Wireless Communication Networks & Systems

Spring 2025

Week # 8

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%): Wk8
  - 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:

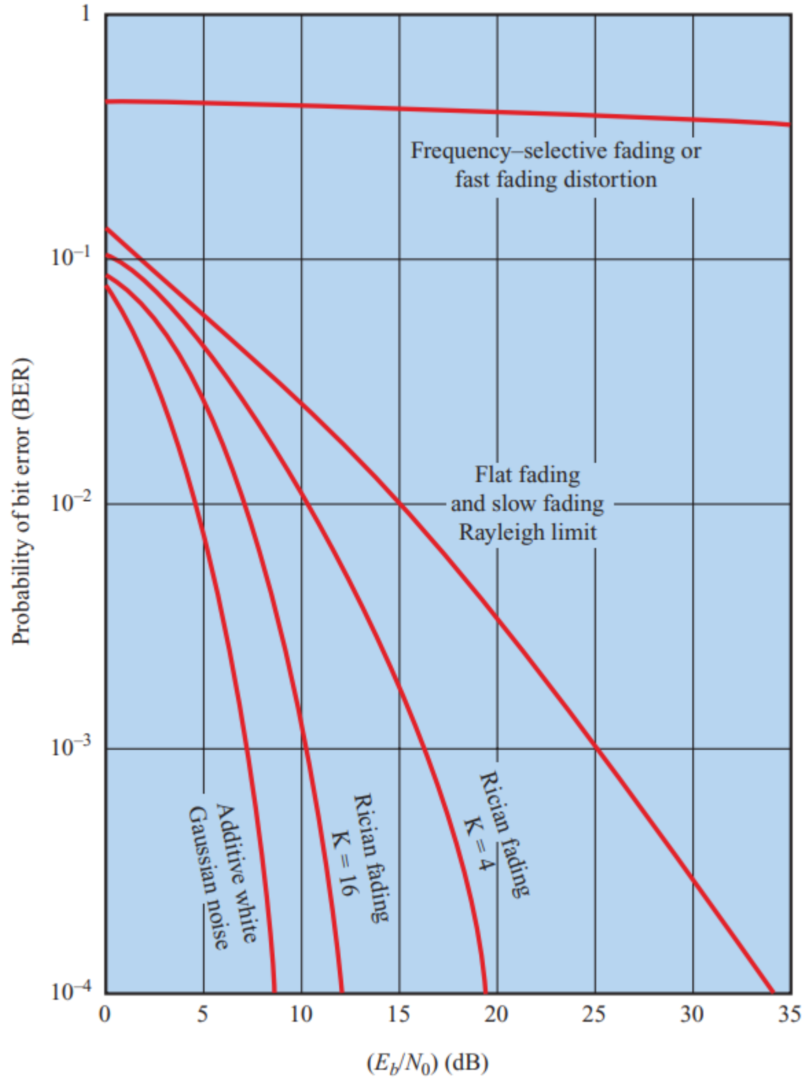
CLO 02 :

- 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

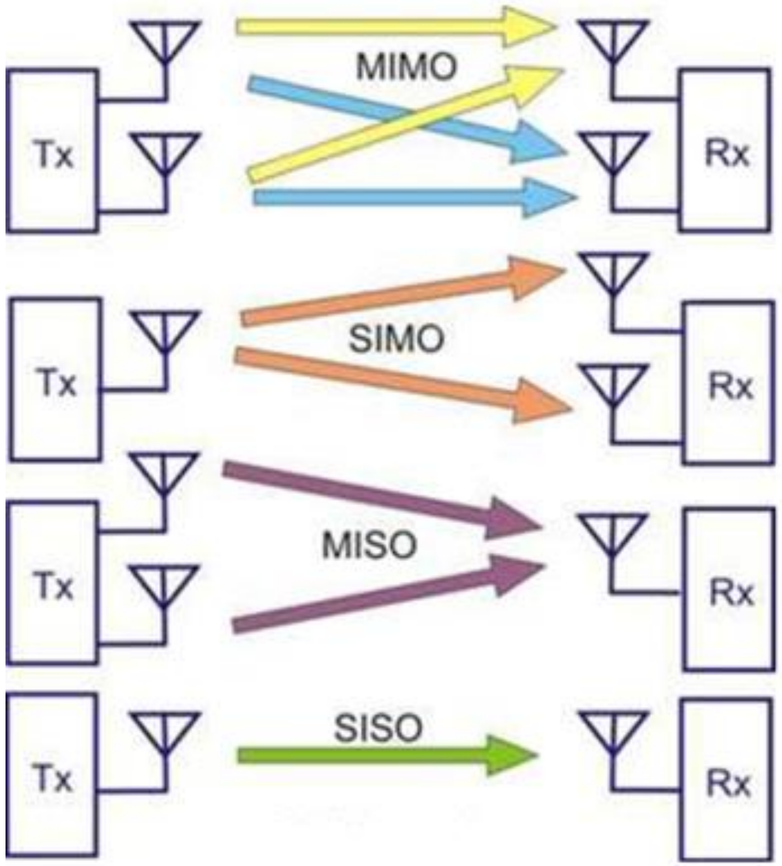
The efforts to compensate for the errors and distortions introduced by <u>Noise, Multipath, and Fading</u> in Wireless transmission fall into the following categories:

- <u>Equalization, Diversity techniques, MIMO and Beamforming (Chapter 6)</u>
- 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

MIMO



MIMO Model:

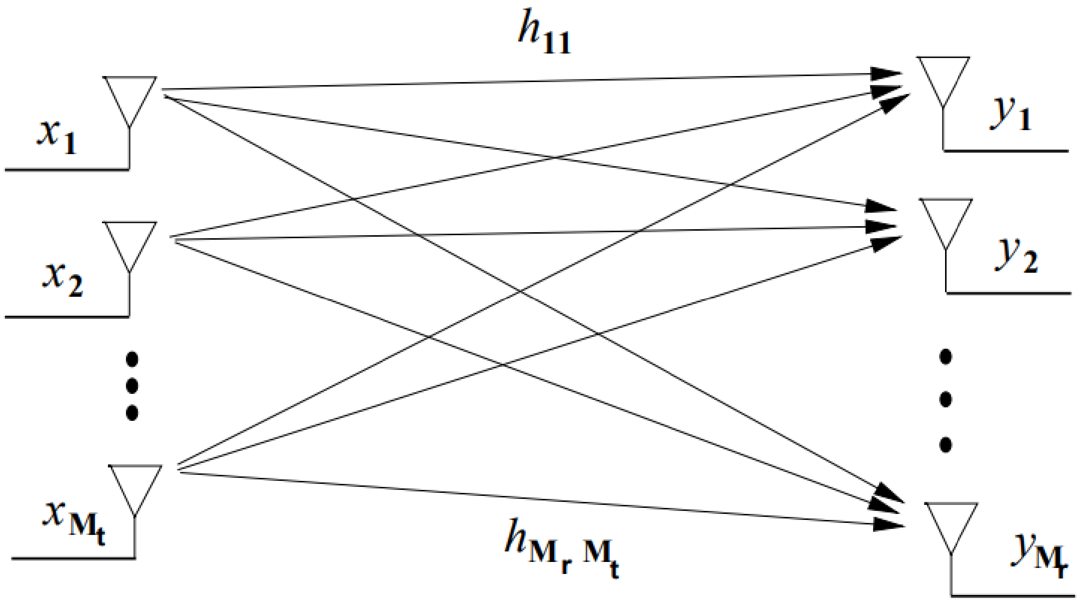
Here,

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.



