MIMO-OFDM Wireless Communications with MATLAB®

Chapter 1. The Wireless Channel : Propagation and Fading

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WILEY

Chapter 1. Kablosuz Kanal
: Yayılım ve Sönümlenme

- Reflection: Yansıma (binalar, yer vs.)
- Diffraction Kırınım (yüzeylerde keskin düzensizlikler varsa) küçük açıklıklar.
- Scattering Saçılım (trafik işaretleri, lambalar, vs.)
- Fading Sönümlenme → Çok yollu (multipath) → Gölgelme (shadowing)
- Multipath fading
- Shadowing

HF 3-30MHz   UHF 300~3000GHz   SHF 3~30GHz

4G UMTS GSM
↑ ↑ ↑ ↑
LTE, 5G, 3G, 2G
↓ MHz
800 ~ 2.5 GHz

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Chapter 1. Kablosuz Kanal
: Yayılım ve Sönümlenme

- 1.1 LARGE-SCALE FADING
  - 1.1.1 General Path Loss Model
  - 1.1.2 Okumura/Hata Model
  - 1.1.3 IEEE 802.16d Model
- 1.2 SMALL-SCALE FADING
  - 1.2.1 Parameters for Small-Scale Fading
  - 1.2.2 Time-Dispersive vs. Frequency-Dispersive Fading
  - 1.2.3 Statistical Characterization and Generation of Fading Channel

