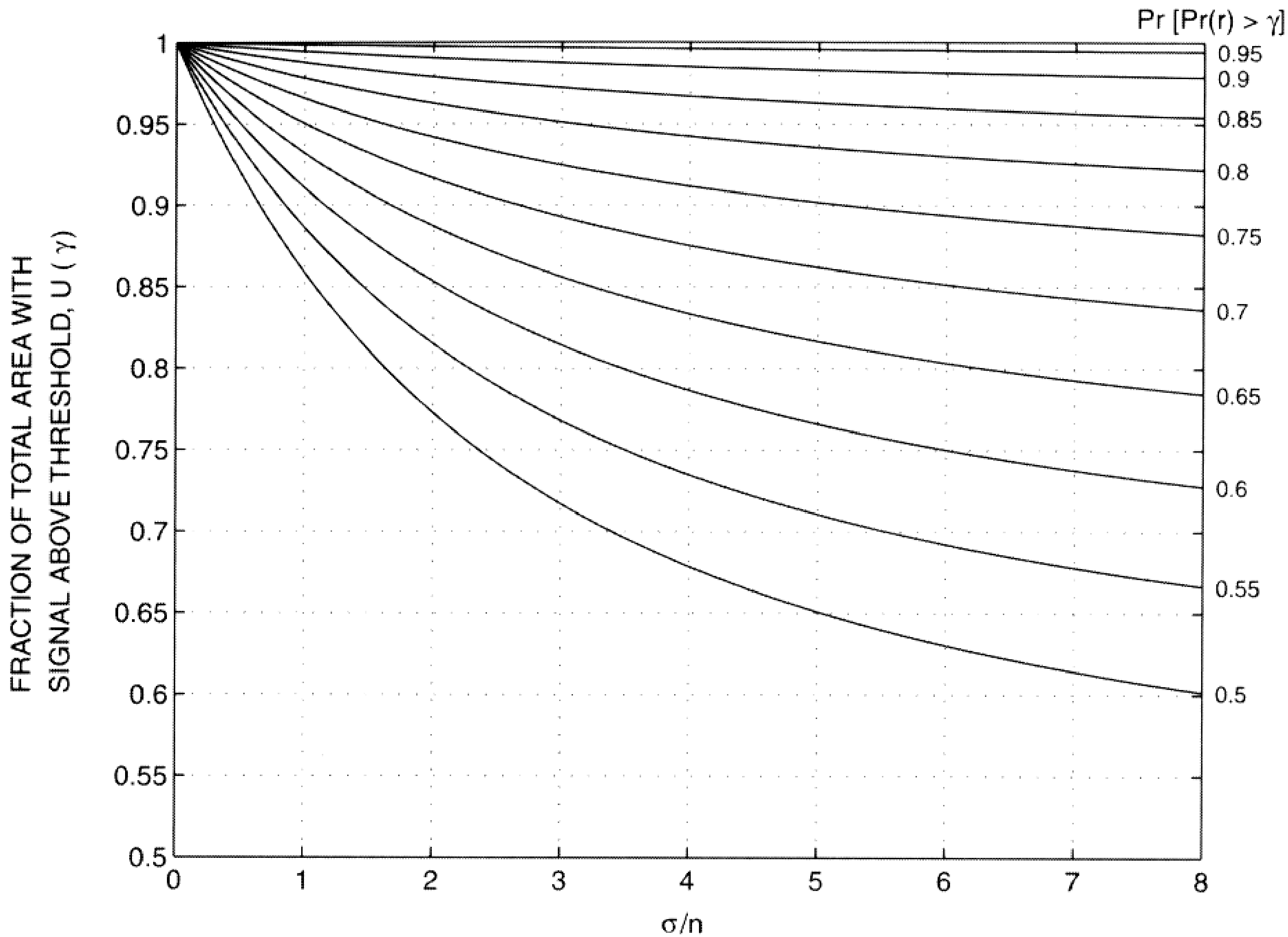

Figure 4.18 Family of curves relating fraction of total area with signal above threshold, $U(\gamma)$ as a function of probability of signal above threshold on the cell boundary.

