Wireless Communication Channel

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- Free space propagation
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- Rayleigh/Ricean fading
- Delay spread & Coherent Bandwidth
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- Performance in fading channel

전파 환경 : 요소

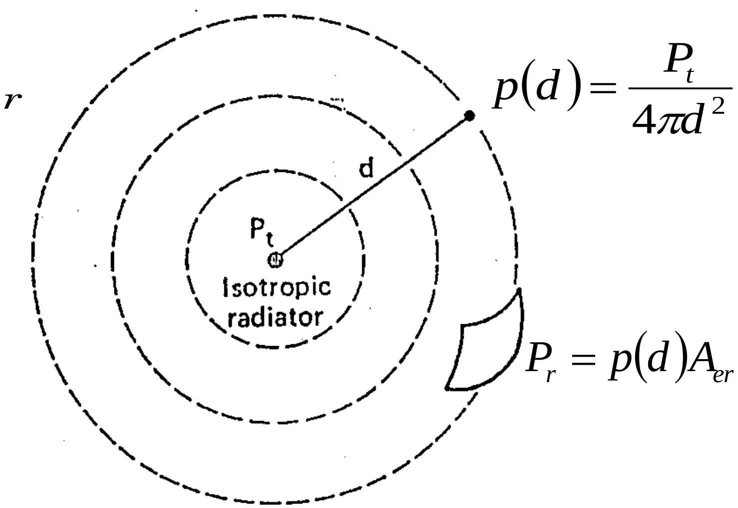
- Path Loss (Free space propagation,....)
- Shadowing
- Rayleigh/Ricean Fading
- Delay Spread & Coherent Frequency
- Doppler Shift & Coherent Time

Free Space Propagation

- Received Power: $P_r = P_t G_t \left(\dfrac{A_r}{4\pi d^2} \right) n_r$

  n_r : R_X antenna efficiency

- R_X antenna gain: $G_r = \dfrac{4\pi A_r}{\lambda^2} n_r$



- Received Power:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

  – $P_r \uparrow$, as $\lambda \uparrow$ for a fixed G_r

  – P_r does not change with λ for a fixed A_r

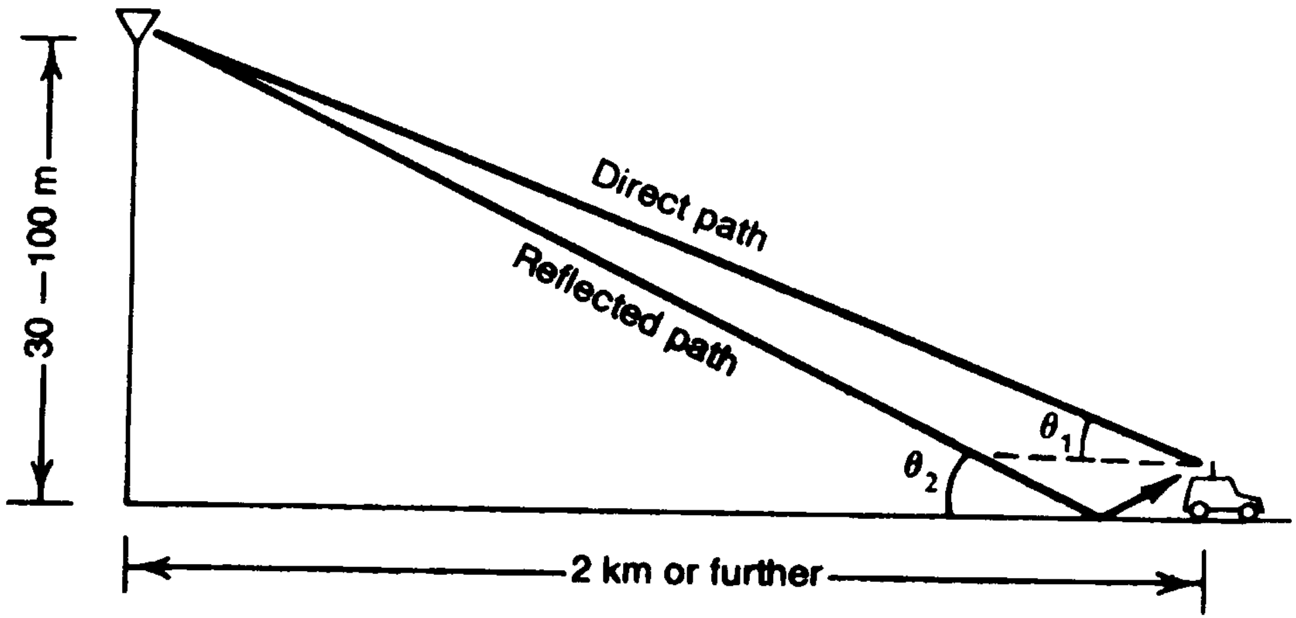
$$\frac{P_{r2}}{P_{r1}} = \left(\frac{d_1}{d_2}\right)^2$$

$$\text{Power ratio(dB)} = 10\log\frac{P_{r2}}{P_{r1}} = 20\log\frac{d_1}{d_2}$$

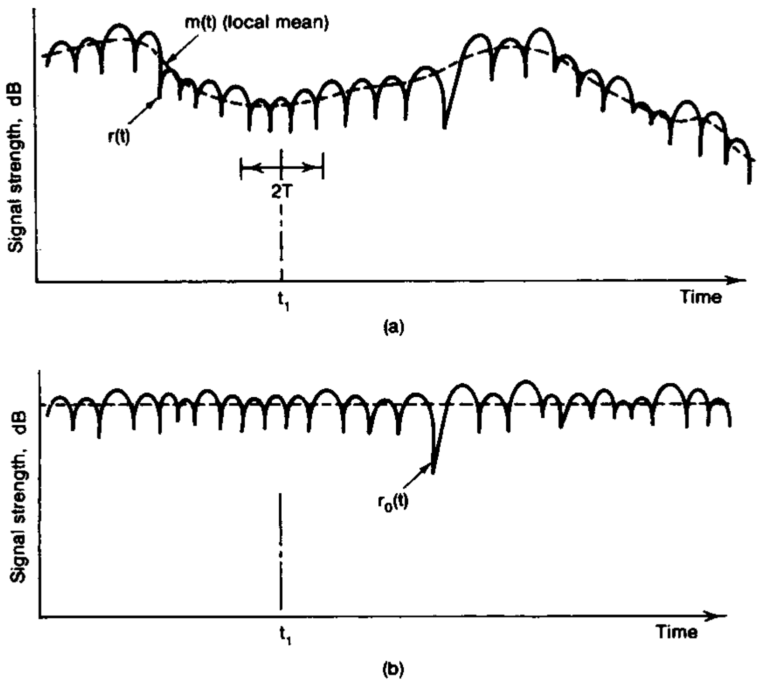
Ex) $d_2 = 2d_1$ $\quad$ Power ratio $= -6dB \quad (-6dB/oct)$