Chapter 1. Kablosuz Kanal

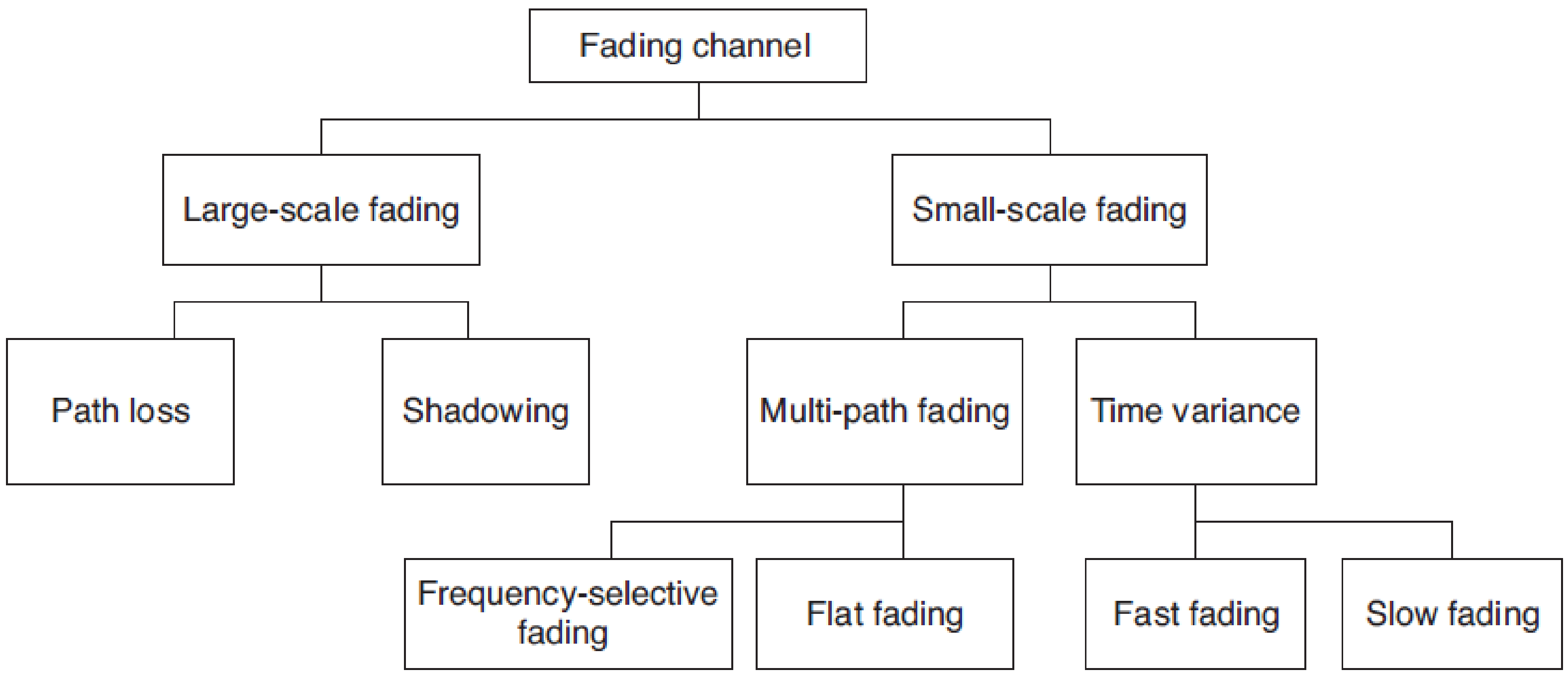

Figure 1.1 Sönümlü Kanalların Sınıflandırması

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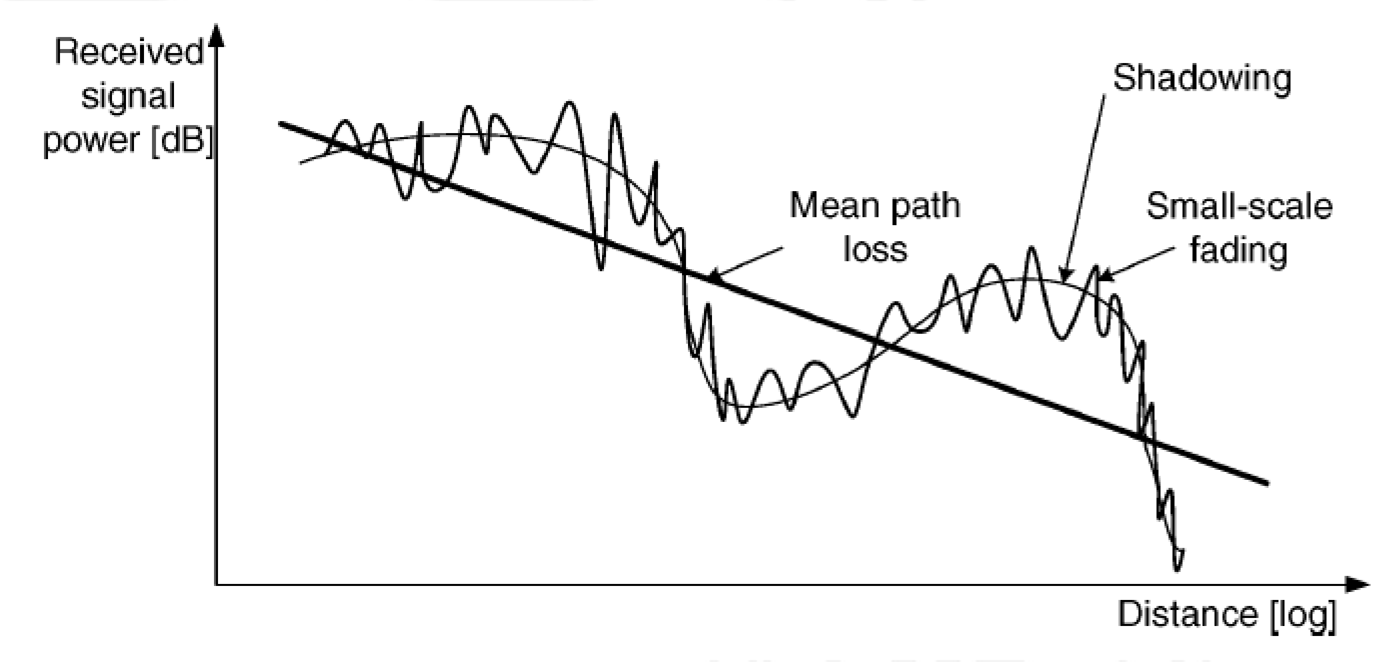

Figure 1.2 Large-scale fading vs. small-scale fading

Chapter 1. Kablosuz Kanal

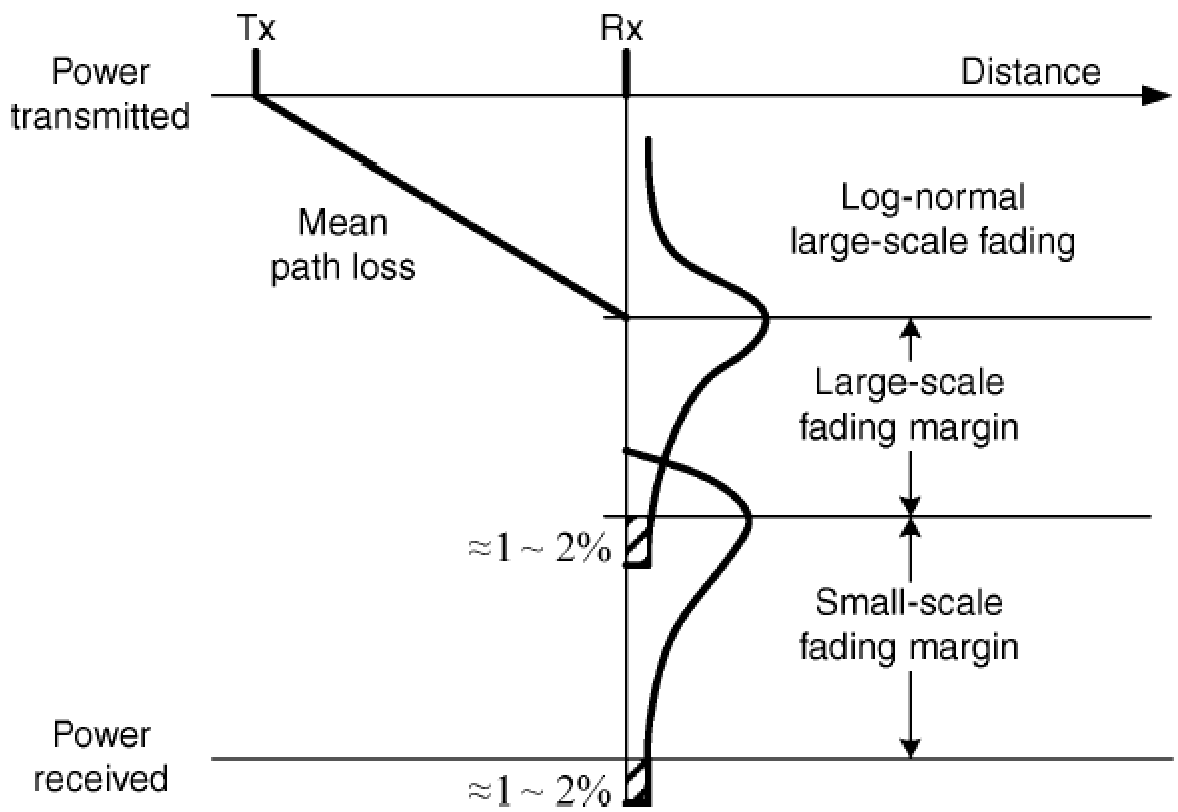

Figure 1.3 Link budget for the fading channel(1994 IEEE. Reproduced from Greenwood, D. and Hanzo, L., “Characterization of mobile radio channels,” in Mobile Radio Communications, R. Steele(ed.), pp. 91–185,1994, with permission from Institute of Electrical and Electronics Engineers (IEEE).)

