# MIMO-OFDM Wireless Communications with MATLAB®

## Chapter 1. The Wireless Channel : Propagation and Fading

Yong Soo Cho | Jaekwon Kim
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# 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 ← LTE, UMTS ← 5G, 3G, GSM ← 2G

LTE: 800~2.5GHz

5G (çok geniş olacak) 3.5GHz 28GHz



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# Chapter 1. Kablosuz Kanal
# : Yayılım ve Sönümlenme

- 1.1 LARGE-SCALE FADING (mesafe ile alakalı, gölgeleme ile alakalı.
  - 1.1.1 General Path Loss Model → yol kaybı
  - 1.1.2 Okumura/Hata Model
  - 1.1.3 IEEE 802.16d Model
- 1.2 SMALL-SCALE FADING (multipath,
  - 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



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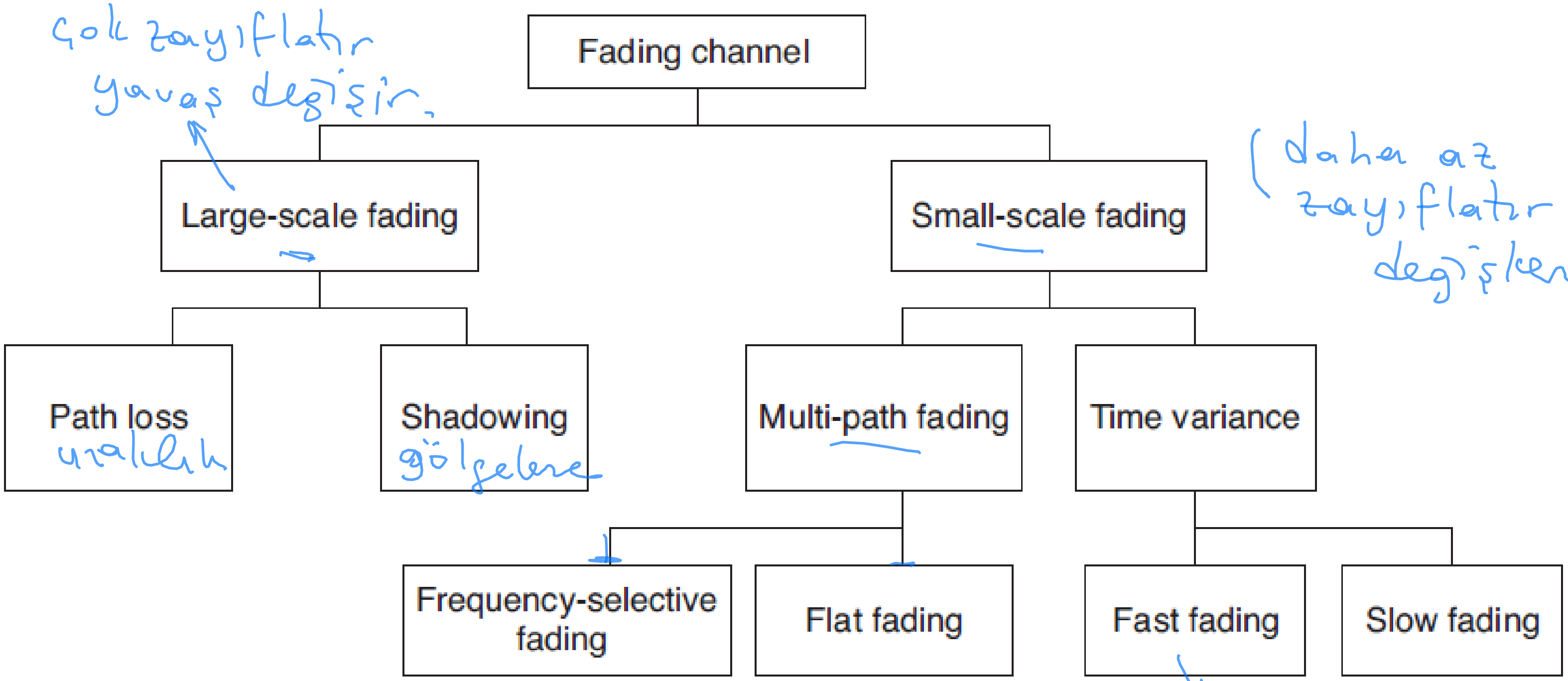


