Wireless Communication Networks & Systems

Spring 2025

Week # 07

Course Learning Outcomes (CLOs):

CLO # 01	Demonstrate an in-depth understanding of wireless network system's architecture, protocols, and Services.	**Cog. 3**
CLO # 02	Explore advanced technologies and features in wireless networks related to coverage, capacity, interference management, and mobility.	**Cog. 3**
CLO # 03	Examine the evolution of Wi-Fi networks, highlighting architectural differences across its various standards.	**Cog. 4**
CLO # 04	Analyze key cellular concepts used in cellular networks and the architectural advancements in 5G and beyond.	**Cog. 4**

Assessment Roadmap till Midterm:

Homework:	20%	Inclusive Recitation session
Quiz:	20%	Inclusive Class participation
Midterm Exam:	20%	
Final Exam:	20%	
Research:	20%	Four milestones (5% each)

- Research Part – I (2.5%): Wk7
  - Group Formation
  - Brief project presentation (5 slides)
    - Tool selection
    - Wireless Network topology/deployment
    - Protocol/wireless standard (LAN, WAN)
    - Performance indicator (e.g. delay, data rate, packet loss)
    - Application of advanced Wireless techniques

- Midterm Exam (20%): Wk8, 26th Feb 2025
  Recitation session slot- 1 to 2:15 pm @ Room: W242

Wireless Communication Technology:

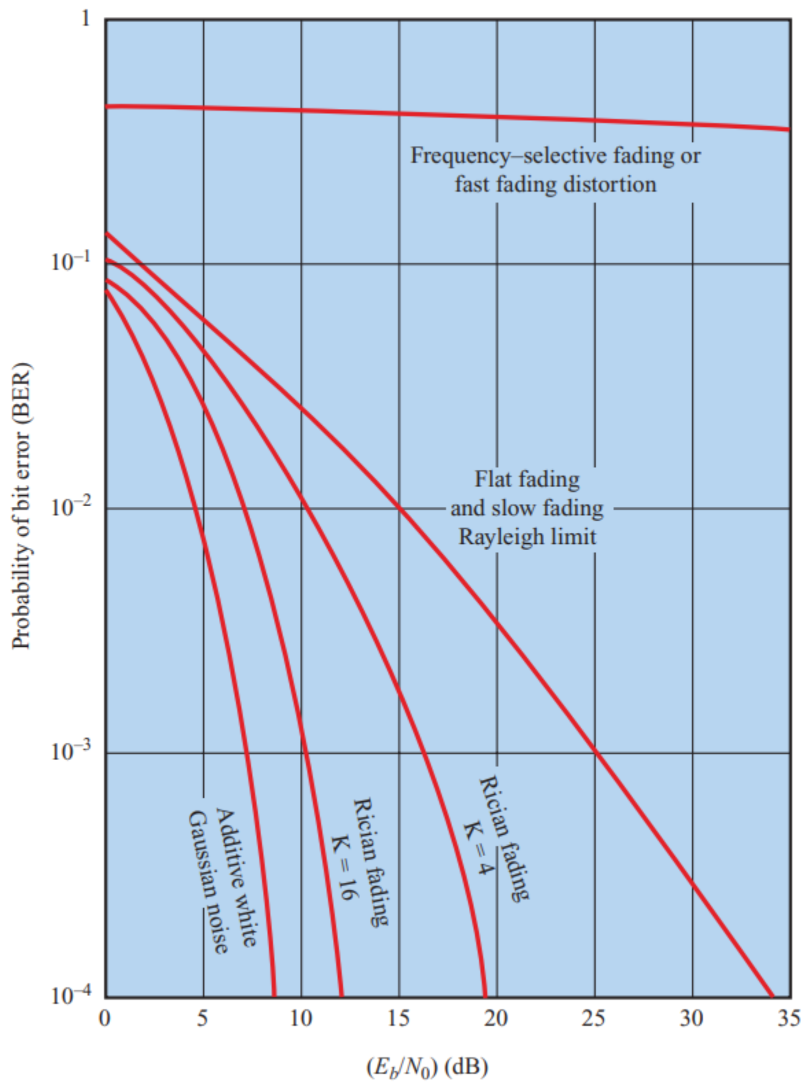
CLO 02 :

- Chapter 05 – Overview of Wireless Communications
- Chapter 06 – The wireless channel
- Chapter 07 – Signal Encoding Techniques
- Chapter 08 – Orthogonal Frequency division multiplexing
- Chapter 09 – Spread Spectrum
- Chapter 10 – Coding and Error Control

The Wireless Channel: Correction Mechanism

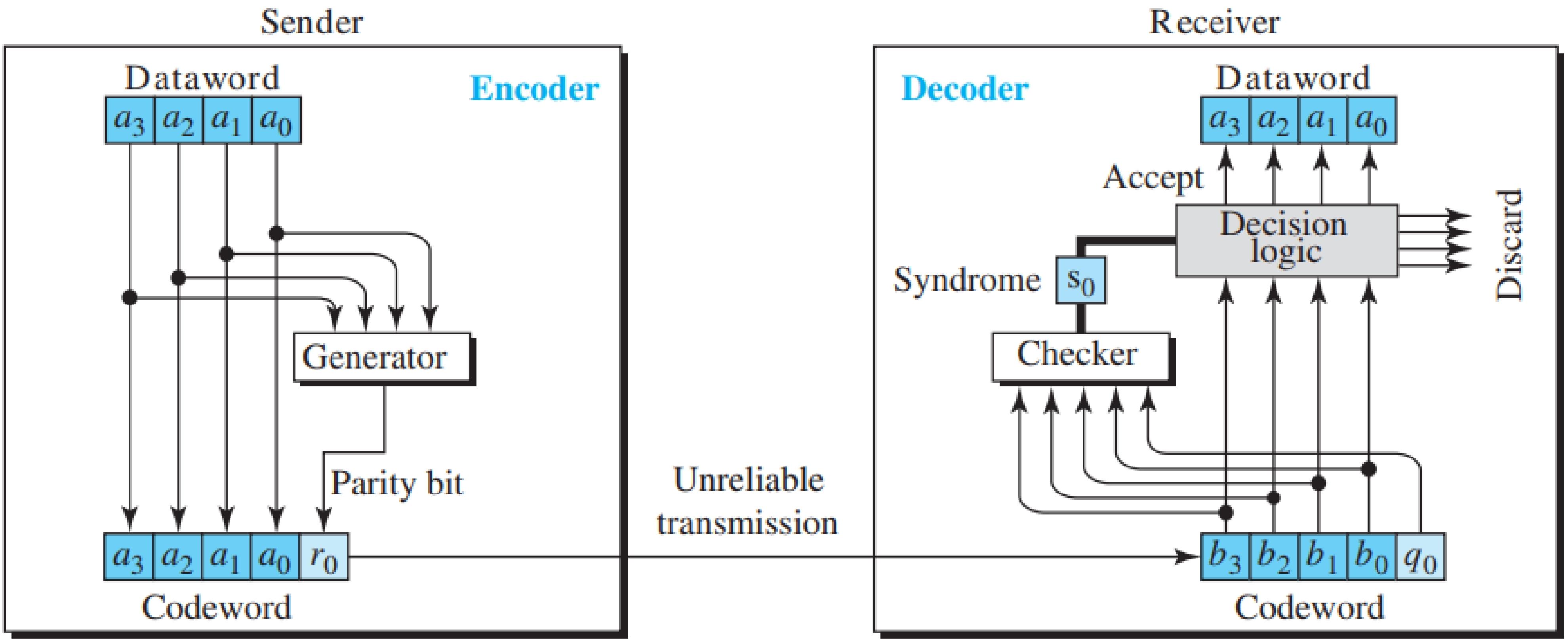
The efforts to compensate for the errors and distortions introduced by Noise, Multipath, and Fading in Wireless transmission fall into the following categories:

- Equalization, Diversity techniques, MIMO and Beamforming (Chapter 6)
- Adaptive modulation and coding (Chapter 07)
- Orthogonal frequency division multiplexing – OFDM (Chapter 08)
- Spread spectrum- SS (Chapter 09)
- Error correction codes or Channel coding (Chapter 10).