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

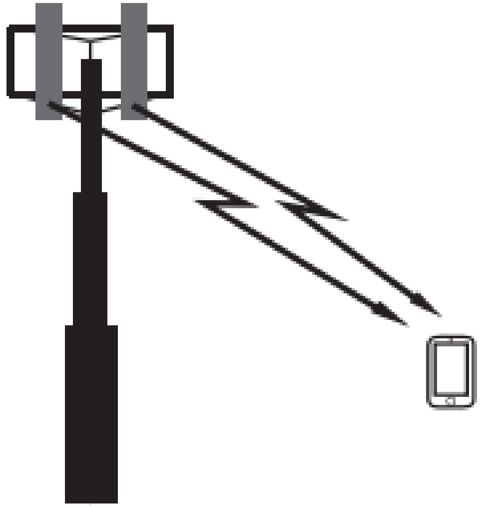
$$\mathbf{Y} = \mathbf{H} \cdot \mathbf{X} + \mathbf{N}$$

MIMO
Diversity Gain
Target: Improvement in BER performance

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

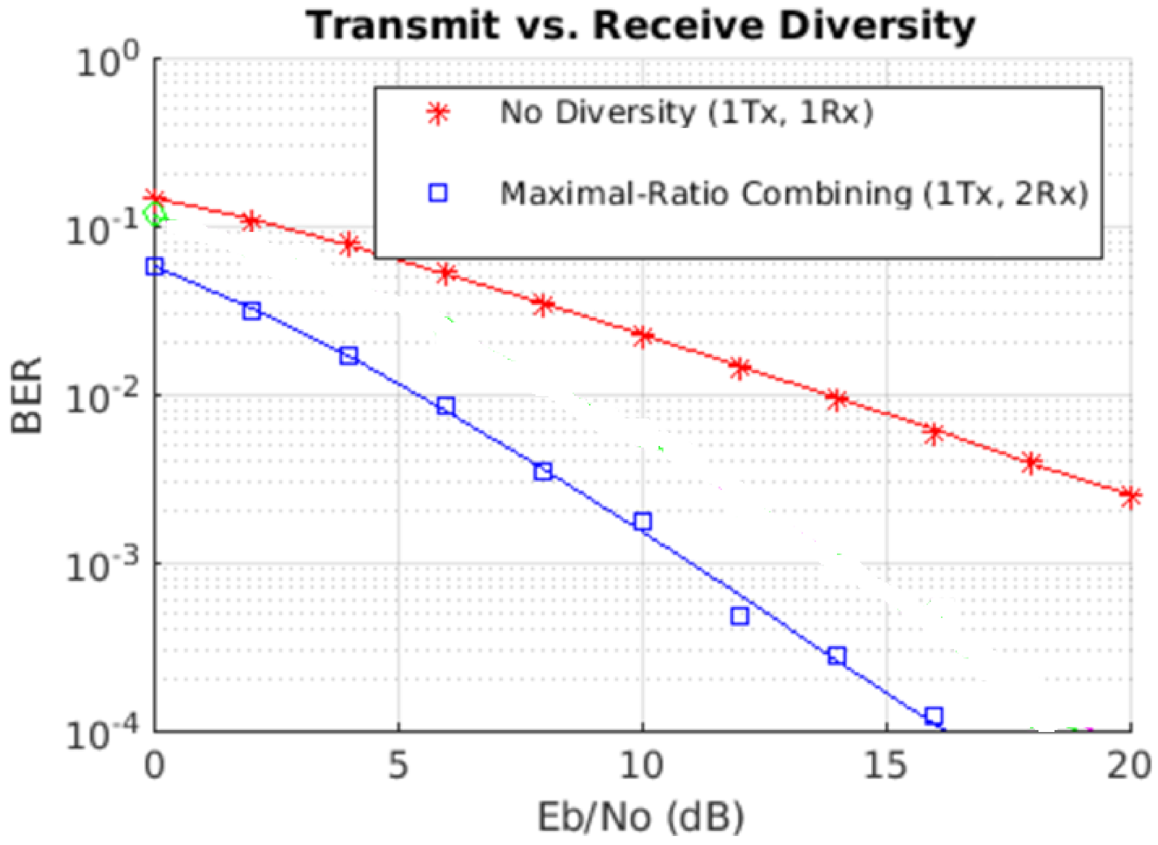
MIMO Model: Diversity Gain

<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

Capacity Gain through MIMO system diversity is as follows:

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

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
Multiplexing Gain
Target: Improvement in Channel Capacity

MIMO Model: Multiplexing Gain

- In MIMO systems, the Singular Value Decomposition (SVD) of the channel matrix provides insights into the channel's properties, such as how many data streams the MIMO system can send simultaneously (multiplexing). Here, SVD is a key matrix factorization technique used to decompose a matrix into simpler components.

- Consider a MIMO channel with $M_r \times M_t$ channel gain matrix H known to both the transmitter and the receiver. The channel matrix H is equal to its singular value decomposition (SVD)

$$\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathbf{H}}$$

Where,

U = $M_r \times M_r$ Unitary Matrix $\mathbf{U}\mathbf{U}^{\mathbf{H}} = \mathbf{I}_{\mathbf{M_r}}$

V = $M_t \times M_t$ Unitary Matrix $\mathbf{V}^{\mathbf{H}}\mathbf{V} = \mathbf{I}_{\mathbf{M_t}}$

Σ = $M_r \times M_t$ diagonal matrix of singular values σ_i, which represent the strength of each channel path.

MIMO Model: Multiplexing Gain

Example 10.1: Find the equivalent parallel channel model for a MIMO channel with channel gain matrix

$$\mathbf{H} = \begin{bmatrix} .1 & .3 & .7 \\ .5 & .4 & .1 \\ .2 & .6 & .8 \end{bmatrix}$$

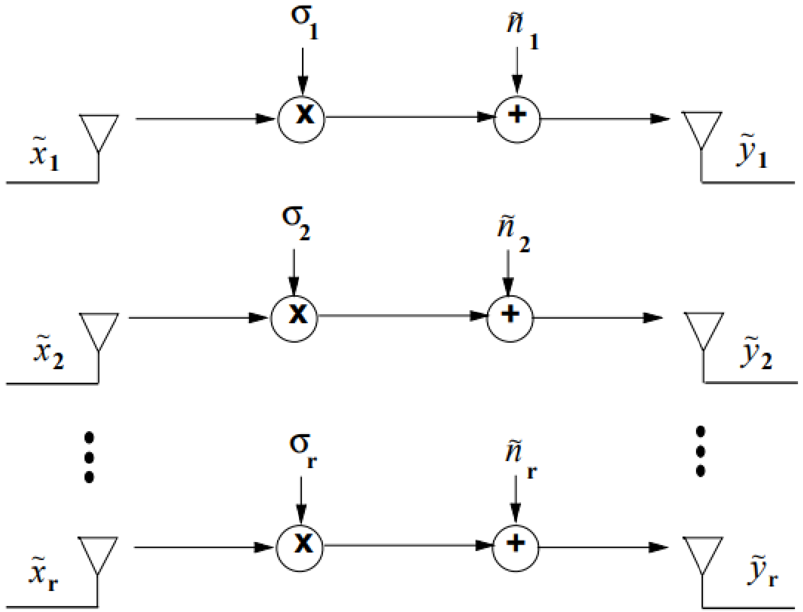
Solution: The SVD of $\mathbf{H}$ is given by

$$\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{\mathbf{H}}$$

$$\mathbf{H} = \begin{bmatrix} -0.555 & .3764 & -.7418 \\ -.3338 & -.9176 & -.2158 \\ -.7619 & 0.1278 & .6349 \end{bmatrix} \boxed{\begin{bmatrix} 1.3333 & 0 & 0 \\ 0 & .5129 & 0 \\ 0 & 0 & .0965 \end{bmatrix}} \begin{bmatrix} -.2811 & -.7713 & -.5710 \\ -.5679 & -.3459 & .7469 \\ -.7736 & .5342 & -.3408 \end{bmatrix}.$$

Thus, since there are 3 nonzero singular values, $R = 3$, leading to three parallel channels, with channel gains $\sigma_1 = 1.3333$, and $\sigma_2 = .5129$, and $\sigma_3 = .0965$, respectively. Note that the channels have diminishing gain, with a very small gain on the third channel. Hence, this last channel will either have a high error probability or a low capacity.

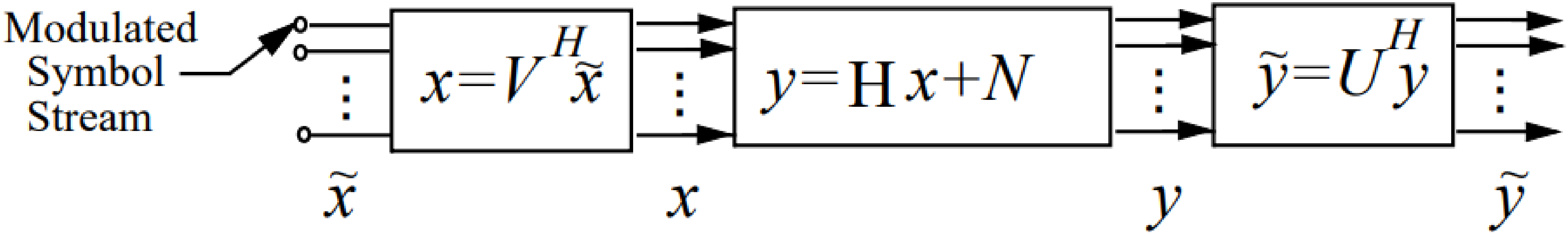
MIMO Model: Multiplexing Gain



- The transmit precoding and receiver shaping transform the MIMO channel into R parallel independent channels with channel gain σ_i

- By sending independent data across each of the parallel channels, the MIMO channel can support R times the data rate of a system with just one transmit and receive antenna, leading to a multiplexing gain of R.