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2-D Propagation Raster data

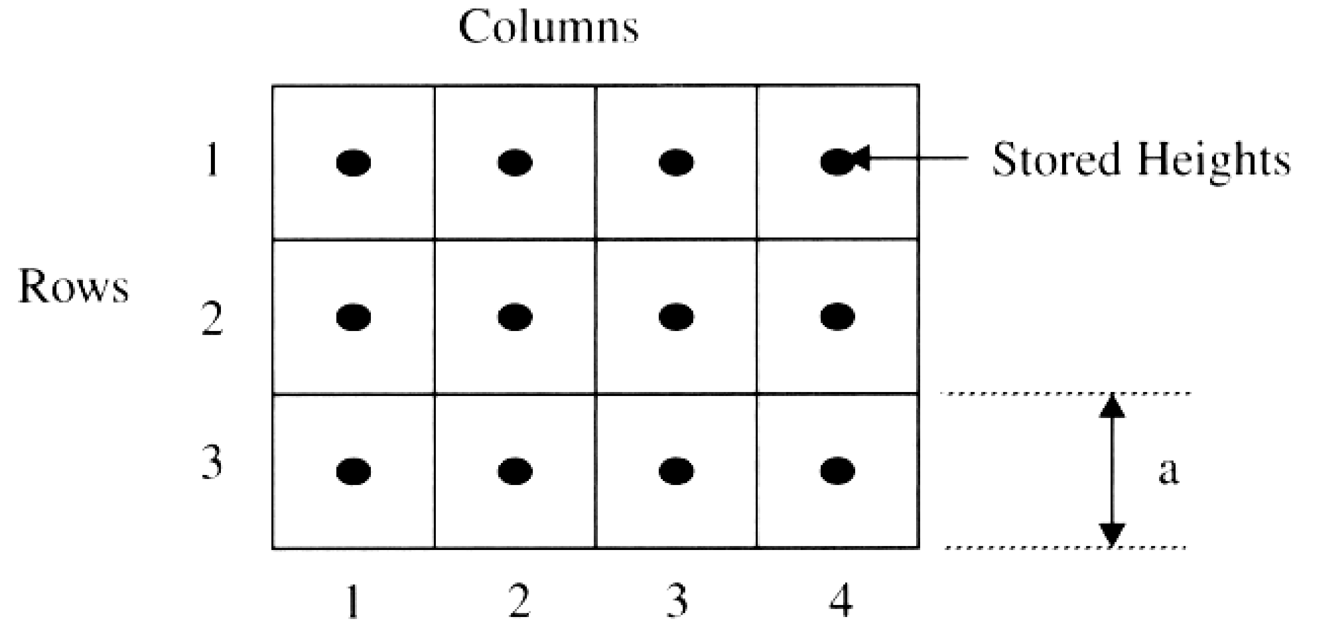

Figure 4.19 Illustration of a two-dimensional array of elevation information.

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Representing propagation

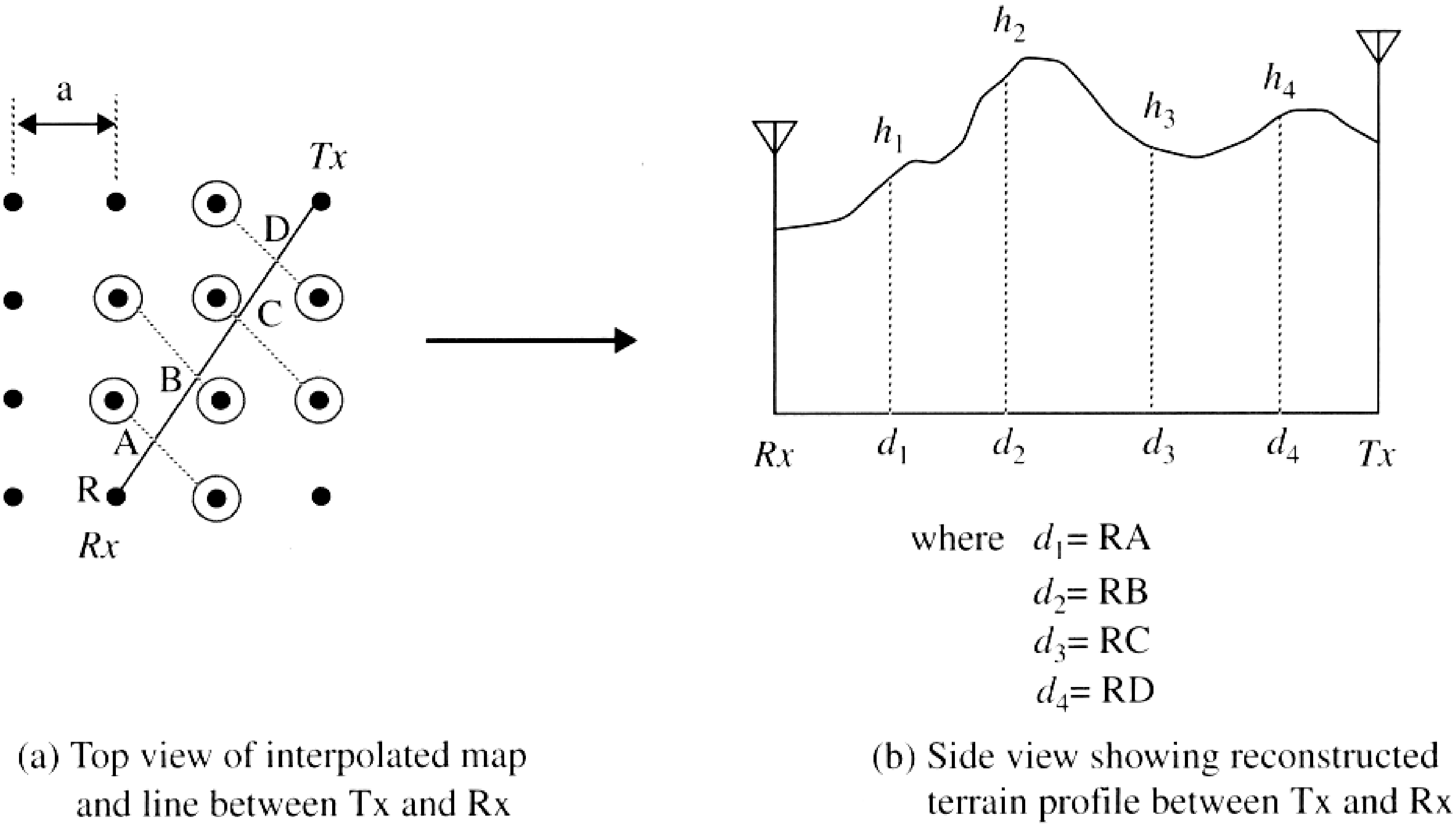

Figure 4.20 Illustration of terrain profile reconstruction using diagonal interpolation.

