Delay Spread and Coherence Bandwidth

- Delay spread (T_d)
  - Difference of the propagation delays of the longest and shortest paths (with significant energy)
    $$T_d = \max_{i,j} |\tau_i(t) - \tau_j(t)|$$
  - Delay coherence → frequency coherence: how quickly the channel changes in frequency
  - At time t, frequency response is
    $$H(f,t) = \sum_i a_i(t) e^{-j2\pi f \tau_i(t)}$$
  - For multiple paths, differential phase=$2\pi f\left(\tau_i(t) - \tau_k(t)\right)$
  - The phase changes significantly as f changes by $\frac{1}{2T_d}$

Delay Spread and Coherence Bandwidth

- Coherence Bandwidth (W_c)

$$W_c = \frac{1}{2T_d}$$

  - Multipath spread ↑, coherence bandwidth ↓
- Flat fading v.s. Frequency selective fading
- Flat fading: $W_c \gg W$
  - Delay spread <<symbol time $\frac{1}{W}$ → one filter tap is sufficient to represent the channel
- Flat fading: $W_c \ll W$
  - Channel is represented by multiple taps

Delay Spread and Coherence Bandwidth

- In most literature, T_d is defined by the r.m.s. delay spread

$$\sigma_\tau = \sqrt{\overline{\tau^2} - \tau^2}$$

$$\overline{\tau^2} = \frac{\sum_i a_i^2(t)\tau_i^2(t)}{\sum_i a_i^2(t)}$$

$$\tau = \frac{\sum_i a_i^2(t)\tau_i(t)}{\sum_i a_i^2(t)}$$

- In some literature,
  - If W_c is defined as BW over which frequency correlation is above 0.9, $W_c \approx \frac{1}{50\sigma_\tau}$
  - If W_c is defined as BW over which frequency correlation is above 0.5, $W_c \approx \frac{1}{5\sigma_\tau}$

Doppler Spread and Coherence Time

- $h_l[m] = \sum_i a_i^b\left(\frac{m}{W}\right) sinc(l - W\tau_i(m/W))$

  $$= \sum_i a_i \left(\frac{m}{W}\right) e^{-j2\pi f_c \tau_i(m/W)} sinc(l - W\tau_i(m/W))$$

  - Phase of the *i*-th path change greatly at intervals of $1/(4D_i)$
  - $D_i = f_c\tau_i'(t)$: Doppler shift of the i-th path
- Doppler Spread (D_s) :

  $$D_s = \max_{i,j} f_c|\tau_i'(t)\text{-}\tau_j'(t)|$$

  Largest difference between Doppler shifts

  When the Doppler shifts are different, the fastest changes in the filter taps are significant over delay changes of $\frac{1}{4D_s}$.

Doppler Spread and Coherence Time

- Coherence time T_c
  The interval over which $h_l[m]$ changes significantly.
  $$T_c = \frac{1}{4D_s}$$
  - Doppler spread ↑, the coherence time ↓
- Fast fading v.s. slow fading
  - Fast fading: $T_c \ll$ delay requirement of the application
  - Slow fading: $T_c \gg$delay requirement of the application
  - For voice transmission, the delay requirement is less than 100 ms. For data, the delay requirement is laxer.
  - If signal BW $\gg D_s$, effects of Doppler spread is negligible.

Doppler Spread and Coherence Time

- In some literature, coherence time has a different definition:
- T_c is a statistical measure of the time duration over which the channel is enssentially invariant.
- Usually, $T_c \approx 1/D_s$
- If T_c is defined by the time duration over which the time correlation is above 0.5,

$$T_c \approx \frac{9}{16\pi D_s}$$

- Another popular definition is geometric mean of above two values:

$$T_c \approx 0.423/D_s$$

Outline

2.1 Wireless channels

2.2 Outage probability and error probability over fading channels

- 2.2.1 Average error probabilities over Rayleigh fading channels
- 2.2.2 Outage probability for Rayleigh fading channels

2.3 Diversity Techniques

AWGN Channel

- Recall the AWGN channel

$$y[m] = x[m] + w[m]$$

  - $SNR = \frac{E[|x[m]|^2]}{E[|w[m]|^2]} = \frac{E_s}{N_0}$ depends only the transmit energy
- For BPSK signaling, $x[m] \in \{\pm\sqrt{E_s}\}$
  - $x[m]$ is detected by

$$\hat{x}[m] = \begin{cases} \sqrt{E_s}, & \Re\{y[m]\} \geq 0 \\ -\sqrt{E_s}, & \Re\{y[m]\} < 0 \end{cases}$$

  - The error probability is

$$P_e = Q\left(\frac{\sqrt{E_s}}{\sqrt{N_0/2}}\right) = Q\left(\sqrt{2SNR}\right) < e^{-SNR} \qquad Q(x) < e^{-x^2/2}$$

  - P_e decays exponentially in SNR
  - It demands SNR= 7 dB to have $P_e = 10^{-3}$

Coherent detection in fading channel

- In flat fading channel

$$y = hx + w$$

  - Rayleigh fading $h \sim CN(0,1)$
  - AWGN $w \sim CN(0,N_0)$
- Assume h is known at rx $\Rightarrow$ coherent detection

$$r = \frac{h^*}{|h|}y = |h|x + \frac{h^*}{|h|}w$$

  - The nose $h^*w/|h| \sim CN(0,N_0)$
- With BPSK signaling, the coherent detection is

$$\hat{x} = \begin{cases} \sqrt{E_s}, & \Re\{r\} \geq 0 \\ -\sqrt{E_s}, & \Re\{r\} < 0 \end{cases}$$

Average error probabilities over Rayleigh fading channels (1)

- For a given channel h, the error probability is

$$P_{e|h} = Q\left(\frac{\sqrt{E_s}|h|}{\sqrt{N_0/2}}\right) = Q\left(\sqrt{2|h|^2 SNR}\right)$$