$d_2 = 10d_1$ $\quad$ Power ratio $= -20dB \quad (-20dB/dec)$

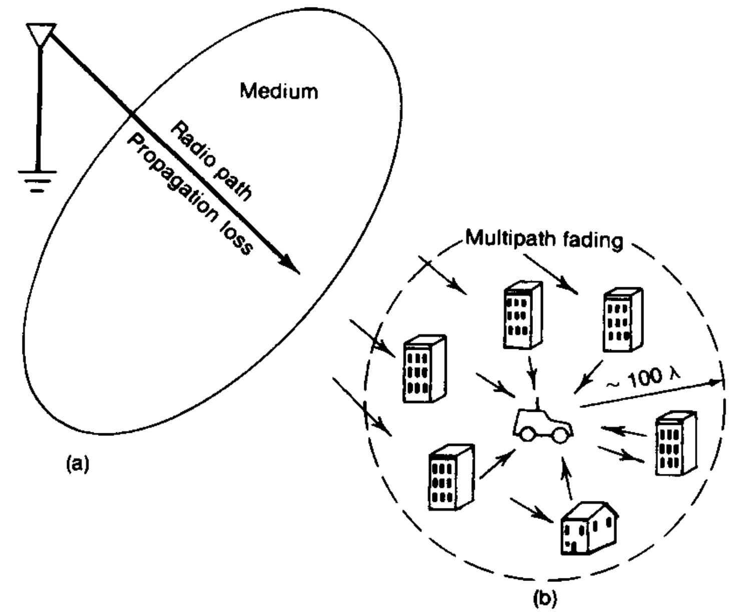
실질적 환경: d^{-4}


30 — 100 m
Direct path
Reflected path
θ_1
θ_2
2 km or further

Shadowing



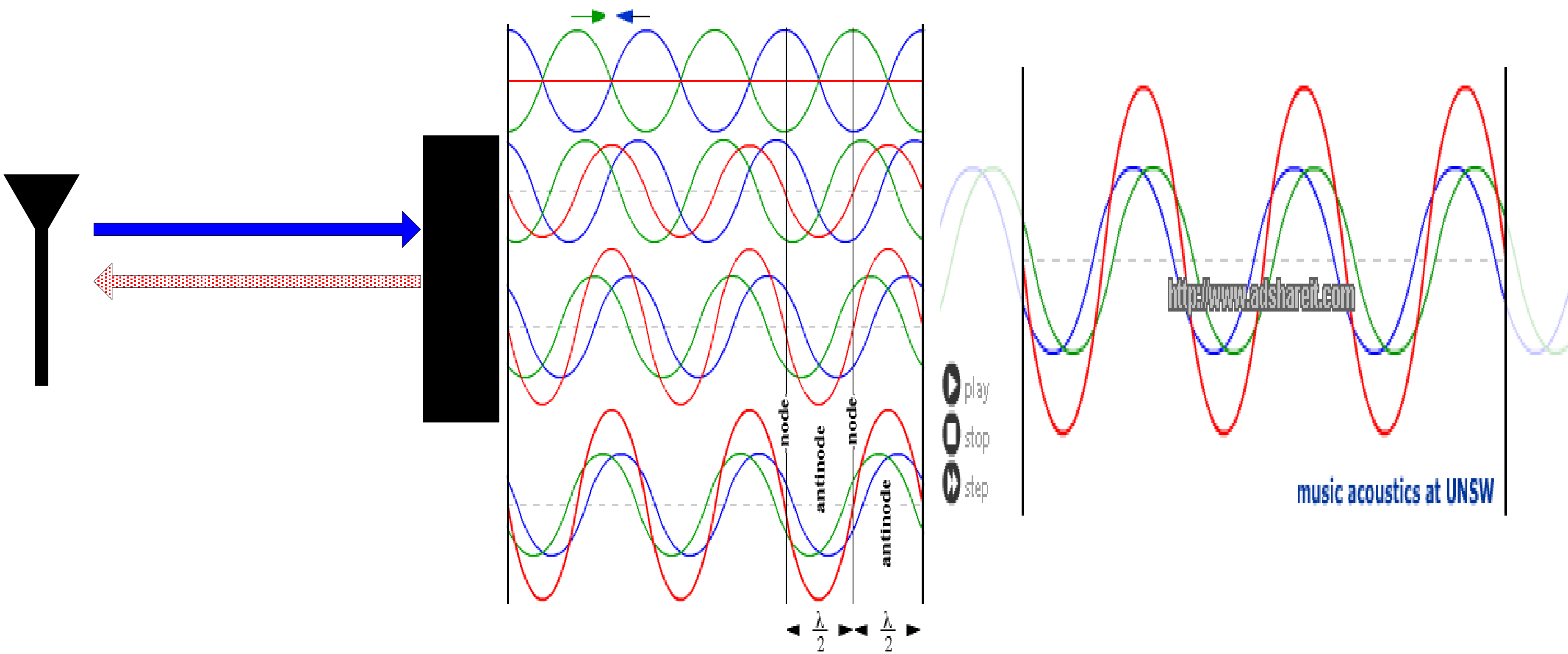
m(t) (local mean)
r(t)
2T
Signal strength, dB
t_1
Time
(a)
$r_0(t)$
Signal strength, dB
t_1
Time
(b)



Medium
Radio path
Propagation loss
(a)
Multipath fading
~ 100 λ
(b)