The Wireless Channel: Correction Mechanism

Channel coding or Error correction codes

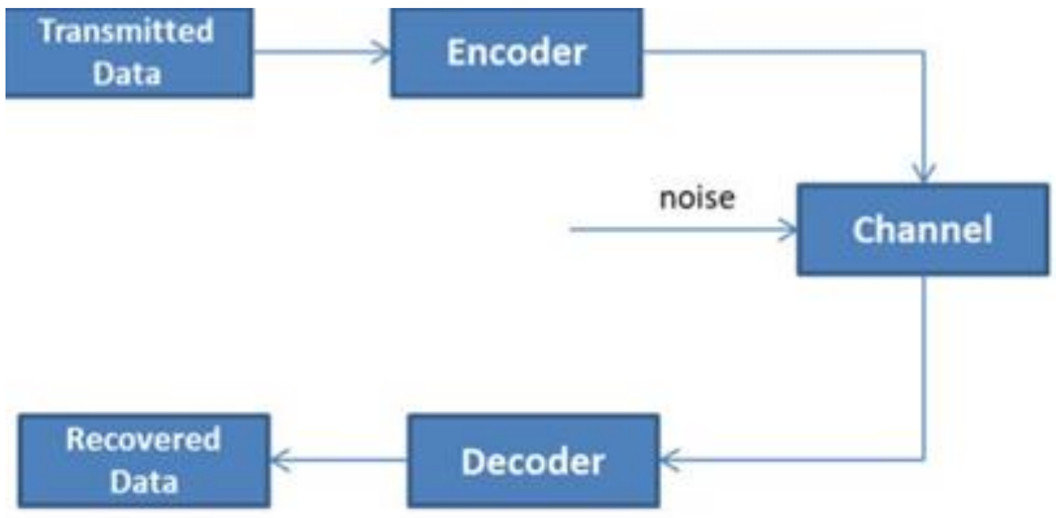


The Wireless Channel: Correction Mechanism

Channel coding – Error correction codes:

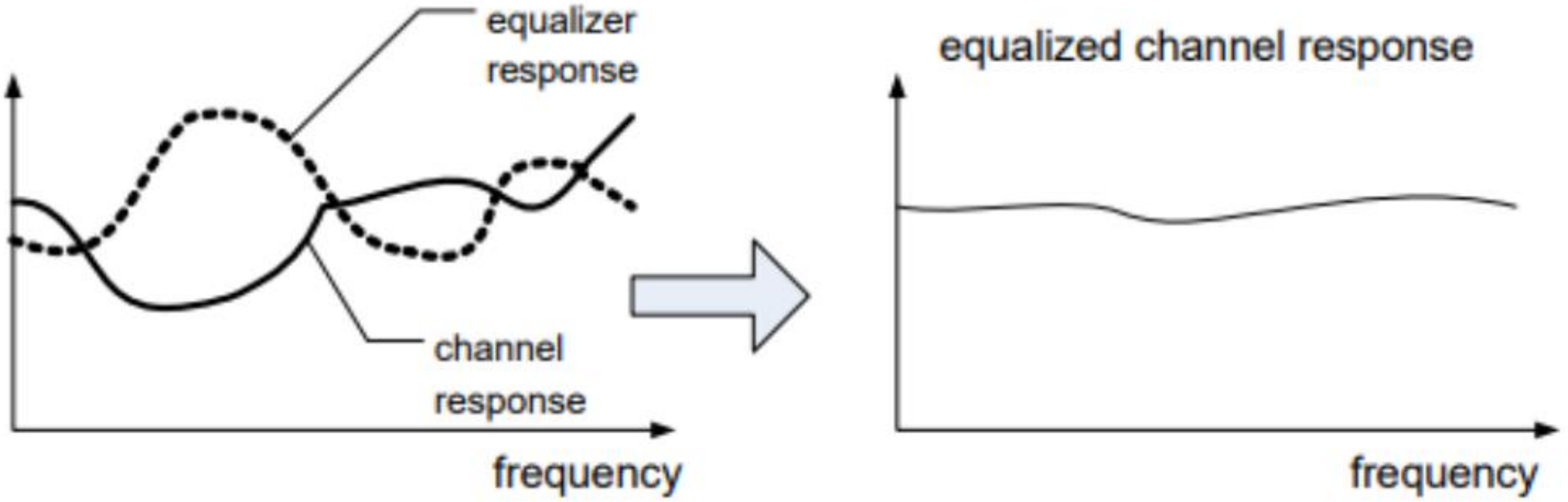
- In Channel coding, the transmitter adds a number of additional, redundant bits to each transmitted block of data. These additional bits are calculated as a function of the information data bits.

- For each incoming block of bits (data plus error-correcting code), the receiver calculates a new error-correcting code from the incoming data bits. If the calculated code matches the incoming code, then the receiver assumes that no error has occurred in this block of bits.



The Wireless Channel: Correction Mechanism

Equalization



The Wireless Channel: Correction Mechanism

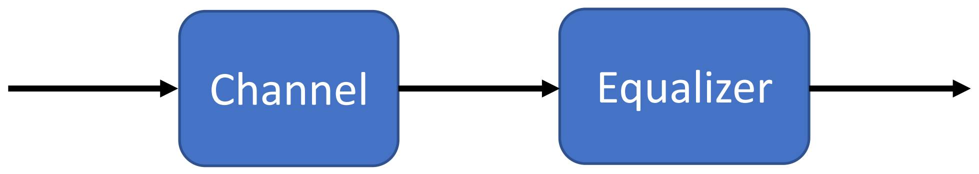
Equalization:

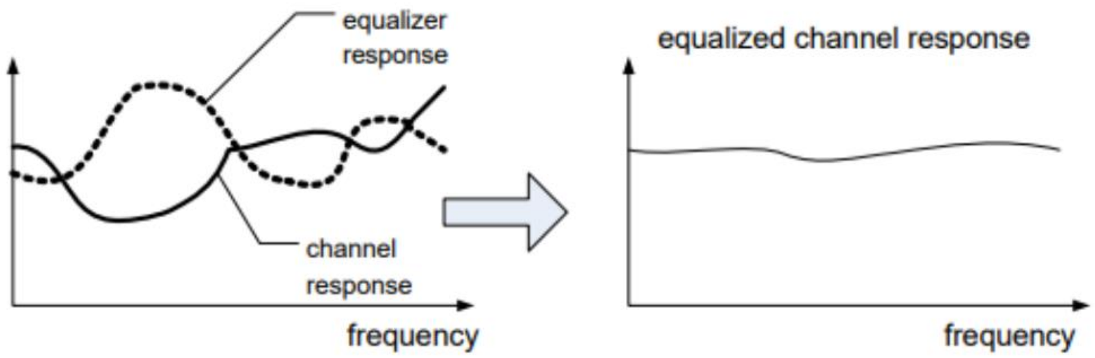
- The transmitted signal is attenuated and distorted by the transmission medium. The process of Equalization compensates for the distortion caused by the medium/channel.

- Equalization is the process of reversal of the distortion incurred by a signal transmitted through a channel.

- The objective of the equalization is to determine and apply a filter that nullifies channel distortion impact

- The Equalizer can be considered as a filter that has a characteristic that is the inverse of that of the transmission medium.