Figure 1.1 Sönümlü Kanalların Sınıflandırması



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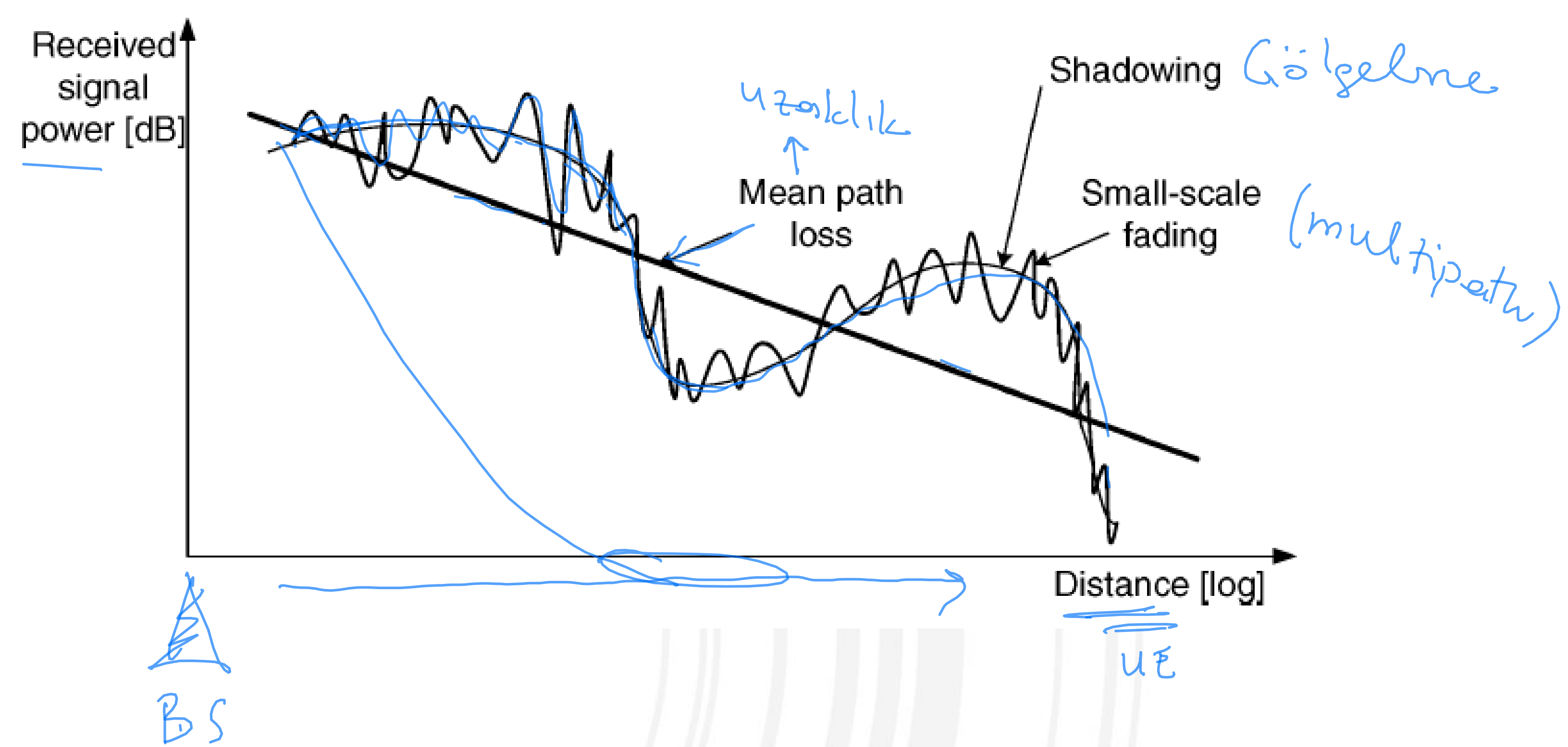


