Wireless Communications (ITC731)

Lecture Note 6

9-April-2013

Prof. Young-Chai Ko

Summary

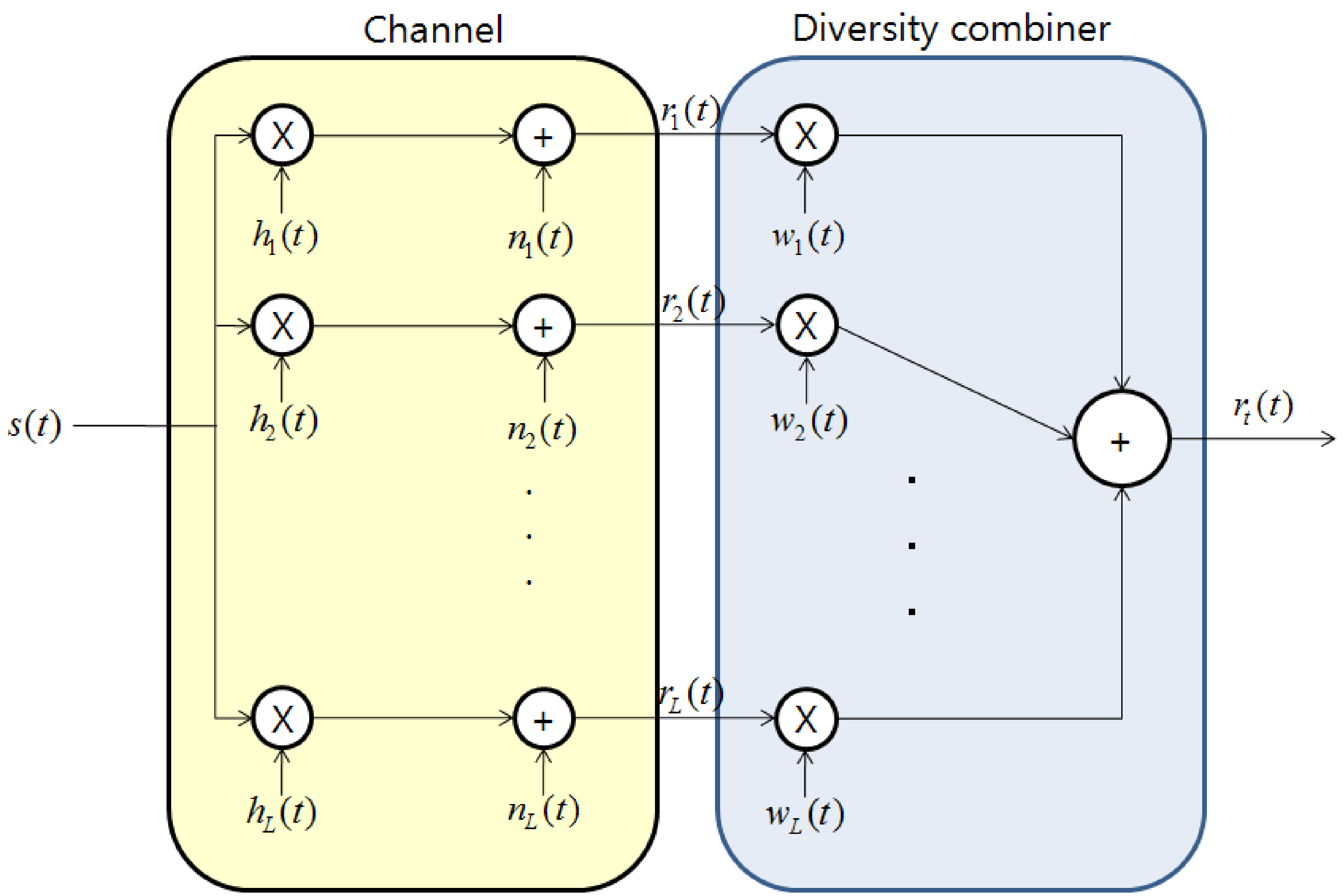
- Receive diversity
  - Maximal ratio combining
  - Equal gain combining
  - Selection combining
  - Switched combining
- Transmit diversity
  - Channel known at the transmitter
  - Channel unknown at the transmitter
- Transmit-Receive diversity
- Multi-user diversity

Receiver Diversity

- Maximal ratio combining
- Equal gain combining
- Selection combining
- Switched combining

Linear Receiver Antenna Diversity Combining

- Block diagram



Combined received signal

$$r_t(t) = \sum_{l=1}^{L} w_l(t) r_l(t)$$

$$= \sum_{l=1}^{L} w_l(t)(h_l(t)s(t) + n_l(t))$$

Maximal Ratio Combining

- MRC maximizes the received signal-to-noise ratio.
  - What is the optimum weight vector to maximize the SNR of the combined signal $r_t(t)$?
- Optimum weight vector

$$r_t(t) \quad = \quad \sum_{l=1}^{L} w_l r_l(t) = \sum_{l=1}^{L} w_l h_l(t) s(t) + \sum_{l=1}^{L} w_l n_l((t)$$

  - Combined output SNR

$$\gamma_t = \frac{|\sum_{l=1}^{L} w_l h_l|^2 E_s}{\sum_{l=1}^{L} |w_l|^2 N_0} = \frac{E_s}{N_0} \frac{|\sum_{l=1}^{L} w_l h_l|^2}{\sum_{l=1}^{L} |w_l|^2}$$

  - Cauchy-Schwartz inequality

$$\left| \sum_{l=1}^{L} w_l h_l \right|^2 \leq \left| \sum_{l=1}^{L} w_l \right|^2 \left| \sum_{l=1}^{L} h_l \right|^2$$

Equality hold iff $w_l = c h_l^*(t)$ with an arbitrary constant value of c.

- Using the optimal weight vector, we have

$$\gamma_t \leq \frac{E_s}{N_0} \sum_{l=1}^{L} |h_l|^2 = \frac{E_s}{N_0} \sum_{l=1}^{L} \alpha_l^2 = \sum_{l=1}^{L} \gamma_l$$

where $\gamma_l = \dfrac{\Omega_l E_s}{N_0}$, that is, SNR at each branch.

- Maximal ratio combining

$$\gamma_t = \sum_{l=1}^{L} \gamma_l$$

$$w_l = c h_l^*(t) \text{ for an arbitrary constant value of } c$$

Received Output SNR of MRC

- Received output SNR of MRC

$$\gamma_t = \sum_{l=1}^{L} \gamma_l$$

  - Average received output SNR

$$\bar{\gamma}_t = \sum_{l=1}^{L} \bar{\gamma}_l$$

    - If $\Omega_l = \Omega$ for $l = 1, \ldots, L$ (identical channels) and hence , $\bar{\gamma}_l = \bar{\gamma}$

$$\bar{\gamma}_t = L\bar{\gamma}$$

Average BER/SER of MRC

- Average BER/SER

$$P(e) = \int_0^\infty P(e|\gamma_t) p_{\gamma_t}(\gamma_t) d\gamma_t$$

  - For example for BPSK,

$$P(e|\gamma_t) = Q\left(\sqrt{2\gamma_t}\right) = Q\left(\sqrt{2\sum_{l=1}^{L}\gamma_l}\right)$$

  - or it can be written as

$$P(e) = \underbrace{\int_0^\infty \cdots \int_0^\infty}_{L\text{-fold}} P(e|\gamma_1, \cdots, \gamma_L) p_{\gamma_1, \cdots, \gamma_L}(\gamma_1, \cdots, \gamma_L)\, d\gamma_1 \cdots d\gamma_L$$

  - For independent channels,

$$p_{\gamma_1, \cdots, \gamma_L}(\gamma_1, \cdots, \gamma_L) = \prod_{l=1}^{L} p_{\gamma_l}(\gamma_l)$$

- Note that

$$
\begin{aligned}
Q(\sqrt{2\gamma_t}) &= Q\left(\sqrt{2\sum_{l=1}^{L}\gamma_l}\right) \\
&= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \exp\left[-\frac{\sum_{l=1}^{L}\gamma_l}{\sin^2\phi}\right] d\phi \\
&= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \prod_{l=1}^{L} \exp\left[-\frac{\gamma_l}{\sin^2\phi}\right] d\phi
\end{aligned}
$$

- Average BER of BPSK using MRC

$$
\begin{aligned}
P(e) &= \int_0^{\infty}\cdots\int_0^{\infty}\frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{l=1}^{L}\exp\left[-\frac{\gamma_l}{\sin^2\phi}\right]\prod_{l=1}^{L}p_{\gamma_l}(\gamma_l)d\gamma_1\cdots d\gamma_L \\
&= \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\left\{\int_0^{\infty} e^{-\frac{\gamma_1}{\sin^2\phi}}p_{\gamma_1}(\gamma_1)d\gamma_1\cdots\int_0^{\infty} e^{-\frac{\gamma_L}{\sin^2\phi}}p_{\gamma_L}(\gamma_L)\,d\gamma_L\right\} \\
&= \frac{1}{\pi}\int_0^{\frac{\pi}{2}}\prod_{l=1}^{L}M_{\gamma_l}\left(-\frac{1}{\sin^2\phi}\right)\,d\phi
\end{aligned}
$$