1.1 Büyük Çağlı Sönümlenme
1.1.1 Genel Yol Kaybı Modeli

- $$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \quad (1.1)$$

$$PL_F(d)[dB] = 10\log\left(\frac{P_t}{P_r}\right) = -10\log\left(\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right) \quad (1.2)$$

$$PL_F(d)[dB] = 10\log\left(\frac{P_t}{P_r}\right) = -10\log\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right) \quad (1.3)$$

1.1.1 Genel Yol Kaybı Modeli

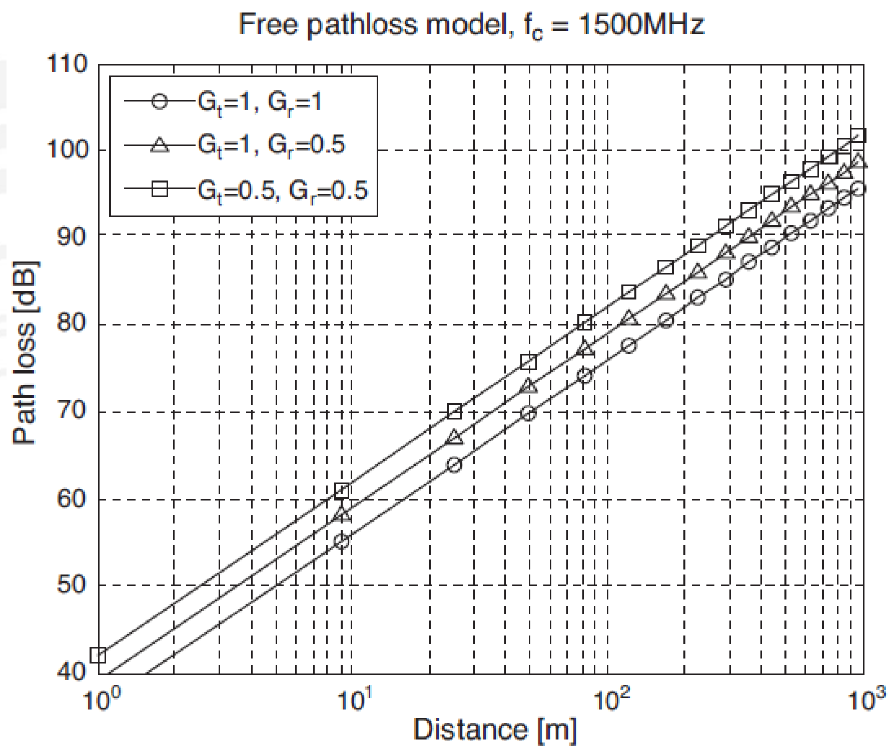

Figure 1.4 Free-space path loss model

$$PL_{LD}(d)[dB] = PL_F(d_0) + 10n\log\left(\frac{d}{d_0}\right) \quad (1.4)$$

1.1.1 Genel Yol Kaybı Modeli

Environment	Path Loss Exponent ( )
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

Table 1.1 Path loss exponent [2].

1.1.1 Genel Yol Kaybı Modeli

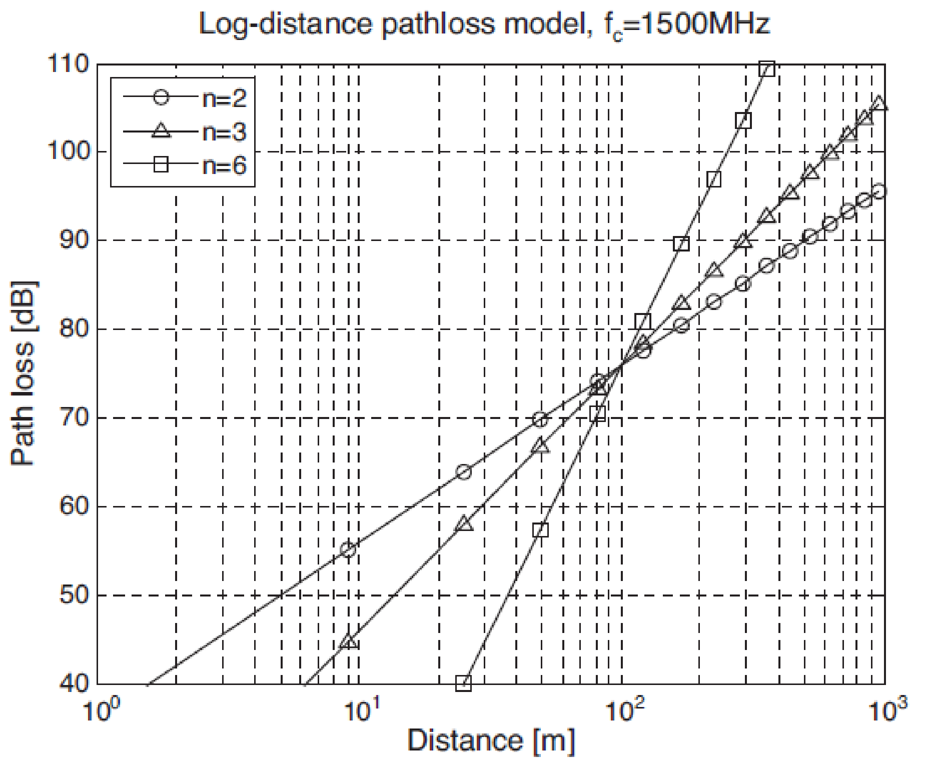

Figure 1.5 Log-distance pathloss model

$$PL(d)[dB] = \overline{PL}(d) + X_\sigma = \overline{PL}_F(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \quad (1.5)$$