MIMO Model: Multiplexing Gain



- The parallel decomposition of the channel is obtained by defining a transformation on the channel input and output through transmit precoding and receiver shaping.

- The transmit precoding and receiver shaping transform the MIMO channel into R parallel single-input single-output (SISO) channels.

$$
\begin{aligned}
\tilde{\mathbf{y}} &= \mathbf{U}^H(\mathbf{H}\mathbf{x}+\mathbf{n}) \\
&= \mathbf{U}^H(\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}\mathbf{x}+\mathbf{n}) \\
&= \mathbf{U}^H(\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}\mathbf{V}^H\tilde{\mathbf{x}}+\mathbf{n}) \\
&= \mathbf{U}^H\mathbf{U}\boldsymbol{\Sigma}\mathbf{V}\mathbf{V}^H\tilde{\mathbf{x}}+\mathbf{U}^H\mathbf{n} \\
&= \boldsymbol{\Sigma}\tilde{\mathbf{x}}+\tilde{\mathbf{n}},
\end{aligned}
$$

Where **Σ** is the diagonal matrix of singular values of H

MIMO Model: Multiplexing Gain

2. Find the SVD of the following matrix

$$\mathbf{H} = \begin{bmatrix} .7 & .6 & .2 & .4 \\ .1 & .5 & .9 & .2 \\ .3 & .6 & .9 & .1 \end{bmatrix}$$

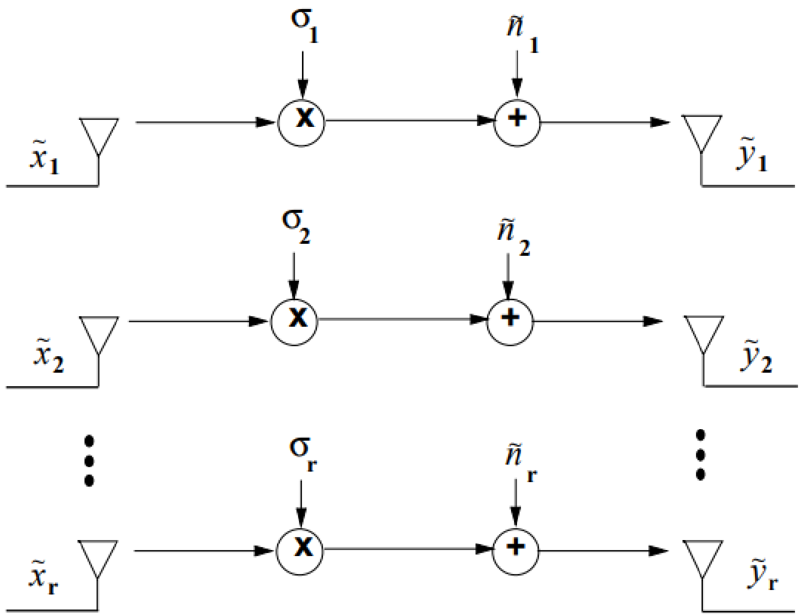
```python
import numpy as np

# Define the matrix
A = np.array([[0.7, 0.6, 0.2, 0.4],
              [0.1, 0.5, 0.9, 0.2],
              [0.3, 0.6, 0.9, 0.1]])

# Perform Singular Value Decomposition (SVD)
U, S, Vh = np.linalg.svd(A)

# Print the results
print("U (Left singular vectors):")
print(U)
print("\nSingular values (S):")
print(S)
print("\nVh (Right singular vectors,
transposed):")
print(Vh)
```

```
U (Left singular vectors):
[[ 0.47831669  0.86853622 -0.12983828]
 [ 0.58961251 -0.42718099 -0.68547319]
 [ 0.65082274 -0.25131899  0.71642762]]

Singular values (S):
[1.70338053 0.71522507 0.13018404]

Vh (Right singular vectors, transposed):
[[ 0.34580045  0.57080018  0.7115586   0.21975797]
 [ 0.68490547  0.21914758 -0.61091642  0.33114946]
 [ 0.42627476  0.07079983  0.01452811 -0.90170181]
 [-0.47918303  0.78812999 -0.34677719 -0.17023608]]
```

MIMO Model: Multiplexing Gain

Capacity Gain through MIMO system multiplexing is as follows:

$$C = \max_{\rho_i : \sum_i \rho_i \leq \rho} \sum_i B \log_2 \left(1 + \sigma_i^2 \rho_i\right).$$



Where,

ρ : SNR (P/ No)

i = Rank of Matrix H (The rank of a matrix is also the maximum number of linearly independent rows/columns of the matrix.

σi= Singular value of Path i

ρi : SNR (Pi/ No) of Path i

The rank of the channel matrix H is determined by calculating the number of non-zero eigenvalues. A full-rank channel matrix (with all eigenvalues being non-zero) allows for maximum spatial multiplexing, which means the MIMO System can fully exploit the multiple antennas for transmitting independent data streams. If some eigenvalues are, the MIMO system cannot utilize all the antennas for multiplexing, and the capacity is reduced.

MIMO Model: Multiplexing Gain

4. Consider the 4×4 MIMO channels given below. What is the maximum multiplexing gain of each, i.e., how many independent scalar data streams can be supported reliably?

$$\mathbf{H}_1 = \begin{bmatrix} 1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & -1 \end{bmatrix}$$

Three unique col.

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 & 1 & -1 \\ 1 & 1 & -1 & 1 \\ 1 & -1 & 1 & 1 \\ 1 & -1 & -1 & -1 \end{bmatrix}.$$

Four unique col. or rows

Hint: The rank of a matrix H, denoted as rank(H), is the maximum number of linearly independent rows or columns in the matrix. This is equivalent to the dimension of the row space or column space of the matrix.

MIMO
Diversity Vs Multiplexing Gain
Target: BER Vs Capacity

MIMO Model: Multiplexing & Diversity

- The multiple antennas are extensively used to improve wireless system performance. One option is to obtain capacity gain by decomposing the MIMO channel into parallel channels and multiplexing different data streams onto these channels. This capacity gain is also referred to as a multiplexing gain.

- Alternatively, In MIMO 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.

- It is also possible to adapt the diversity and multiplexing gains relative to channel conditions. Specifically, in poor channel states more antennas can be used for diversity gain, whereas in good states more antennas can be used for multiplexing. Adaptive techniques that change antenna use to trade off diversity and multiplexing based on channel conditions

End of Chapter # 06

Wireless Communication Technology:

<u>CLO 02 :</u>

- Chapter 05 – Overview of Wireless Communications
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- Chapter 07 – Signal Encoding Techniques
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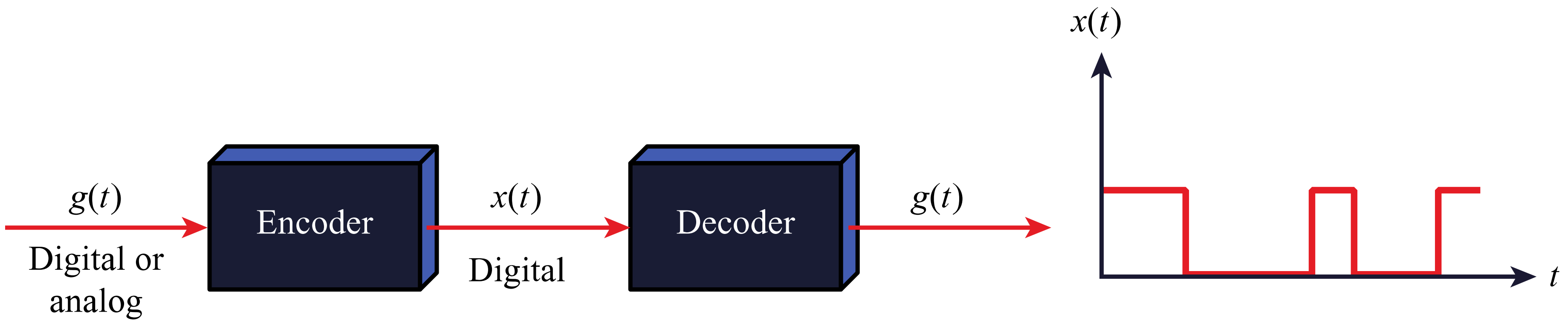
- Chapter 10 – Coding and Error Control

Signal Encoding Techniques:

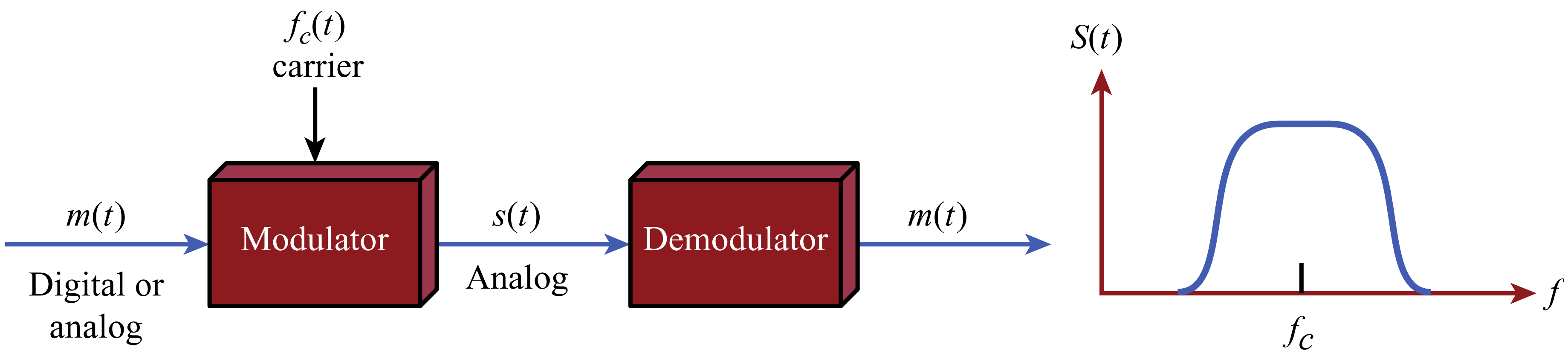
- Encoding is a process of converting user information (such as text, audio, video, or other data) into a specific format for transmission over a channel.

- This process involves transforming the original data into a sequence of signals or symbols that can be efficiently sent over a communication medium, such as wires, radio waves, or optical fibers.

Signal Encoding Techniques:



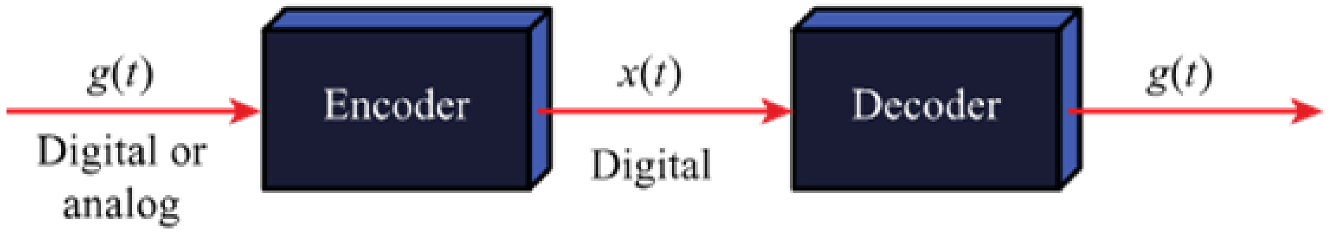
(a) Encoding onto a digital signal



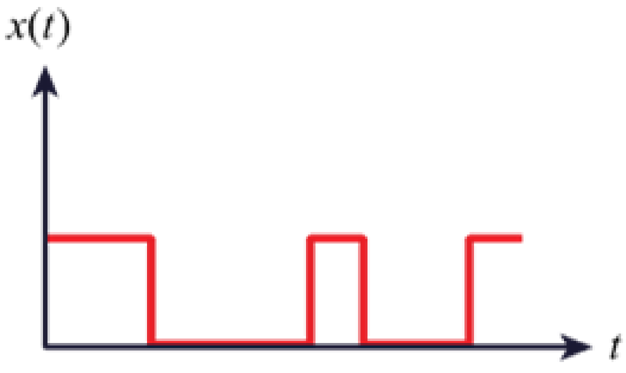
(b) Modulation onto an analog signal

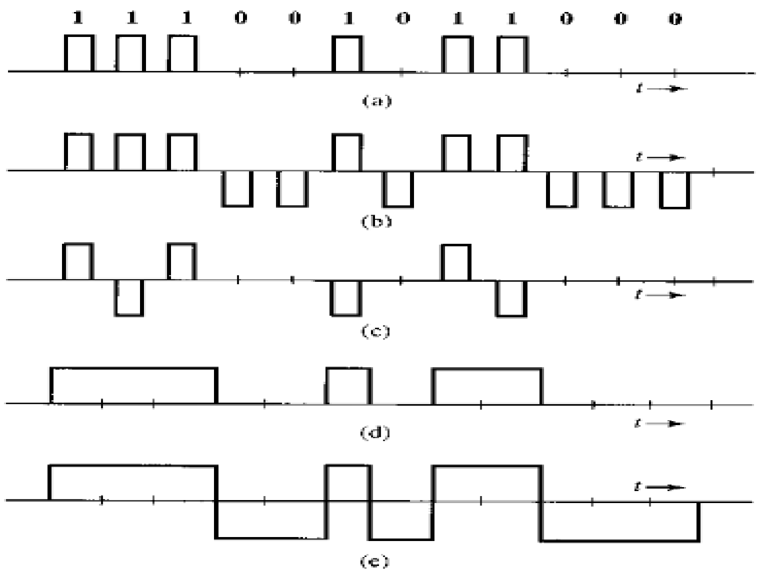
Signal Encoding Techniques:

User information Encoding into Digital Signal



(a) Encoding onto a digital signal



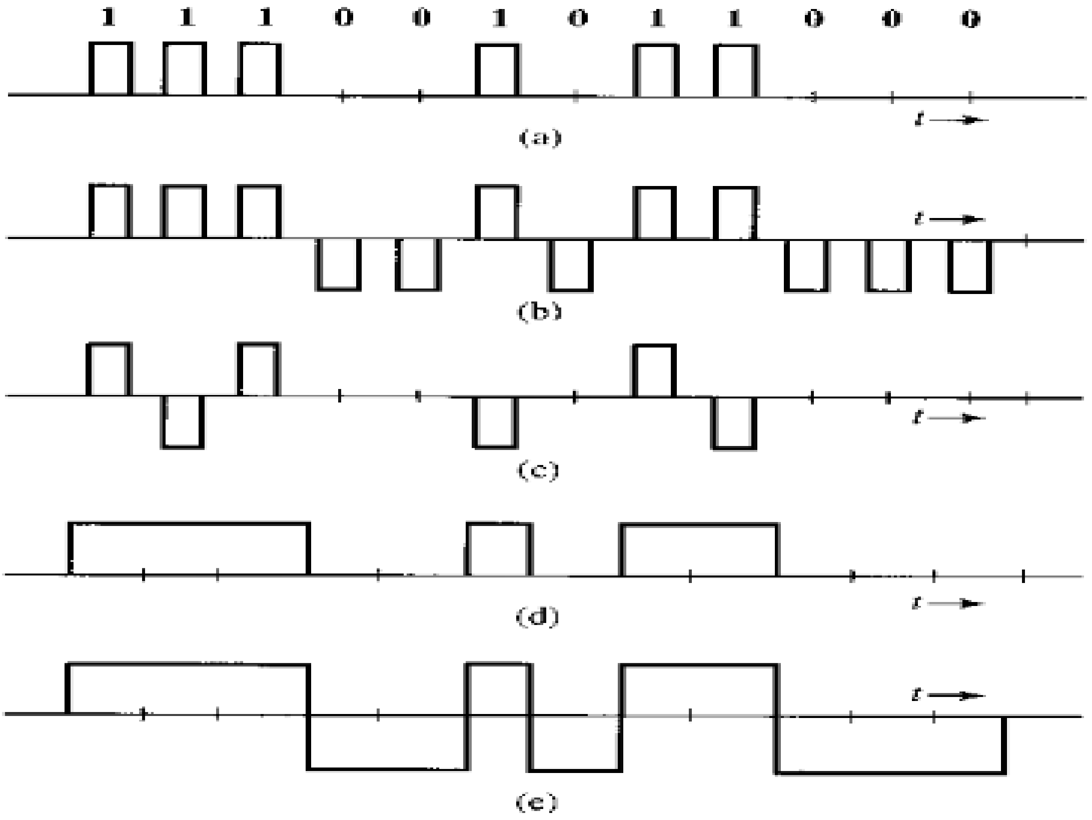


a. ON-OFF (return to zero, RZ)
b. Polar RZ
c. Bipolar RZ
d. ON-OFF NRZ
e. Polar NRZ

Encoding into Digital Signal:

<u>Main design parameters for the selection of Encoding Schemes coding :</u>

- Signal Spectrum
- Favorable power spectral density
- Power efficiency
- Error detection and correction capability
- Adequate timing content for synchronization