- In Rayleigh fading, $|h|^2$ is exponential with $\mathbf{E}[|h|^2]=1$
- The average error probability is

$$\begin{aligned}
P_e &= \int_0^\infty Q(\sqrt{2uSNR})e^{-u}du \\
&= \frac{1}{\sqrt{2\pi}}\int_0^\infty \int_{\sqrt{2uSNR}}^\infty e^{-\frac{t^2}{2}} e^{-u} dt du \\
&= \frac{1}{\sqrt{2\pi}}\int_0^\infty \int_0^{\frac{t^2}{2SNR}} e^{-u} e^{-\frac{t^2}{2}} du dt \\
&= \frac{1}{\sqrt{2\pi}}\int_0^\infty \left(1 - e^{-\frac{t^2}{2SNR}}\right) e^{-\frac{t^2}{2}} dt \\
&= \frac{1}{2} - \frac{1}{\sqrt{2\pi}}\int_0^\infty e^{-\frac{t^2(1+SNR)}{2SNR}} dt \\
&= \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{1+SNR}}\right)
\end{aligned}$$

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{t^2}{2}} dt$$

Average error probabilities over Rayleigh fading channels (2)

- For Rayleigh fading channel, the error probability is

$$P_e = \frac{1}{2}\left(1 - \sqrt{\frac{SNR}{1+SNR}}\right)$$

- At high SNR,

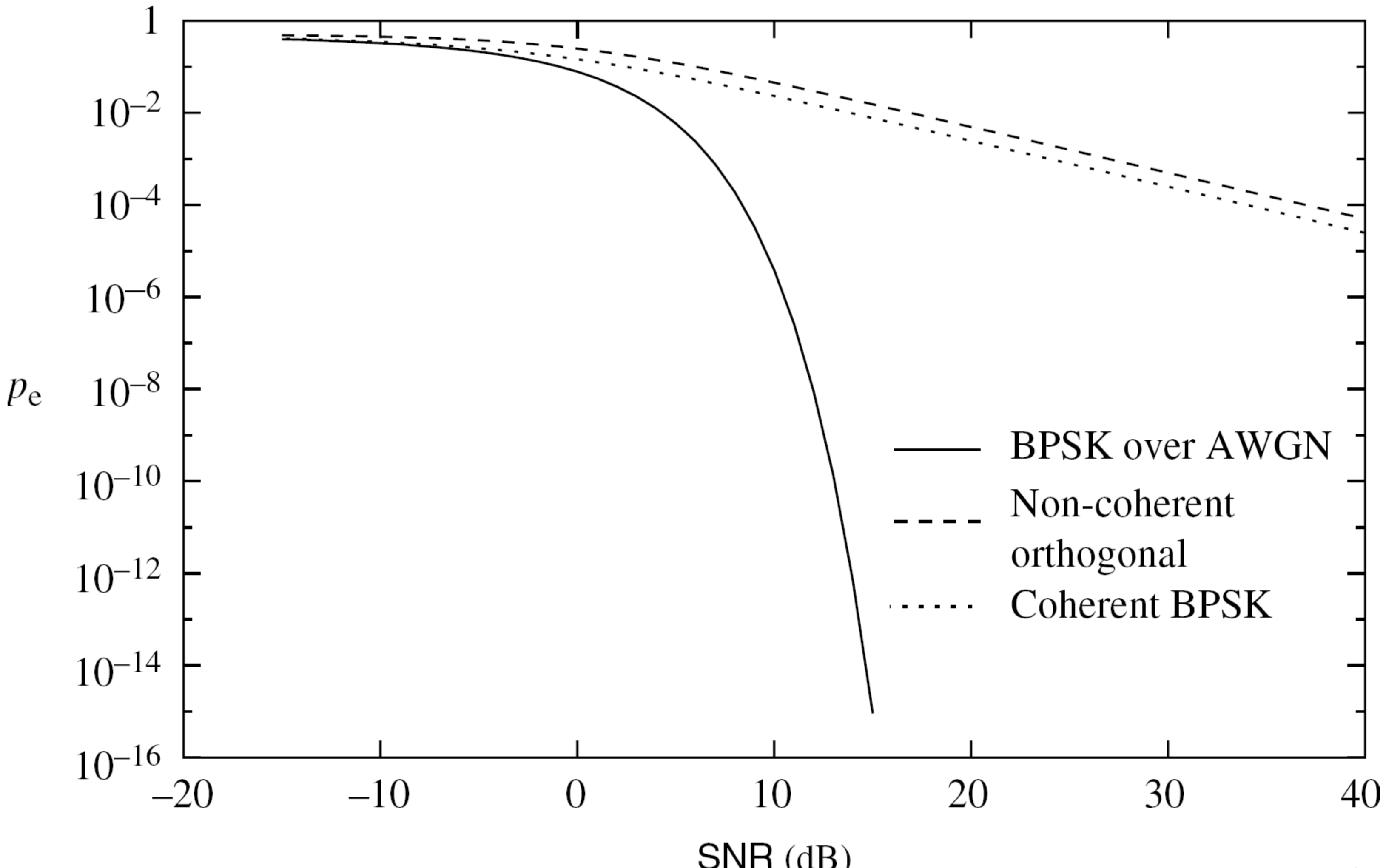
$$\sqrt{\frac{SNR}{1+SNR}} = 1 - \frac{1}{2SNR} + \mathcal{O}\left(\frac{1}{SNR^2}\right) \approx 1 - \frac{1}{2SNR}$$

$$\Rightarrow \boxed{P_e \approx \frac{1}{4SNR}}$$

  - P_e decays inversely with SNR
  - It demands SNR= 24 dB to have $P_e = 10^{-3}$

    $\Rightarrow$ 17 dB loss compared with AWGN

Average error probabilities over Rayleigh fading channels (3)