Rayleigh / Ricean Fading

- Rayleigh Fading의 발생



• Rayleigh Fading

- Multipath fading

  Short-term fading

  Fast fading

$$r_o(t)\,dB = r(t)\,dB - m(t)\,dB$$

- Received signal

$$
\begin{aligned}
e(t) &= \sum_{m=1}^{N} A_m \cos(w_c t + \theta_m(t)) = \mathrm{Re}\{\sum_{m=1}^{N} A_m e^{j\theta_m(t)} e^{jw_c t}\} \\
&= \sum_{m=1}^{N} A_m \cos\theta_m(t)\cos\omega_c t - A_m \sin\theta_m(t)\sin\omega_c t \\
&= \sum_{m=1}^{N} A_m \cos\theta_m(t)\cos\omega_c t - \sum_{m=1}^{N} A_m \sin\theta_m(t)\sin\omega_c t \\
&= i(t)\cos\omega_c t - q(t)\sin\omega_c t
\end{aligned}
$$

$i(t)$ & $q(t)$ are Gaussian r.v. (Central limit theorem)

- # Rayleigh Distribution

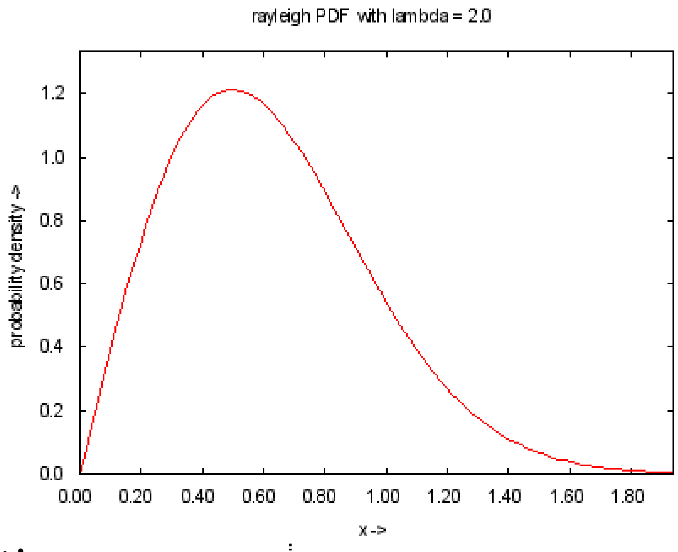
$$e(t) = i(t)\cos w_c t - q(t)\sin w_c t$$
$$= r(t)\cos(w_c t + \theta(t))$$

Complex number representation

$\tilde{e}(t) = i(t) + jq(t) = r(t)e^{j\theta(t)}$

$r(t) = \sqrt{i^2(t) + q^2(t)} =$ Envelope of $e(t)$

$$\theta(t) = \tan^{-1}\frac{q(t)}{i(t)}$$



Let i, q represent $i(t), q(t)$

i, q: Gaussian r.v. with σ^2

$\Pr(r) = \frac{r}{\sigma^2}\exp(-\frac{r^2}{2\sigma^2})$ Rayleigh distribution

θ: Uniform distribution $[0, 2\pi)$

$$E[r] = \int_0^\infty r\,\mathrm{Pr}(r)dr = \sqrt{\frac{\pi}{2}}\sigma = 1.2533\sigma$$

$$E[r^2] = E[i^2 + q^2] = 2\sigma^2 = \overline{r^2}$$

$$\sigma_{r^2} = \sigma^2\sqrt{\left(2 - \frac{\pi}{2}\right)} = 0.66\sigma$$

$$\mathrm{Pr}(r) = \frac{2r}{\overline{r^2}}\exp\left(-\frac{r^2}{\overline{r^2}}\right)$$

Short term Rx signal power of $e(t)$: $\dfrac{r^2(t)}{2}$

Mean Rx signal power : $\dfrac{E[r^2]}{2} = \sigma^2 = \dfrac{\overline{r^2}}{2}$

• Ricean Fading

- Line of sight, or Dominant signal component exists.

$$e(t) = r(t)\cos(\omega_c t + \theta(t)) + r_{los}(t)\cos(\omega_c t + \theta_{los}(t)) + n(t)$$

- Envelope PDF:

$$P_r(r) = \frac{r}{\sigma^2}\exp\left[-\frac{r^2 + r_{los}{}^2}{2\sigma^2}\right] \bullet \mathrm{I}_o\left(\frac{r\, r_{los}}{\sigma^2}\right)$$

where $I_0(t)$ is the modified Bessel function.

- Ricean parameter

$$K = 10\log\frac{r_{los}^2/2}{E\left[r^2\right]/2} = 10\log\frac{\mathrm{LOS}}{\mathrm{Diffuse}}$$

Delay Spread & Coherence Bandwidth

- Delay spread (power delay profile)
- Coherent Bandwidth(Bc)

  : 상관 계수가 0.5 이하가 되기 위하여 필요한 주파수 간격

- Correlation at f_1 and f_2

$$R(\Delta f) = < S(f_1)\,S(f_2) >,\ \ \Delta f = |f_1 - f_2|$$

- Correlation coefficient

$$\rho(\Delta f) = \frac{Cov\left(S(f_1), S(f_2)\right)}{\sigma_{S(f_1)}\sigma_{S(f_2)}}$$

$$= \frac{Cor\left(S(f_1), S(f_2)\right) - E\left[S(f_1)\right]E\left[S(f_2)\right]}{\left(\sigma_{S(f_1)}\right)^2}$$

$$= \frac{R(\Delta f) - \left\langle S(f_1)\right\rangle^2}{E\left[S^2(f_1)\right] - E^2\left[S(f_1)\right]}$$

$$= \frac{R(\Delta f) - \left\langle S(f_1)\right\rangle^2}{R(0) - \left\langle S(f_1)\right\rangle^2}$$

- Coherent bandwidth for amplitude

$$B_c = \frac{1}{2\pi\Delta} \quad ; \quad for \ \text{AM}$$

$$\text{Open Area}: \Delta < 0.2\mu s \rightarrow Bc = 800KHz$$

$$\text{Suburban} \quad : \Delta \approx 0.5\mu s \rightarrow Bc = 300KHz$$

$$\Delta: \text{rms delay spread}$$

- Coherent bandwidth for phase

$$B_c' = \frac{1}{4\pi\Delta} \quad ; \quad for \ \text{FM/PM}$$

- Wideband vs. Narrowband

- CDMA vs. TDMA

Doppler Spread & Coherent Time

- Describe the time varying nature of the channel (Vehicle movement….)