- For i.i.d. Rayleigh channels, MGF of SNR at each branch is given as

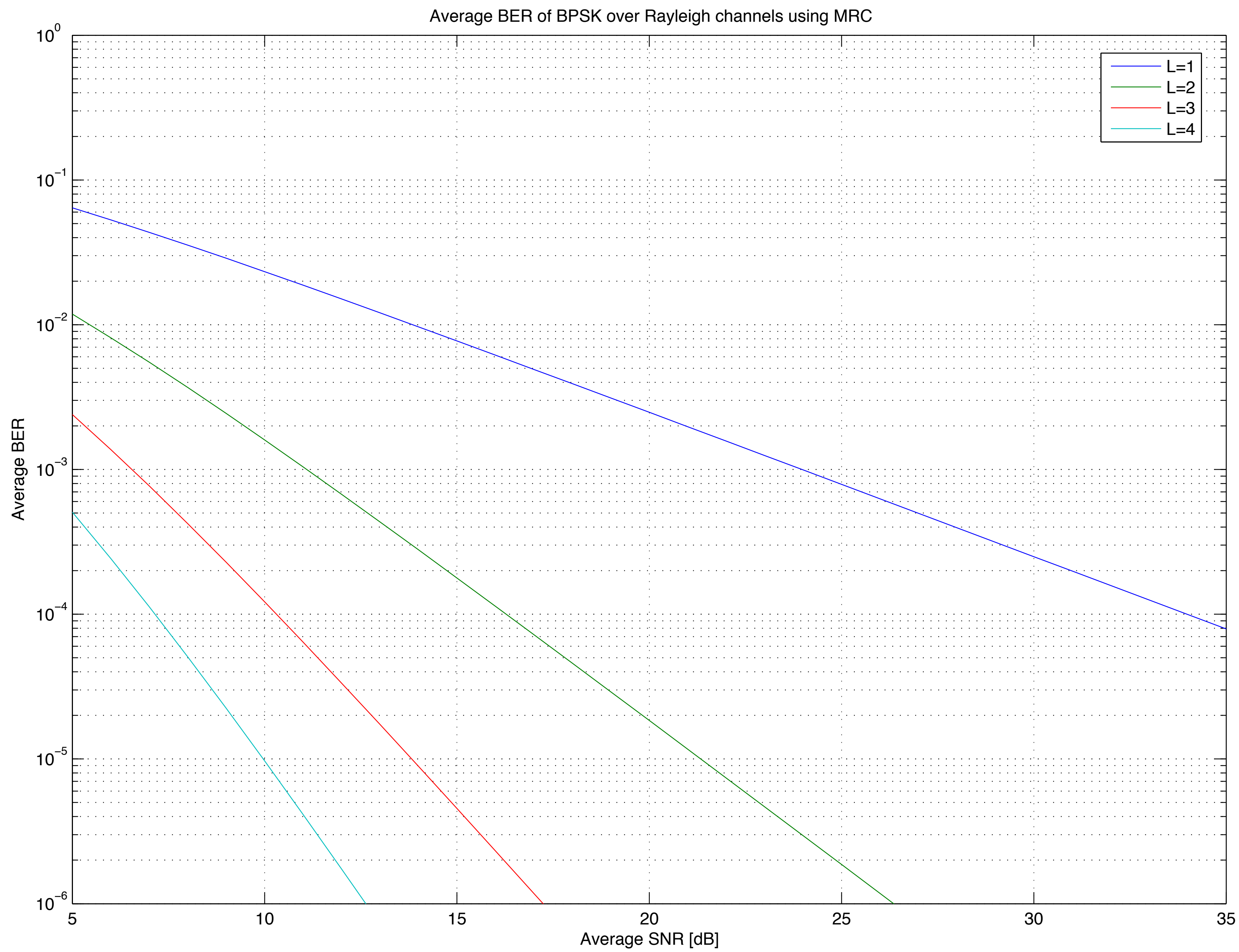
$$M_{\gamma_l}(s) = (1-\bar{\gamma}s)^{-1}$$

  - Then BER of MRC over Rayleigh channels is

$$\begin{aligned} P(e) &= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left(1+\frac{\bar{\gamma}}{\sin^2\phi}\right)^{-L} d\phi \\ &= \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left(\frac{\sin^2\phi}{\sin^2\phi+\bar{\gamma}}\right)^{L} d\phi \\ &= I_L(\bar{\gamma}) \\ &= \frac{1}{2} - \left(\frac{1}{2}-A(\bar{\gamma})\right)\sum_{l=0}^{L}\binom{2l}{l}\cdot (A(\bar{\gamma}))^l(1-A(\bar{\gamma}))^l \end{aligned}$$

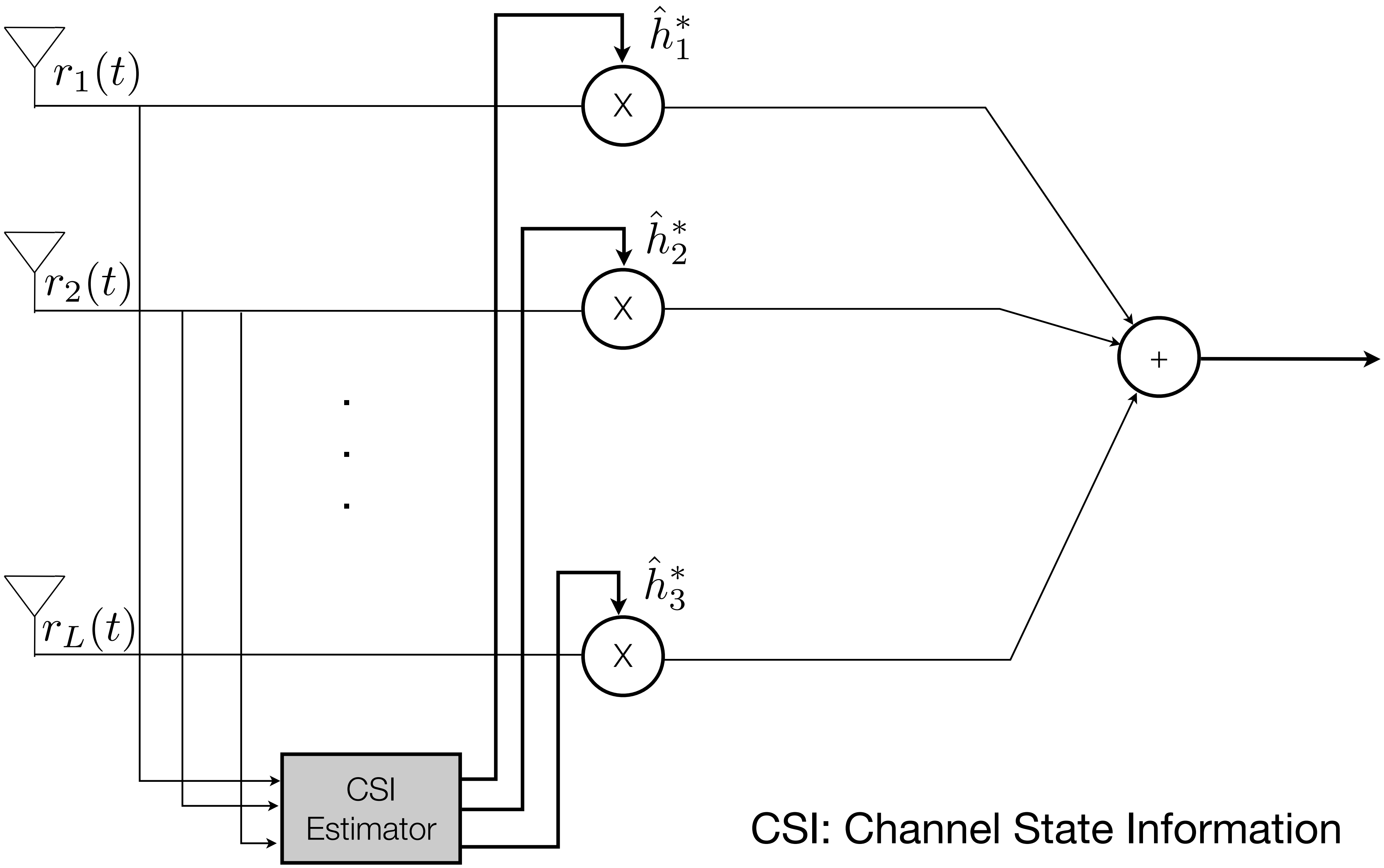
where $A(\bar{\gamma}) = \frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}}{1+\bar{\gamma}}}\right]$