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Algorithm for line of sight (LOS)

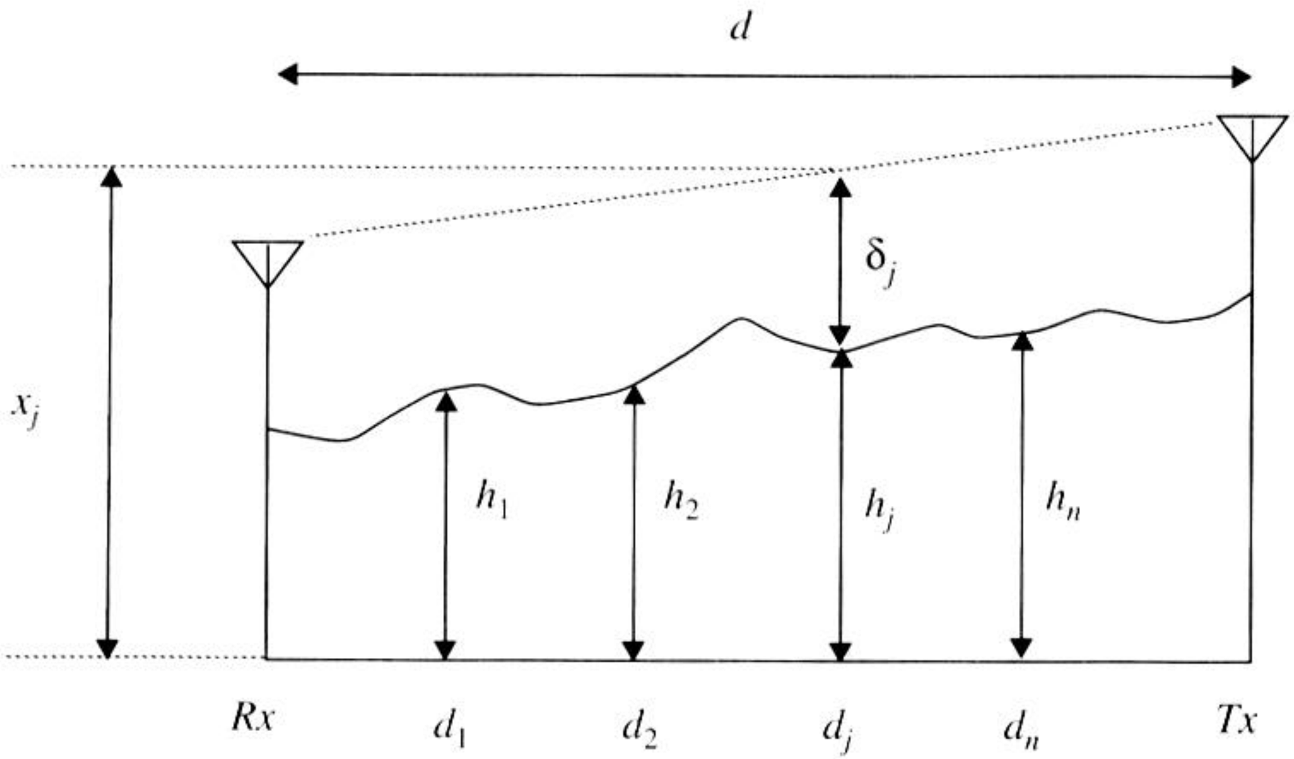

Figure 4.21 Illustration of line-of-sight (LOS) decision making process.

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Multiple diffraction computation