1.1.1 Genel Yol Kaybı Modeli

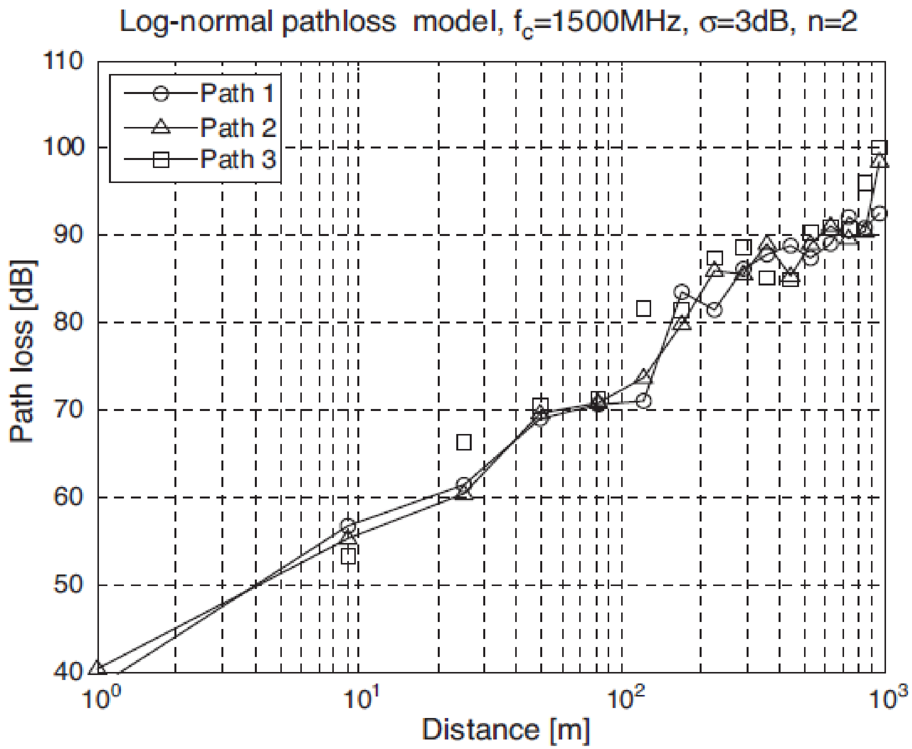

Figure 1.6 Log-normal shadowing path loss model

1.1.2 Okumura/Hata Modeli

$$PL_{Ok}(d)[dB] = PL_F + A_{MU}(f,d) - G_{Rx} - G_{Tx} + G_{AREA} \qquad (1.6)$$

$$PL_{Hata,U}(d)[dB] = 69.55 + 26.16\log f_c - 13.82\log h_{Tx} - C_{Rx} + \left(44.9 - 6.55\log h_{Tx}\right)\log d \qquad (1.7)$$

$$C_{Rx} = 0.8 + \left(1.1\log f_c - 0.7\right)h_{Rx} - 1.56\log f_c \qquad (1.8)$$

1.1.2 Okumura/Hata Modeli

$$C_{Rx} = \begin{cases} 8.29\left(\log\left(1.54h_{Rx}\right)\right)^2 - 1.1 & if\ 150MHz \le f_c \le 200MHz \\ 3.2\left(\log\left(11.75h_{Rx}\right)\right)^2 - 4.97 & if\ 200MHz \le f_c \le 1500MHz \end{cases} \qquad (1.9)$$

$$PL_{Hata,SU}(d)[dB] = PL_{Hata,U}(d) - 2\left(\log\frac{f_c}{28}\right)^2 - 5.4 \qquad (1.10)$$

$$PL_{Hata,O}(d)[dB] = PL_{Hata,U}(d) - 4.78\left(\log f_c\right)^2 + 18.33\log f_c - 40.97 \qquad (1.11)$$