BER of BPSK over Rayleigh Channels using MRC



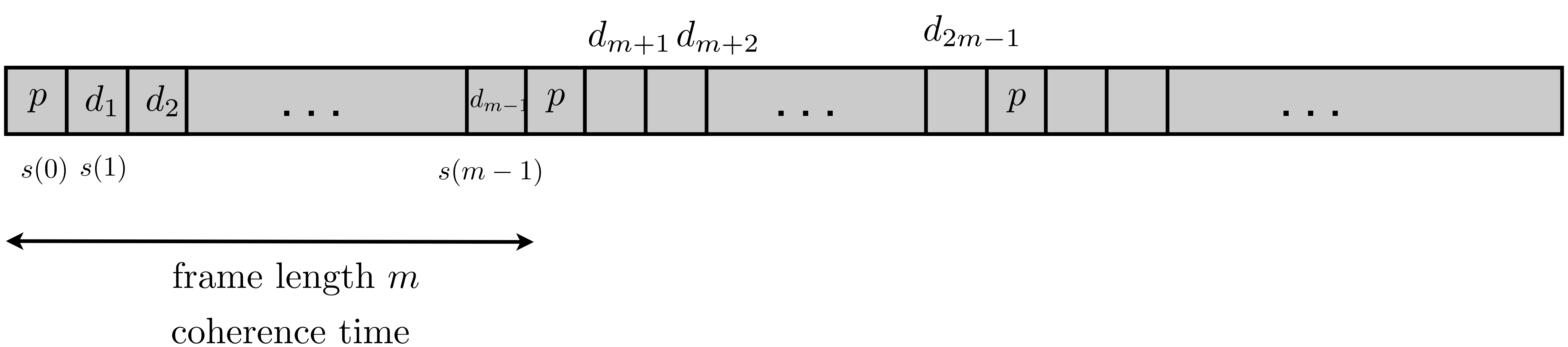
Channel Estimation

- MRC requires channel estimation at every diversity branch.



CSI: Channel State Information

- How does CSI estimator work?
  - Popular channel estimation
    - Pilot symbol assisted modulation (PSAM)
    - Idea of PSAM: Insert known symbols (pilots) into the stream of useful information symbols.



- Discrete-time received signal

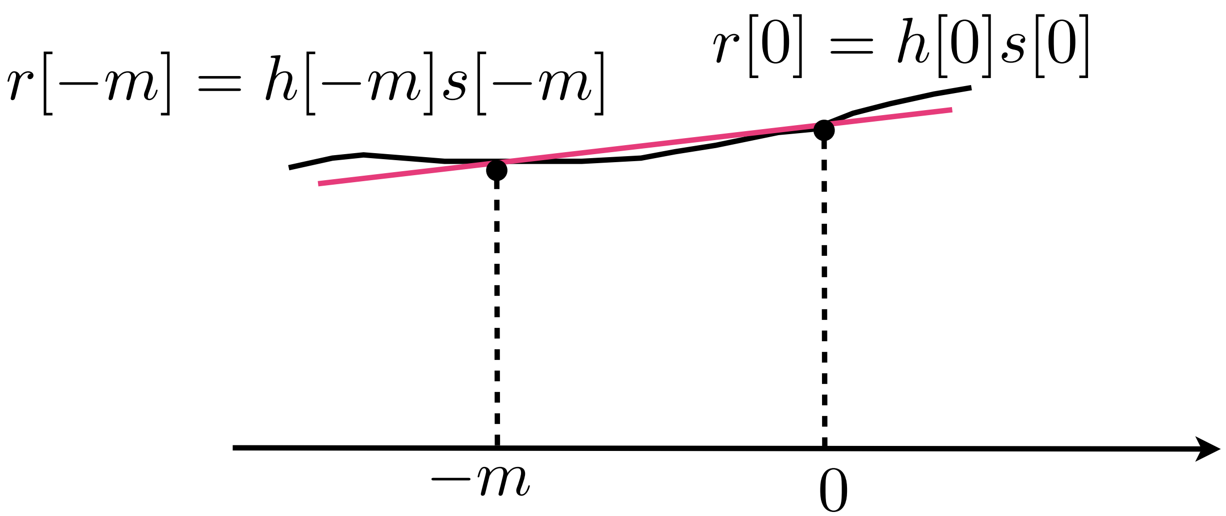
$$r[k] = h[k]s[k] + n[k]$$

  - Without loss of generality, we can write
    - $s[km]$: pilot signal for k integer.
    - Surrounded by information data $s[k]$ for $-\lfloor \frac{M}{2} \rfloor \leq k \leq \lfloor \frac{M}{2} \rfloor$

- Estimation approach
  - Simple approach (Linear regression)
  - Optimal approach

Channel Estimation using Linear Regression

Let us ignore the effect of noise.



$$\hat{h}[k] = \left(\frac{ph[0] - ph[-m]}{0 - (-m)}(k - 0) + ph[0] \right) \cdot \frac{1}{p}$$

$$\hat{h}[k] = \frac{k}{m}(h[0] - h[-m]) + h[0], \quad \text{for } -m+1 \le k \le -1$$

$$\hat{h}[k] = \frac{k}{m}(h[1] - h[0]) + h[1], \quad \text{for } -1 \le k \le m-1$$

.
.
.

Channel Estimation using Optimal Approach

- $\hat{h}[k]$: weighted sum of the surrounding K+1 received pilots

$$\hat{h}[k] = \sum_{i=-\lfloor \frac{K}{2} \rfloor}^{\lfloor \frac{K}{2} \rfloor} \lambda(i,k) r(im)$$

$\lambda(i,k)$: weighted depends on the symbol portion k within the frame length m.

- Optimal approach: find $\lambda(i,k)$ to minimize the variance of channel estimation error such that

$$\begin{aligned} \sigma_\epsilon^2 &= E[\epsilon^2[k]] \\ &= E\left[|h[k] - \hat{h}[k]|^2 \right] \\ &= E\left[|h[k] - \sum_{i=-\lfloor \frac{K}{2} \rfloor}^{\lfloor \frac{K}{2} \rfloor} \lambda(i,k) r(im)|^2 \right] \end{aligned}$$

$$\lambda_{\text{opt}}(i,k) = \min_{\lambda(i,k)} \sigma_\epsilon^2$$

- Solution

$$\frac{\partial \sigma_\epsilon^2}{\partial \lambda(i,k)} = 0 \quad \text{for } \lfloor -\frac{K}{2} \rfloor \le i \le \lfloor \frac{K}{2} \rfloor$$

That is,

$$\begin{aligned} \frac{\partial \sigma_\epsilon^2}{\partial \lambda(\lfloor -\frac{K}{2} \rfloor, k)} &= 0 \\ \frac{\partial \sigma_\epsilon^2}{\partial \lambda(\lfloor -\frac{K}{2} + 1 \rfloor, k)} &= 0 \\ &\vdots \\ \frac{\partial \sigma_\epsilon^2}{\partial \lambda(\lfloor \frac{K}{2} \rfloor, k)} &= 0 \end{aligned} \quad \Longrightarrow \quad K+1 \text{ equations}$$

and note that

$$\frac{\partial \sigma_\epsilon^2}{\partial \lambda(i,k)} = 2E\left[(h^*[k] - \sum_{j=-\lfloor \frac{K}{2} \rfloor}^{\lfloor \frac{K}{2} \rfloor} \lambda(i,k) r[im] \right] = 0 \quad \text{for } \lfloor -\frac{K}{2} \rfloor \le i \le \lfloor \frac{K}{2} \rfloor$$

- We can simply write the above K+1 equations in matrix form such as

$$\begin{bmatrix} R_{rr}(0) & R_{rr}(1) & \cdots & R_{rr}(k) \\ R_{rr}(1) & R_{rr}(2) & \cdots & R_{rr}(k-1) \\ \vdots & & \vdots & \\ R_{rr}(k) & R_{rr}(k-1) & \cdots & R_{rr}(0) \end{bmatrix} \begin{bmatrix} \lambda\left(\left\lfloor -\frac{K}{2} \right\rfloor, k\right) \\ \lambda\left(\left\lfloor -\frac{K}{2} \right\rfloor + 1, k\right) \\ \vdots \\ \lambda\left(\left\lfloor \frac{K}{2} \right\rfloor, k\right) \end{bmatrix} = \begin{bmatrix} R_{h^*r}\left(-\left\lfloor K2 \right\rfloor, k\right) \\ R_{h^*r}\left(-\left\lfloor K2 \right\rfloor + 1, k\right) \\ \vdots \\ R_{h^*r}\left(\left\lfloor K2 \right\rfloor, k\right) \end{bmatrix}$$

where $R_{rr}(i,j) = E[r[im] \cdot r[jm]] = R(|i-j|)$

$$R_{h^*r}\left(\lfloor \frac{K}{2} + n \rfloor, k\right) = \sum_{j=-\lfloor \frac{K}{2} \rfloor}^{\lfloor \frac{K}{2} \rfloor} \lambda(j,k) R_{rr}(\lfloor \frac{K}{2} + n - j \rfloor)$$

$$\begin{aligned} R_{h^*r} &= E\left[h^*[k] r[im]\right] \\ &= E\left[h^*[k](h[im]\overbrace{s[jm]}^{=p} + n[jm])\right] \\ &= E[h^*[k]h[jm]]p \\ &= pJ_0(2\pi f_m |k - jm|) \end{aligned}$$

Now straightforward to solve for $\lambda(i,k)$.

13년 4월 8일 월요일

Other Linear Diversity Combining

- Combining Schemes
  - Equal gain combining (EGC)
  - Selection combining (SC)
  - Switched and stay combining (SSC)
- Most of performance evaluation can be computed by MGF approach while PDF based approach is not often feasible.