Outage probability for Rayleigh fading channels

- In flat fading channel

$$y = hx + w$$

- Given the channel h, the receive SNR is random,

$$\rho = \frac{E_s |h|^2}{N_0}$$

  - ρ is exponentially distributed with $\bar{\rho} = \frac{E_s}{N_0} = SNR$

- *Outage probability*(P_{out})
  - P_{out}=Pr{Channel is in deep fade}
  - P_{out}=Pr{SNR is dropped below a threshold ρ_{th}}

$$P_{out} = \Pr\{\rho < \rho_{th}\} = \int_0^{\rho_{th}} \frac{1}{\bar{\rho}} e^{-\rho/\bar{\rho}} d\rho = 1 - e^{-\rho_{th}/\bar{\rho}}$$

  - At high SNR, the outage probability is approximated by

$$P_{out} \approx \frac{\rho_{th}}{\bar{\rho}} = \frac{\rho_{th}}{SNR}$$ $\Rightarrow$ inversely proportional to SNR

Outline

2.1 Wireless channels

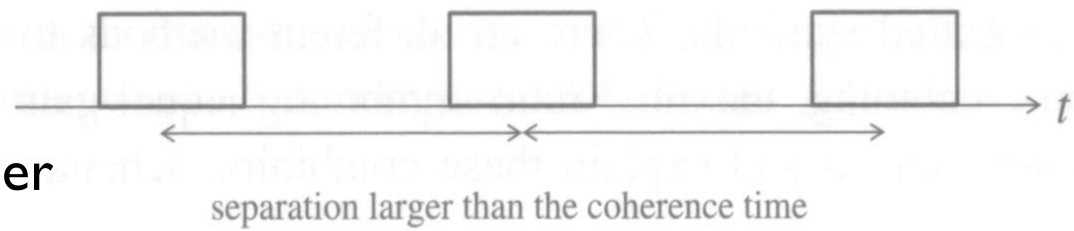
2.2 Outage probability and error probability over fading channels

2.3 Diversity Techniques

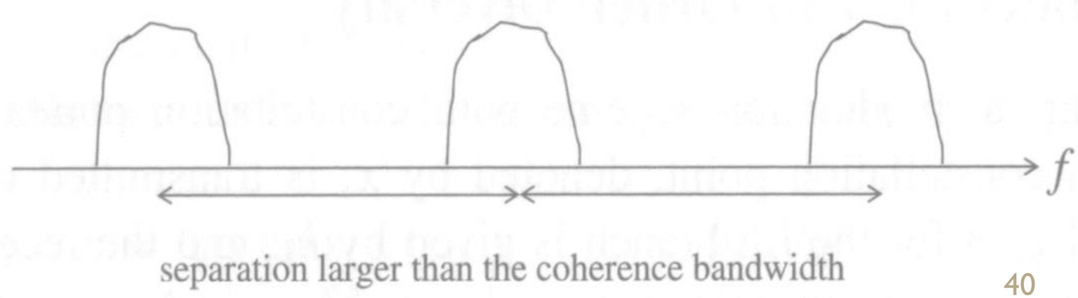
- 2.3.1 Diversity in time, frequency, and space domains
- 2.3.2 Maximal Ratio Combining
- 2.3.3 Selection Combining

Time/Frequency Diversity

- *Time Diversity*
  - Transmit the same signal several times in different time-slots
  - In slow fading, it takes a long time to transmit another replica



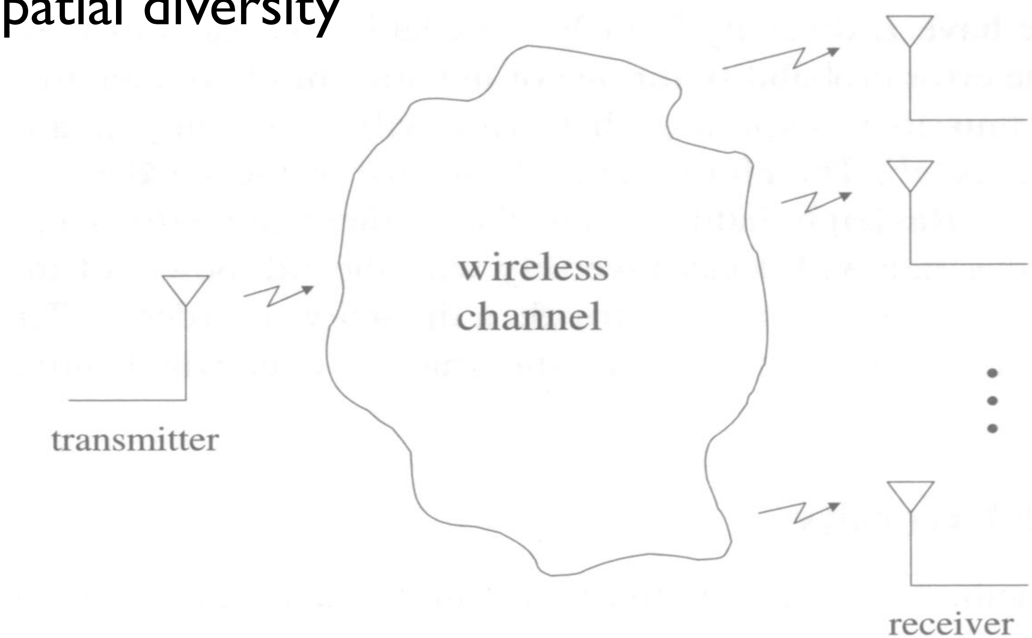
- *Frequency Diversity*
  - Transmit a few replicas over different frequency band
  - With delay spread = $200\mu s$, minimum frequency separation is 5KHz



Spatial Diversity

- "Space" can be used as a resource to provide diversity
- Assume that the rx has multiple antennas
  - Different replica of the signal are picked up at each signal
  - The separation between antennas is assumed at least $\lambda/2$
  - The received signals undergo <u>different channel fades</u>