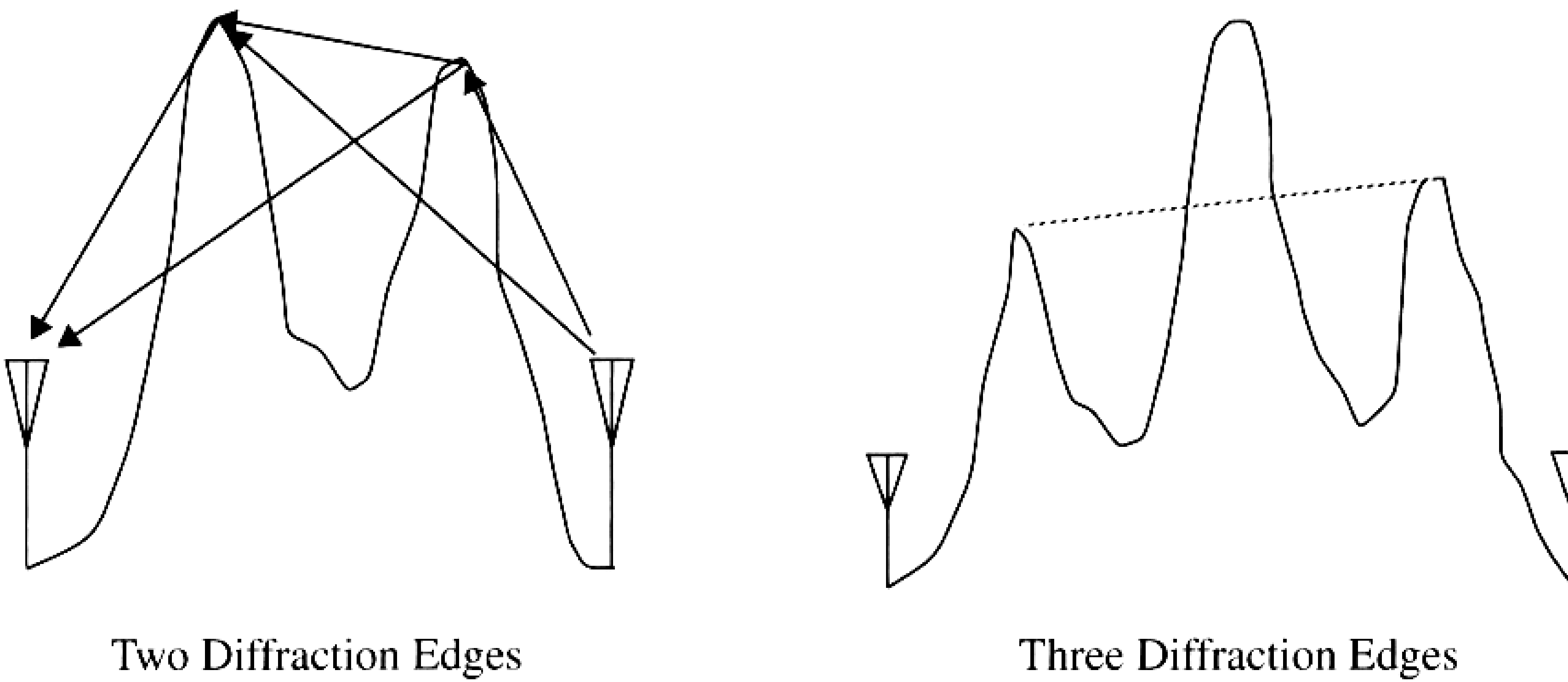

Figure 4.22 Illustration of multiple diffraction edges.

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Okumura Model

- The most widely used model for signal prediction in urban areas.
- The curves were developed from extensive measurements.
- The curves were drawn for TX-antenna height of 200m and RX-antenna height of 3m.

$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{re}) - G(h_{te}) - G_{AREA}$$

Where

L_{50} is the median path loss (50%)

L_F is the free space path loss

$A_{mu}(f,d)$ is the median attenuation relative to free space

$G(h_{re}), G(h_{te})$ are antenna height gain factors

G_{AREA} is the gain due to the type of environment

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Okumura Model

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) \qquad 1000\text{m} > h_{te} > 30\,\text{m}$$

$$G(h_{re}) = 10\log\left(\frac{h_{re}}{3}\right) \qquad h_{re} \le 3\,\text{m}$$

$$G(h_{re}) = 20\log\left(\frac{h_{re}}{3}\right) \qquad 10\text{m} > h_{re} > 3\,\text{m}$$