- Doppler Spread (f_d)
  ： A measure of spectral broadening
  - When the Tx signal freq = f_c,
    the Rx signal freq = $(f_c - f_d) \sim (f_c + f_d)$
  - f_d : function of f_c, q, velocity, (V/λ).

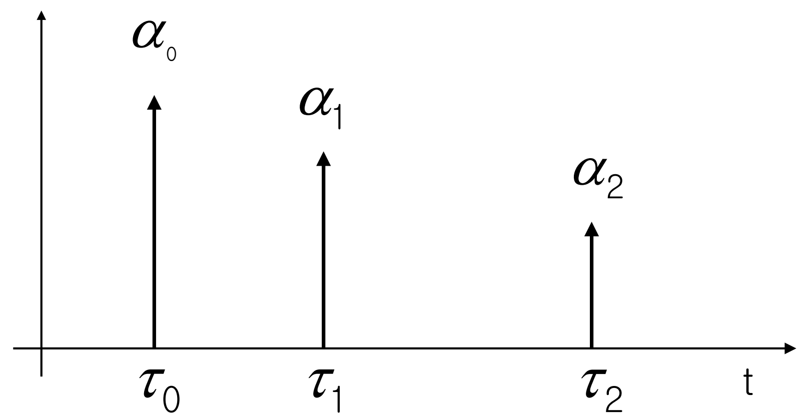
- Coherence time(Tc)
  : time duration over which two rx signal
  have a strong amplitude correlation
  fm is the maximum *fd*

$$T_c = 1/f_m, \quad 9/16\pi f_m, \quad 0.423/f_m$$

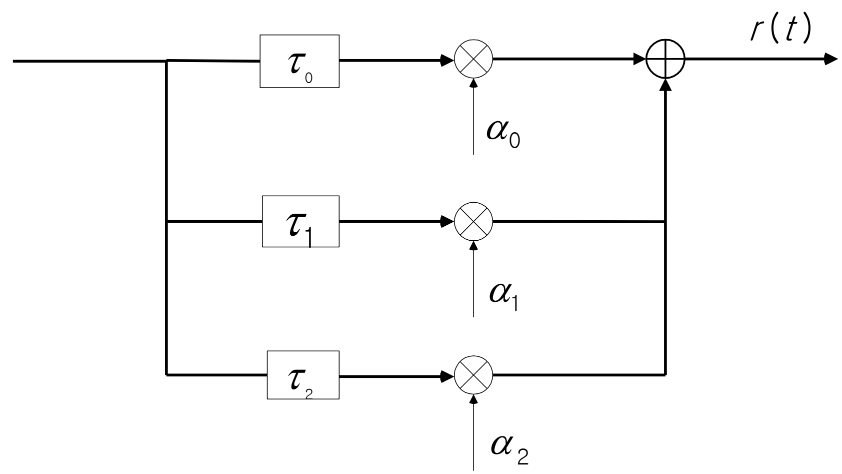
- Interleaving

Channel Model

- Channel Impulse Function



- Channel Representation



ITU-R Channel

- ITU-R Vehicular Channel Specification

Tap	Channel A		Channel B		Doppler Spectrum
	Relative Delay(nsec)	Avg. Power (dB)	Relative Delay(nsec)	Avg. Power (dB)	
1	0	0.0 (48.5%)	0	-2.5 (32.3%)	CLASSIC
2	310	-1.0 (38.5%)	300	0 (57.4%)	CLASSIC
3	710	-9.0 (6%)	8900	-12.8 (3%)	CLASSIC
4	1090	-10.0 (4.9%)	12900	-10.0 (6%)	CLASSIC
5	1730	-15.0 (1.5%)	17100	-25.2 (0.2%)	CLASSIC
6	2510	-20.0 (0.5%)	20000	-16.0 (1.4%)	CLASSIC

Propagation prediction model

- Okumura 모델
- Hata 모델
- Lee 모델
- Longley – Rice 모델
- Cost – 231 Hata 모델
- Ray – Tracing 모델

• Okumura 모델

- 실측값을 바탕으로 전파감쇠 중앙값 예측곡선도시
  - 다양한 전파 환경과 지형의 보정인자
  - 기지국, 이동국 유효 안테나 높이에 따른보정인자
- 경로거리
- Carrier frequency
  - VHF (200 MHz)
  - UHF (453, 922, 1310, 1430, 1920 MHz)

- 주위환경: Urban, Suburban,

  Open area(rural area)

- 지형
  - Quasi smooth terrain
  - Irregular terrain

    (Rolling-hill terrain, General sloped terrain,

    Mixed land-sea,...)