  $\Rightarrow$ provide spatial diversity



System model of L^{th} order diversity

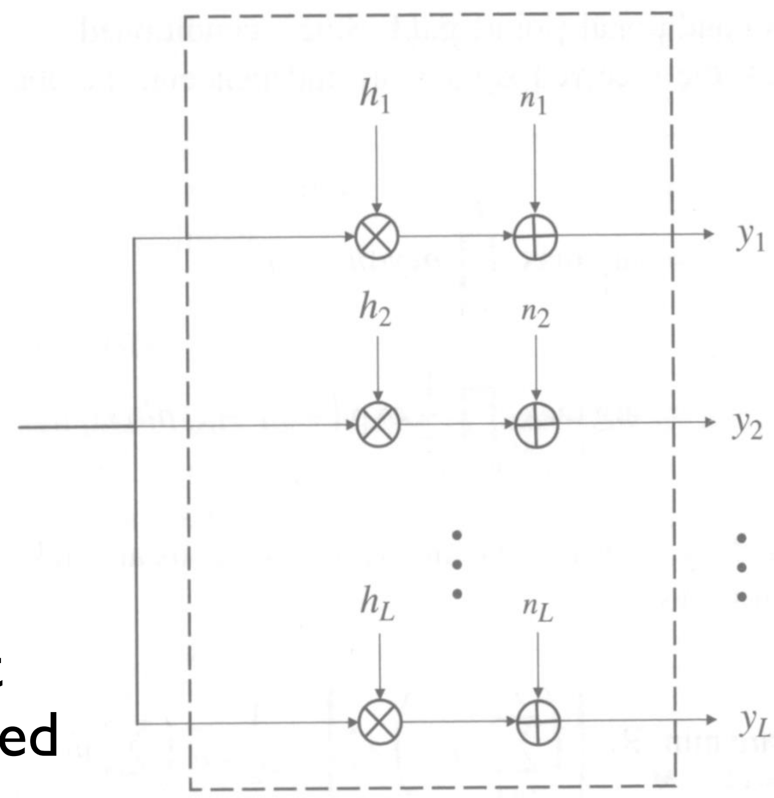
- Consider a BPSK symbol $x \in \{\pm\sqrt{E_s}\}$ is transmitted over L diversity branches

$$y_1 = h_1 x + w_1$$
$$y_2 = h_2 x + w_2$$
$$\vdots$$
$$y_L = h_L x + w_L$$

  - AWGN $w_l \sim CN(0,N_0)$
  - Rayleigh fading, $h_l \sim CN(0,1)$
  - SNR of the l^{th} branch

$$\rho_\ell = E_s |h_\ell|^2 / N_0$$

- Signals obtained thru different diversity branches are combined to detect the symbol x



Diversity Combining Methods

- Optimum combining:
  - Maximal Ratio Combining (MRC)
- Suboptimal combining:
  - Equal Gain Combining (EGC)
  - Selection Combining (SC)
  - Switch-and-Stay Combining (SSC)

- Diversity order

$$d = -\lim_{SNR \longrightarrow \infty} \frac{\log(P_e)}{\log(SNR)} \quad \textit{or} \quad d = -\lim_{SNR \longrightarrow \infty} \frac{\log(P_{out})}{\log(SNR)}$$

Maximal Ratio Combining (1)

- Assume that $\{h_1, h_2, \ldots, h_L\}$ are known at rx
- The maximal likelihood (ML) decision is

$$
\begin{aligned}
\hat{x} &= \arg \max_{x \in \{\pm\sqrt{E_s}\}} p(y_1, y_2, \cdots, y_L | x) \\
&= \arg \max_{x \in \{\pm\sqrt{E_s}\}} p(y_1|x) \times p(y_2|x) \times \cdots \times p(y_L|x) \\
&= \arg \max_{x \in \{\pm\sqrt{E_s}\}} \prod_{\ell=1}^{L} \frac{1}{\pi N_0} \exp\left(-\frac{|y_\ell - h_\ell x|^2}{N_0}\right) \\
&= \arg \min_{x \in \{\pm\sqrt{E_s}\}} \sum_{\ell=1}^{L} |y_\ell - h_\ell x|^2 \\
&= \arg \max_{x \in \{\pm\sqrt{E_s}\}} \sum_{\ell=1}^{L} 2\Re\{y_\ell h_\ell^* x^*\} - \sum_{\ell=1}^{L} |h_\ell|^2 |x|^2 \\
&= \arg \max_{x \in \{\pm\sqrt{E_s}\}} \Re\left\{\left(\sum_{\ell=1}^{L} y_\ell h_\ell^*\right) x^*\right\}
\end{aligned}
$$

Maximal Ratio Combining (2)

- Optimal decision rule:

$$\hat{x} = \arg \max_{x \in \{\pm\sqrt{E_s}\}} \Re\left\{ \left(\sum_{\ell=1}^{L} h_\ell^* y_\ell \right) x^* \right\}$$

  - Linearly combines the received signals after co-phasing and weighting them with the respective channel gains
  - The branches with better channel gains are emphasized more than others since they are more reliable
  - The resulting combining is maximal ratio combining (MRC)
- Effective channel model of MRC:

$$y = \sum_{\ell=1}^{L} h_\ell^* y_\ell = \left(\sum_{\ell=1}^{L} |h_\ell|^2 \right) x + w'$$

  - Noise $w' = \sum_\ell h_\ell^* w_\ell \sim CN(0, N_0 \sum_\ell |h_\ell|^2)$

Maximal Ratio Combining (3)

- SNR of L branches of diversity with MRC is

$$\rho_{eff} = \frac{\left(\sum_{\ell=1}^{L} |h_\ell|^2\right)^2 E_s}{\left(\sum_{\ell=1}^{L} |h_\ell|^2\right) N_0} = \sum_{\ell=1}^{L} \frac{E_s |h_\ell|^2}{N_0} = \sum_{\ell=1}^{L} \rho_\ell$$

  - ρ_{eff} is Chi-Square distributed with $2L$ degrees of freedom

$$p_{\rho_{eff}}(u) = \frac{u^{L-1} \exp(-\frac{u}{E_s/N_0})}{(E_s/N_0)^L (L-1)!}, \quad u > 0$$