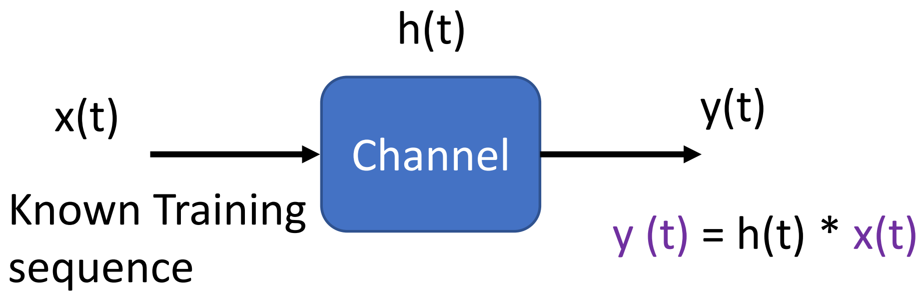


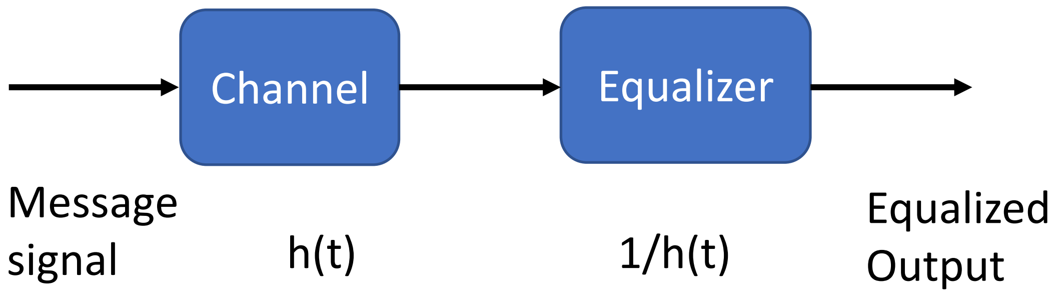


The Wireless Channel: Correction Mechanism

Equalization:

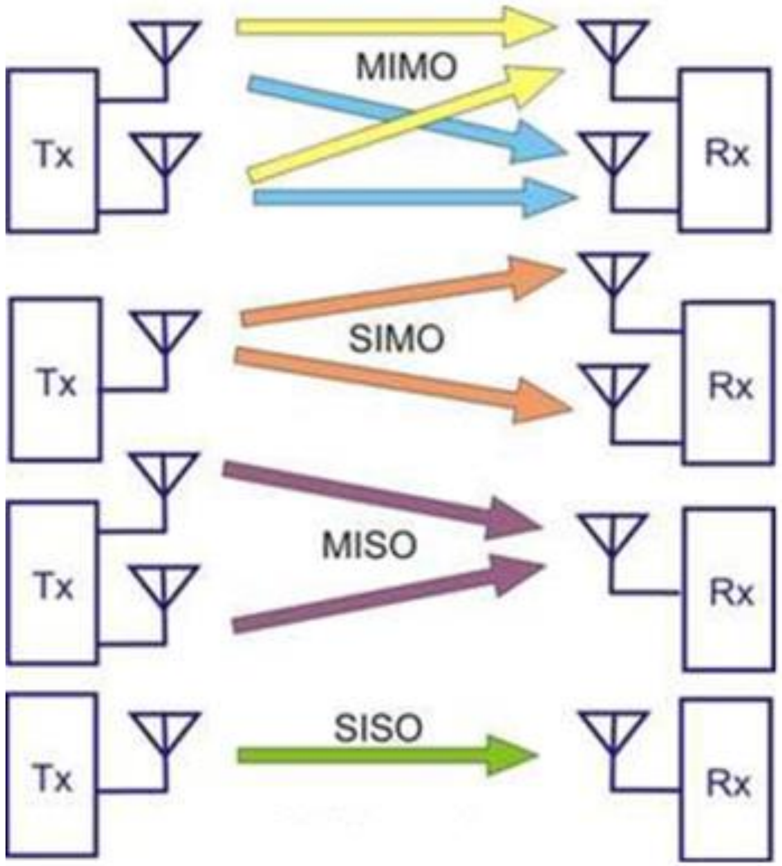
- In the Equalization process, a training sequence (Pilot signal) is transmitted first through a transmission channel.
- Then, the receiver compares the received training sequence with the expected training sequence and calculates the impulse response of a channel h(t).
- Periodically, a new training sequence is sent to account for changes in the transmission environment.
- For Rayleigh channels, or worse, it may be necessary to include a new training sequence with every single block of data.





The Wireless Channel: Correction Mechanism

Diversity Techniques



The Wireless Channel: Correction Mechanism

Diversity Techniques

- In wireless communication, diversity techniques refer to methods used to improve the reliability and quality of communication by exploiting different transmission or reception paths to mitigate the effects of fading, interference, and signal attenuation.

- The main goal of diversity techniques is to reduce the probability of signal degradation due to the unpredictable nature of wireless channels, such as multipath effect and fading.

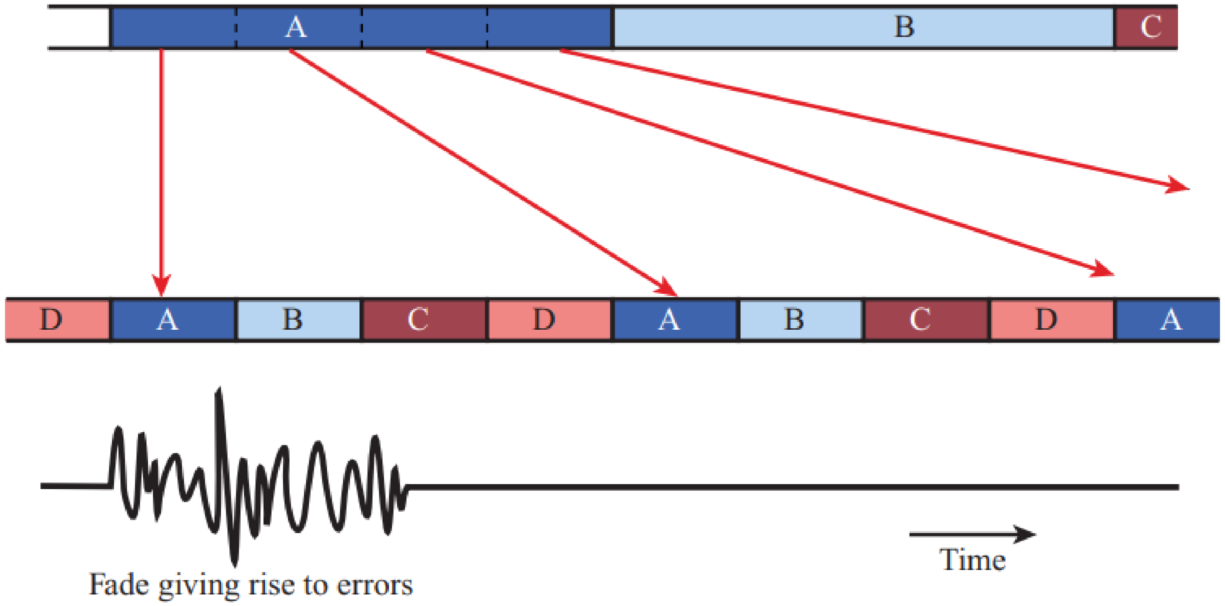
- There are several types of diversity techniques, which involve either Space, Frequency, or Time. These techniques allow for multiple copies of the transmitted signal to be received.

The Wireless Channel: Correction Mechanism

Diversity Techniques – Time Diversity

- It involves transmitting the same signal at different times or over different time slots, ensuring that the signal has multiple opportunities to be received successfully, even if it experiences fading or interference in some time instances.

- Time interleaving is a technique where data symbols are rearranged and spread over time. This helps protect against burst errors (i.e., errors that occur due to a fade or interference at a particular time).