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1.1.2 Okumura/Hata Modeli

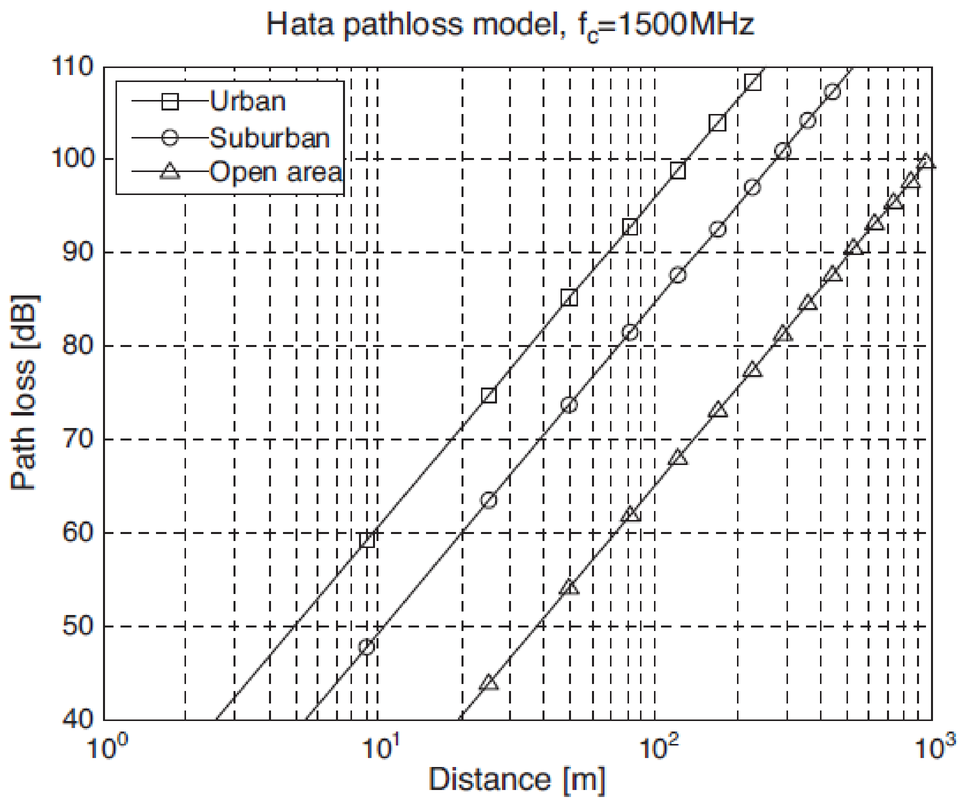

Figure 1.7 Hata path loss model

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1.1.3 IEEE 802.16d

$$PL_{802.16}(d)[dB] = PL_F\left(d_0\right) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + C_f + C_{Rx} \quad \text{for } d > d_0 \tag{1.12}$$

$$C_f = 6\log_{10}(f_c / 2000) \tag{1.13}$$

$$C_{Rx} = \begin{cases} -10.8\log_{10}(h_{Rx} / 2) & \text{for Type A and B} \\ -20\log_{10}(h_{Rx} / 2) & \text{for Type C} \end{cases} \tag{1.14}$$

$$C_{Rx} = \begin{cases} -10\log_{10}(h_{Rx} / 3) & \text{for } h_{Rx} \le 3m \\ -20\log_{10}(h_{Rx} / 3) & \text{for } h_{Rx} > 3m \end{cases} \tag{1.15}$$

1.1.3 IEEE 802.16d

Parameter	Type A	Type B	Type C
a	4.6	4	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20

Table 1.2 Types of IEEE 802.16d path loss models.

1.1.3 IEEE 802.16d

Parameter	Type A	Type B	Type C
a	4.6	4	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20

Table 1.3 Parameters for IEEE 802.16d type A, B, and C models.

1.1.3 IEEE 802.16d

$$20\log_{10}\left(\frac{4\pi d_0^{'}}{\lambda}\right) = 20\log_{10}\left(\frac{4\pi d_0^{'}}{\lambda}\right) + 10\gamma\log_{10}\left(\frac{d_0^{'}}{d_0}\right) + C_f + C_{Rx} \tag{1.16}$$

$$d_0^{'} = d_0 10^{-\left(\frac{C_f + C_{Rx}}{10\gamma}\right)} \tag{1.17}$$

$$PL_{M802.16}(d)[dB] = \begin{cases} 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) & \text{for } d \le d_0^{'} \\ 20\log_{10}\left(\frac{4\pi d_0^{'}}{\lambda}\right) + 10\gamma\log_{10}\left(\frac{d}{d_0}\right) + C_f + C_{Rx} & \text{for } d > d_0^{'} \end{cases} \tag{1.18}$$