Chi-Square Random Variable

Let $X_1, X_2, \ldots, X_n$ be i.i.d. Gaussian random variables, $X_i \sim CN(0,\sigma^2)$.
$X = X_1^2 + X_2^2 + \ldots + X_n^2$ is a Chi-Square r.v. with n degrees of freedom.
If $n = 2m$, the PDF and CDF of X are

PDF: $$p(x) = \frac{x^{m-1} \exp(-\frac{x}{2\sigma^2})}{(m-1)!(2\sigma^2)^m}, \quad x > 0$$

CDF: $$F(x) = 1 - \exp\left(-\frac{x}{2\sigma^2}\right) \sum_{k=0}^{m-1} \frac{1}{k!} \left(\frac{x}{2\sigma^2}\right)^k, \quad x > 0$$

Maximal Ratio Combining (4)

- Outage Probability with MRC

$$P_{out} = \Pr\{\rho_{eff} < \rho_{th}\}$$
$$= 1 - \exp\left(-\frac{\rho_{th}}{E_s/N_0}\right)\sum_{k=0}^{L-1}\frac{1}{k!}\left(\frac{\rho_{th}}{E_s/N_0}\right)^k$$

(ex) Let $x=\rho_{th}N_0/E_s$. At high SNR, $x\rightarrow 0$. Assume that $L=3$, and P_{out} is approximated by

$$P_{out} = 1 - e^{-x}\left(1 + x + \frac{x^2}{2}\right)$$
$$= 1 - \left(1 - x + \frac{x^2}{2!} - \frac{x^3}{3!} + \mathcal{O}(x^4)\right)\left(1 + x + \frac{x^2}{2!}\right)$$
$$= x^3/3! + \mathcal{O}(x^4)$$
$$\approx \left(\frac{\rho_{th}}{E_s/N_0}\right)^3/3! \propto (E_s/N_0)^{-3}$$

- Outage probability decays with $1/(SNR)^L$

Maximal Ratio Combining (5)

- Average error probability with MRC

$$P_{e,MRC} = \int_0^\infty Q\left(\sqrt{2u}\right) p_{\rho_{eff}}(u)du$$
$$= \frac{1}{\sqrt{2\pi}} \int_0^\infty \int_{\sqrt{2u}}^\infty e^{-\frac{t^2}{2}} p_{\rho_{eff}}(u)dtdu$$
$$= \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-\frac{t^2}{2}} \int_0^{t^2/2} p_{\rho_{eff}}(u)dudt$$
$$= \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-\frac{t^2}{2}} \left(1 - \exp\left(-\frac{t^2/2}{E_s/N_0}\right) \sum_{k=0}^{L-1} \frac{1}{k!} \left(\frac{t^2/2}{E_s/N_0}\right)^k\right) dt$$
$$= \frac{1}{2} - \sum_{k=0}^{L-1} \frac{1}{\sqrt{2\pi}} \int_0^\infty e^{-\frac{t^2}{2}\frac{E_s+N_0}{E_s}} \frac{1}{k!} \left(\frac{t^2/2}{E_s/N_0}\right)^k dt$$
$$= \frac{1}{2} - \frac{1}{2} \sum_{k=0}^{L-1} \frac{1}{k!} \left(\frac{N_0}{2E_s}\right)^k \frac{1}{\sqrt{2\pi}} \int_{-\infty}^\infty e^{-\frac{t^2}{2}\frac{E_s+N_0}{E_s}} t^{2k} dt$$
$$= \frac{1}{2} - \frac{1}{2} \left(\frac{E_s}{E_S + N_0}\right) \sum_{k=0}^{L-1} \left(\frac{N_0}{E_S + N_0}\right)^k \frac{(2k)!}{4^k k! k!}$$

For $X \sim N(0,1)$
$$\mathbf{E}[X^{2k}] = \frac{(2k)!}{2^k k!}$$

Hard to obtain diversity order

Maximal Ratio Combining (6)

- To study the behavior of average error probability, use the upper bound on Q-function

$$Q(x) \le \tfrac{1}{2} e^{-x^2/2}$$

- $P_{e,MRC} = \int_0^\infty Q\left(\sqrt{2u}\right) p_{\rho_{eff}}(u) du$

$$\le \frac{1}{2}\int_0^\infty e^{-u} \frac{u^{L-1}\exp(-\frac{u}{E_s/N_0})}{(E_s/N_0)^L (L-1)!} du$$

$$= \frac{1}{2(E_s/N_0)^L (L-1)!}\int_0^\infty u^{L-1} \exp\left(-\frac{u(E_s+N_0)}{E_s}\right) du$$

$$= \frac{1}{2(E_s/N_0)^L (L-1)!} \frac{(L-1)!}{\left(\frac{E_s+N_0}{E_s}\right)^L}$$

$$= \frac{1}{2}\left(1+(E_s/N_0)\right)^{-L} \le \tfrac{1}{2}(E_s/N_0)^{-L}$$

$$\int_0^\infty u^k e^{-au} du = \frac{k!}{a^{k+1}}$$

- Average error probability decays with SNR^{-L}

Selection Combining (1)

- At any time interval, one branch with largest SNR is used in demodulation

$$k = \arg \max_{\ell=1,\cdots,L} \frac{E_s |h_\ell|^2}{N_0} = \arg \max_{\ell=1,\cdots,L} |h_\ell|$$

$\Rightarrow$ *Selection combining (SC)*

- The selected signal is

$$y = h_k x + n_k$$

- The effective SNR of selection combining is

$$\rho_{eff} = \max_{\ell=1,\cdots,L} \frac{E_s |h_\ell|^2}{N_0} = \frac{E_s}{N_0} \left(\max_{\ell=1,\cdots,L} |h_\ell|^2 \right)$$

Selection Combining (2)