Figure 1.2 Large-scale fading vs. small-scale fading




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# Chapter 1. Kablosuz Kanal

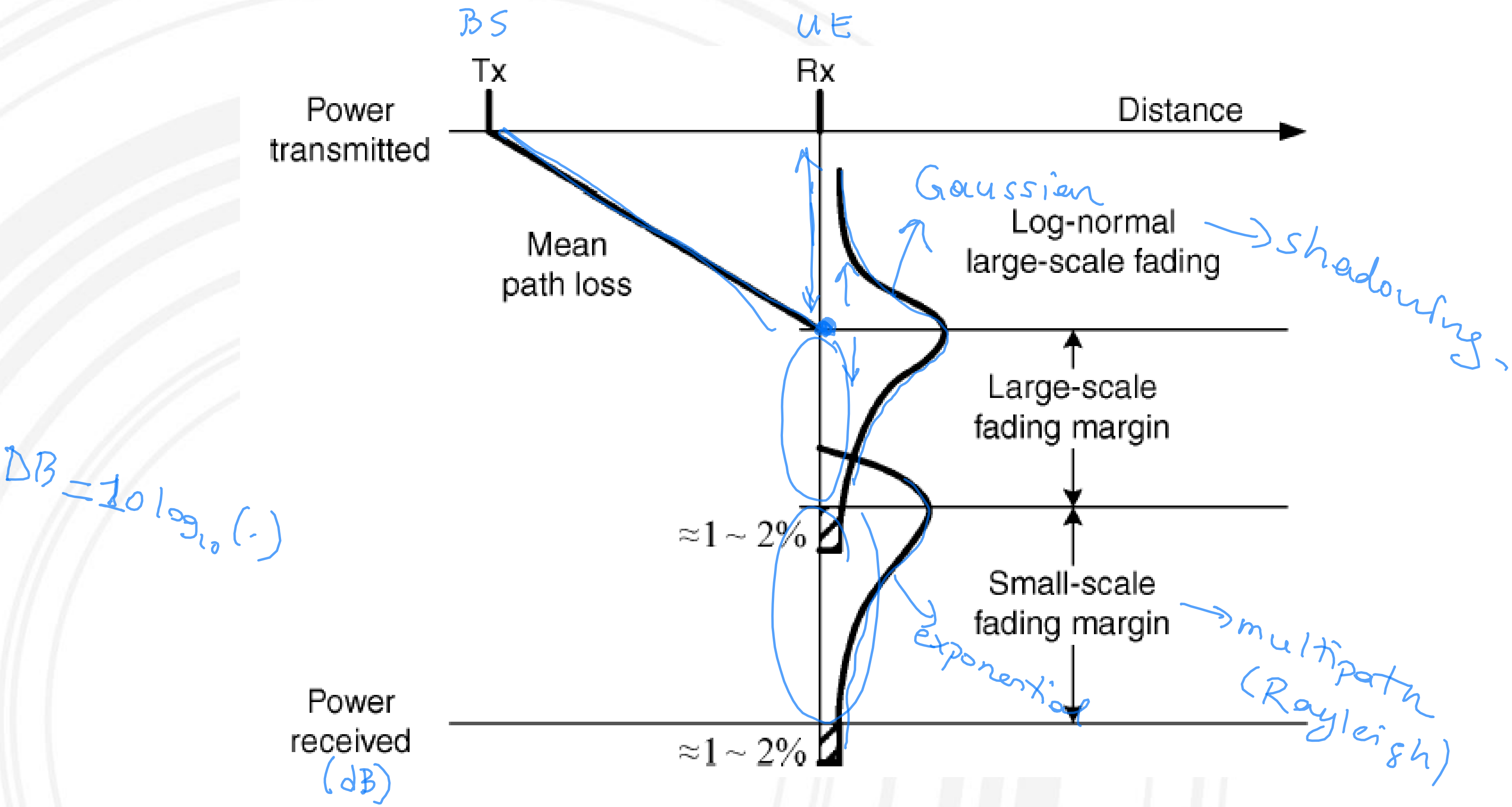


Figure 1.3 Link budget for the fading channel(1994 IEEE. Reproduced from Greenwood, D. and Hanzo, L., “Characterization of mobile radio channels,” in Mobile Radio Communications, R. Steele(ed.), pp. 91–185,1994, with permission from Institute of Electrical and Electronics Engineers (IEEE).)




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# 1.1 Büyük Çağlı Sönümlenme

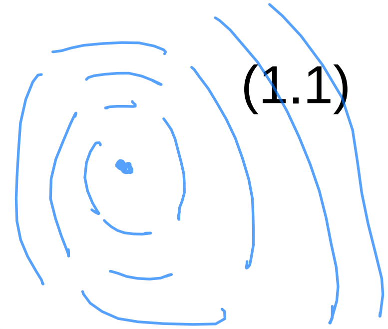
## 1.1.1 Genel Yol Kaybı Modeli

Friis denklemi (Path Loss)

$\lambda = \frac{c}{f} = \frac{3\times10^8}{24\times10^8} = \frac{1}{8}$ metre — WiFi 2.4 GHz = f

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

trans pow., tx ant gain, rx ant gain, dalga boyu, donanımdaki kayıplar, uzaklık, received power



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

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

anten kazancı olmadan

$PL_F = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$ → free space pathloss.



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# 1.1.1 Genel Yol Kaybı Modeli

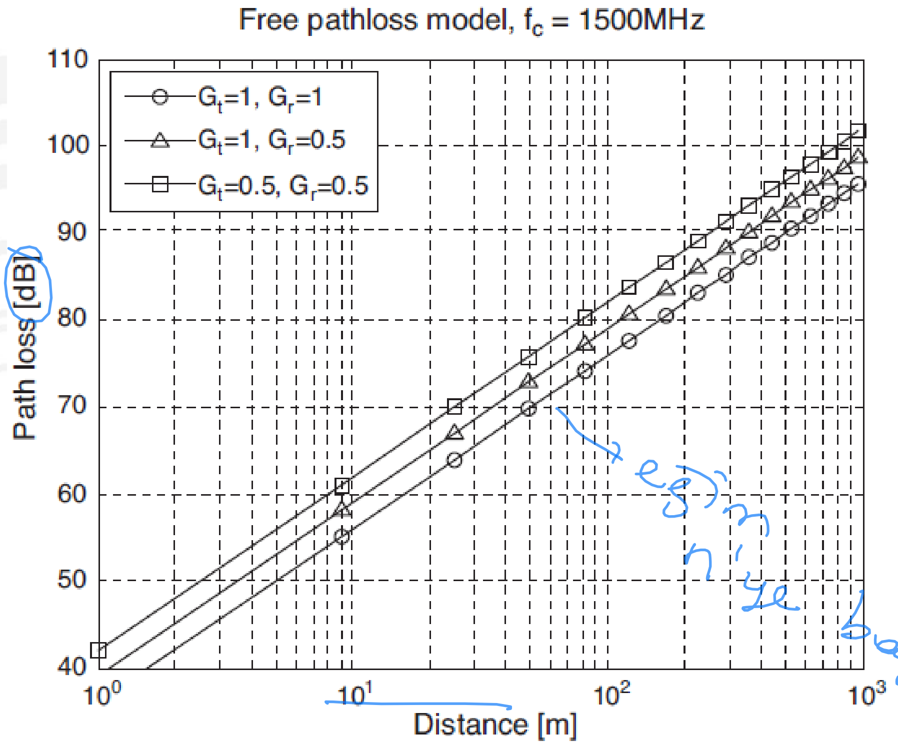


Figure 1.4 Free-space path loss model

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



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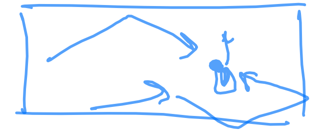
# 1.1.1 Genel Yol Kaybı Modeli



urban: şehir içi

| 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].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# 1.1.1 Genel Yol Kaybı Modeli