- Antenna height gain factor

– 모델 파라메타

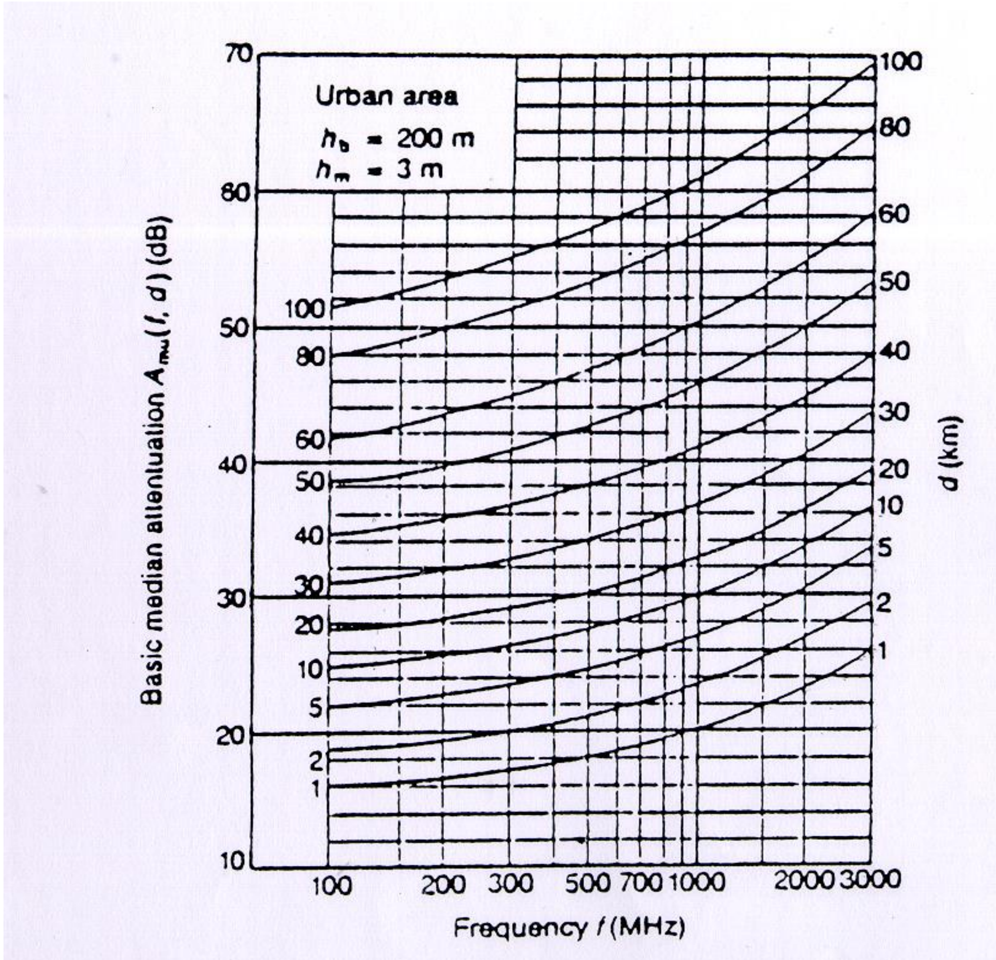
• 주파수	150MHz ~ 2,000MHz
• 경로거리	1km ~ 100km
• 기지국 유효 안테나 높이	30m ~ 1000m (200m)
• 이동국 안테나 높이	1m ~ 10m (3m)
• 경로내 지형종류	준완만 지형, 불규칙한 지형
• 이동국 주위환경	도심지, 준시가지, 개방지

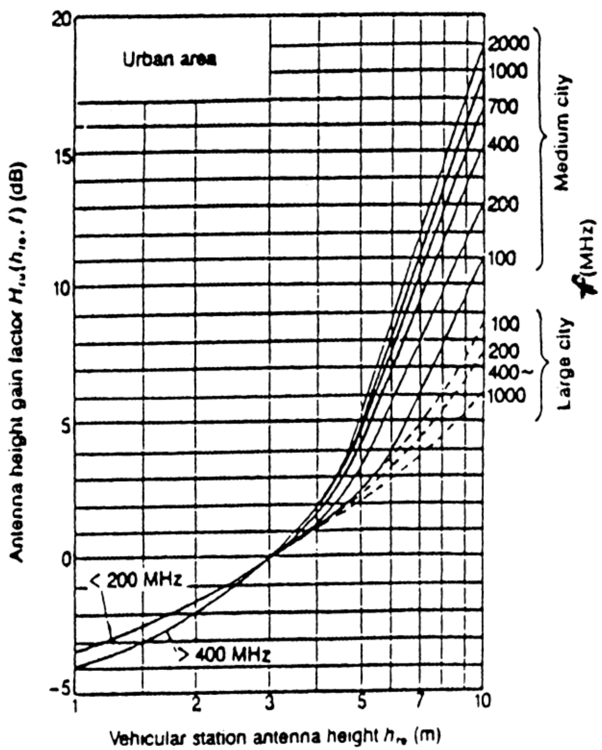
– 기준 전파감쇠 중앙값 예측

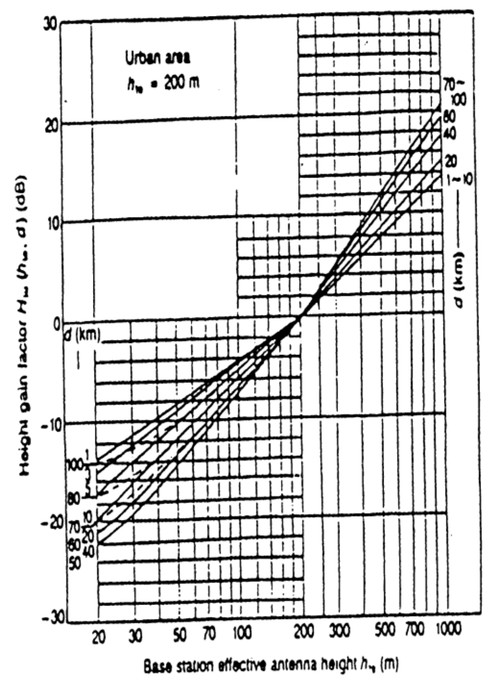
$$L_{50}(dB) = L_F + A_{mu}(f,d) - H_{tu}(h_{te},d) - H_{ru}(h_{re},f)$$

- L_{50} 손실의 median value
- L_F free space손실
- $A_{mu}(f,d)$ 기준손실 중앙값 (w.r.t. L_F)
- $H_{tu}(h_{te}, d)$ 기지국 유효 안테나 높이 이득인자
- $H_{ru}(h_{re}, f)$ 이동국 유효 안테나 높이 이득인자
- f 주파수
- d 경로거리
- h_{te}, h_{re} 유효 안테나 높이

- 예측절차
  - 해당 주파수와 경로거리, 유효 안테나 높이를 참조하여 기준 전파감쇠 중앙값 예측
  - 준완만 지형상의 도심지에서 전파감쇠 중앙값을 기준 값으로 설정 (quasi-smooth, urban)
  - 준완만 지형상의 도심지 이외의 지역에 대한 예측은 해당 보정인자 적용
- 한계: 수식화 되지 않은 예측


Urban area
h_b = 200 m
h_m = 3 m
Basic median attenuation $A_{mu}(f, d)$ (dB)
70
60
50
40
30
20
10
100
80
60
50
40
30
20
10
5
2
1
d (km)
100
200
300
500
700
1000
2000
3000
Frequency f (MHz)


Urban area
Antenna height gain factor $H_{ru}(h_{re}, f)$ (dB)
Vehicular station antenna height h_{re} (m)
2000
1000
700
400
200
100
Medium city
f (MHz)
100
200
400~
1000
Large city
< 200 MHz
> 400 MHz