Equal Gain Combining

- Let us rewrite the channel gain as

$$h_l(t) = \alpha_l(t) e^{j\theta_l(t)}$$

- Then, EGC compensates only the phase distortion of the channel so that the weight is given as

$$w_l = e^{-j\theta_l(t)}$$

$$r_c(t) = [r_1(t) \;\; r_2(t) \;\; \cdots r_L(t)] \cdot [w_1 \;\; w_2 \;\; w_L]$$

$$= s(t) \sum_{l=1}^{L} \alpha_l + \sum_{n=1}^{L} e^{-j\theta_l(t)} n_l(t)$$

Combined output SNR of EGC

$$\gamma_{\mathrm{EGC}} = \frac{\left(\sum_{l=1}^{L} \alpha_l\right)^2 E_s}{\sum_{l=1}^{L} N_l}$$

N_l : AWGN power spectral density on the lth path

E_s : Energy (in joules) per symbol

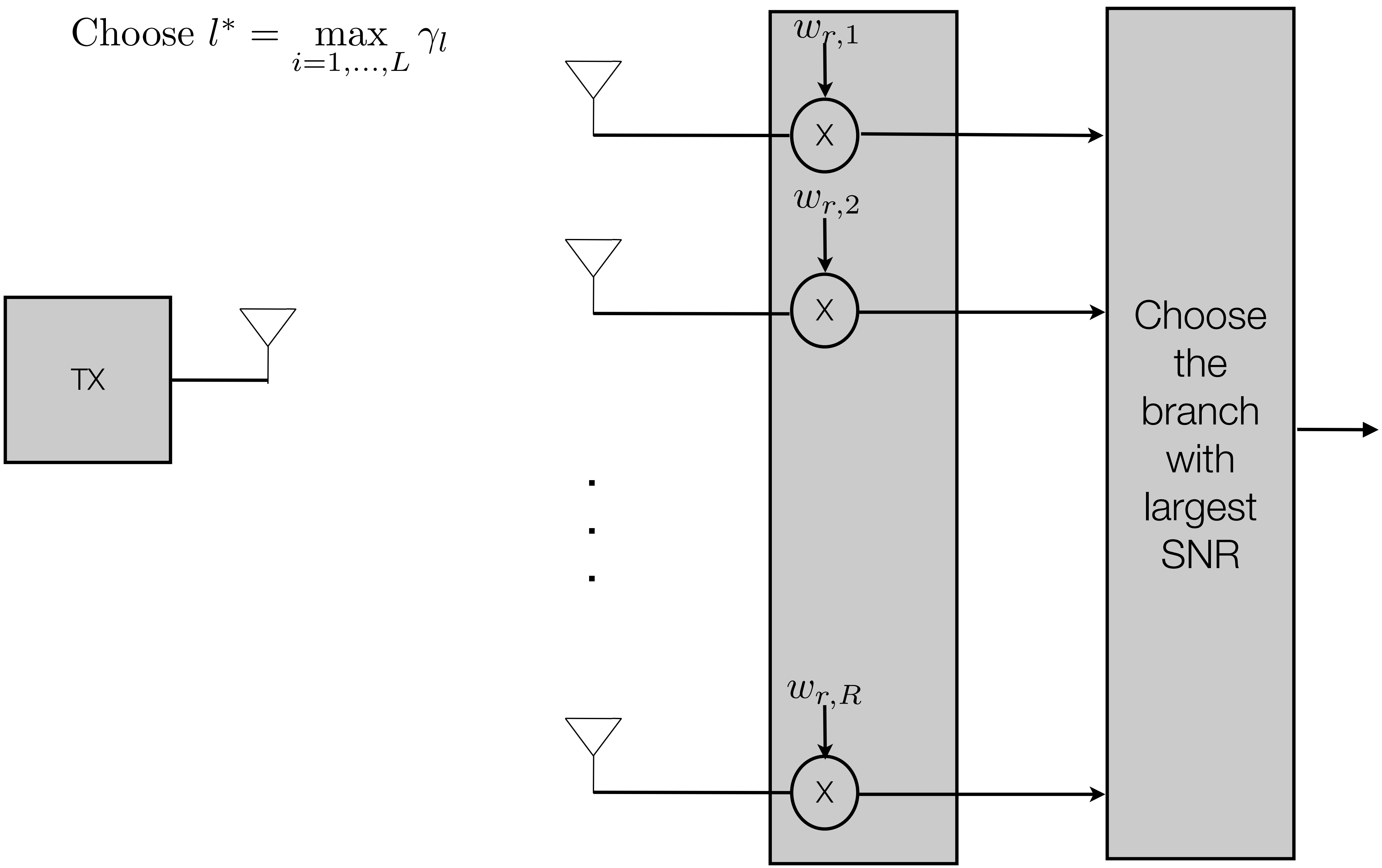
For i.i.d. Rayleigh case, the average output SNR can be shown as

$$\bar{\gamma}_{\mathrm{EGC}} = \bar{\gamma}\left[1 + (L-1)\frac{\pi}{4}\right]$$

Selection Combining

- Selection combining chooses the branch with the largest SNR

$$\text{Choose } l^* = \max_{i=1,\ldots,L} \gamma_l$$



Combined output SNR

$$\gamma_{\text{sc}} = \max\{\gamma_1, \gamma_2, \cdots, \gamma_L\}$$

CDF

$$P_{\gamma_{\text{sc}}}(\gamma) = \Pr[\gamma_1 \le \gamma,\ \gamma_2 \le x, \cdots, \gamma_L \le x]$$

$$= \prod_{l=1}^{L} P_{\gamma_l}(\gamma) \quad \text{(independent case)}$$

$$= \prod_{l=1}^{L} \left[1 - e^{-\gamma/\bar{\gamma}_l}\right] \quad \text{(independent Rayleigh case)}$$

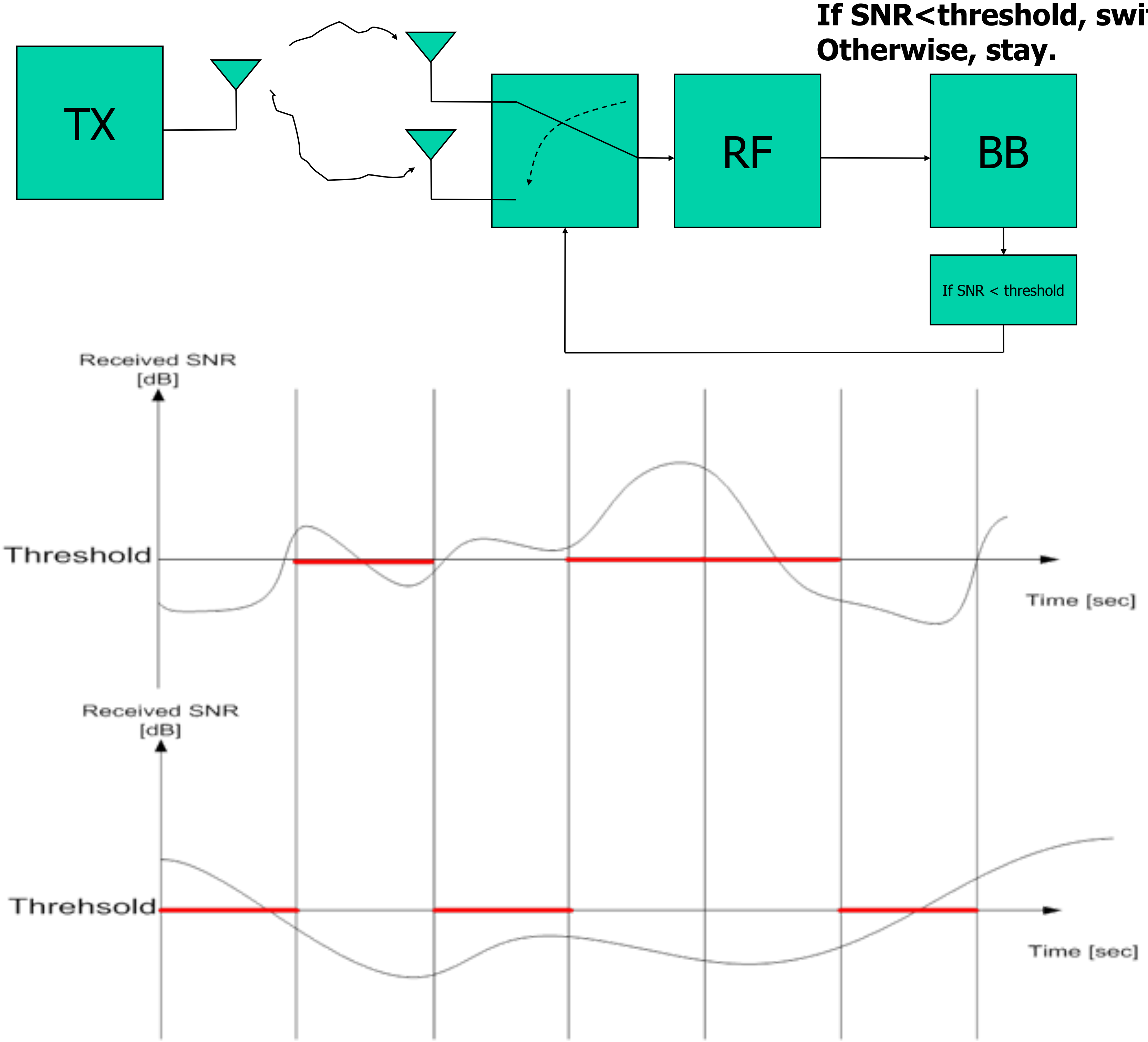
$$= \left[1 - e^{-\gamma/\bar{\gamma}}\right]^L \quad \text{(i.i.d. Rayleigh case)}$$

PDF

$$p_{\gamma_{\mathrm{sc}}}(\gamma) = \frac{L}{\bar{\gamma}} \left[1 - e^{-\gamma/\bar{\gamma}}\right]^{L-1} e^{-\gamma/\bar{\gamma}}$$

Switched Combining

If SNR<threshold, switch.
Otherwise, stay.