$X_\sigma$: shadowing (log-normal) distributed → dB değeri Gauss dağılımlı

$X_\sigma \sim N(0, \sigma)$

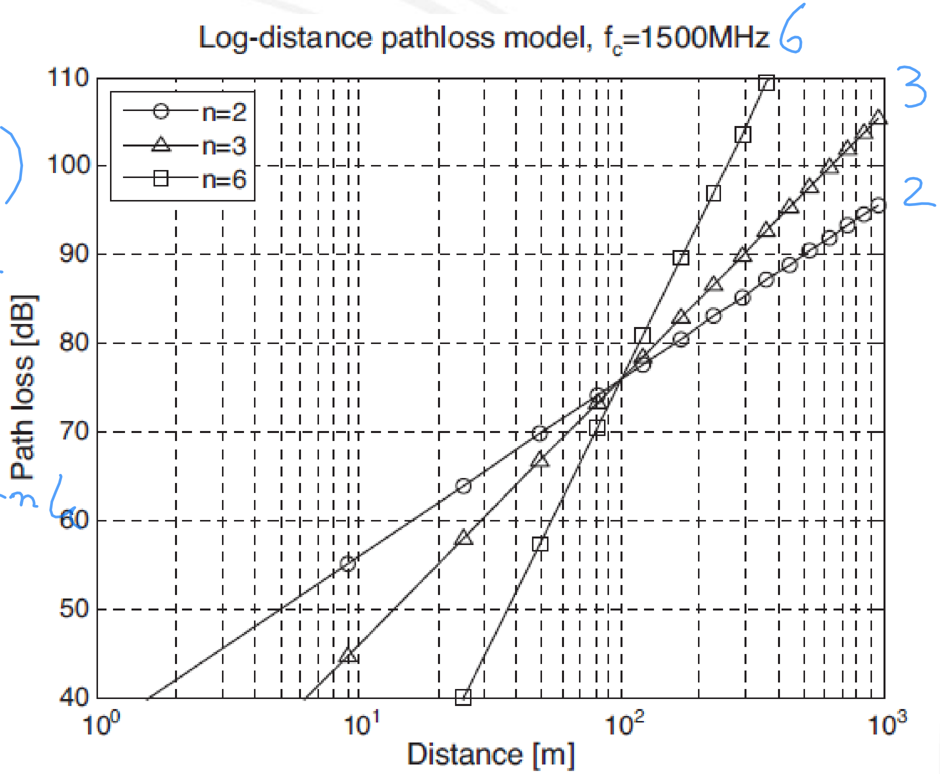


Figure 1.5 Log-distance pathloss model

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




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# 1.1.1 Genel Yol Kaybı Modeli

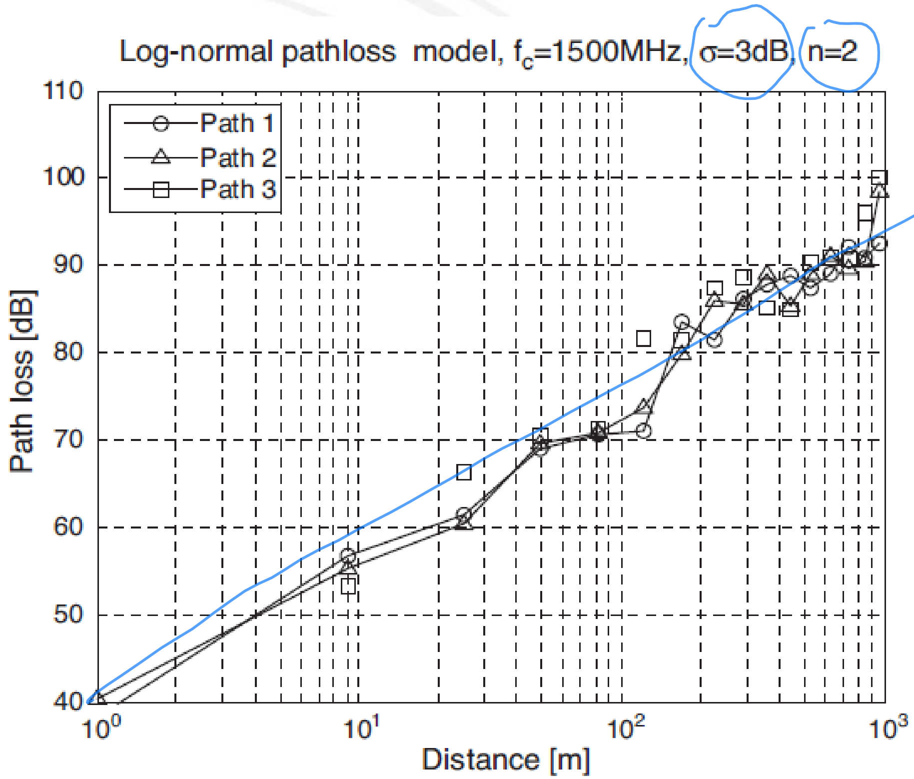


Figure 1.6 Log-normal shadowing path loss model



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# 1.1.2 Okumura/Hata Modeli

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

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

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



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# 1.1.2 Okumura/Hata Modeli

büyük kapsama

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

GSM, 3G

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

(daha az kayıp)