- CDF of ρ_{eff}

$$
\begin{aligned}
F_{\rho_{eff}}(u) &= Pr\{\tfrac{E_s}{N_0}\max_\ell |h_\ell|^2 \le u\} \\
&= Pr\{\max(|h_1|^2, |h_2|^2, \cdots, |h_L|^2) \le \tfrac{uN_0}{E_s}\} \\
&= Pr\{|h_1|^2 \le \tfrac{uN_0}{E_s}, |h_2|^2 \le \tfrac{uN_0}{E_s}, \cdots, |h_L|^2 \le \tfrac{uN_0}{E_s}\} \\
&= \textstyle\prod_{i=1}^{L} Pr\{|h_i|^2 \le \tfrac{uN_0}{E_s}\} \\
&= \left(1 - \exp(-\tfrac{uN_0}{E_s})\right)^L
\end{aligned}
$$

- PDF of ρ_{eff}

$$
\begin{aligned}
p_{\rho_{eff}}(u) &= \tfrac{\partial}{\partial u} F_{\rho_{eff}}(u) = \tfrac{\partial}{\partial u}\left(1 - \exp(-\tfrac{uN_0}{E_s})\right)^L \\
&= \tfrac{L}{E_s/N_0}\exp(-\tfrac{u}{E_s/N_0})\left(1 - \exp(-\tfrac{u}{E_s/N_0})\right)^{L-1}
\end{aligned}
$$

Selection Combining (3)

- Outage probability of selection combining

$$P_{out,SC} = Pr\{\rho_{eff} < \rho_{th}\} = F_{\rho_{eff}}(\rho_{th})$$
$$= \left(1 - \exp(-\frac{\rho_{th}}{E_s/N_0})\right)^L$$

- At high SNR,

$$P_{out,SC} \approx \left(\frac{\rho_{th}}{E_s/N_0}\right)^L$$

  - Outage probability decays with $(E_s/N_0)^{-L}$

Selection Combining (4)

- Average error probability of selection combining

$$P_{e,SC} = \int_0^\infty Q\left(\sqrt{2u}\right) p_{\rho_{eff}}(u)du$$

$$\leq \int_0^\infty \tfrac{1}{2}e^{-u} p_{\rho_{eff}}(u)du$$

$$= \int_0^\infty \tfrac{1}{2}e^{-u} \tfrac{L}{E_s/N_0} \exp(-\tfrac{u}{E_s/N_0}) \left(1 - \exp(-\tfrac{u}{E_s/N_0})\right)^{L-1} du$$

  - At high SNR, ($1 - e^{-x} \approx x$)

$$\approx \int_0^\infty \tfrac{1}{2}e^{-u} \tfrac{L}{E_s/N_0} \exp(-\tfrac{u}{E_s/N_0}) \left(\tfrac{u}{E_s/N_0}\right)^{L-1} du$$

$$= \tfrac{L}{2(E_s/N_0)^L} \int_0^\infty \exp(-\tfrac{u(E_s+N_0)}{E_s}) u^{L-1} du$$

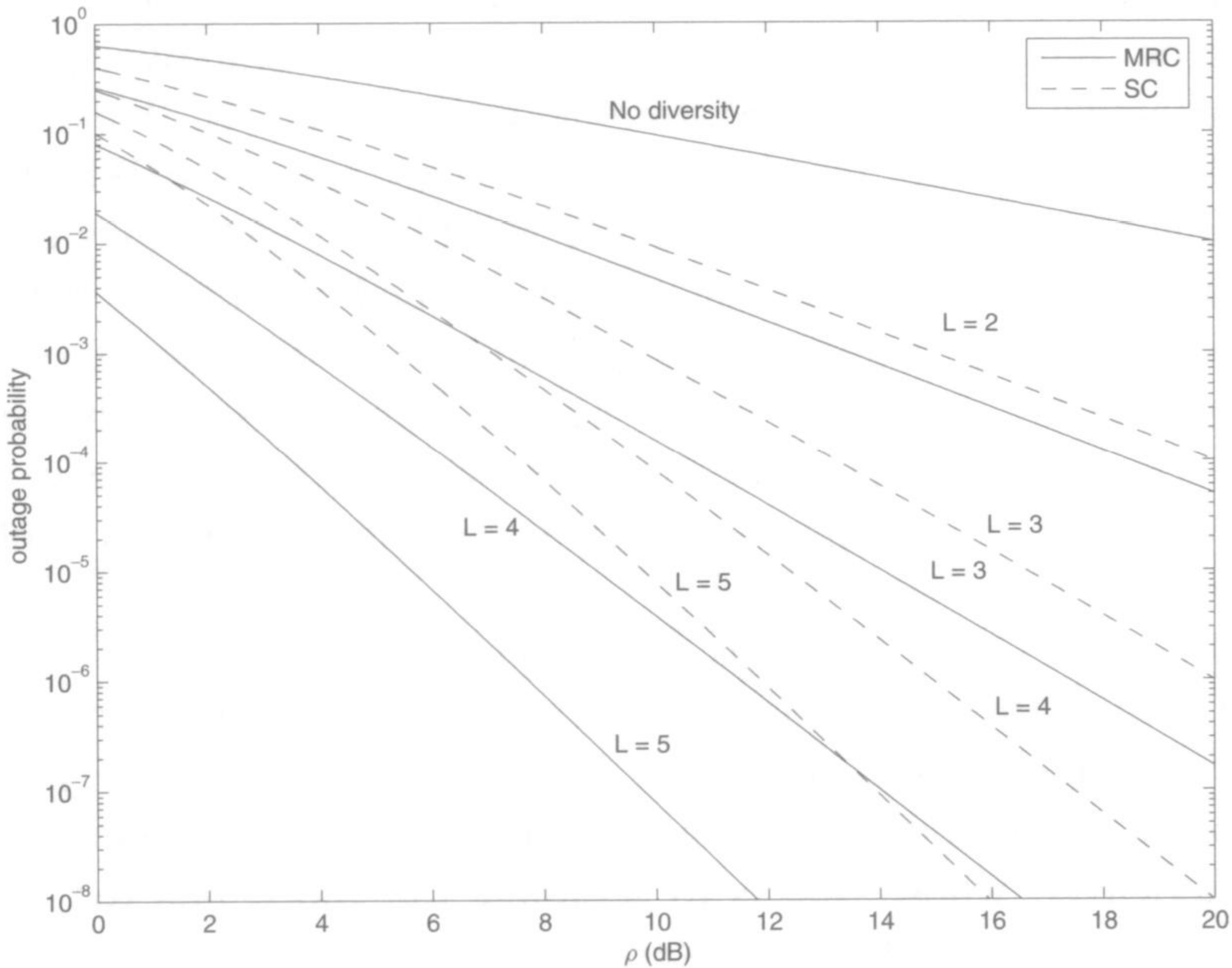
$$= \tfrac{L}{2(E_s/N_0)^L} (L-1)! \left(\tfrac{E_s/N_0}{1+E_s/N_0}\right)^L$$