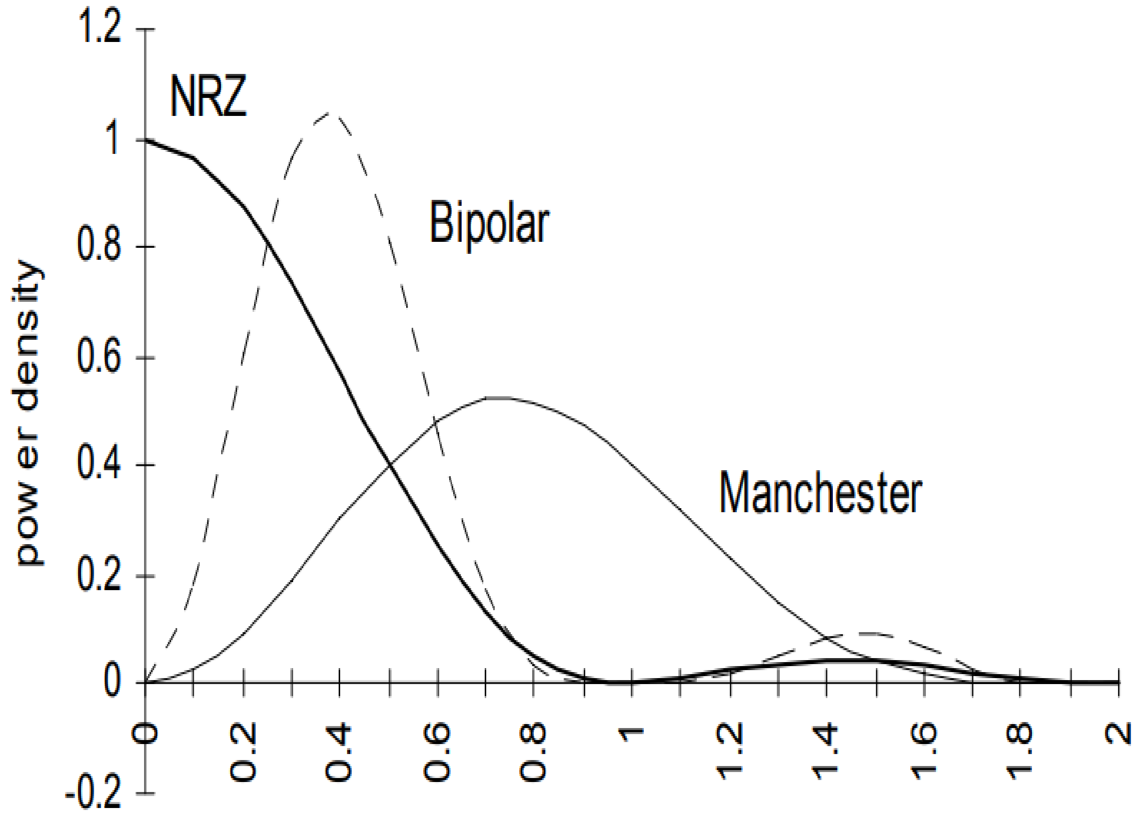


Encoding into Digital Signal:

Signal Spectrum: Several signal spectrum aspects are important while selecting the Encoding scheme. For instance:

- A lack of high-frequency components means that less bandwidth is required for transmission.

- A lack of a DC component is also desirable while selecting encoding schemes. With no DC component, alternating current (AC) coupling via transformer is possible, this provides excellent electrical isolation, reducing interference.

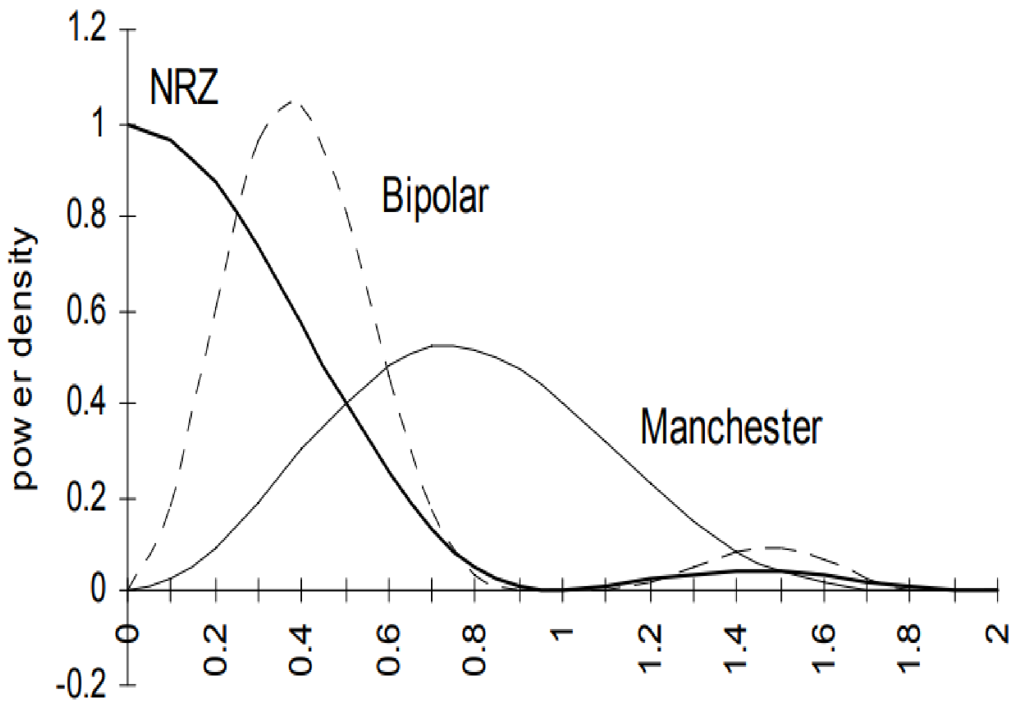


Encoding into Digital Signal:

<u>Signal Spectrum:</u>

- In practice, it usually happens that the transfer function of a channel is worse near the band edges. Therefore, a good signal design should concentrate the transmitted power toward the middle of the transmission bandwidth.

- In such a case, less distortion should be present in the received signal. To meet this objective, the Encoding scheme can be designed to shape the spectrum of the transmitted signal.

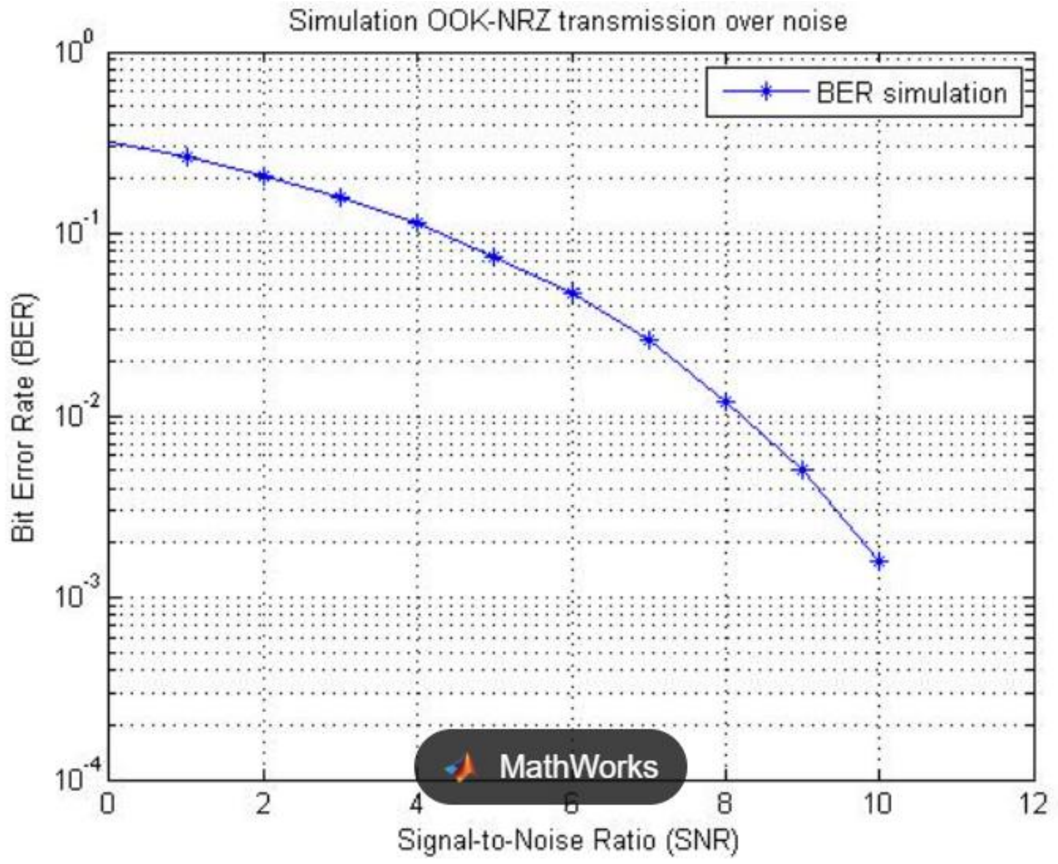


Encoding into Digital Signal:

<u>Signal interference and noise immunity:</u>

- When the received signal is corrupted by noise, the receiver should be able to recover the signal with a low error probability.