suburban

urban

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

open area




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# 1.1.2 Okumura/Hata Modeli

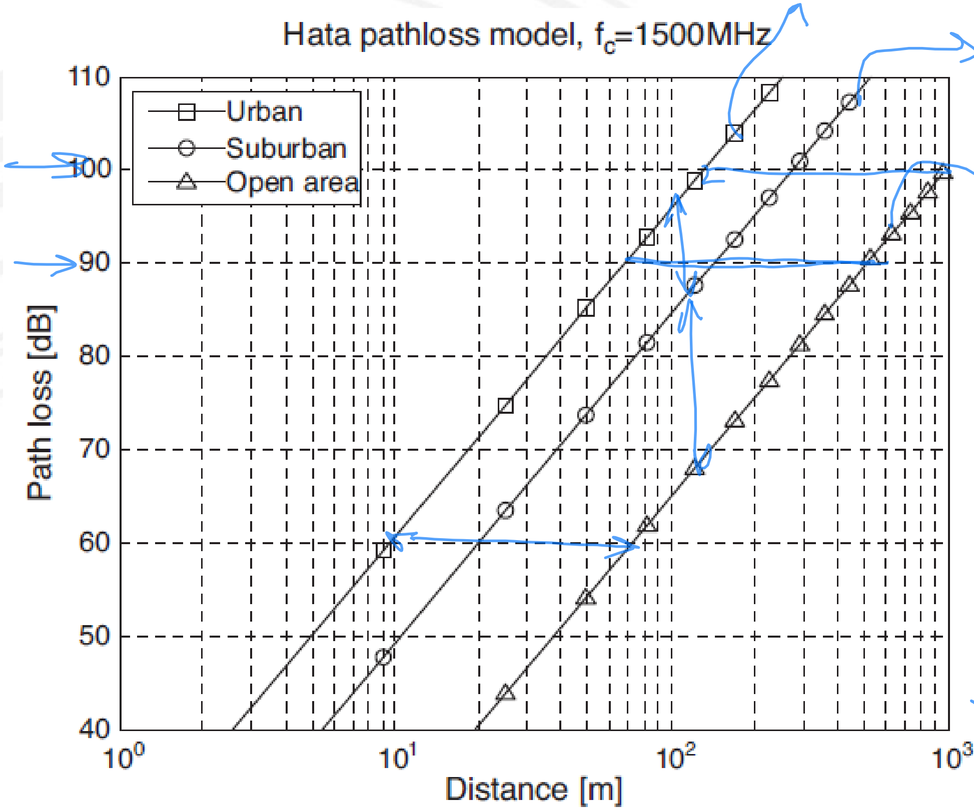


Figure 1.7 Hata path loss model

~100 dB kayıp isteniyorsa
urban ~ 100m
suburban ~ 300m
open ~ 1000m



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# 1.1.3 IEEE 802.16d

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

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

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

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




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# 1.1.3 IEEE 802.16d

Macro cell suburban ART→BRT hilly terrain, moderate to heavy tree density

MC sub. ART→BRT intermediate path loss

MC suburban ART→BRT flat terrain light tree density

| 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.




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# 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.