$$= \tfrac{L!}{2} (1 + E_s/N_0)^{-L} \approx \tfrac{L!}{2} (E_s/N_0)^{-L}$$

$$\int_0^\infty u^k e^{-au} du = \frac{k!}{a^{k+1}}$$

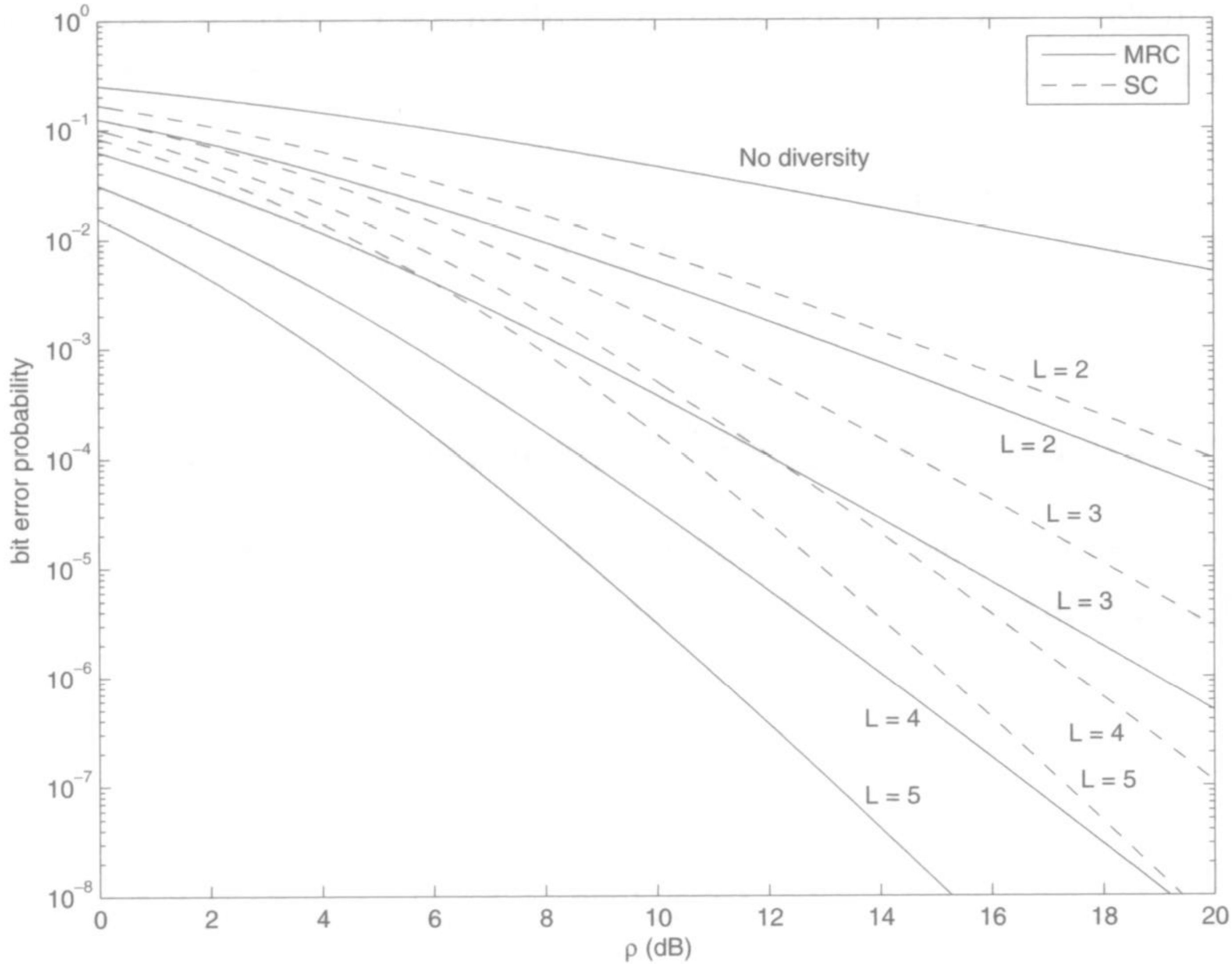
  - Average error probability decays with $(E_s/N_0)^{-L}$

MRC v.s. SC (1)



MRC
SC
No diversity
L = 2
L = 3
L = 3
L = 4
L = 4
L = 5
L = 5
outage probability
ρ (dB)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
2
4
6
8
10
12
14
16
18
20

MRC v.s. SC (2)

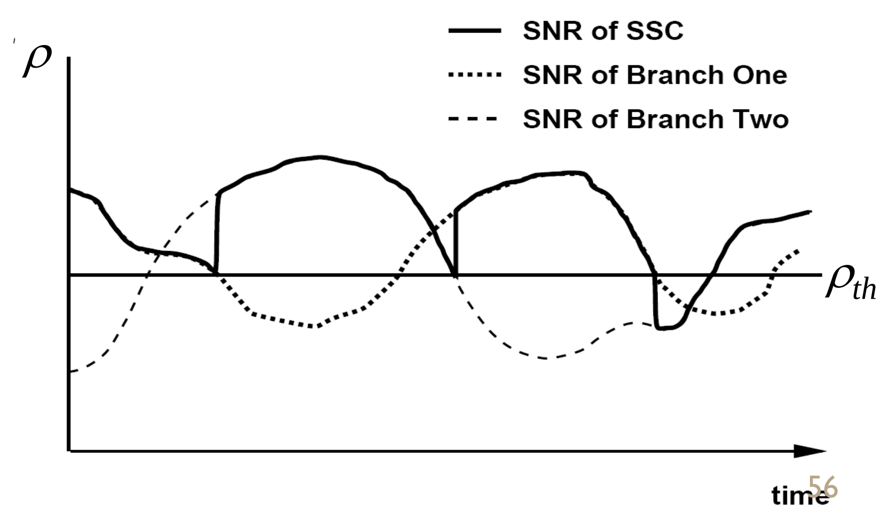


MRC
SC
No diversity
L = 2
L = 2
L = 3
L = 3
L = 4
L = 4
L = 5
L = 5
bit error probability
ρ (dB)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
0
2
4
6
8
10
12
14
16
18
20