1.1.3 IEEE 802.16d

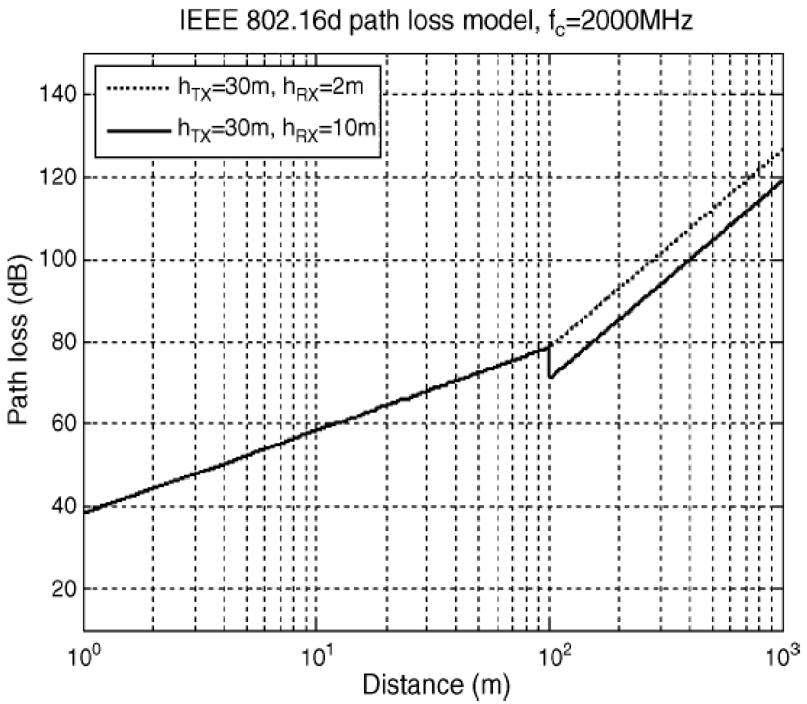


Figure 1.8 IEEE 802.16d path loss model

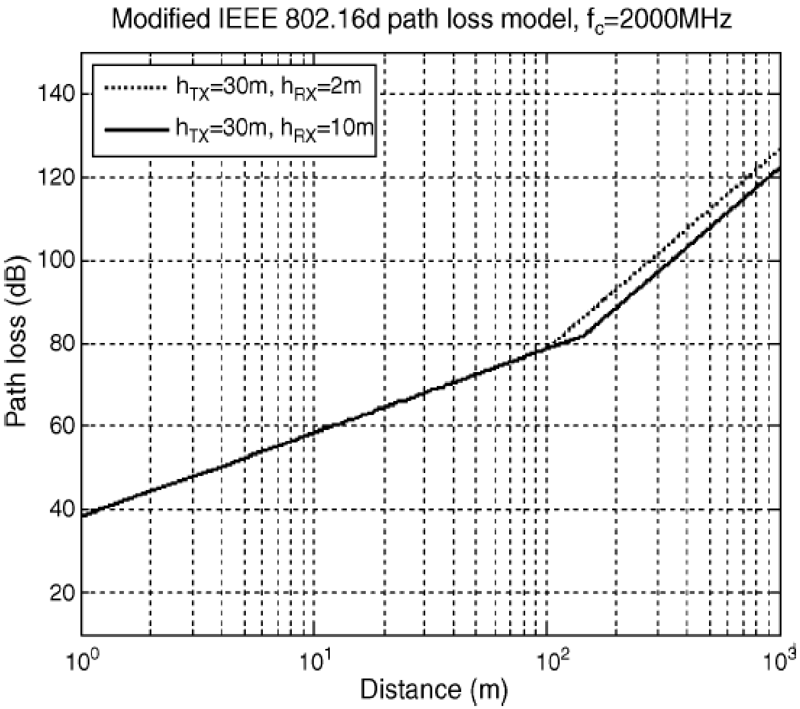


Figure 1.9 Modified IEEE 802.16d path loss model

1.2 Küçük Çaplı Sönümlenme
1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme

- Power Delay Profile
- Tap
- Relative Delay
- Relative average power
- Mean excess delay
- RMS Delay Spread

(a) Frequency-non-selective fading channel

(b) Frequency-selective fading channel

1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme

Tap	Relative delay (ns)	Average Power (dB)
1	0	0.0
2	110	-9.7
3	190	-19.2
4	410	-22.8

Table 1.4 Power delay profile: example (ITU-R Pedestrian A Model).

1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme

- Düz sönümlenme

$$B_S << B_C \quad T_S >> \sigma_\tau \qquad (1.19)$$

- Frekans seçici sönümlenme

$$B_S > B_C \quad T_S > \sigma_\tau \qquad (1.20)$$

- $$\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)}$$ Mean excess delay (1.21)

- $$\sigma_\tau = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}$$ RMS Delay Spread (1.22)

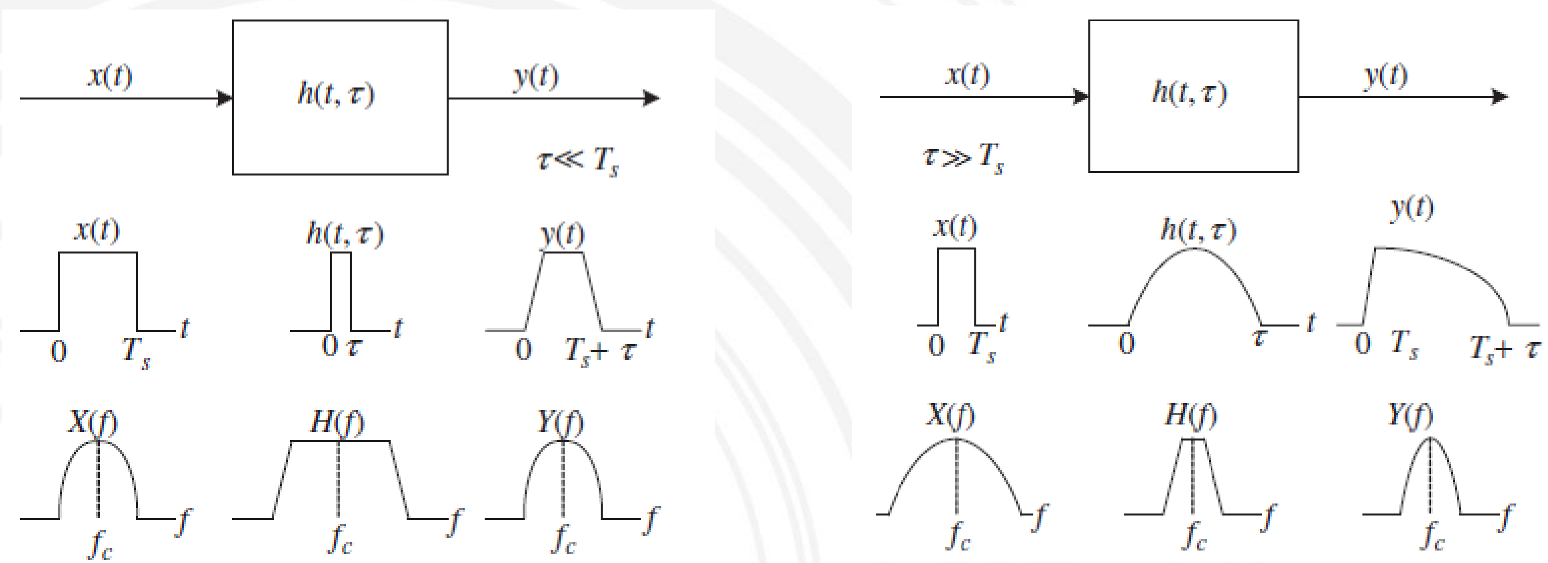
$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} \qquad (1.23)$$