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# 1.1.3 IEEE 802.16d

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

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

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




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# 1.1.3 IEEE 802.16d

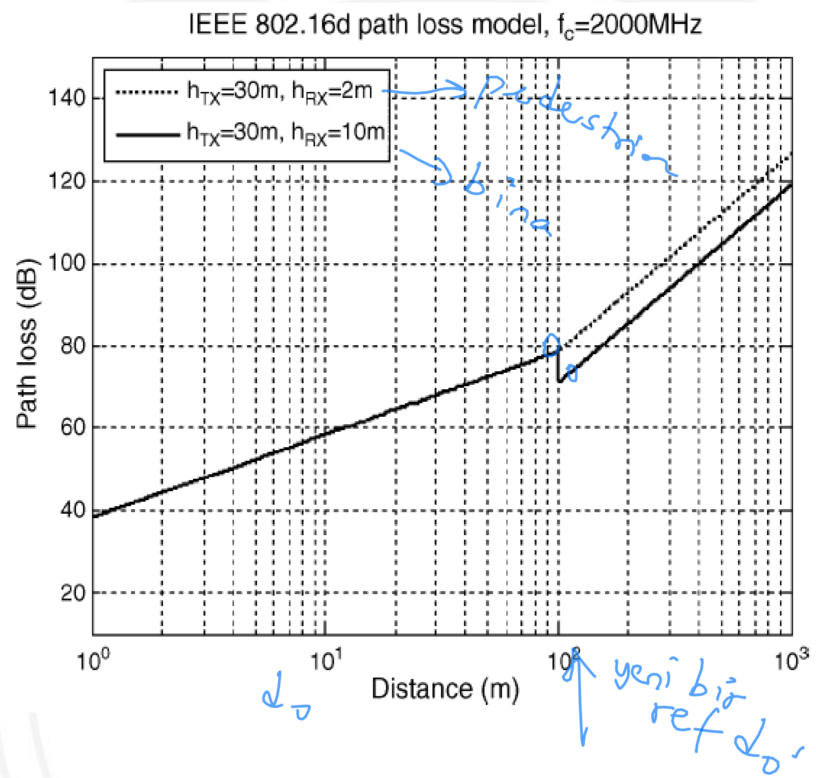


Figure 1.8 IEEE 802.16d path loss model

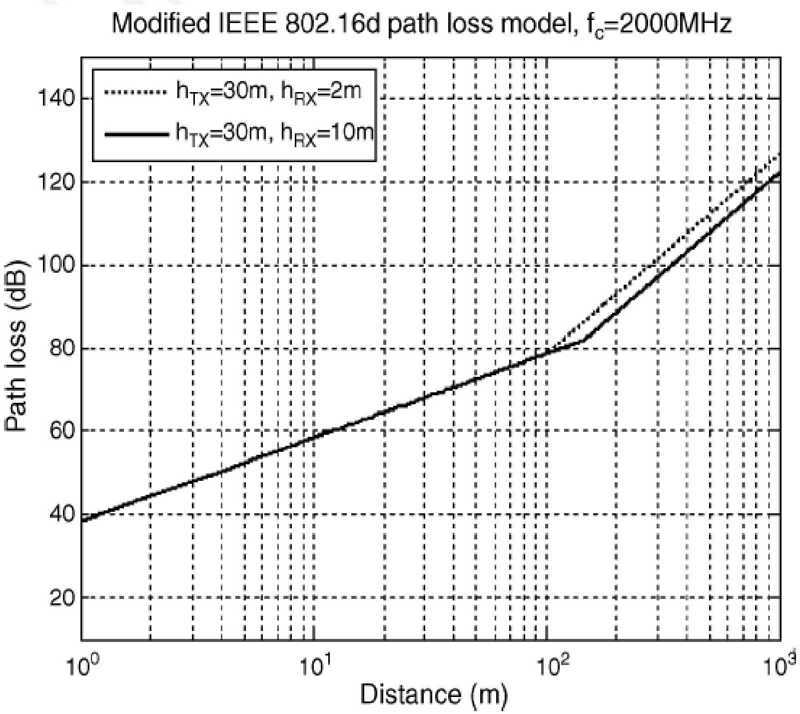


Figure 1.9 Modified IEEE 802.16d path loss model



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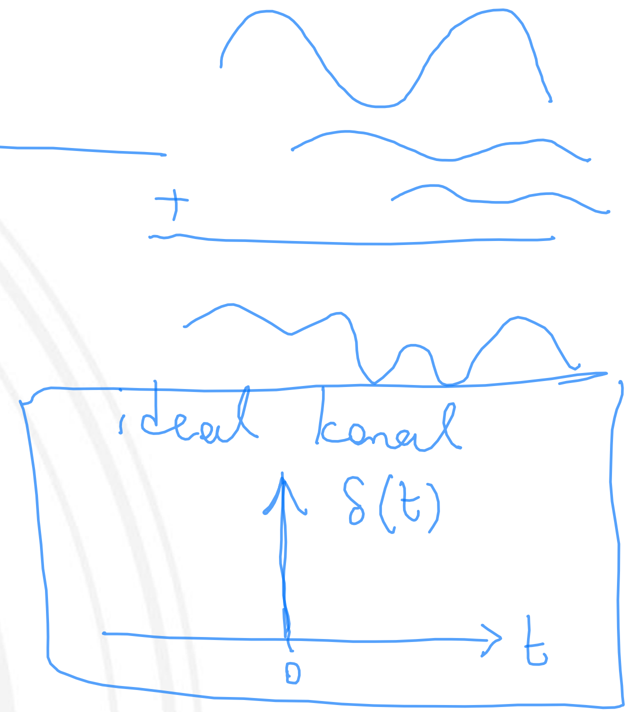
# 1.2 Küçük Çaplı Sönümlenme

## 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



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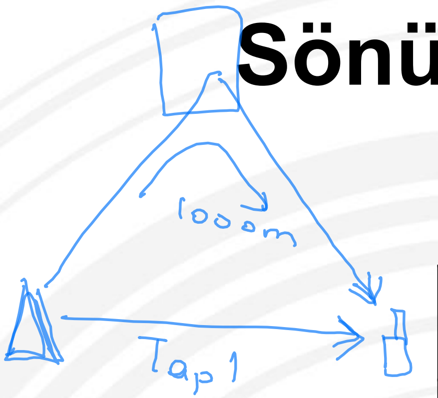
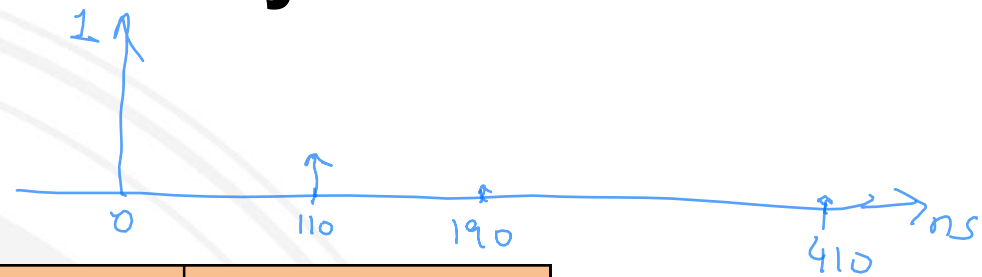
# 1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme




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

1000m fazladan

$\frac{1000}{3\times10^8} = 10^{-6}\,\frac{10}{3} = 3.3\,\mu sn$

$\frac{10}{3\times10^8} = \frac{100\times10^{-9}}{3} = 33\,nsn$

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

Yaya



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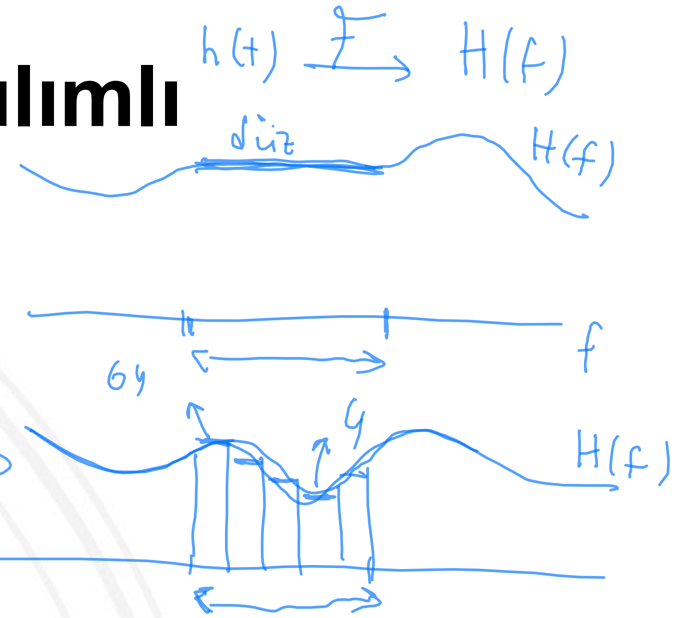
# 1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme




- Düz sönümlenme

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

- Frekans seçici sönümlenme

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

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

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

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

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# 1.2.1 Time-Dispersive vs. Frequency-Dispersive Fading

- $B_C \approx \dfrac{1}{\sigma_\tau}$ Tutarlılık Bandı (1.24)

- $B_C \approx \dfrac{1}{50\sigma_\tau}$ 0.9 ilintili tutarlılık bandı (1.25)

- $B_C \approx \dfrac{1}{5\sigma_\tau}$ 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)

ϕ 0.9 0.5

→ indoor ~ 100nsn → $B_c$ 10M 200kHz 2MHz

outdoor ~ 1000nsn → $B_c$ 1MHz 20kHz 200kHz

Coherence bandwidth

OFDM resource block bant genişliği hesabında kullanılır.

çok düz bir sönümlenme için

açık alanda tek tük yüksek binalar varsa $\sigma_\tau$ yüksek olur.




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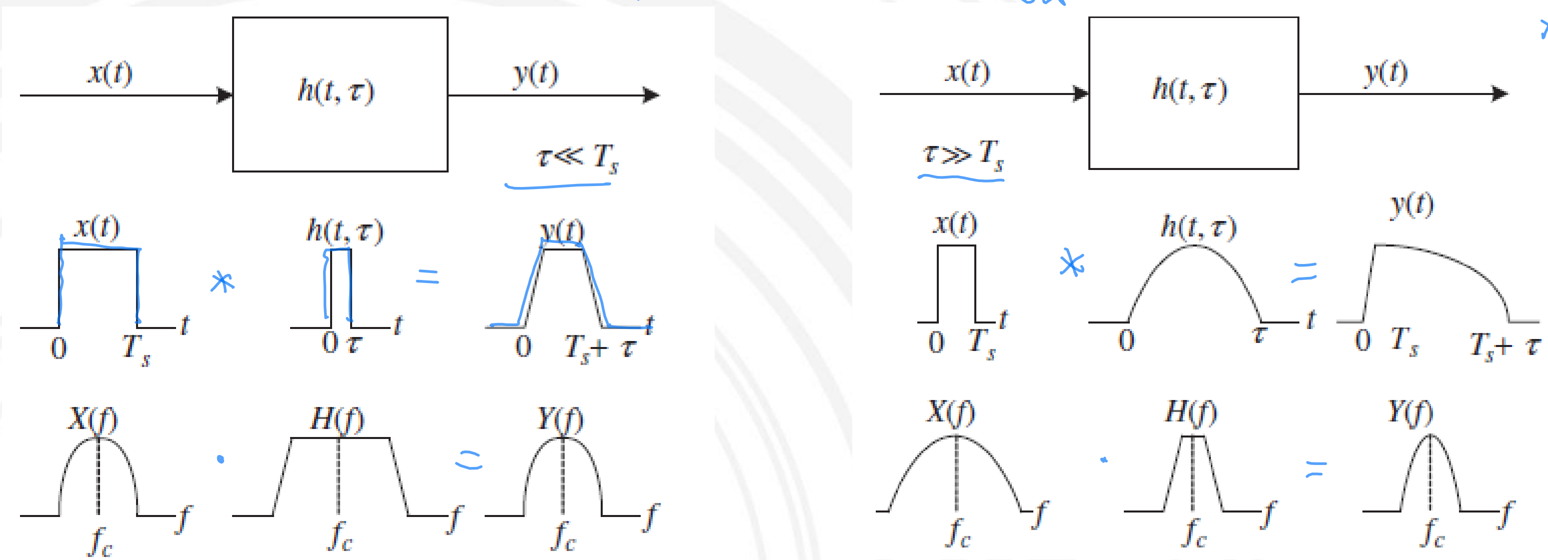
# 1.2 Küçük Çaplı Sönümlenme

## 1.2.1 Zaman ve Frekans Yayılımlı Sönümlenme

Ts : sembol süresi → tasarlayabilirim    τ : saçılım süresi → kontrol edemem

pratikte, günümüzden Ts > τ olacak şekilde tasarlanır.