Switch and Stay Combining

- Selection combining can achieve full diversity by switching to the branch with largest SNR
  - May require switch operations frequently
- *Switch and Stay Combining (SSC)*
  1. Rx switches to the branch with largest SNR and stays
  2. When the SNR of the selected branch drops below ρ_{th}, switch to the other branch with highest SNR
- Outage probability

$$P_{out,SSC} = \prod_{\ell=1}^{L} Pr(\rho_\ell < \rho_{th})$$
$$= \left(1 - \exp(-\frac{\rho_{th}}{E_s/N_0})\right)^L$$
$$= P_{out,SC}$$



Equal Gain Combining

- *Equal Gain Combining (EGC)*: simply co-phase and combine all branches of signals with equal gain

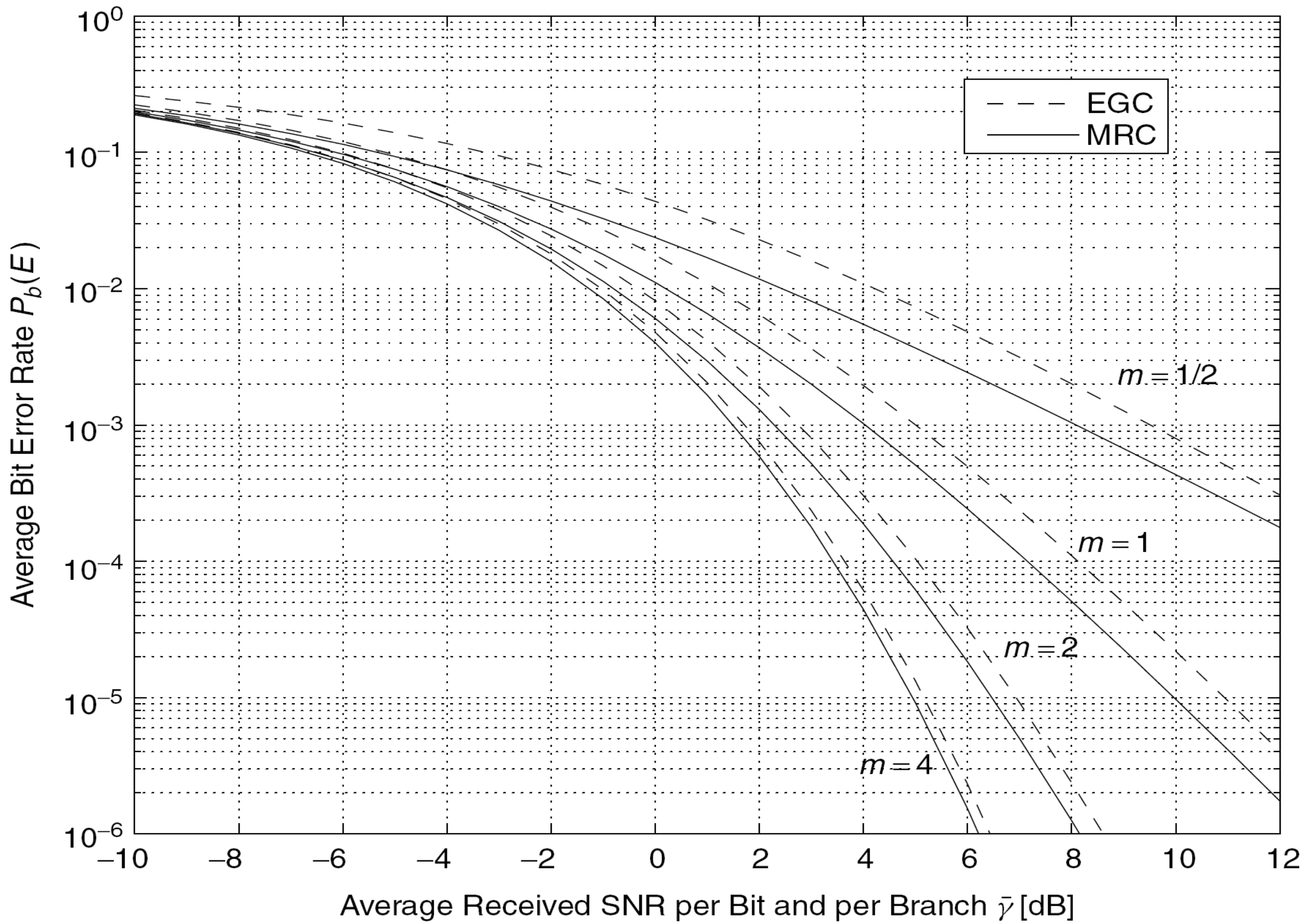
$$y = \sum_{\ell=1}^{L} \frac{h_\ell^*}{|h_\ell|} y_\ell = \left(\sum_{\ell=1}^{L} |h_\ell| \right) x + w'$$

  - AWGN $w' \sim CN(0, LN_0)$
- Effective SNR of EGC

$$\rho_{eff} = \frac{E_s}{LN_0} \left(\sum_{\ell=1}^{L} |h_\ell| \right)^2$$

- BER Performance is comparable to MRC within 1dB

Average BER over Nakagami-*m fading channels with MRC and* EGC (*L = 4*).



References