Urban area
h_{re} = 200 m
Height gain factor H_{tu} (h_{te}, d) (dB)
Base station effective antenna height h_{te} (m)
d (km)
d (km)

- Hata의 공식
  - Okumura가 도출해 낸 여러 예측 Curve를 수식의 형태로 간소화
  - 수식화된 예측 Okumura curve
    - 기준 전파감쇠 중앙값 예측곡선
    - 주변 환경에 대한 보정인자 예측곡선
    - 유효 안테나 높이 이득인자 예측곡선
  - 수식화 되지 않은 예측 Okumura curve
    - 전파경로 대한 보정인자

- 시가지 $$L_{50}(dB) = 69.55 + 26.16\log_{10} f_c - 13.82\log_{10} h_b - a(h_m) + (44.9 - 6.55\log_{10} h_b)\log_{10} R$$

  * 이동국 유효 안테나 높이 이득인자

  중소도시 $a(h_m) = (1.1 * \log_{10} f_c - 0.7) * h_m - (1.56\log_{10} f_c - 0.8)$

  대도시 $a(h_m) = 8.29 * (\log_{10} 1.54h_m)^2 - 1.10(dB), f_c \le 200MHz$

  $= 3.2 * (\log_{10} 11.75h_m)^2 - 4.97(dB), f_c \le 400MHz$

- 준시가지 $L_{50}(dB) = L_{50}(\text{시가지}) - 2\{\log_{10}(f_c/28)\}^2 - 5.4$

- 개방지 $L_{50}(dB) = L_{50}(\text{시가지}) - 4.78(\log_{10} f_c)^2 + 18.33\log_{10} f_c - 40.94$

Performance in Rayleigh Fading

- Tx : $s(t) = \cos(\omega_c t)$
- Rx : $r(t) = \alpha(t)\cos(\omega_c t + \theta(t))$

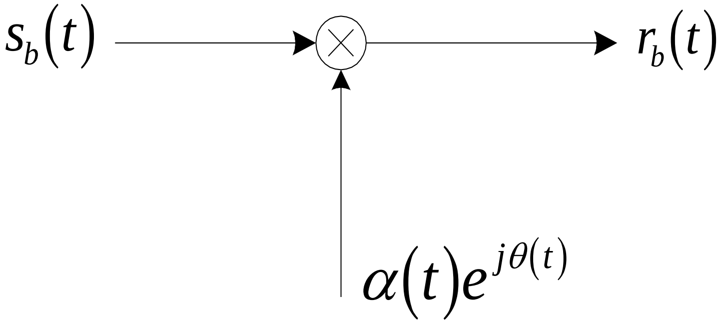
$$= \sum_{m=1}^{N} A_m \cos(\omega_c t + \theta_m(t))$$

$$= \mathrm{Re}\left[\sum_{m=1}^{N} A_m e^{j\theta_m(t)} e^{j\omega_c t}\right]$$

$$= i(t)\cos\omega_c t - q(t)\sin\omega_c t$$

$$= \sqrt{i^2(t) + q^2(t)}\,\cos(\omega_c t + \theta(t))$$

- Multiplicative channel



$$r_b(t) = s_b(t)\alpha(t)e^{j\theta(t)}$$

- Static

BPSK : Prob. of error $P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$

- Fading

$$E_b = P \cdot T = \frac{\alpha^2}{2} T$$

$$P(Error|\alpha) = Q\left(\sqrt{\frac{\alpha^2 T}{N_0}}\right)$$

$$\Pr(Error) = \int_0^\infty f_\alpha(\alpha) P(Error|\alpha) \cdot d\alpha$$

$$= \int_0^\infty \frac{\alpha}{P} \exp\left(-\frac{\alpha^2}{2P}\right) \int_{\sqrt{\frac{\alpha^2 T}{N_0}}}^\infty \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx \cdot d\alpha$$

$$Let \quad y=\frac{\alpha}{\sqrt{P}}, \quad then \quad \sqrt{\frac{\alpha^2 T}{N_0}}=y\sqrt{\frac{PT}{N_O}}, \quad d\alpha=\sqrt{P}dy$$

$$\Pr(Error)=\int_0^\infty\int_{y\sqrt{\frac{PT}{N_O}}}^\infty \frac{y}{\sqrt{2\pi}}e^{-\frac{x^2+y^2}{2}}dxdy$$

$$y=r\sin\theta, \quad x=r\cos\theta$$

$$\Pr(Error)=\int_0^\infty\int_0^{\tan^{-1}\sqrt{\frac{N_O}{PT}}}\frac{r^2\sin\theta}{\sqrt{2\pi}}e^{-\frac{r^2}{2}}d\theta dr$$

$$=\frac{1}{\sqrt{2\pi}}\int_0^\infty r^2e^{-\frac{r^2}{2}}dr\int_0^{\tan^{-1}\sqrt{\frac{N_O}{PT}}}\sin\theta d\theta$$

$$=\frac{1}{\sqrt{2\pi}}\sqrt{\frac{\pi}{2}}\left(1-\cos\left(\tan^{-1}\sqrt{\frac{N_O}{PT}}\right)\right)$$

$$=\frac{1}{2}\left(1-\frac{1}{\sqrt{1+N_O/PT}}\right)=\frac{1}{2}\left(1-\frac{1}{\sqrt{1+N_O/E_b}}\right)$$