(a) Frequency-non-selective fading channel    (b) Frequency-selective fading channel

flat fading

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

frekanstaki saçılım → Doppler

Alıcı ve/veya verici hareket halindeyse

$f_m = \frac{v}{c} f_c$ → taşıyıcı frekans; v → Bağıl hız; $f_m$ → Doppler kayması

$f_m = \frac{v}{\lambda}$ → λ dalga boyu

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

- Tutarlılık zamanı $T_C \approx \frac{9}{16\pi f_m}$ → 0.5 ilinti (1.30)

$f_m \uparrow \Rightarrow T_c \downarrow$ Tutarlılık zamanı

- Tutarlılık zamanı $T_C = \sqrt{\frac{9}{16\pi f_m^2}} = \frac{0.423}{f_m}$ sık kullanılır (1.31)

v = 3 m/sn yaya

$f_m = \frac{3}{3\times 10^8} \times 20\times 10^8 = 20 Hz$

$T_c = \frac{0,423}{20} \simeq 21$ msn

v = 100 m/sn $f_c = 2$ GHz

$f_m = \frac{100}{3\times 10^8} \times 20\times 10^8 = 667$ Hz

$\frac{0,423}{667} = 0,6$ msn çok hızlı değişen



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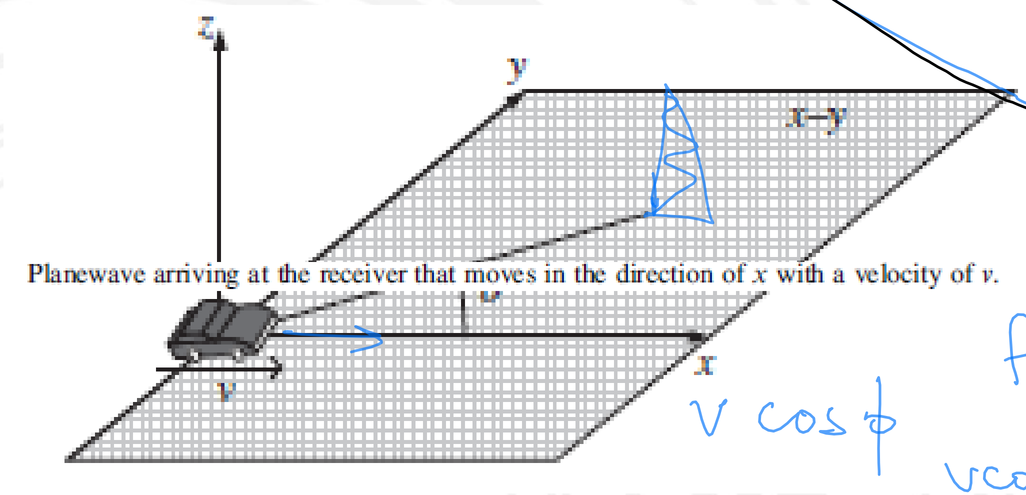
# 1.2.3 Statistical Characterization and Generation of Fading Channel




Her bir yol farklı bir açıdan geliyor
$v\cos\phi$
$v\cos\phi_1, v\cos\phi_2, \ldots, v\cos\phi_n$

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

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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

- Alıcıdaki sinyal

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

- Kanal modeli

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

- Yol gecikmesi sembol zamanından kısaysa

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



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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

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

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

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

- Rayleigh dağılımlı olarak modellenebilir

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



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## 1.2.3 Statistical Characterization and Generation of Fading Channel

autocorrelation $\xrightarrow{\mathcal{F}}$ power spectral density

özilinti

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

$$= \frac{\Omega_p}{2}E_{\theta}\left[\cos\left(2\pi f_m \tau \cos\alpha\right)\right]$$

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

$$\boldsymbol{\tau} = \left[\tau_1, \tau_2, \cdots, \tau_I\right]$$

$$\boldsymbol{\theta} = \left[\theta_1, \theta_2, \cdots, \theta_I\right] \tag{1.44}$$

$$\Omega_p = E\left[h_I^2(t)\right] + E\left[h_Q^2(t)\right] = \sum_{i=1}^{I} C_i^2$$




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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

$$\phi_i = 2\pi\{(f_c + f_i)\tau_i - f_i t\}$$

$$f_i = \frac{v}{\lambda}\cos\theta_i$$

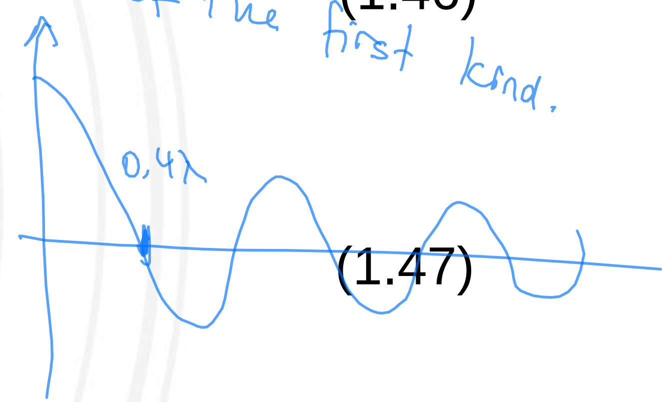
rastgele 0–2π

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

$$= \frac{\Omega_p}{2}\frac{1}{2\pi}\int_{-\pi}^{\pi}\cos(2\pi f_m\tau\cos\theta)\,d\theta = \frac{\Omega_p}{2}J_0(2\pi f_m\tau) \qquad (1.45)$$

bessel function of the zeroth order of the first kind.

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




$$\gamma_{\tilde{y}\tilde{y}}(\tau) = \gamma_{h_I h_I}(\tau)\cos 2\pi f_c\tau - \gamma_{h_I h_Q}\sin 2\pi f_c\tau$$

$$= \frac{\Omega_p}{2}J_0(2\pi f_m\tau)\cos 2\pi f_c\tau \qquad (1.47)$$

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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

- Klasik Doppler skeptrumu

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

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

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



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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi


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

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

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

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



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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

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

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

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



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# 1.2.3 Sönümlü Kanalın İstatistiksel Karakterizasyonu ve Üretimi

- Rice sönümlenmesi

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

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

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



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# 1.2.3 Statistical Characterization and Generation of Fading Channel

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

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



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