CDF of γ_{SSC}

$$P_{\gamma_{\text{SSC}}}(\gamma) = \begin{cases} \Pr[(\gamma_1 \le \gamma_T) \text{ and } (\gamma_2 \le \gamma)] & \gamma < \gamma_T \\ \Pr[(\gamma_T \le \gamma_1 \le \gamma) \text{ or } (\gamma_1 \le \gamma_T \text{ and } \gamma_2 \le \gamma)], & \gamma \ge \gamma_T \end{cases}$$

which can be expressed in terms of the CDF of the individual branches $P_\gamma(\gamma)$

$$P_{\gamma_{\text{SSC}}}(\gamma) = \begin{cases} P_\gamma(\gamma_T)P_\gamma(\gamma), & \gamma < \gamma_T \\ P_\gamma(\gamma) - P_\gamma(\gamma_T) + P_\gamma(\gamma)P_\gamma(\gamma_T), & \gamma \ge \gamma_T \end{cases}$$

PDF of γ_{SSC}

$$p_{\gamma_{\text{ssc}}}(\gamma) = \frac{dP_{\gamma_{ssc}}(\gamma)}{d\gamma} = \begin{cases} P_\gamma(\gamma_T)p_\gamma(\gamma), & \gamma < \gamma_T \\ (1 + P_\gamma(\gamma_T))p_\gamma(\gamma), & \gamma \ge \gamma_T \end{cases}$$

MGF of SSC

$$\mathcal{M}_{\gamma_{ssc}}(s) = P_\gamma(\gamma_T)\mathcal{M}_\gamma(s) + \int_{\gamma_T}^{\infty} p_\gamma(\gamma)e^{s\gamma}\, d\gamma$$

For Rayleigh case, we can show the MGF as

$$\mathcal{M}_{\gamma_{ssc}}(s) = (1 - s\bar{\gamma})^{-1}(1 - e^{-\gamma_T/\bar{\gamma}} + e^{-(1-s\bar{\gamma})\gamma_T/\bar{\gamma}})$$

Average output SNR of SSC

$$\bar{\gamma}_{\text{ssc}} = P_\gamma(\gamma_T) \int_0^\infty \gamma p_\gamma(\gamma)\, d\gamma + \int_{\gamma_T}^\infty \gamma p_\gamma(\gamma)\, d\gamma$$

$$= P_\gamma(\gamma_T)\bar{\gamma} + \int_{\gamma_T}^\infty \gamma p_\gamma(\gamma)\, d\gamma$$

Rayleigh case

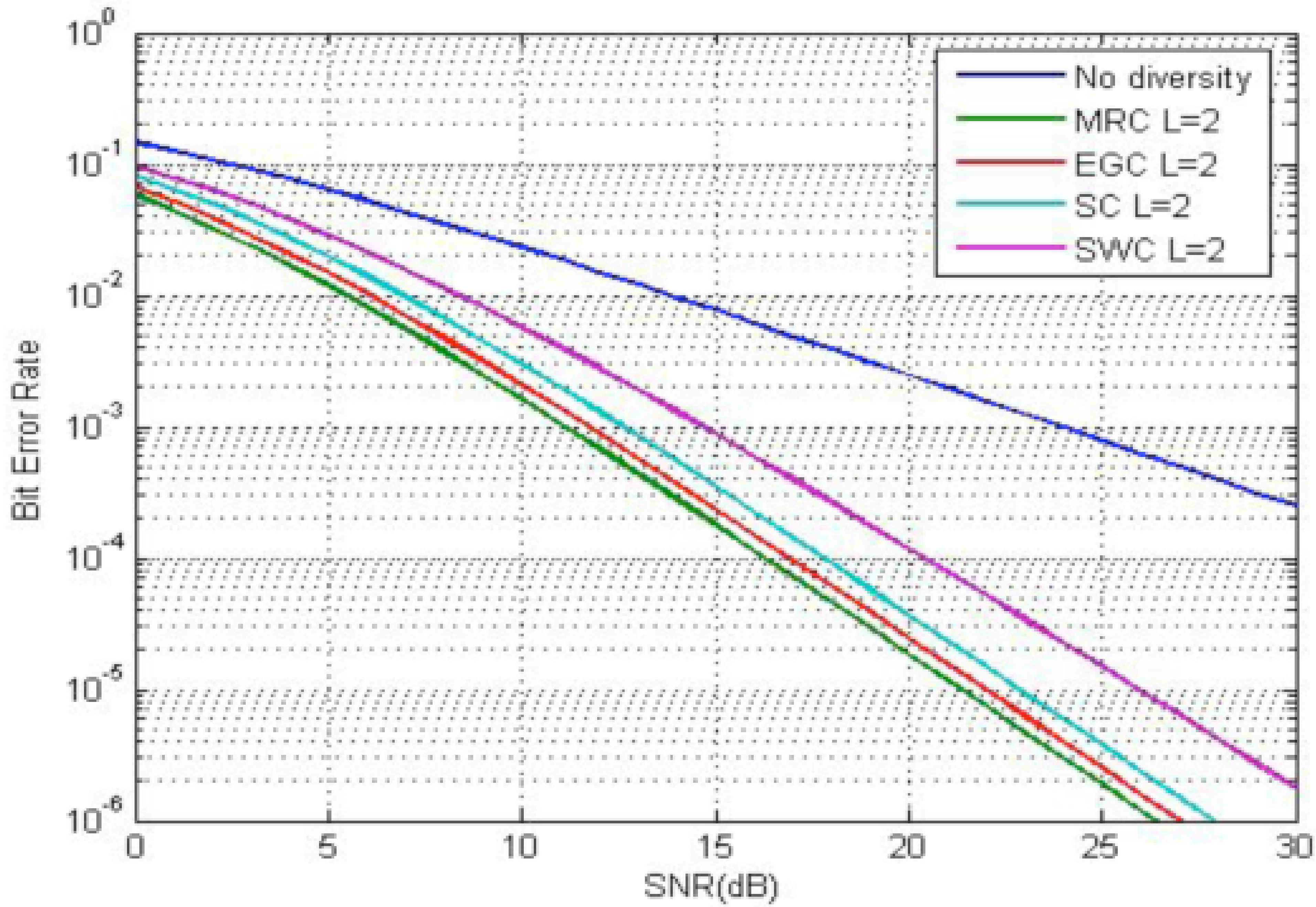
$$\bar{\gamma}_{\text{ssc}} = \bar{\gamma}\left(1 + \frac{\gamma_T}{\bar{\gamma}} e^{-\gamma_T/\bar{\gamma}}\right)$$

Optimal threshold

$$\max_{\gamma_T} \gamma_{\text{ssc}} \qquad \frac{d\bar{\gamma}_{\text{ssc}}}{d\gamma_T} = e^{-\gamma_T/\bar{\gamma}} - \frac{\gamma_T}{\bar{\gamma}} e^{-\gamma_T/\bar{\gamma}} = 0$$