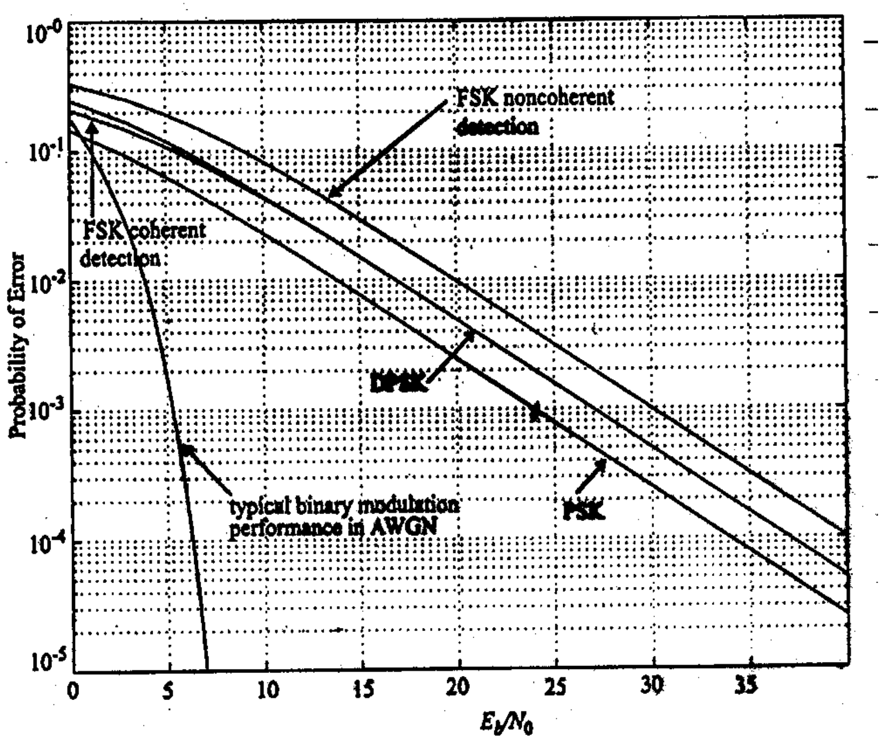
$$\cong\frac{1}{4(E_b/N_O)} \quad ; \quad \text{BPSK}$$

- FSK (Coherent detection)

$$\Pr(Error) \cong \frac{1}{2(E_b/N_O)}$$

- DPSK (Differential decoding)

$$\Pr(Error) \cong \frac{1}{2(E_b/N_O)}$$



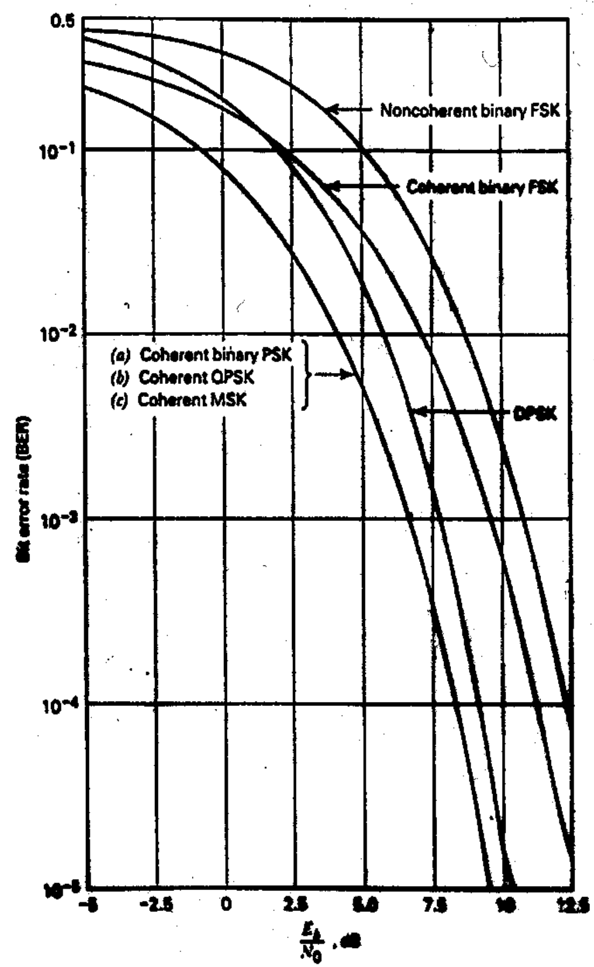
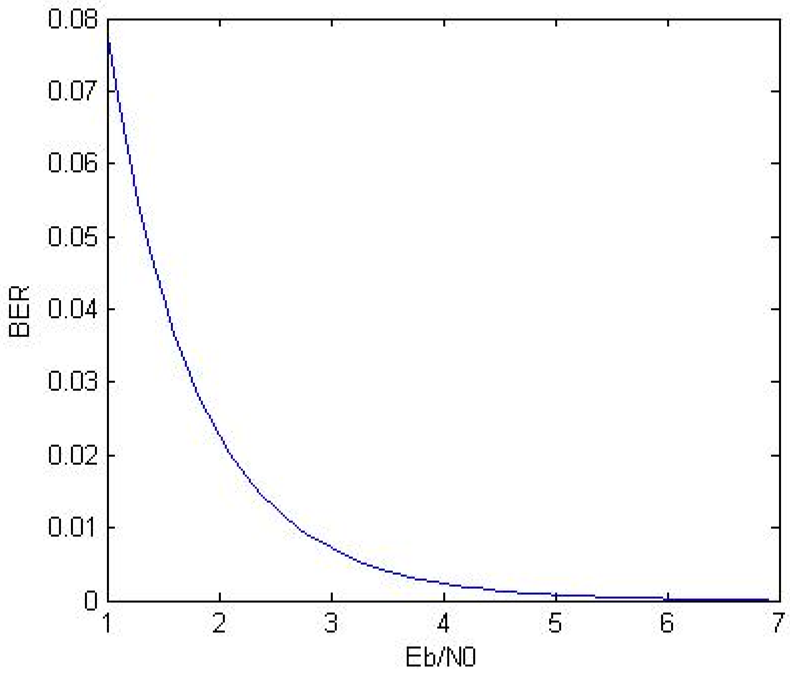
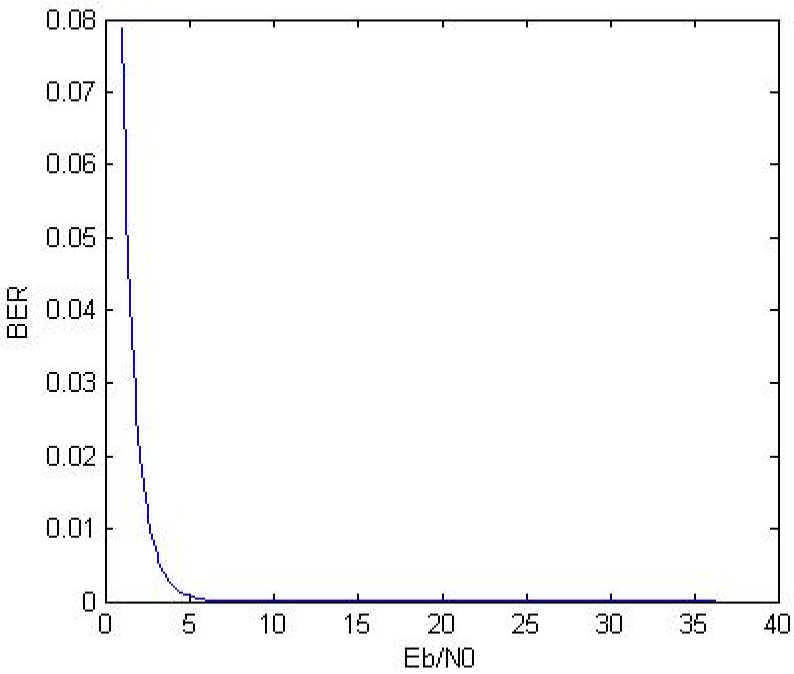


Figure 8.32 Comparison of the noise performances of different PSK and FSK schemes.