1.2.1 Time-Dispersive vs. Frequency-Dispersive Fading

- $B_C \approx \frac{1}{\sigma_\tau}$ Tutarlılık Bandı (1.24)
- $B_C \approx \frac{1}{50\sigma_\tau}$ 0.9 ilintili tutarlılık bandı (1.25)
- $B_C \approx \frac{1}{5\sigma_\tau}$ 0.5 ilintili tutarlılık bandı (1.26)
- Hızlı sönümlenme $T_S > T_C$, $B_S > B_D$ (1.27)
- Yavaş sönümlenme $T_S << T_C$, $B_S >> B_D$ (1.28)

1.2 Küçük Çaplı Sönümlenme

1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme



(a) Frequency-non-selective fading channel

(b) Frequency-selective fading channel

Figure 1.10 Characteristics of fading due to time dispersion over multi-path channel

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1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme

- Tutarlılık zamanı $T_C \approx \frac{1}{f_m}$ $\quad B_D = 2 f_m$ (1.29)

- Tutarlılık zamanı $T_C \approx \frac{9}{16\pi f_m}$ (1.30)

- Tutarlılık zamanı $T_C = \sqrt{\frac{9}{16\pi f_m}} = \frac{0.423}{f_m}$ (1.31)

1.2.3 Statistical Characterization and Generation of Fading Channel

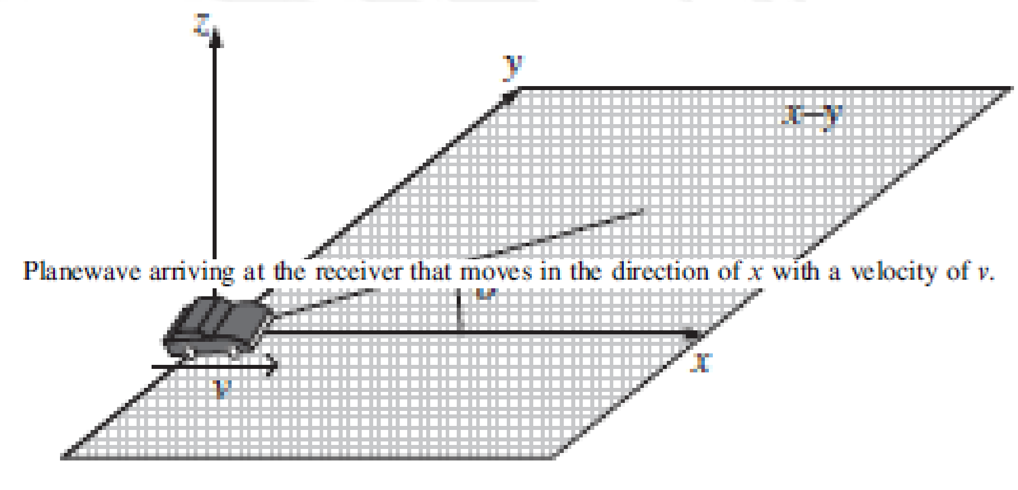

Figure 1.11 Planewave arriving at receiver moves in the direction of x with a velocity of v

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

- Alıcıdaki sinyal

$$y(t) = \sum_{i=1}^{I} C_i e^{-j\phi_i(t)} x(t - \tau_i) \qquad \phi_i(t) = 2\pi\left\{\left(f_c + f_i\right)\tau_i - f_i\right\} \tag{1.35}$$

- Kanal modeli

$$h(t,\tau) = \sum_{i=1}^{I} C_i e^{-j\phi_i(t)} \delta(t - \tau_i) \tag{1.36}$$

- Yol gecikmesi sembol zamanından kısaysa

$$h(t,\tau) = \sum_{i=1}^{I} C_i e^{-j\phi_i(t)} \delta(t - \hat{\tau}) = h(t)\delta(t - \hat{\tau}) \tag{1.37}$$

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

$$\tilde{y}(t) = h_I(t)\cos 2\pi f_c t - h_Q(t)\sin 2\pi f_c t \tag{1.38}$$

$$h_I(t) = \sum_{i=1}^{I} C_i \cos\phi_i(t) \tag{1.39}$$

$$h_Q(t) = \sum_{i=1}^{I} C_i \sin\phi_i(t) \tag{1.40}$$

- Rayleigh dağılımlı olarak modellenebilir

$$\begin{aligned}\gamma_{\tilde{y}\tilde{y}}(\tau) &= E\left[\tilde{y}(t)\tilde{y}(t+\tau)\right] \\ &= E\left[h_I(t)h_I(t+\tau)\right]\cos 2\pi f \tau - E\left[h_Q(t)h_I(t+\tau)\right]\sin 2\pi f \tau \\ &= \gamma_{h_I h_I}(\tau)\cos 2\pi f_c \tau - \gamma_{h_I h_Q}(\tau)\sin 2\pi f_c \tau\end{aligned} \tag{1.41}$$

1.2.3 Statistical Characterization and Generation of Fading Channel

$$\gamma_{h_I h_I}(\tau) = E_{\boldsymbol{\tau},\boldsymbol{\theta}}\left[h_I(t)h_I(t+\tau)\right] = \frac{\Omega_p}{2} E_{\theta_i}\left[\cos 2\pi f_i \tau\right]$$
$$= \frac{\Omega_p}{2} E_\theta\left[\cos\left(2\pi f_m \tau \cos\alpha\right)\right] \qquad (1.42)$$

$$\gamma_{h_I h_Q}(\tau) = E_{\boldsymbol{\tau},\boldsymbol{\theta}}\left[h_I(t)h_Q(t+\tau)\right] = \frac{\Omega_p}{2} E_\theta\left[\sin\left(2\pi f_m \tau \cos\theta\right)\right] \qquad (1.43)$$

$$\boldsymbol{\tau} = \left[\tau_1, \tau_2, \cdots, \tau_I\right]$$
$$\boldsymbol{\theta} = \left[\theta_1, \theta_2, \cdots, \theta_I\right] \qquad (1.44)$$
$$\Omega_p = E\left[h_I^2(t)\right] + E\left[h_Q^2(t)\right] = \sum_{i=1}^{I} C_i^2$$