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Okumura Model

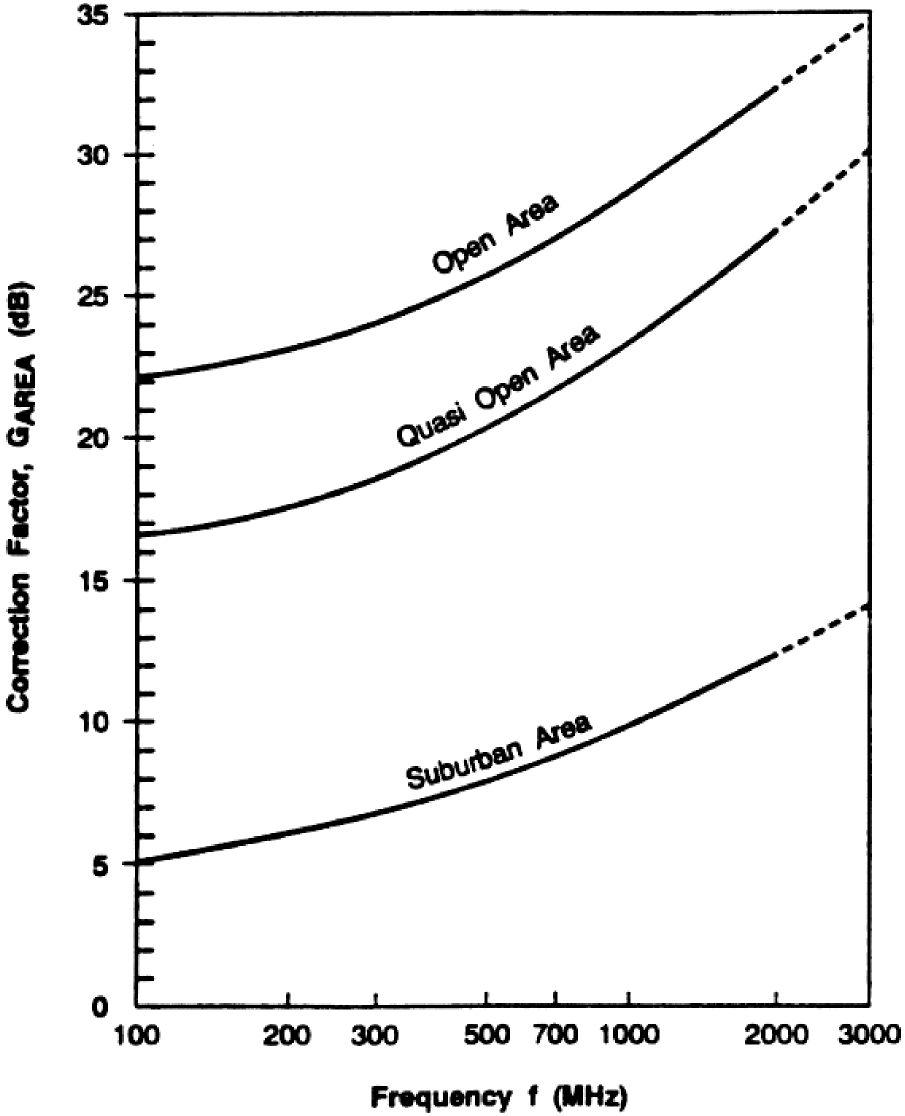

Figure 4.24 Correction factor, G_{AREA}, for different types of terrain [from [Oku68] © IEEE].

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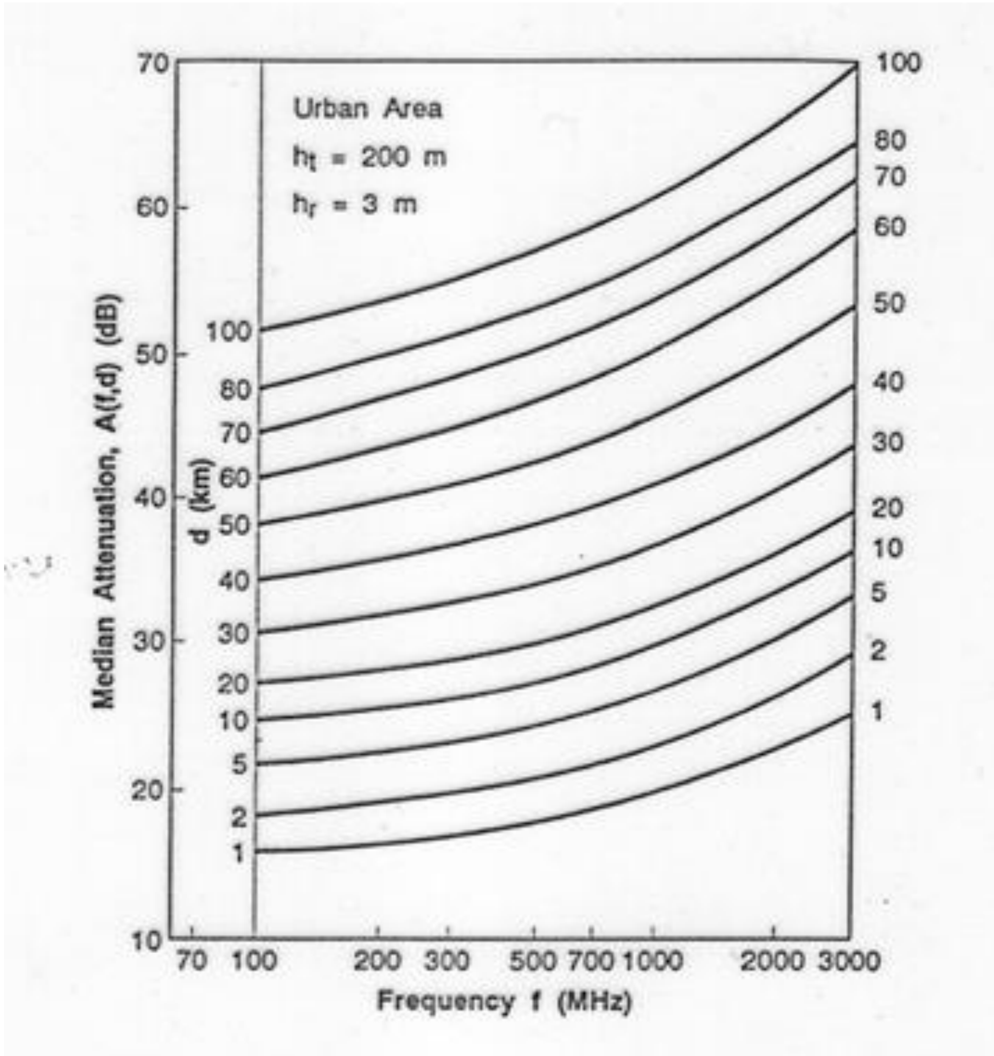
Okumura model