• BER of BPSK (linear)

$$BER\ :\ P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$





• Pdf of SNR

$$f_\alpha(\alpha) = \frac{\alpha}{\sigma^2} e^{-\frac{\alpha^2}{2\sigma^2}}$$

$$SNR = \gamma = \frac{\alpha^2}{2N} = g(\alpha)$$

$$f_\gamma(\gamma)\,d\gamma = f_\alpha(\alpha)\,d\alpha$$

$$f_\gamma(\gamma) = f_\alpha(\alpha)\frac{d\alpha}{d\gamma} = \frac{f_\alpha\left(g^{-1}(\gamma)\right)}{(d\gamma/d\alpha)}$$

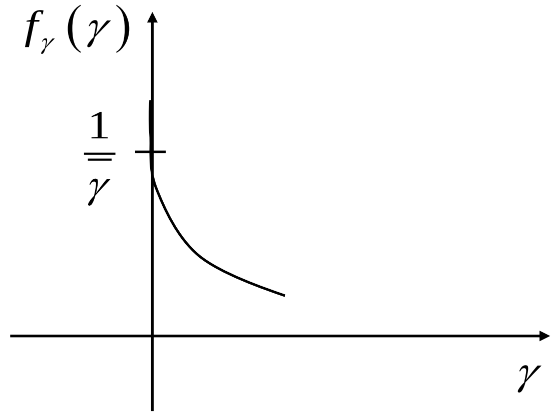
$$\alpha = \sqrt{2\gamma N},$$

$$\frac{d\gamma}{d\alpha} = \frac{dg}{d\alpha} = \frac{2\alpha}{2N} = \frac{\alpha}{N} = \frac{\sqrt{2\gamma N}}{N} = \sqrt{\frac{2\gamma}{N}}$$

$$f_\gamma(\gamma) = \frac{\sqrt{2\gamma N}}{\sigma^2} e^{-2\gamma N/2\sigma^2} \sqrt{\frac{N}{2\gamma}}$$

$$= \frac{N}{\sigma^2} e^{-\gamma N/\sigma^2} = \frac{1}{\bar{\gamma}} e^{-\frac{\gamma}{\bar{\gamma}}}$$

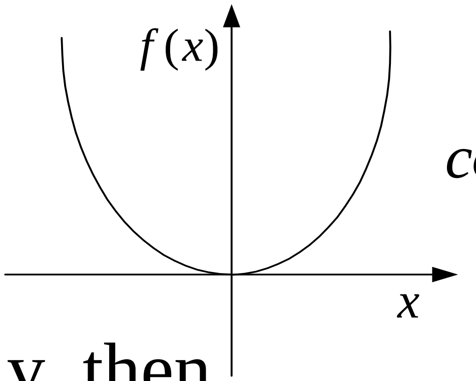
$$\left(\because\ \overline{SNR} = \frac{E\left[\alpha^2\right]}{2N} = \frac{2\sigma^2}{2N} = \bar{\gamma}\right)$$



Jensen's Inequality

- If f is a convex fn. & x is a r.v. then

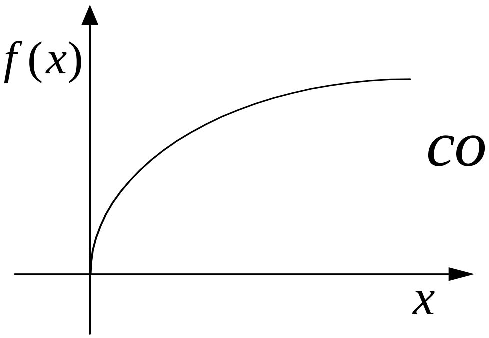
$$E\{f(x)\} \geq f(E\{x\})$$



convex

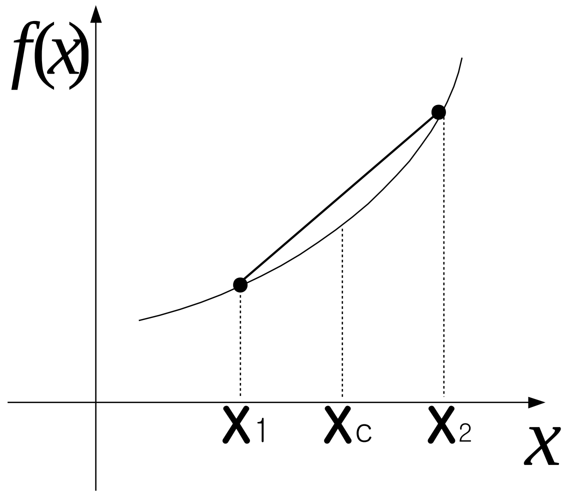
- If f is a concave fn. & x is a r.v. then

$$E\{f(x)\} \leq f(E\{x\})$$



concave

Jensen's Inequality



$RV : X$ (예) $x = x_1 \quad prob = \dfrac{1}{2}$

$x = x_2 \quad prob = \dfrac{1}{2}$

$x_c = (x_1 + x_2)/2$

$$E\{f(x)\}$$

$$= p_1 f(x_1) + p_2 f(x_2)$$

$$= \frac{1}{2} f(x_1) + \frac{1}{2} f(x_2)$$

$$f(E\{x\})$$

$$= f(p_1 x_1 + p_2 x_2)$$

$$= f\left(\frac{x_1}{2} + \frac{x_2}{2}\right)$$

$$E\{f(x)\} \geq f(E\{x\})$$