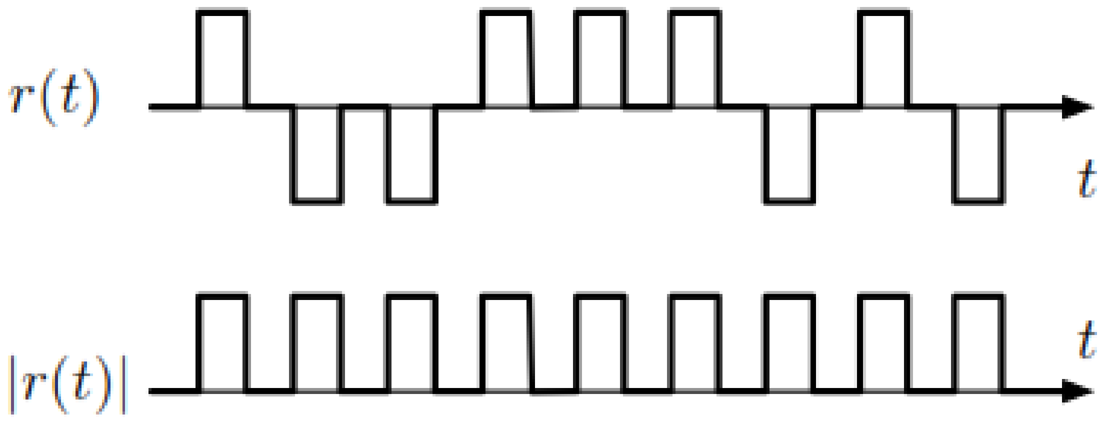
- Certain codes exhibit superior performance in the presence of noise. This is usually expressed in terms of BER.



Encoding into Digital Signal:

Clocking or Synchronization:

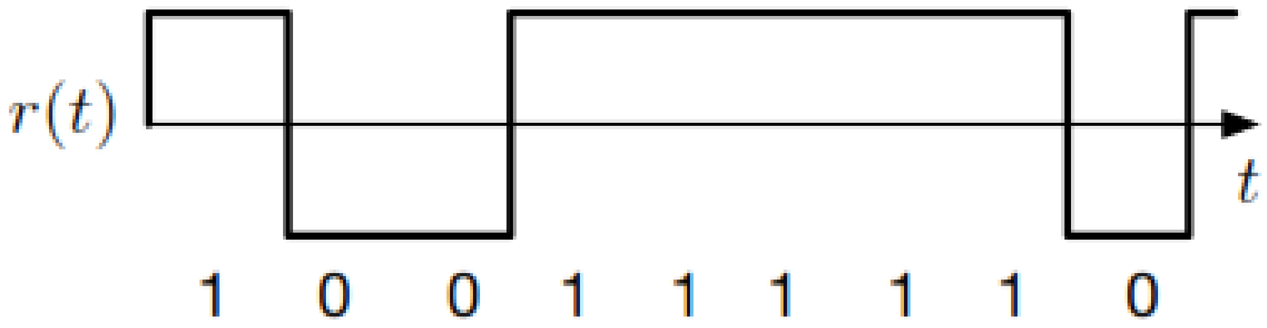
- The receiver must determine the beginning and end of each bit position, this is no easy task.
- One rather expensive approach is to provide a separate clock channel to synchronize the transmitter and receiver.
- The alternative is to provide some synchronization mechanism that is based on the transmitted signal. This can be achieved with suitable encoding.



Encoding into Digital Signal:

<u>Clocking or Synchronization:</u>

NRZ codes can be problematic. Long strings of 1’s or 0’s can cause loss of synchronization. Many codes limit the number of consecutive runs of 1’s or 0’s, and force bit changes after a given number of bits.



Encoding into Digital Signal:

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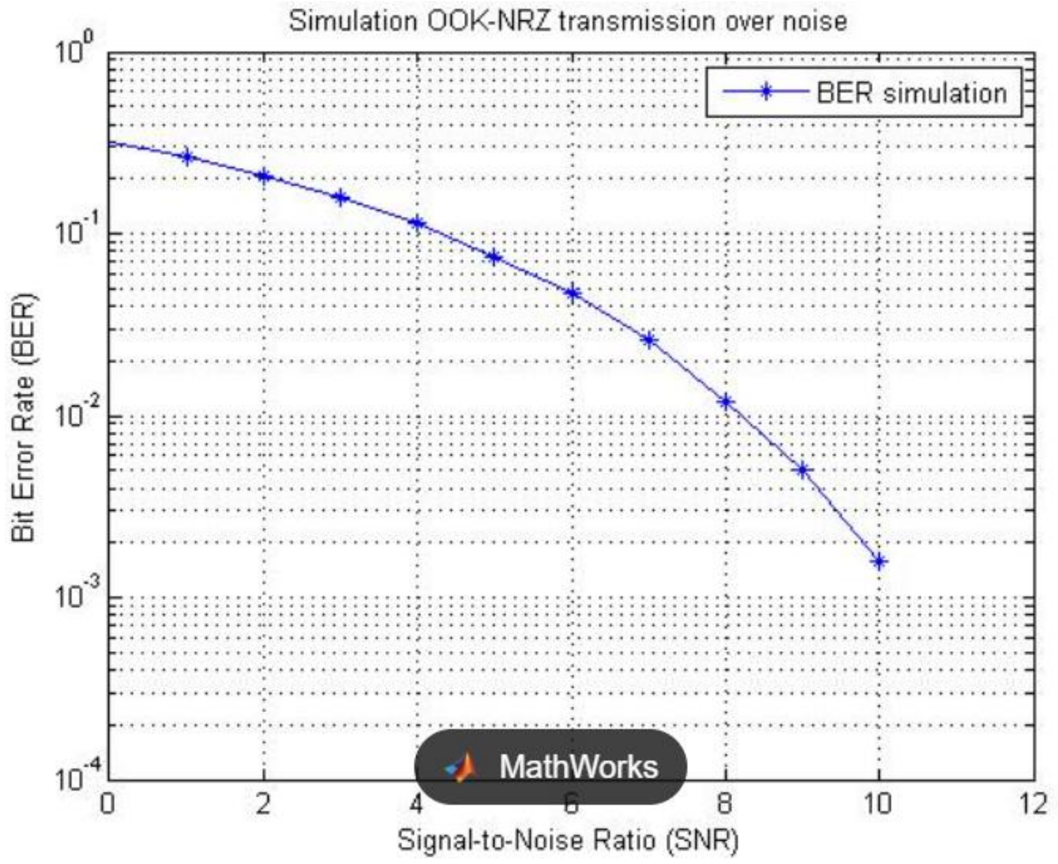
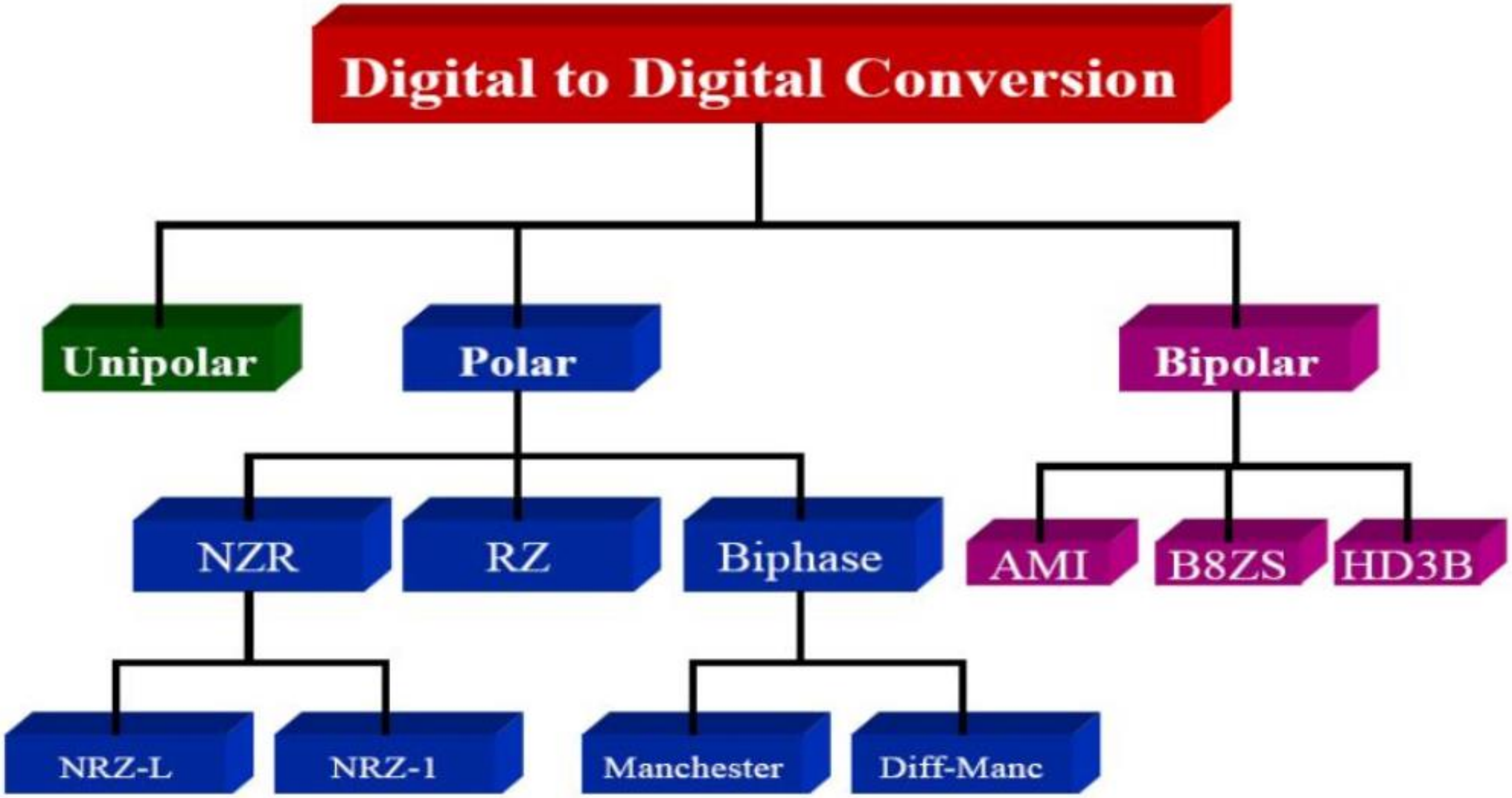