The Wireless Channel: Correction Mechanism

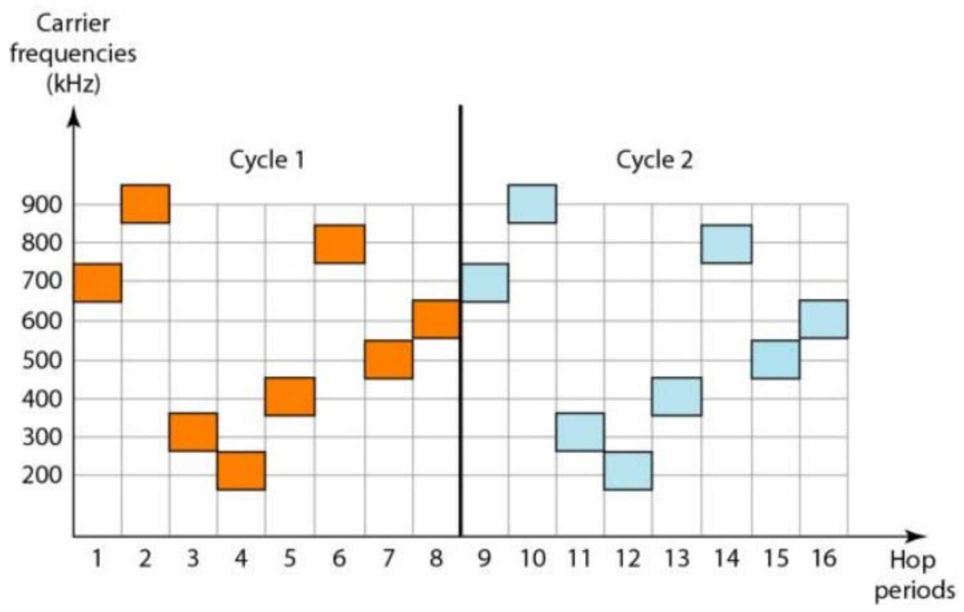
Diversity Techniques – Frequency Diversity

- Frequency diversity involves transmitting the same signal over multiple frequencies or channels that are subject to independent fading.

- This technique helps combat the adverse effects of channel fading and interference, which can be frequency-dependent.

- These frequency channels are typically chosen such that their fading characteristics are not correlated. This ensures that if one frequency experiences deep fading or interference, others may still carry the signal with good quality.

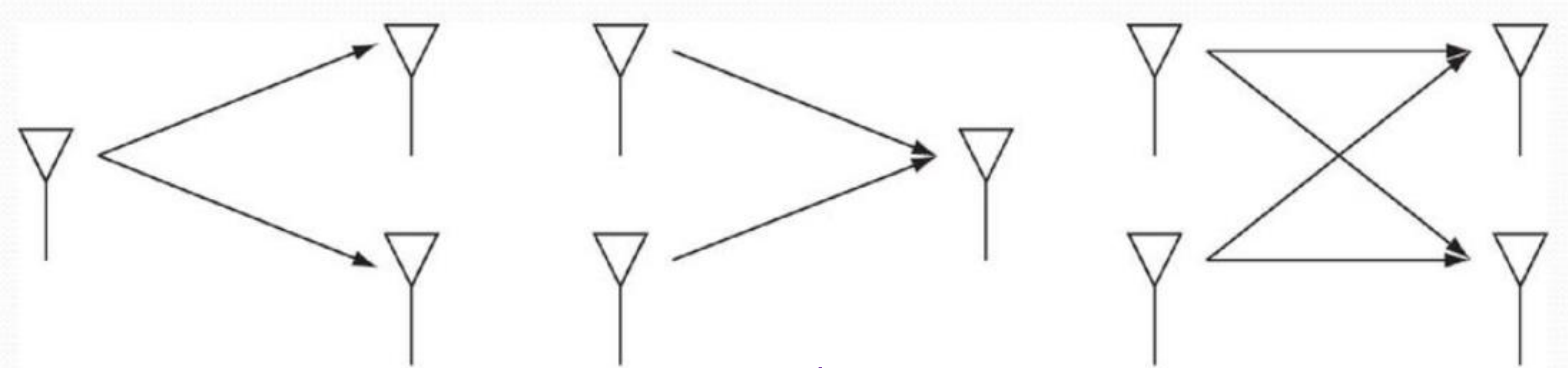
- Application: Frequency Hopping spread spectrum; Orthogonal Frequency division multiplexing.



The Wireless Channel: Correction Mechanism

Diversity Techniques – Space Diversity

Space diversity uses multiple antennas spaced apart (e.g., on the transmitter or receiver side), since each antenna experiences a different signal path, the likelihood that all signals will suffer the same level of fading simultaneously is reduced.

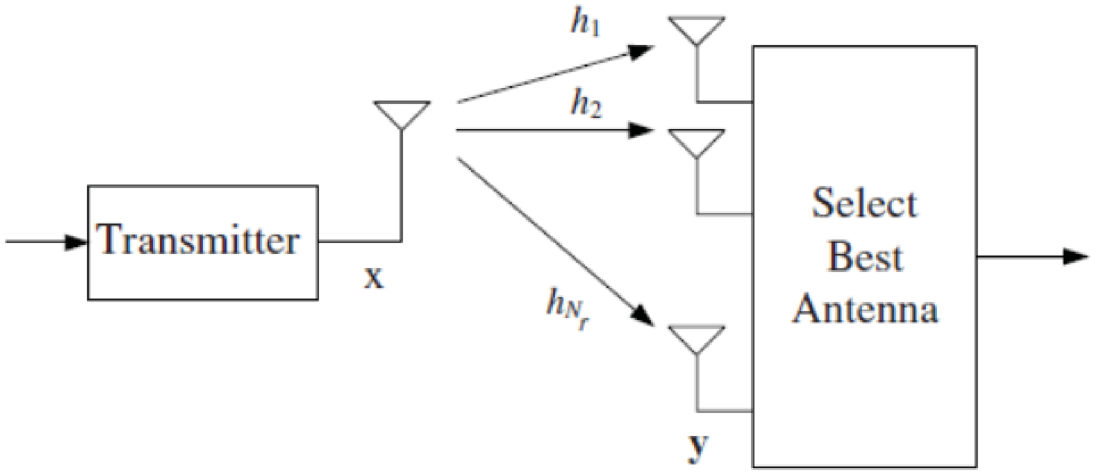


Receiver diversity | Transmitter diversity | MIMO

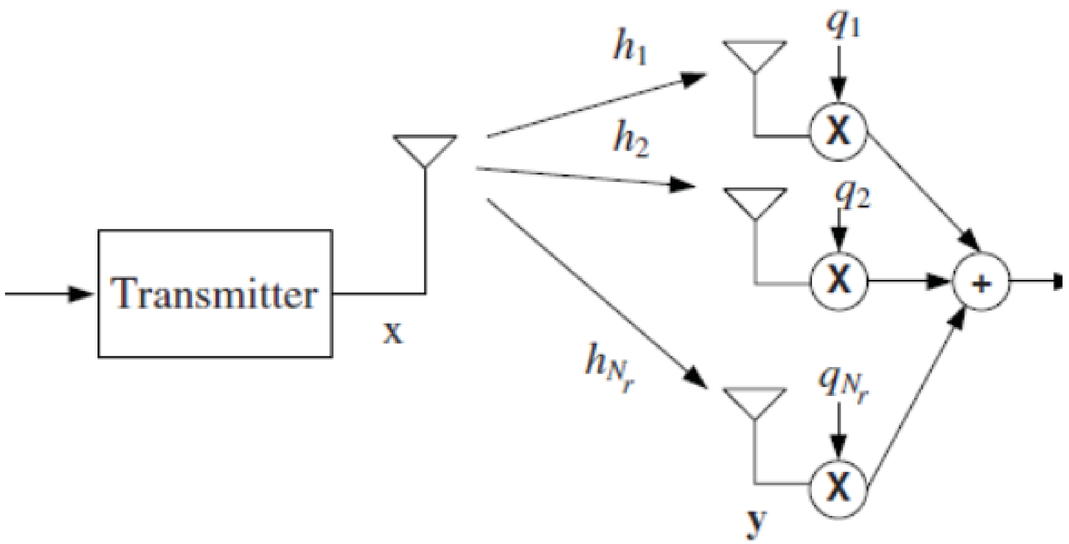
The Wireless Channel: Correction Mechanism

Diversity Techniques :
When these multiple signals are received, there are two basic ways they can be used:

- Selection Diversity: Choose one signal that is acceptable or the best.