$$\gamma_T^* = \bar{\gamma}$$

Comparison of BER Performance of Dual Diversity

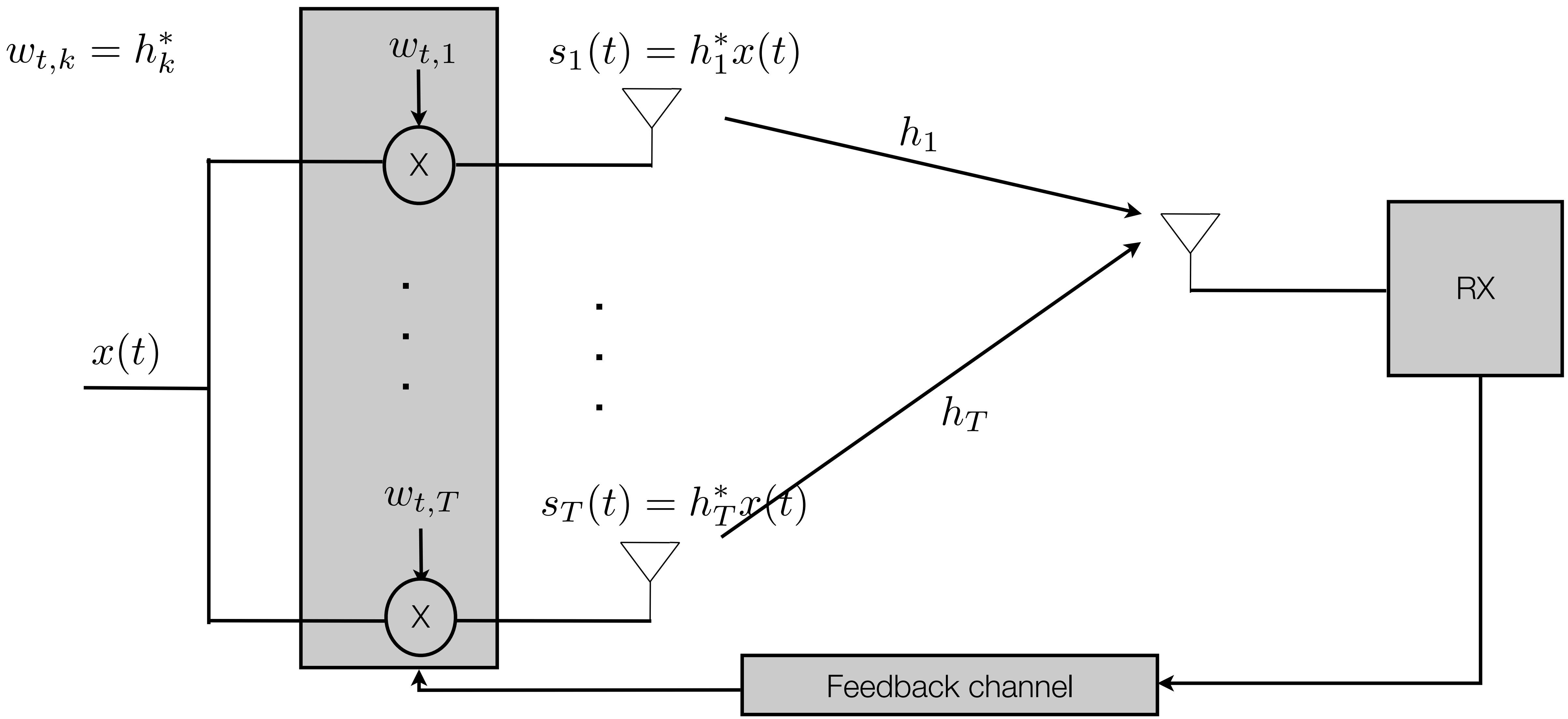


Transmit Diversity

- Two different transmit diversity schemes
  - Channel known at the transmitter
  - Channel unknown at the transmitter

Channel Known at the Transmitter

- Channel state information (CSI) at the transmitter
  - Transmitter knows the CSI, that is, $h_l(t)$, so we have $s_l(t) = h_l^*(t)x(t)$.



- The received signal at the receiver is

$$r(t) = \sum_{l=1}^{L} h_l(t) s_l(t) + n(t) = \sum_{l=1}^{L} |h_l|^2 x(t)$$

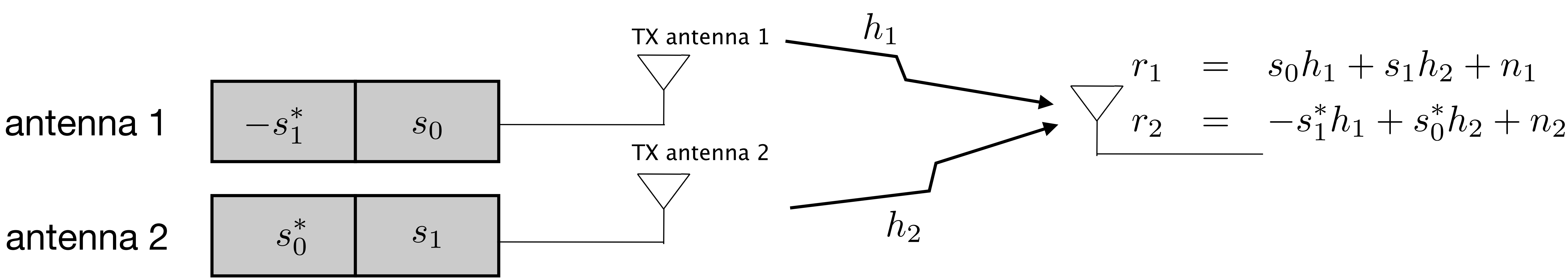
which gives the same diversity gain as the receiver MRC.

- Remark
  - There is a transmit power constraint such that

$$\sum_{l=1}^{L} E[|s_l(t)|^2] \leq P_t$$

Channel Unknown at the Transmitter: Alamouti Scheme

- Alamouti scheme (2x1 case)



[Space-time block code (STBC)]

	antenna1	antenna2
time t	s_0	s_1
time t+T	$-s_1^*$	s_0^*

QPSK example

$$
\begin{aligned}
00 \rightarrow s^1 &= 1+j \\
01 \rightarrow s^2 &= 1-j \\
11 \rightarrow s^3 &= -1+j \\
10 \rightarrow s^4 &= -1-j
\end{aligned}
$$

[Space-time block code (STBC)]

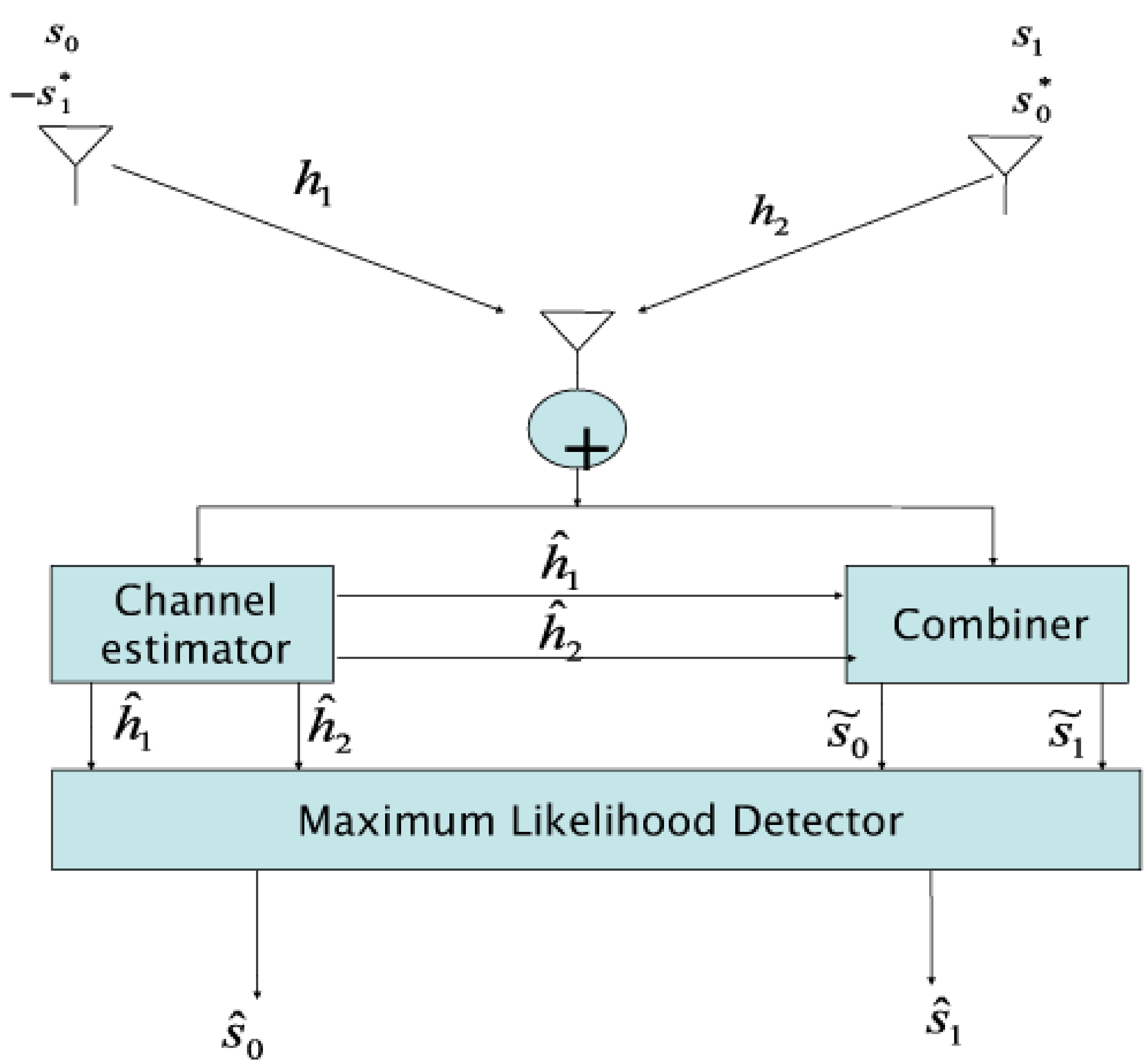
	antenna1	antenna2
time t	s_0	s_1
time t+T	$-s_1^*$	s_0^*

data: $01001011\cdots \quad \Longrightarrow \quad s_0 s_1 s_2 s_4 \cdots = s^2 s^1 s^4 s^3 \cdots$

time	ant1	ant2
T	$1-j$	$1+j$
$2T$	$-1+j$	$1+j$
$3T$	$-1-j$	$-1+j$
$4T$	$1+j$	$-1+j$
	$\vdots$	

$$
\begin{aligned}
r_1 &= s_0 h_1 + s_1 h_2 + n_1 \\
r_2 &= -s_1^* h_1 + s_0^* h_2 + n_2 \\
r_3 &= s_2 h_1 + s_3 h_2 + n_1 \\
r_4 &= = -s_3^* h_1 + s_2^* h_2 + n_2
\end{aligned}
$$