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Hata Model

- d: distance in Km
- h: antenna height in meters
- f: Frequency in MHz

- The Hata model is an empirical formulation of the graphical path loss data provided by Okumura, and is valid from 150Mhz to 1500 Mhz.
- The following calssifications were used by Hata
- Urban Area → $L_{dB} = A + B\log d - E$
- Suburban Area → $L_{dB} = A + B\log d - C$
- Open Area → $L_{dB} = A + B\log d - D$

$$A = 69.55 + 26.16\log f - 13.82 h_b$$

$$B = 44.9 - 6.55\log h_b$$

$$C = 2(\log(f/28))^2 + 5.4$$

$$D = 4.78\log(f/28)^2 + 18.33\log f + 40.94$$

$$E = 3.2(\log(11.75 h_m))^2 - 4.97 \quad \text{for large cities, } f \geq 300MHz$$

$$E = 8.29(\log(1.54 h_m))^2 - 1.1 \quad \text{for large cities, } f < 300MHz$$

$$E = (1.11\log f - 0.7)h_m - (1.56\log f - 0.8) \quad \text{for medium to small cities}$$

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PCS Extension of Hata Model

- COST-231 Hata Model, European standard
- Higher frequencies: up to 2GHz
- Smaller cell sizes
- Lower antenna heights

$$L_{dB} = F + B\log d - E + G$$

$$F = 46.3 + 33.9\log f \; - 13.82\log h_b$$ f >1500MHz

$G = 3$ Metropolitan centers

$G = 0$ Medium sized city and suburban areas

f : 1500 MHz to 2000 MHz
h_{te} : 30 m to 200 m
h_{re} : 1 m to 10 m
d : 1 km to 20 km

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Measured data from San Francisco

Transmitter Antenna Height	1900 MHz LOS			1900 MHz OBS	
	n_1	n_2	σ(dB)	n	σ(dB)
Low (3.7 m)	2.18	3.29	8.76	2.58	9.31
Medium (8.5 m)	2.17	3.36	7.88	2.56	7.67
High (13.3 m)	2.07	4.16	8.77	2.69	7.94

Figure 4.26 Parameters for the wideband microcell model at 1900 MHz [from [Feu94] © IEEE].

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Partition losses

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]
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 I-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]

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

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]
Commercial absorber	38	9.6 GHz	[Vio88]
Commercial absorber	51	28.8 GHz	[Vio88]
Commercial absorber	59	57.6 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	2	9.6 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	2	28.8 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	5	57.6 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	1	9.6 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	4	28.8 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	8	57.6 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	4	9.6 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	6	28.8 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	14	57.6 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	19	9.6 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	32	28.8 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	59	57.6 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	39	9.6 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	46	28.8 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	57	57.6 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	47	9.6 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	46	28.8 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	53	57.6 GHz	[Vio88]

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Partition losses

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

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Partition losses

Table 4.5 Average Floor Attenuation Factor in dB for One, Two, Three, and Four Floors in Two Office Buildings [Sei92b]

Building	FAF (dB)	σ (dB)	Number of locations
Office Building 1:			
Through One Floor	12.9	7.0	52
Through Two Floors	18.7	2.8	9
Through Three Floors	24.4	1.7	9
Through Four Floors	27.0	1.5	9
Office Building 2:			
Through One Floor	16.2	2.9	21
Through Two Floors	27.5	5.4	21
Through Three Floors	31.6	7.2	21