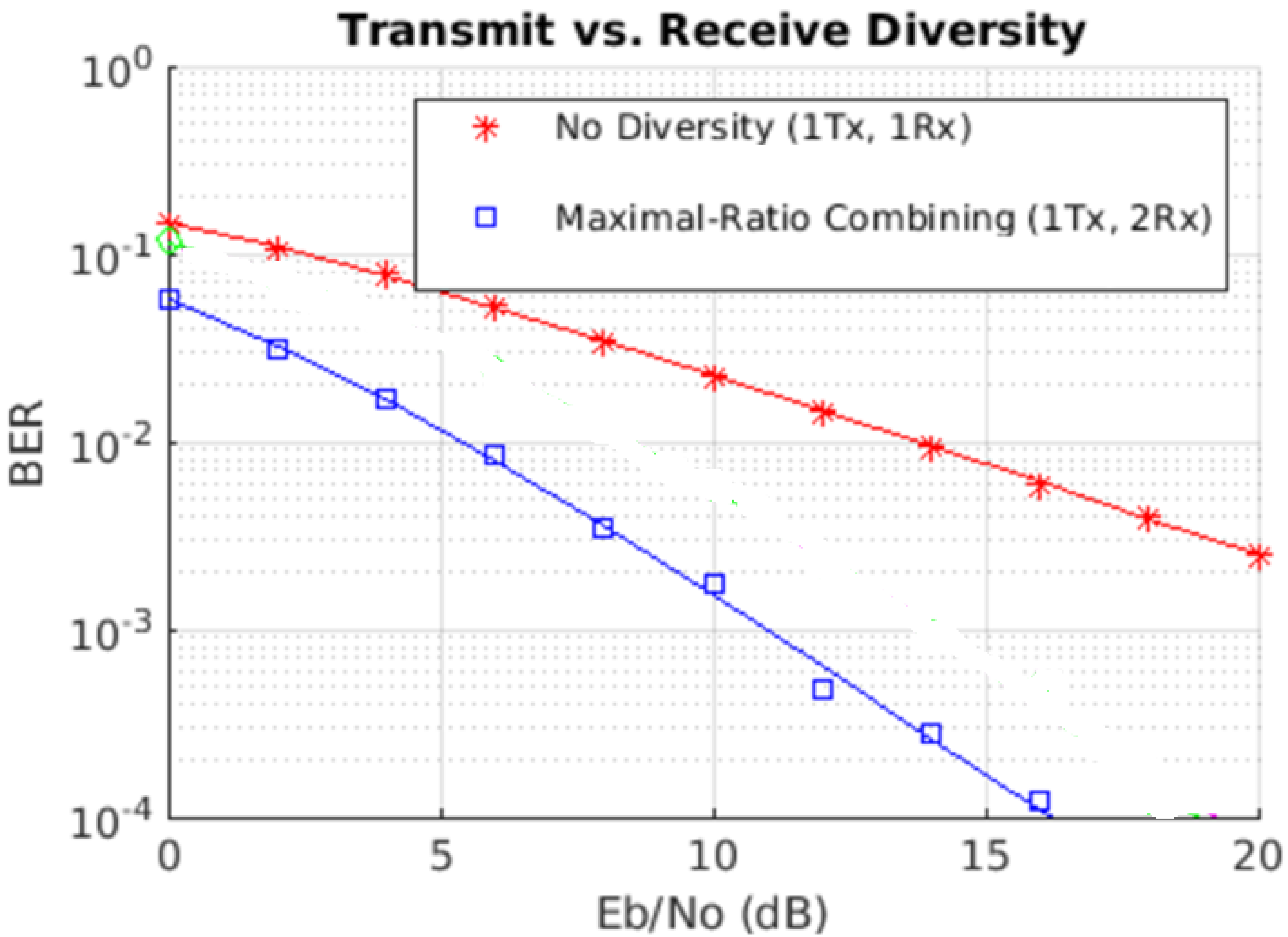


- Diversity Combining: Combine the best signal with the other signals. Adjust the gain and phase so they add together to improve the overall output signal. Example: Maximum Ratio combining (MRC)