Encoding into Digital Signal:



Encoding into Digital Signal:

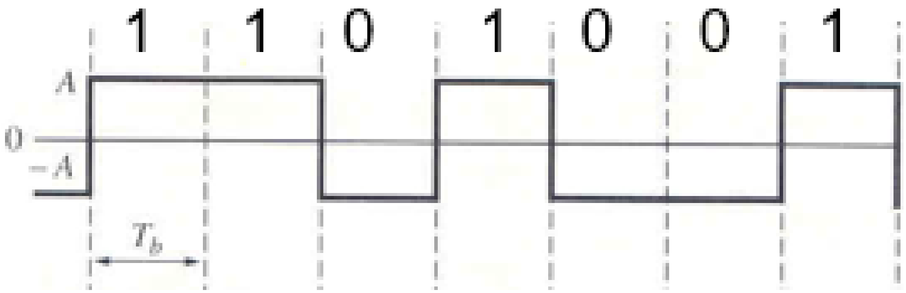
Polar NRZ

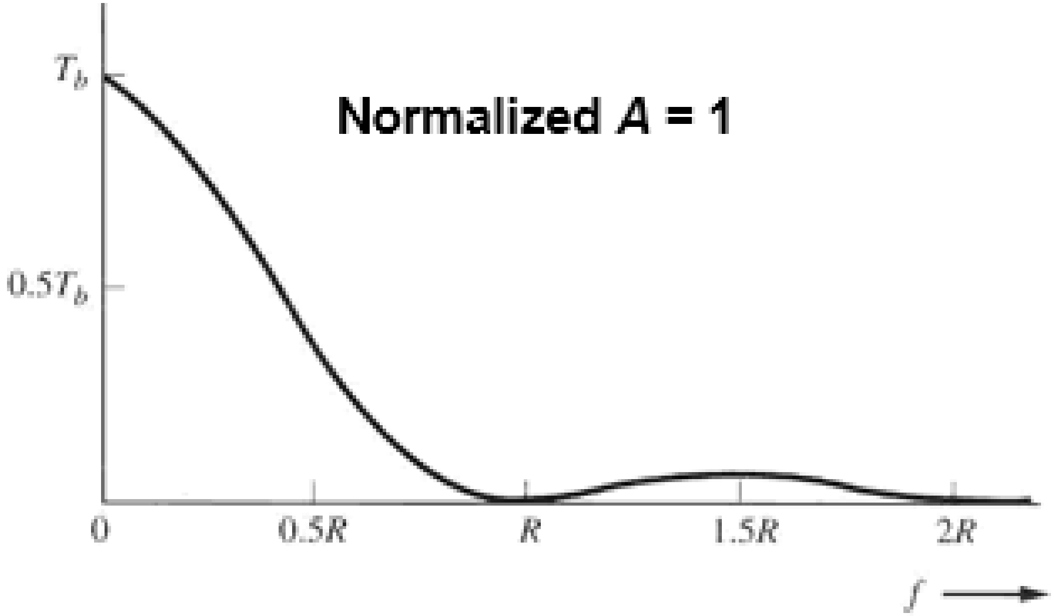
Advantages:

- Fairly easy to generate
- Bit error probability performance is the best.
- Low Bandwidth requirement

Disadvantages:

- It has a large power spectral density near DC.
- Dual supply voltages ±V
- Poor clock recovery, a string of 1s or 0s wil cause a loss of clock signal.





Encoding into Digital Signal:

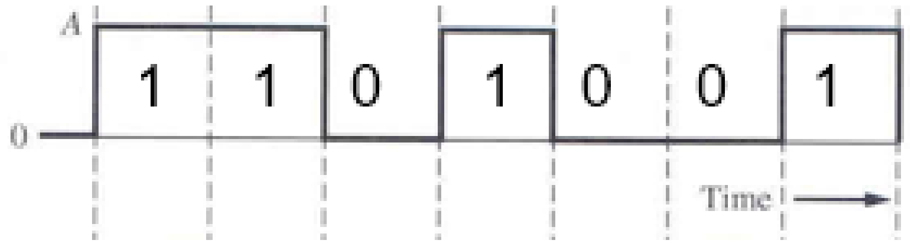
Uni-polar NRZ

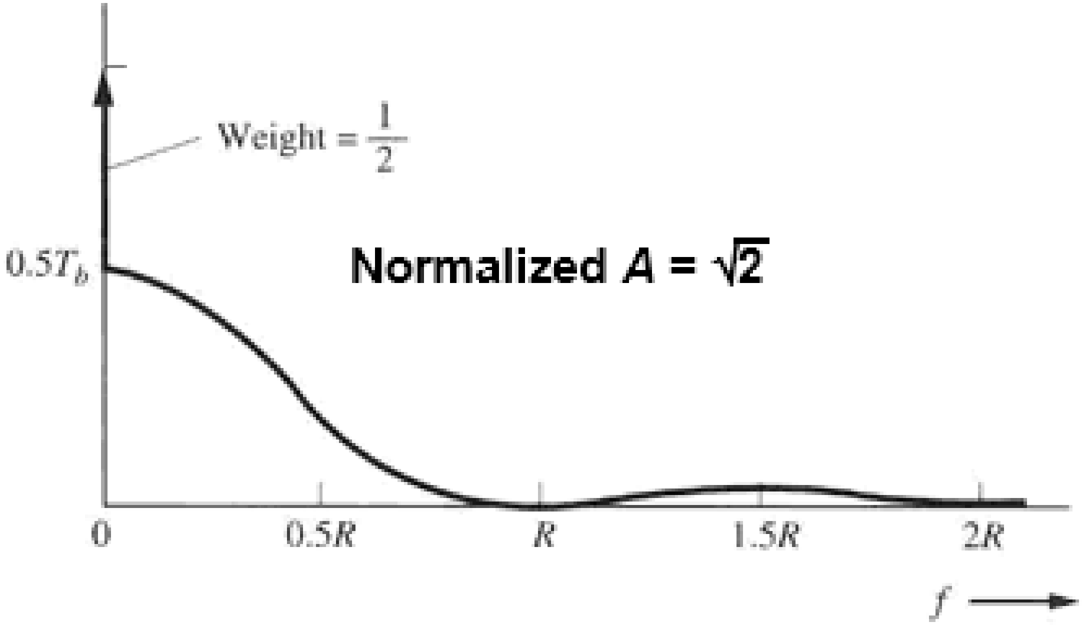
Advantages:

- Easy to generate (0, +5V)
- Single supply voltage
- Low Bandwidth requirement
- Efficient in terms of power requirement

Disadvantages:

- It has a large power spectral density near DC.
- Poor clock recovery, a string of 1s or 0s will cause a loss of clock signal.