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Partition losses

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

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Ericsson's indoor model

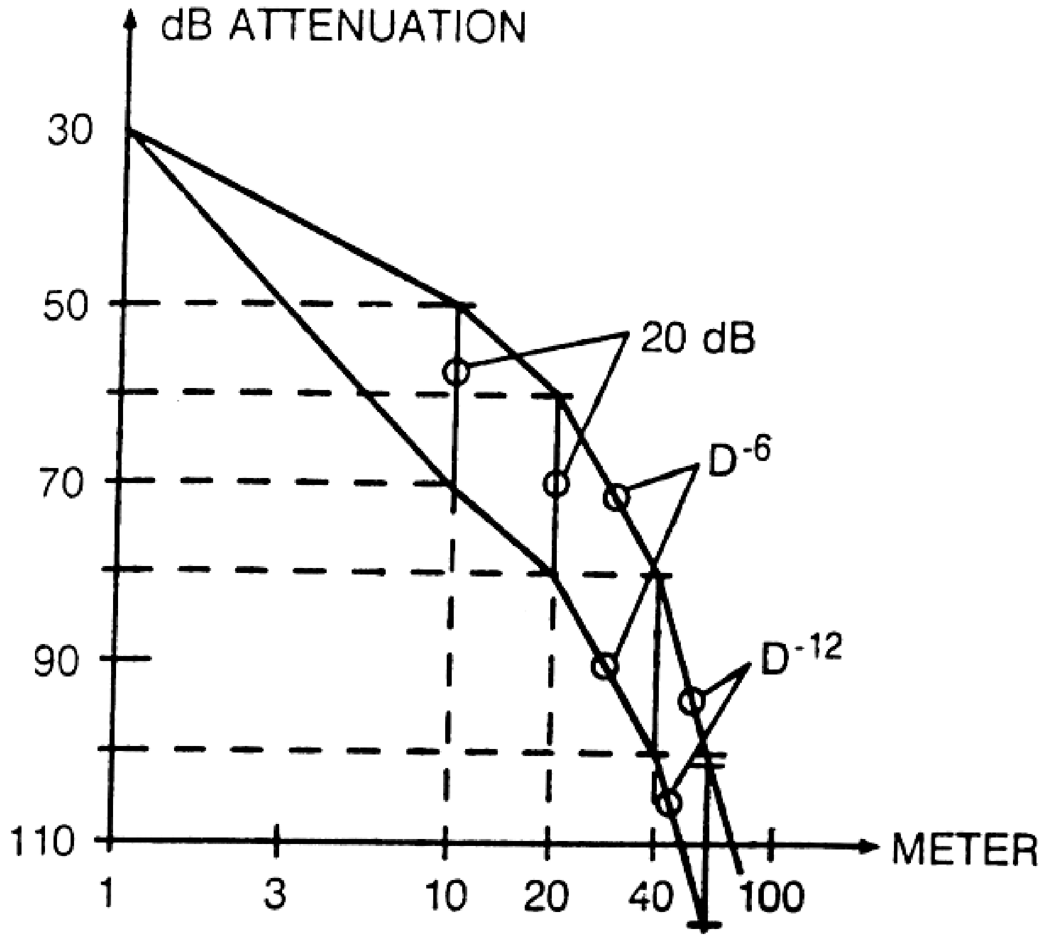

Figure 4.27 Ericsson in-building path loss model [from [Ake88] © IEEE].

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Measured indoor path loss

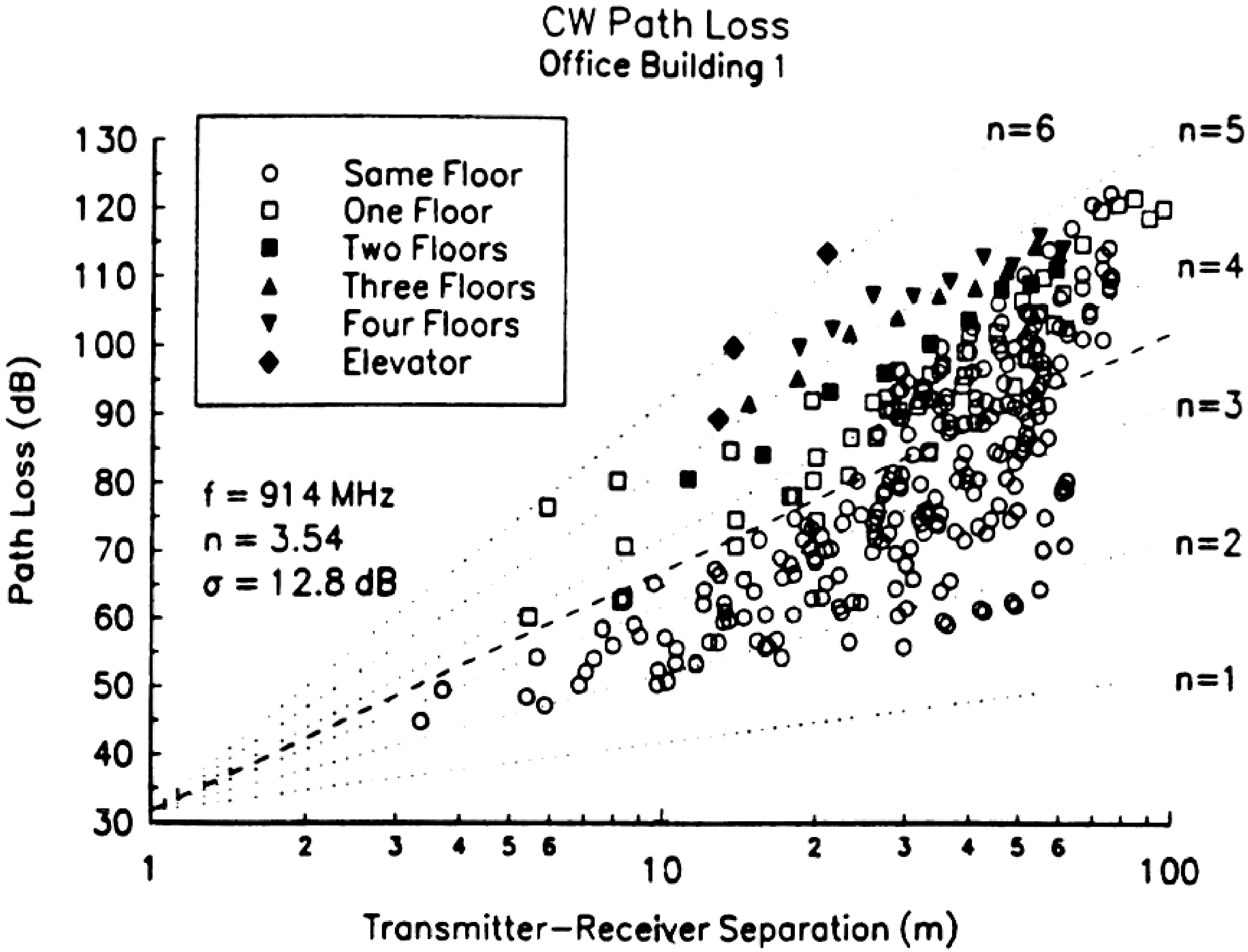

Figure 4.28 Scatter plot of path loss as a function of distance in Office Building 1 [from [Sei92b] © IEEE].