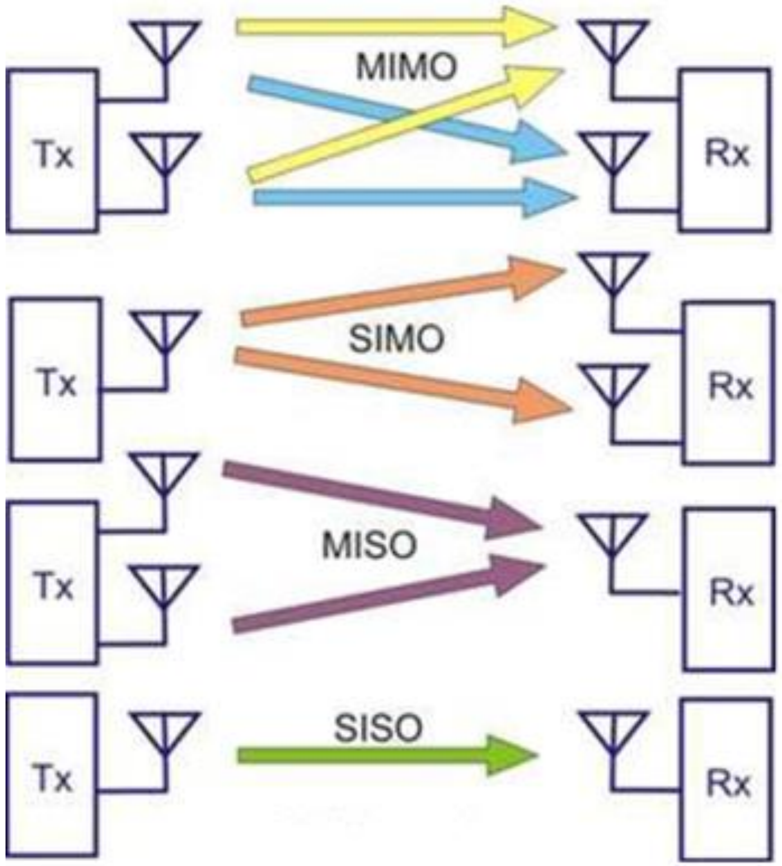
$$C = B \log(1 + SNR)$$

The Wireless Channel: Correction Mechanism



The Wireless Channel: Correction Mechanism

MIMO



The Wireless Channel: Correction Mechanism

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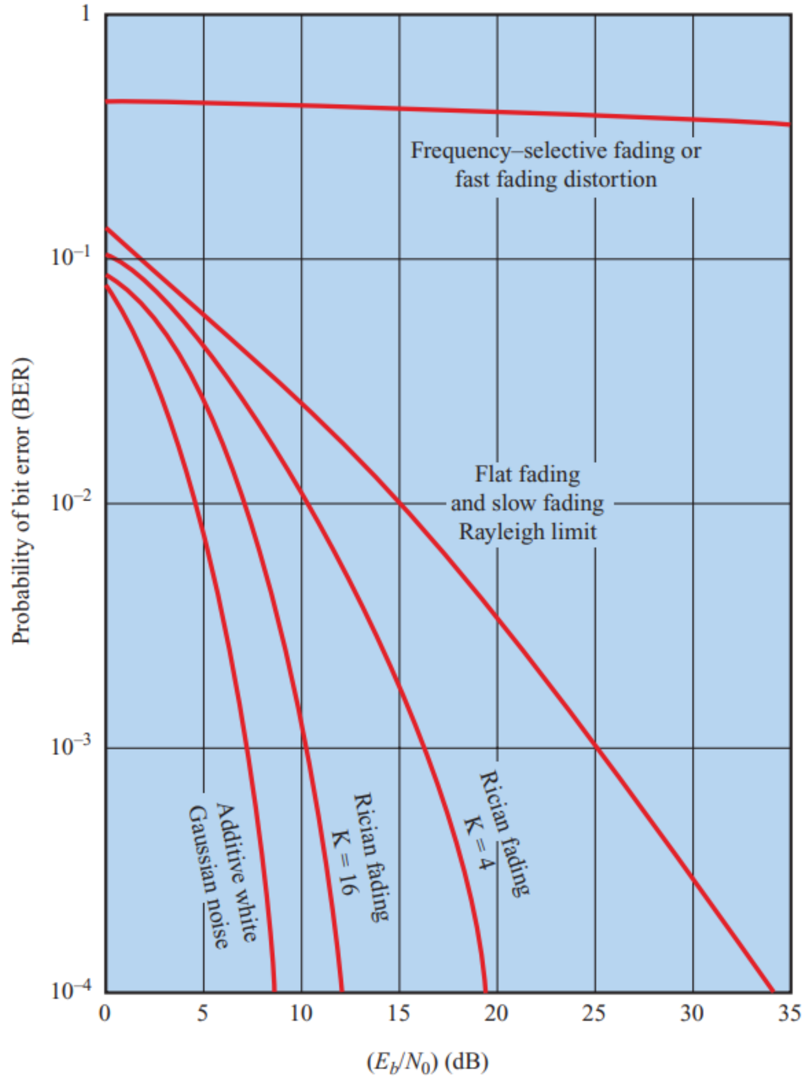
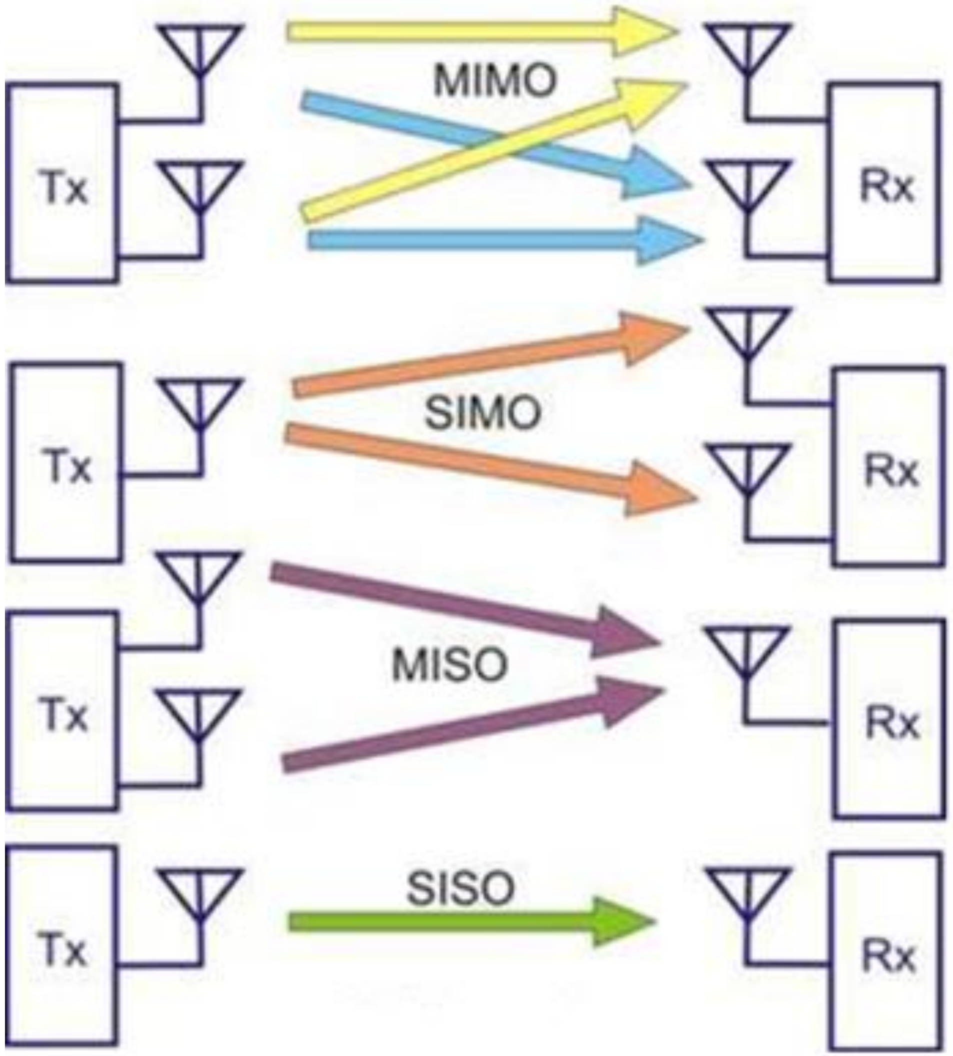


The Wireless Channel: MIMO

- If a transmitter and receiver implement a system with multiple antennas, this is called a multiple-input multiple-output (MIMO) system.

- The MIMO antenna architecture has become a key technology in evolving high-speed wireless networks, including IEEE 802.11 Wi-Fi LANs and 4G/5G systems.

- MIMO exploits the Space diversity to improve wireless systems in terms of coverage, data rate, and reliability.



The Wireless Channel: MIMO

- Modern systems implement up to 4 x 4 (4 input, 4 output) and 8 x 8 MIMO configurations.

- Antenna systems have been approved in specifications for as many as 8, and 16 antenna arrays, more are being envisioned for future technologies.

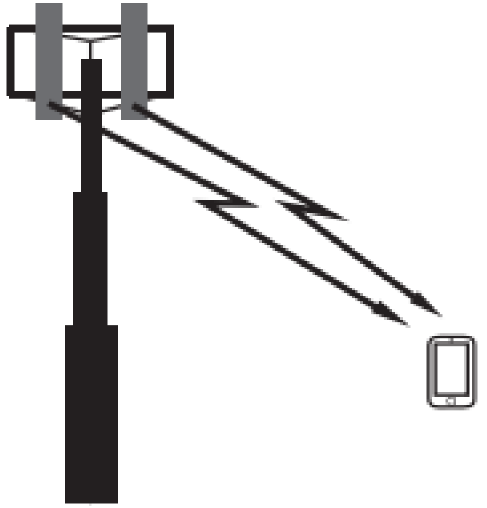
- Question - Why larger antenna array is possible now? [Wi-Fi 7 - Wikipedia]

	WiFi 7	WiFi 6E	WiFi 6	WiFi 5
Launch date	2024 (expected)	2021	2019	2013
IEEE standard	802.11be	802.11ax	802.11ax	802.11ac
Max data rate	46 Gbps	9.6 Gbps	9.6 Gbps	3.5 Gbps
Bands	2.4 GHz, 5 GHz, 6 GHz	2.4 GHz, 5 GHz, 6 GHz	2.4 GHz, 5 GHz	5 GHz
Channel size	Up to 320 MHz	20, 40, 80, 80+80, 160 MHz	20, 40, 80, 80+80, 160 MHz	20, 40, 80, 80+80, 160 MHz
Modulation	4096-QAM OFDMA (with extensions)	1024-QAM sOFDMA	1024-QAM OFDMA	256-QAM OFDM
MIMO	16×16 UL/DL MU-MIMO	8×8 UL/DL MU-MIMO	8×8 UL/DL MU-MIMO	4×4 MIMO DL MIMO
RU	Multi-RUs	RU	RU	/
MAC	MLO	/	/	/

The Wireless Channel: MIMO

The main benefits of MIMO systems are:

- Space diversity or Spatial diversity is accomplished by sending a signal by multiple copies through multiple transmit and/or receive antennas.
- The same data transmitted through multiple antennas effectively increases the received power (or coverage) proportional to the number of transmitting/receiving antennas. This improves signal-to-noise (SNR) for cell edge performance.
- The diverse multipath fading offers multiple “views” of the transmitted data at the receiver, thus increasing robustness.
- In a multipath scenario where each receiving antenna would experience a different interference environment, there is a high probability that if one antenna is suffering a high level of fading, another antenna has sufficient signal level.



Diversity for improved system performance

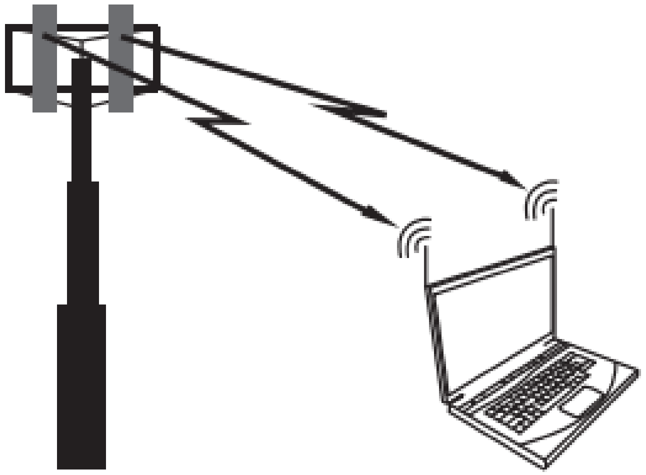
Improvement in BER by improving SNR

The Wireless Channel: MIMO

- Multiple streams or Spatial multiplexing: Multiple, parallel data streams flow between pairs of transmit and receive antennas.