- Detection of space-time block coding signal



$$r_1 = s_0 h_1 + s_1 h_2 + n_1$$
$$r_2 = -s_1^* h_1 + s_0^* h_2 + n_2$$

⇓

$$v_1 = h_1^* r_1 + h_2 r_2^*$$
$$v_2 = h_2^* r_1 - h_1 r_2^*$$

⇓

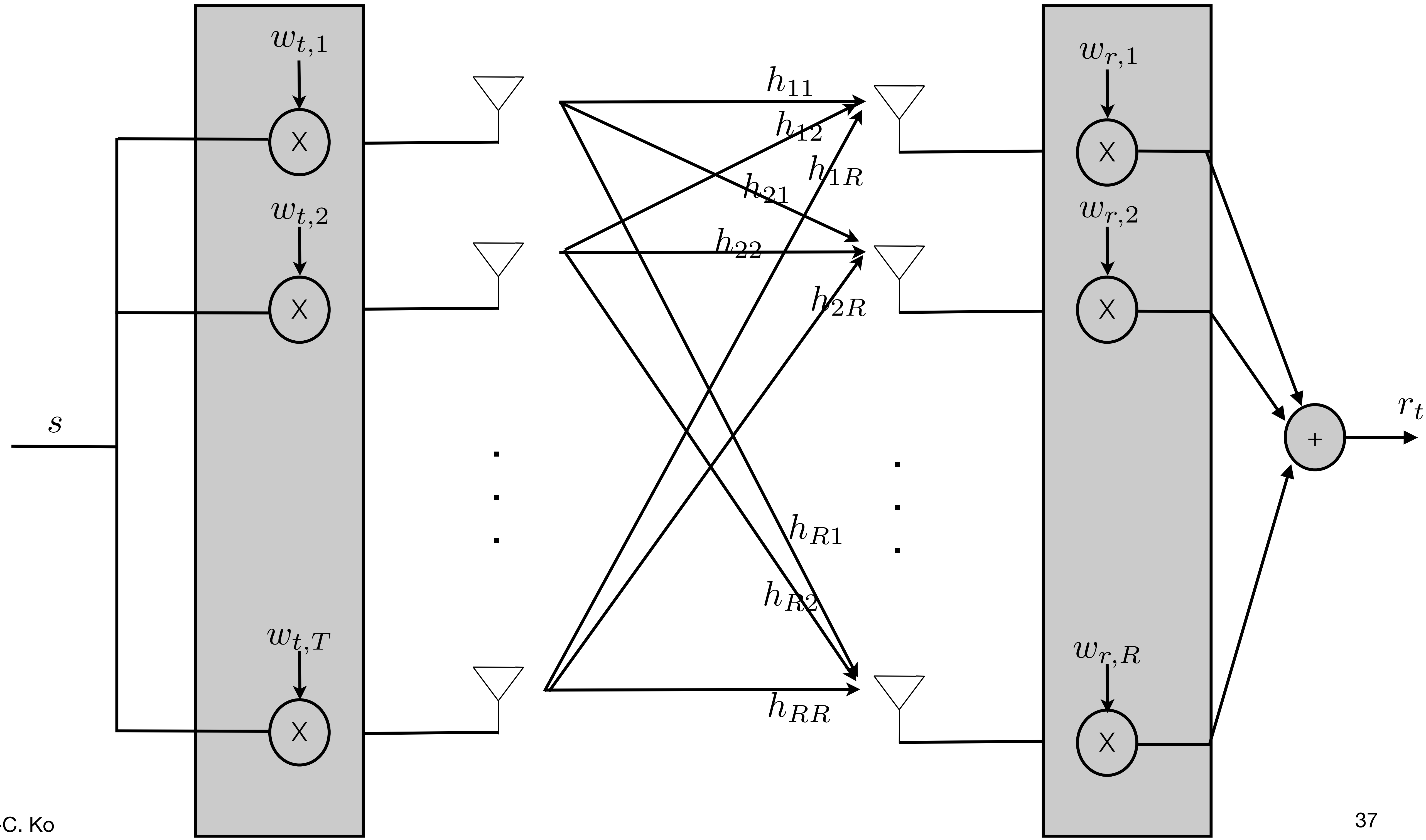
$$v_1 = (|h_1|^2 + |h_2|^2) s_0 + h_1^* n_1 + h_2 n_2^*$$
$$v_2 = (|h_1|^2 + |h_2|^2) s_1 + h_2^* n_1 - h_2 n_2^*$$

- Received SNR

$$\gamma_t = \frac{(|h_1|^2 + |h_2|^2)E_s}{2N_0}$$

  - where the factor of 2 comes from the fact that s_i is transmitted using half the total symbol energy E_s.

Maximal Ratio Transmission (Transmit-Receive Diversity)



Channel Matrix of Multiple-Input Multiple Output Antenna (MIMO) Systems

- Channel matrix for $T \times R$ antenna systems

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1R} \\ h_{21} & h_{22} & \cdots & h_{2R} \\ \vdots & \vdots & \vdots & \vdots \\ h_{T1} & h_{T2} & \cdots & h_{TR} \end{bmatrix}$$

- Received signal

$$\begin{aligned} r_1 &= (w_{t,1}h_{11} + w_{t,2}h_{12} + \cdots + w_{t,T}h_{1T})s + n_1 \\ r_2 &= (w_{t,1}h_{21} + w_{t,2}h_{22} + \cdots + w_{t,T}h_{2T})s + n_2 \\ &\vdots \\ r_R &= (w_{t,1}h_{R1} + w_{t,2}h_{R2} + \cdots + w_{t,T}h_{RT})s + n_R \end{aligned}$$

$\Rightarrow$

$$\mathbf{r} = \mathbf{H}\mathbf{w}_t s + n$$

Optimal Weight for MIMO-MRC

- Combined signal

$$r_t = \mathbf{w}_R^H \mathbf{r}$$

  - Optimal receive weight vector can be easily shown to be given as

$$\mathbf{w}_R = \alpha \mathbf{H} \mathbf{w}_t$$

  - In this case, the received SNR can be written as

$$r_t = \alpha \mathbf{w}_t^H \mathbf{H}^H \mathbf{H} \mathbf{w}_t s + \alpha \mathbf{w}_t^H \mathbf{H}^H \mathbf{n}$$

  - SNR of the combined signal r_t and the optimum weight

$$\mu = \frac{1}{\sigma_n^2} \mathbf{w}_t^H \mathbf{H}^H \mathbf{H} \mathbf{w}_t. \quad \Rightarrow \quad \mathbf{w}_t^{\text{opt}} = \max_{\mathbf{w}_t} \mu$$

- Find the optimal weight vector $\mathbf{w}_t$ to maximize the SNR μ.

  - Recall Rayleigh-Ritz theorem

$$\mathbf{x}^H \mathbf{A} \mathbf{x} \leq ||\mathbf{x}|| \lambda_{\max}$$

where $\mathbf{A}$ is the hermitian matrix, $\mathbf{x}$ is any non-zero complex vector and $\lambda_{\max}$ is the largest eigenvalue of $\mathbf{A}$.

    - Equality holds if and only if $\mathbf{x}$ is the eigenvector corresponding to $\lambda_{\max}$.