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Measured indoor path loss

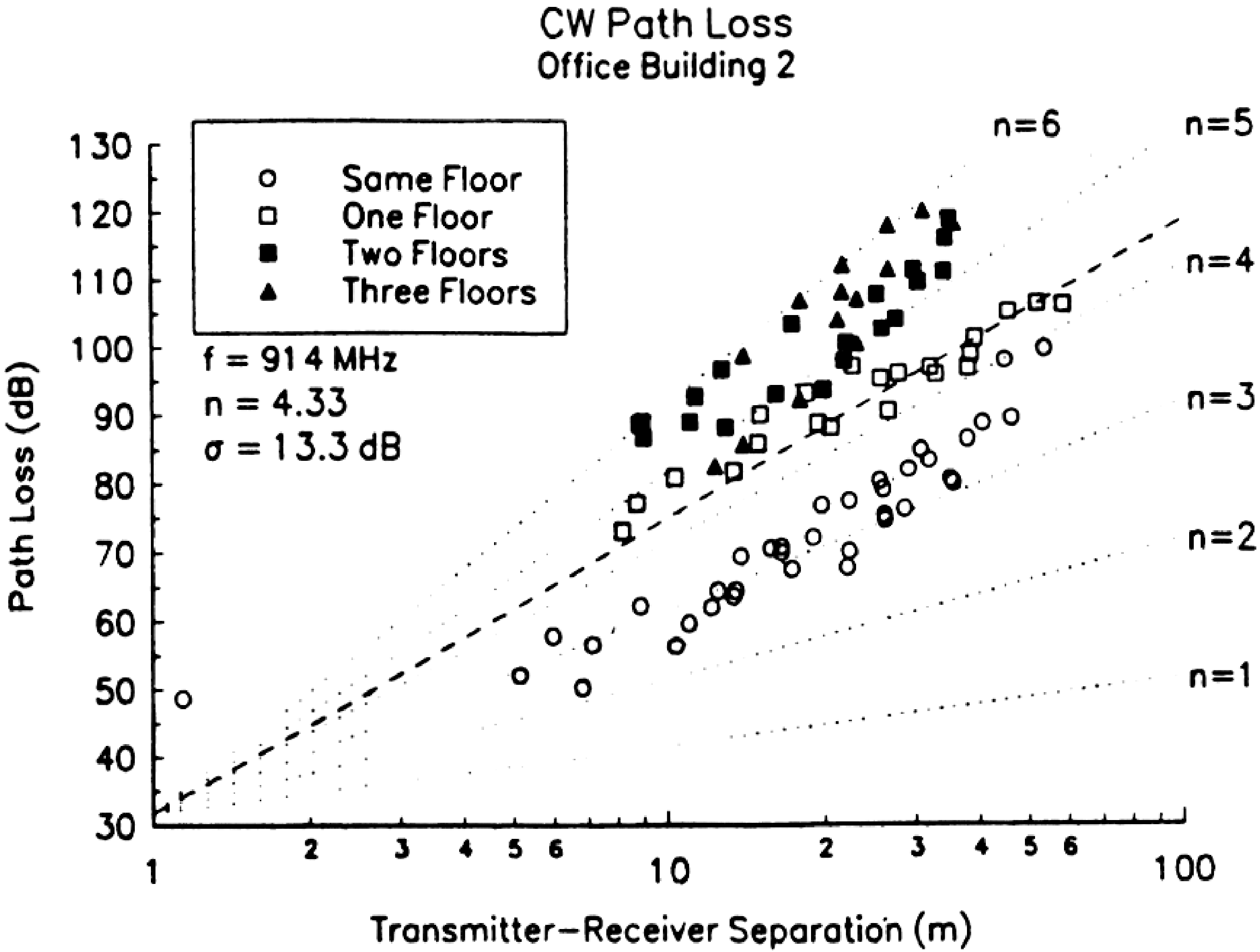

Figure 4.29 Scatter plot of path loss as a function of distance in Office Building 2 [from [Sei92b] © IEEE].

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Measured indoor path loss

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

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Devasirvatham's model

Table 4.8 Free Space Plus Linear Path Attenuation Model [Dev90b]

Location	Frequency	α–Attenuation (dB/m)
Building 1: 4 story	850 MHz	0.62
	1.7 GHz	0.57
	4.0 GHz	0.47
Building 2: 2 story	850 MHz	0.48
	1.7 GHz	0.35
	4.0 GHz	0.23

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