- A source data stream is divided among the transmitting antennas. The gain in channel capacity is proportional to the available number of antennas at the transmitter or receiver, whichever is less.

- Spatial multiplexing is used when transmitting conditions are favorable and for relatively short distances compared to spatial diversity.

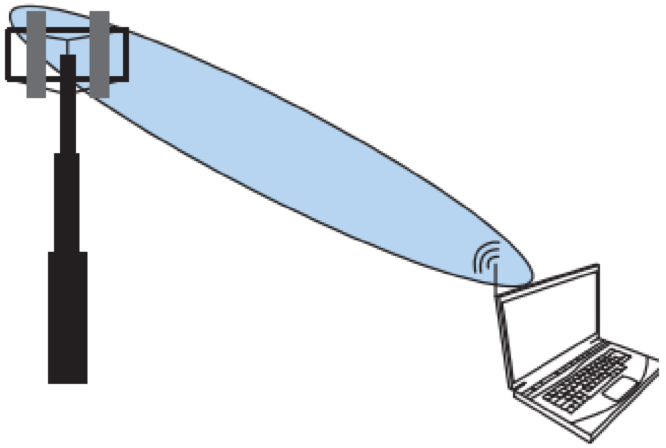


Multi layer transmission ("SU-MIMO") for higher data rates in a given bandwidth

Improvement in data rate by parallel stream transmission.

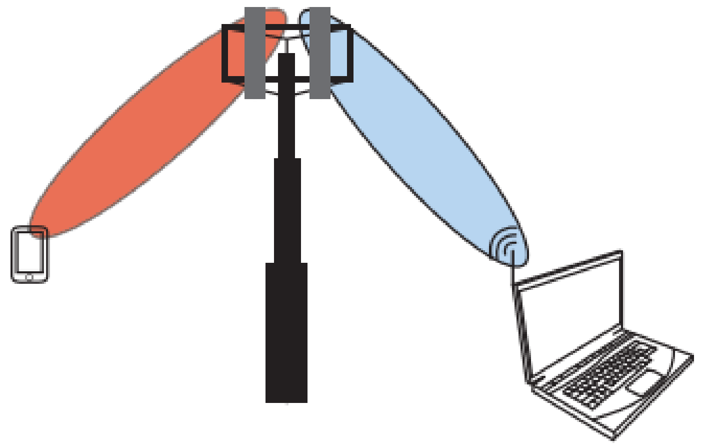
The Wireless Channel: MIMO

- Beam-forming: Multiple antennas can be configured to create directional antenna patterns to focus and increase energy to intended recipients



Beam-forming for improved coverage
(less cells to cover a given area)

- Multi-user MIMO (MU- MIMO): With enough MIMO antennas, directional antenna beams can be established to multiple users simultaneously.



Spatial division multiple access
("MU-MIMO") for improved capacity
(more user per cell)

MIMO Model:

- The multiple antennas can be used to increase data rates through multiplexing or to improve performance (received signal level, probability of error, SNR) through diversity

- By sending data in independent paths, MIMO can also achieve high spectral efficiency (bits/sec/Hz). However, the spectral efficiency gain requires accurate knowledge of the channel information (Channel Gain).

- Multiplexing is obtained by exploiting the structure of the channel gain matrix to obtain independent signaling paths that can be used to send independent data.

- The cost of the performance enhancements obtained through MIMO techniques is the added cost of deploying multiple antennas, the space and power requirements of these extra antennas, and the added complexity required for multi-dimensional signal processing.

MIMO Model:

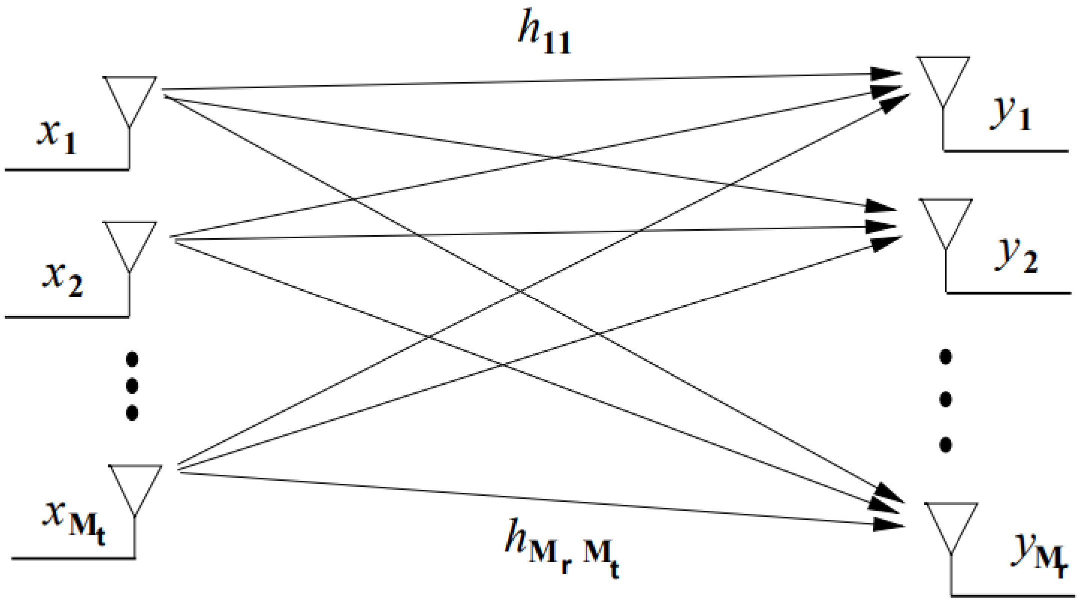
Here,

X = M_t dimensional transmitted symbol

Y = M_r dimensional received symbol

N = M_r dimensional noise vector (AWGN)

H is the $M_r \times M_t$ matrix of channel gains h_{ij} representing the gain from transmit antenna j to receive antenna i.



$$\begin{bmatrix} y_1 \\ \vdots \\ y_{M_r} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1M_t} \\ \vdots & \ddots & \vdots \\ h_{M_r1} & \cdots & h_{M_rM_t} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{M_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{M_r} \end{bmatrix}$$

$$\mathbf{Y = H \cdot X + N}$$

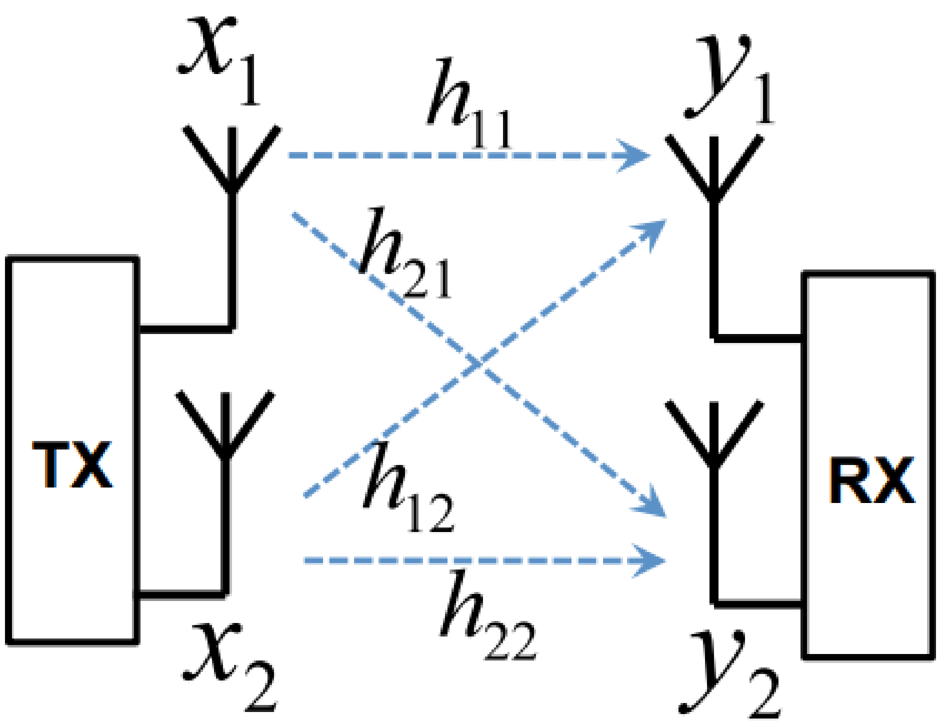
MIMO Model: Example 2X2

Input: X_1, X_2

Output : Y_1, Y_2

Impulse response of the channel: h

$$y_1 = h_{11}x_1 + h_{12}x_2$$
$$y_2 = h_{21}x_1 + h_{22}x_2$$



The multiple antennas must be separated sufficiently far (more than half-wavelength), so the channel impulse response (h_{11}, h_{12}, h_{21}, h_{22}) is uncorrelated which leads to high multiplexing and diversity gains of the MIMO system.