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

$$\gamma_{h_I h_I}(\tau) = \frac{\Omega_p}{2}\int_{-\pi}^{\pi} \cos\left(2\pi f_m \tau \cos\theta\right) p(\theta) G(\theta)\, d\theta$$
$$= \frac{\Omega_p}{2}\frac{1}{2\pi}\int_{-\pi}^{\pi} \cos\left(2\pi f_m \tau \cos\theta\right) d\theta = \frac{\Omega_p}{2} J_0\left(2\pi f_m \tau\right) \tag{1.45}$$

$$\gamma_{h_I h_Q}(\tau) = \frac{\Omega_p}{2}\frac{1}{2\pi}\int_{-\pi}^{\pi} \sin\left(2\pi f_m \tau \cos\theta\right) d\theta = 0 \tag{1.46}$$

$$\gamma_{\tilde{y}\tilde{y}}(\tau) = \gamma_{h_I h_I}(\tau)\cos 2\pi f_c \tau - \gamma_{h_I h_Q} \sin 2\pi f_c \tau$$
$$= \frac{\Omega_p}{2} J_0\left(2\pi f_m \tau\right) \cos 2\pi f_c \tau \tag{1.47}$$

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

- Klasik Doppler skeptrumu

$$S_{h_I h_I}(f) = S_{h_Q h_Q}(f) = F\left[\gamma_{h_I h_I}(t)\right] = \begin{cases} \dfrac{\Omega_p}{2\pi f_m} \dfrac{1}{\sqrt{1/\left(f/f_m\right)^2}} & |f| \le f_m \\ 0 & \text{otherwise} \end{cases} \quad (1.48)$$

$$\gamma_{hh}(\tau) = \frac{1}{2} E\left[h^*(t)h(t+\tau)\right] = \gamma_{h_I h_I}(\tau) + j\gamma_{h_I h_Q}(\tau) \quad (1.49)$$

$$S_{hh}(f) = S_{h_I h_I}(f) + jS_{h_I h_Q}(f) \quad (1.50)$$

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

$$\gamma_{\tilde{y}\tilde{y}}(\tau) = \mathrm{Re}\left[\gamma_{hh}(\tau)e^{j2\pi f_c \tau}\right] \tag{1.51}$$

$$\mathrm{Re}[a] = \frac{a + a^*}{2} \tag{1.52}$$

$$\gamma_{hh}(\tau) = \gamma_{hh}^*(-\tau) \tag{1.53}$$

$$S_{\tilde{y}\tilde{y}}(f) = \frac{1}{2}\left[S_{hh}(f - f_c) + S_{hh}(-f + f_c)\right] = \begin{cases} \dfrac{\Omega_p}{4\pi f_m} \dfrac{1}{\sqrt{1 - \left(\dfrac{f - f_c}{f_m}\right)^2}} & |f - f_c| \le f_m \\ 0 & \text{otherwise} \end{cases} \tag{1.54}$$

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

$$S_{\tilde{y}\tilde{y}}(f)\left|df\right| = \frac{\Omega_p}{4\pi}\left\{G(\theta)p(\theta)+G(-\theta)p(-\theta)\right\}\left|d\theta\right| \quad (1.55)$$

$$\left|df\right| = f_m\left|-\sin\theta d\theta\right| = \sqrt{f_m^2-\left(f-f_c\right)^2}\left|d\theta\right| \quad (1.56)$$

$$S_{\tilde{y}\tilde{y}}(f) = \frac{\Omega_p/4}{\sqrt{f_m^2-\left(f-f_c\right)^2}}\left\{G(\theta)p(\theta)+G(-\theta)p(-\theta)\right\} \quad (1.57)$$

1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

- Rice sönümlenmesi

$$p(\theta)=\frac{1}{K+1}\tilde{p}(\theta)+\frac{K}{K+1}\delta(\theta-\theta_0) \quad (1.58)$$

$$K=\frac{c^2}{2\sigma^2} \quad (1.59)$$

$$\gamma_{h_I h_I}(\tau)=\frac{1}{K+1}\frac{\Omega_p}{2}J_0(2\pi f_m\tau)+\frac{K}{K+1}\frac{\Omega_p}{2}\cos(2\pi f_m\tau\cos\theta) \quad (1.60)$$

1.2.3 Statistical Characterization and Generation of Fading Channel

$$\gamma_{h_I h_Q}(\tau) = \frac{K}{K+1}\frac{\Omega_p}{2}\sin\left(2\pi f_m \tau \cos\theta\right) \tag{1.61}$$

$$S_{hh}(f) = \frac{1}{K+1}S_{hh}^{c}(f) + \frac{K}{K+1}S_{hh}^{d}(f)$$
$$= \begin{cases} \frac{1}{K+1}\frac{\Omega_p}{2\pi f_m}\frac{1}{\sqrt{1-\left(f/f_m\right)^2}} + \frac{K}{K+1}\frac{\Omega_p}{2}\delta\left(f - f_m\cos\theta_0\right) & |f| \le f_m \\ 0 & otherwise \end{cases} \tag{1.62}$$