  - Based on Rayleigh-Ritz theorem. we can find the optimal weight vector, we can find the optimal weight vector as

$$\boxed{\mathbf{w}_t = \sqrt{\Omega} \mathbf{U}_{\max}}$$

where $\mathbf{U}_{\max}$ is the eigenvector corresponding to the largest eigenvalue of the quadratic form

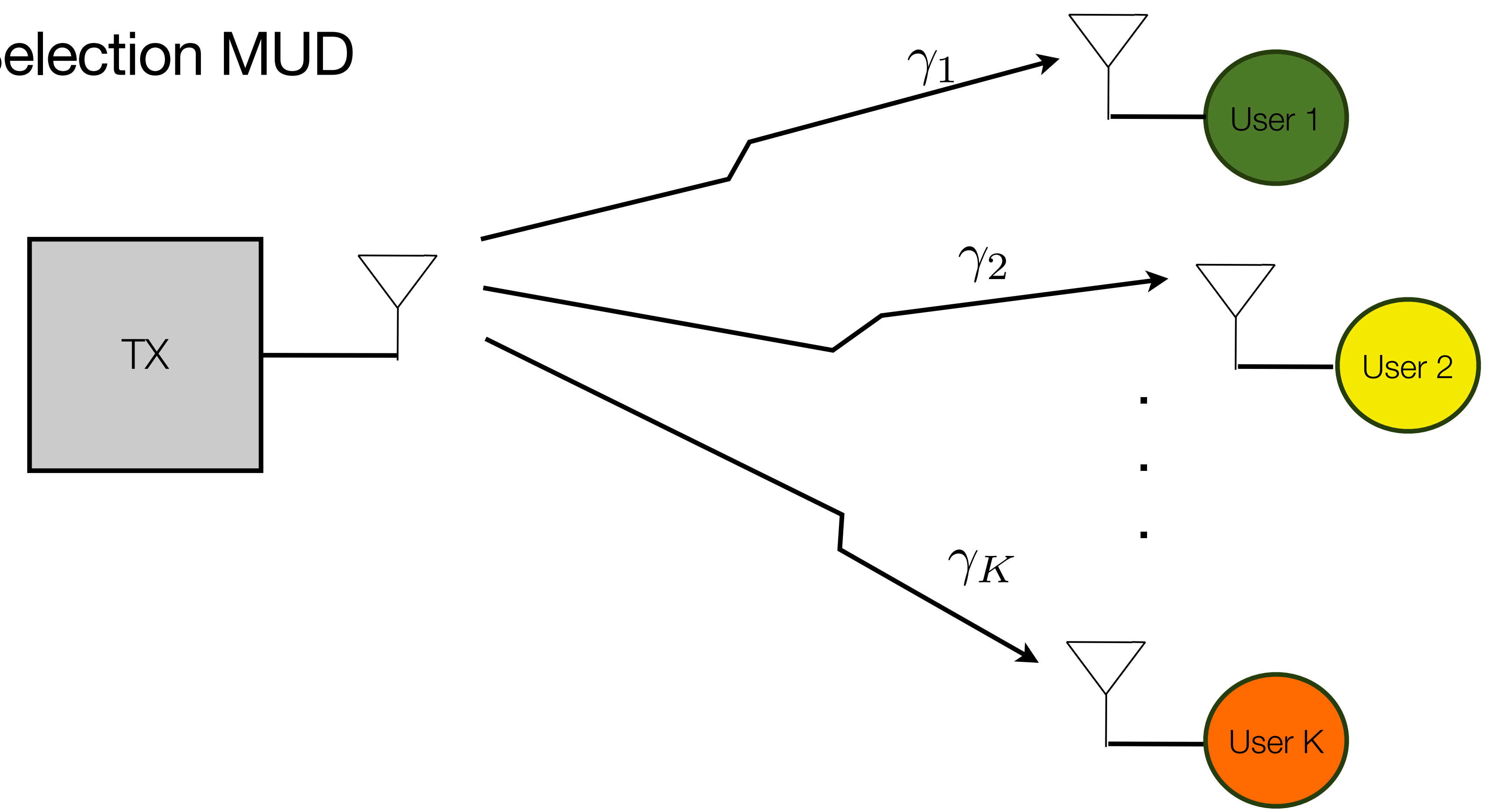
$$F = \mathbf{H}^H \mathbf{H}$$

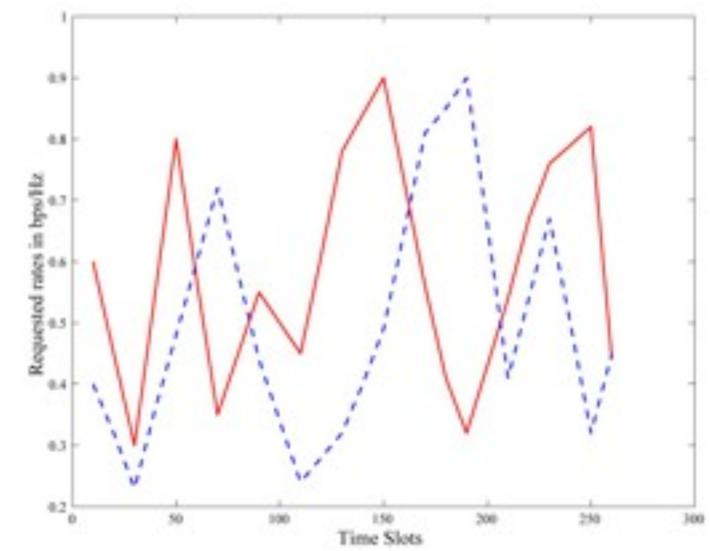
- Combined SNR using the optimal weight vector

$$\mu = \frac{\Omega}{\sigma_n^2}\lambda_{\max}$$

Multi-User Opportunistic Diversity (MUD)

- Motivation
  - In cellular system, a user can have one or two antennas. Hence, obtaining the diversity gain is limited.
- Selection MUD





Choose the user which has the largest SNR among K users!!!

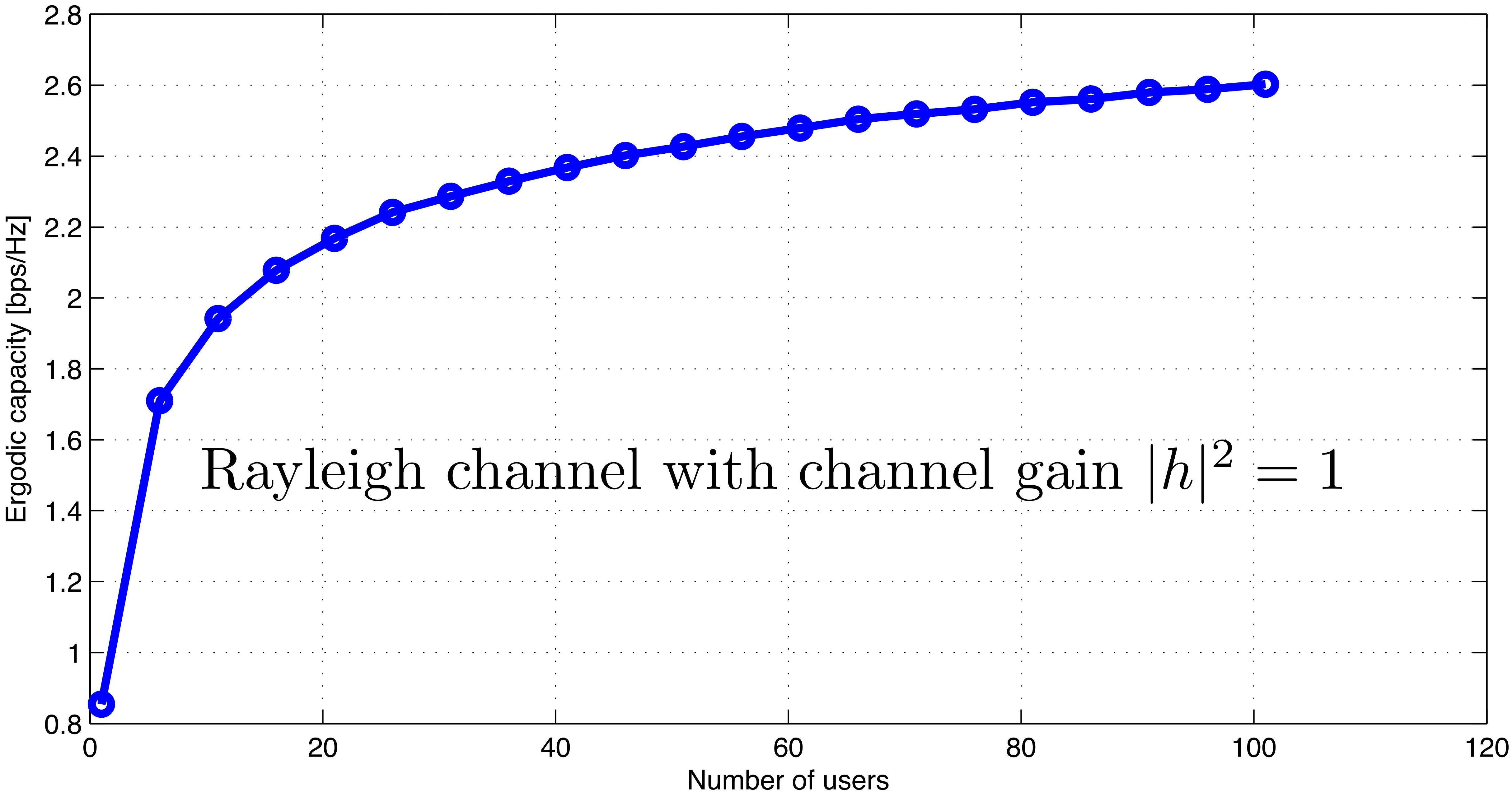
Selected user k

$$k^* = \max_k(\gamma_1, \gamma_2, \cdots, \gamma_K)$$

Ergodic channel capacity

$$C = E[\log_2(1 + \gamma_k^*)]$$

$$= \int_0^\infty \log_2(1 + \gamma_k^*) p_{\gamma_k^*}(\gamma_k^*)\, d\gamma_k$$


Ergodic capacity [bps/Hz]
Number of users
Rayleigh channel with channel gain $|h|^2 = 1$
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0
20
40
60
80
100
120