MIMO Model: Example 2X2

In the presence of Noise: **Y =H·X + n**

Where:

- y is the vector of received signals
- H is the MIMO channel matrix
- x is the vector of transmitted signals
- n is the noise vector

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \qquad \mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \qquad \mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \qquad \mathbf{n} = \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

MIMO Model: How to find H

- In a MIMO system, the channel gain matrix plays a crucial role in describing the relationship between the transmitted signals and the received signals.

- The channel gain matrix **H** is usually estimated or measured through various methods.

- In real systems, the channel gain matrix is usually measured or estimated using a pilot signal that is transmitted by the transmitter.

Y =H·X + N

$$\begin{bmatrix} y_1 \\ \vdots \\ y_{M_r} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1M_t} \\ \vdots & \ddots & \vdots \\ h_{M_r1} & \cdots & h_{M_rM_t} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{M_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{M_r} \end{bmatrix}$$

MIMO Model: How to find H

- Transmit Pilot Signals: The transmitter sends known pilot signals (sequences of symbols with known values) over multiple antennas.

- Receiver Measurements: The receiver, which knows the pilot signal, measures the received signal. The received signal is then used to estimate the channel matrix.

- Channel Estimation Algorithms: The receiver applies estimation algorithms like Least Minimum Mean Squared Error (MMSE) to find the channel gain matrix H.

- In some systems, especially adaptive systems like MIMO, the channel gain matrix is estimated based on feedback from the receiver. The receiver periodically sends channel-related feedback called, channel state information (CSI) to the transmitter.

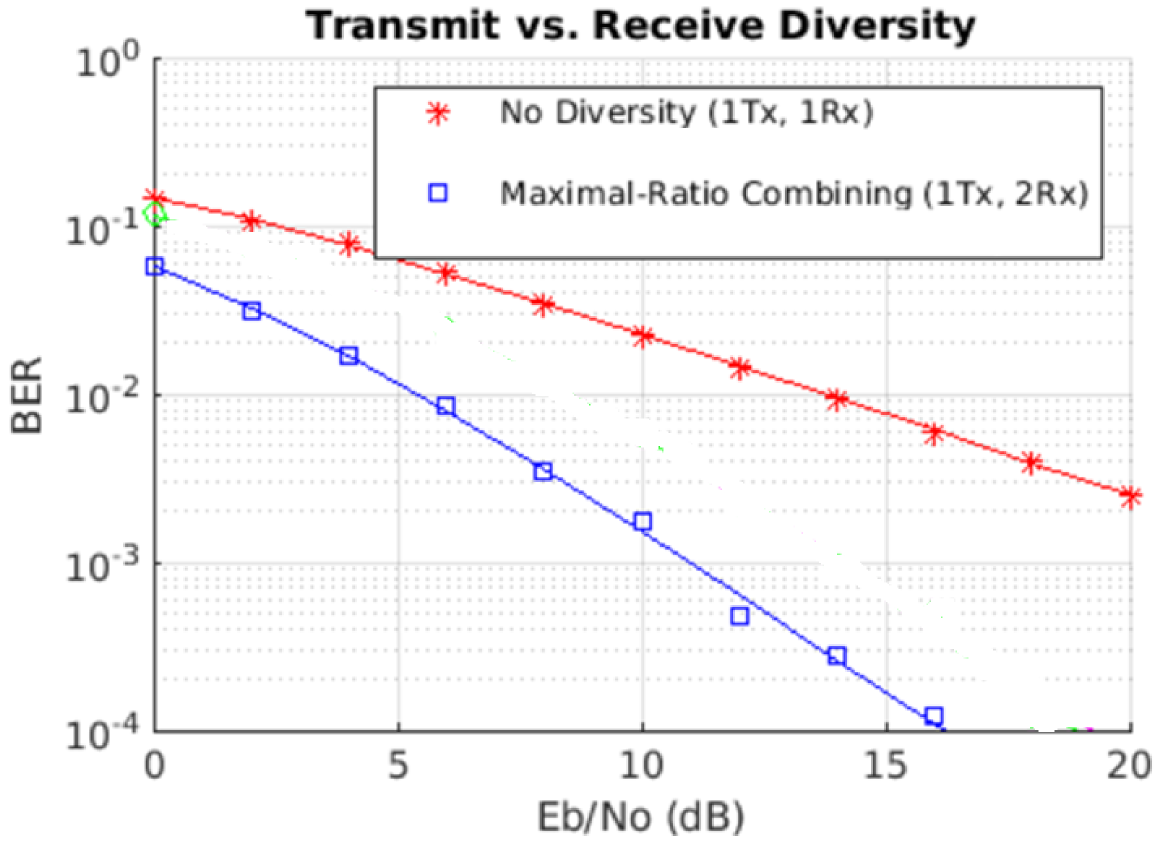
MIMO Model: Diversity Gain

<u>Capacity Gain through MIMO system diversity is as follows:</u>

- In diversity, the same signal is sent multiple times over different spatial paths (antennas), improving reliability by mitigating fading effects and reducing the probability of errors.

- The Shannon capacity formula for an M×N MIMO system (with M transmit antennas and N receive antennas) is given by:

$$C = B\log_2(1 + \lambda_{max}\rho)$$



MIMO Model: Diversity Gain

<u>Capacity Gain through MIMO system diversity is as follows:</u>

$$C = B\log_2(1 + \lambda_{max}\rho)$$

Where

C : Channel capacity

B: Channel bandwidth

ρ : SNR (P/ No)

λ_{max}: is the largest Eigenvalue of the Wishart matrix $W = HH^H$

MIMO Model: Diversity Gain

Capacity Gain through MIMO system diversity is as follows:

Example 10.3: Consider a MIMO channel with gain matrix

$$\mathbf{H} = \begin{bmatrix} .7 & .9 & .8 \\ .3 & .8 & .2 \\ .1 & .3 & .9 \end{bmatrix}$$

Find the capacity of this channel under beamforming assuming channel knowledge at the transmitter and receiver, $B = 100$ KHz, and $\rho = 10$ dB.

Solution The largest singular value of the H matrix is $\sigma^2_{max} = \lambda_{max}$ where λ_{max} is the maximum Eigenvalue of

$$\mathbf{HH}^H = \begin{bmatrix} 1.94 & 1.09 & 1.06 \\ 1.09 & .77 & .45 \\ 1.06 & .45 & .91 \end{bmatrix}$$

and the largest eigenvalue of this matrix is $\lambda_{max} = 3.17$. Thus, $C = B \log_2(1 + \lambda_{max}\rho) = 10^5 \log_2(1 + 31.7) =$ 503 Kbps.

MIMO Model: Diversity Gain

```
import numpy as np

# Define the matrix
A = np.array([[0.7, 0.9, 0.8],
              [0.3, 0.8, 0.2],
              [0.1, 0.3, 0.9]])

W = np.dot(A, A.T)
E = np.linalg.eig(W)

# Print the results
print(W)
print (E)
```

```
[[1.94 1.09 1.06]
 [1.09 0.77 0.45]
 [1.06 0.45 0.91]]
EigResult(eigenvalues=array([3.16990291, 0.0469729 , 0.4031242 ])
```

Thanks!