Encoding into Digital Signal:

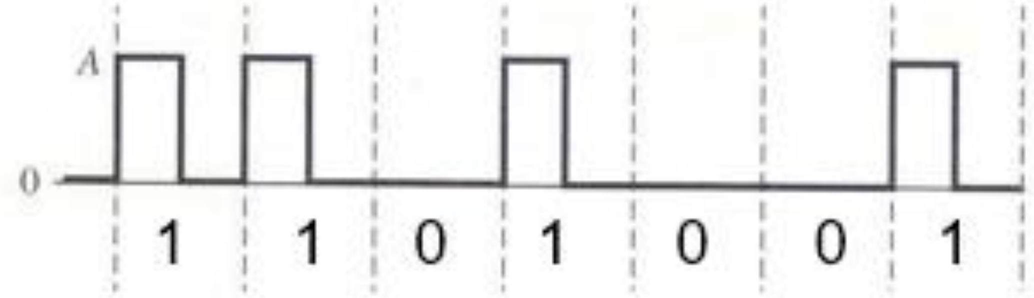
Unipolar RZ

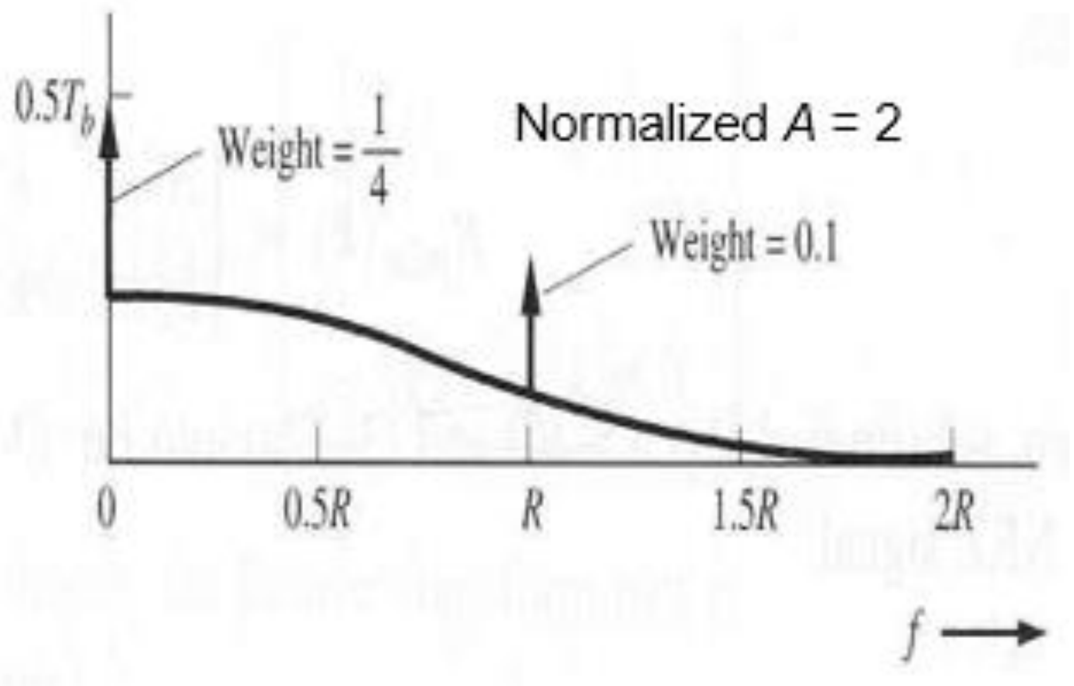
Advantages:

- Good clock recovery due to periodic impulses

Disadvantages:

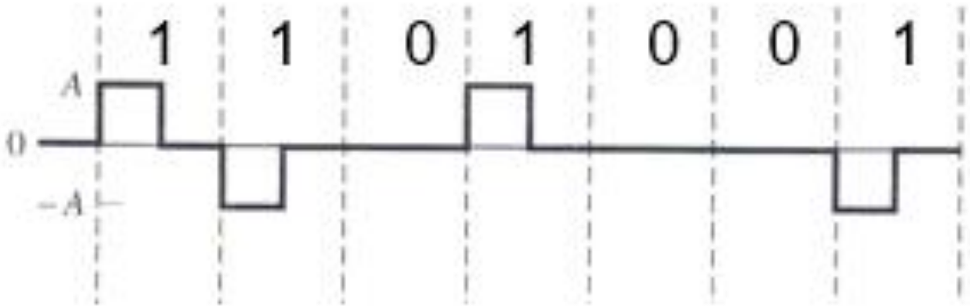
- The first null bandwidth is twice that for the polar NRZ signal or the unipolar NRZ signal.
- The spectrum is not negligible near DC.





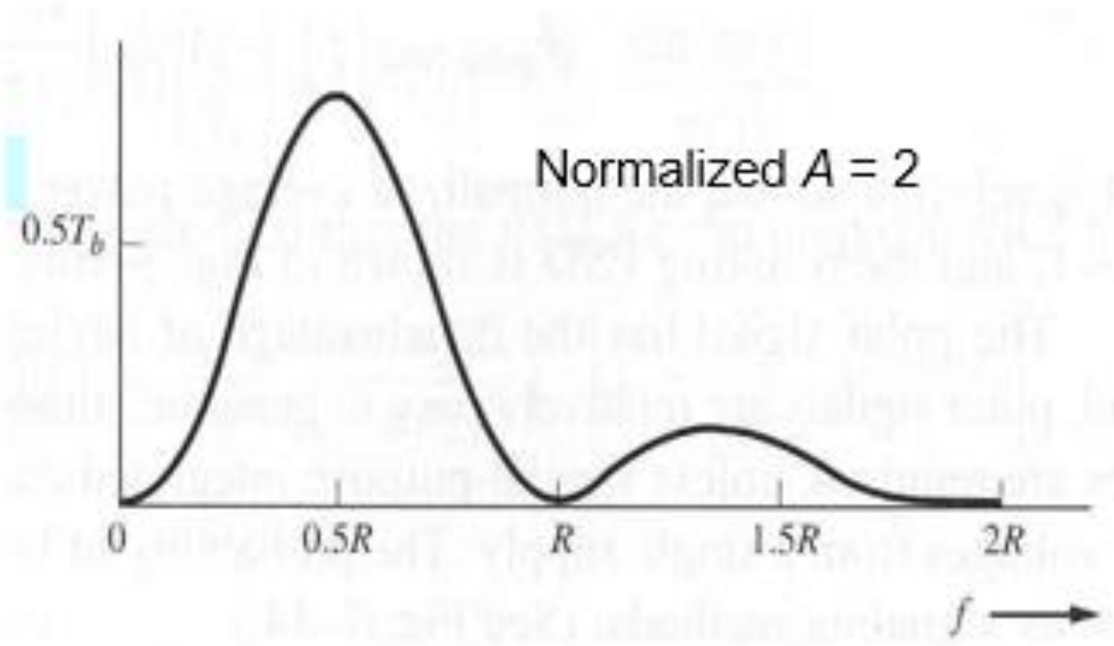
Encoding into Digital Signal:

Bipolar RZ (AMI: Alternate Mark Invert))



Advantages:

- There is a null at DC so that an AC-coupled circuit may be used in the transmission path.
- It has single-error-detection capability
- Good clock recovery



- Disadvantages:
- String of 0's that cause loss of clock signal
- Moderate BW but not as good as unipolar

Or polar NRZ as the first side lobe is larger

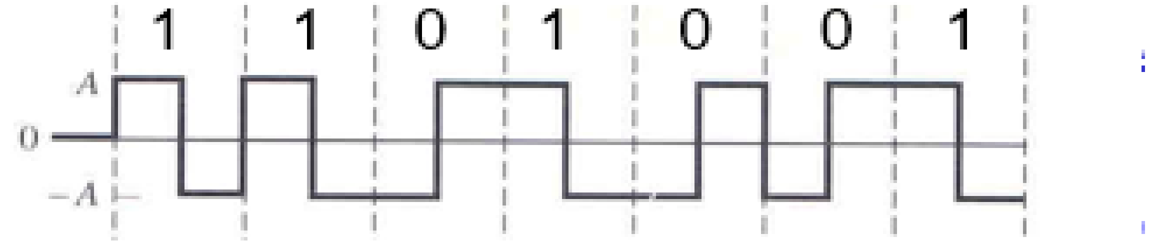
Encoding into Digital Signal:

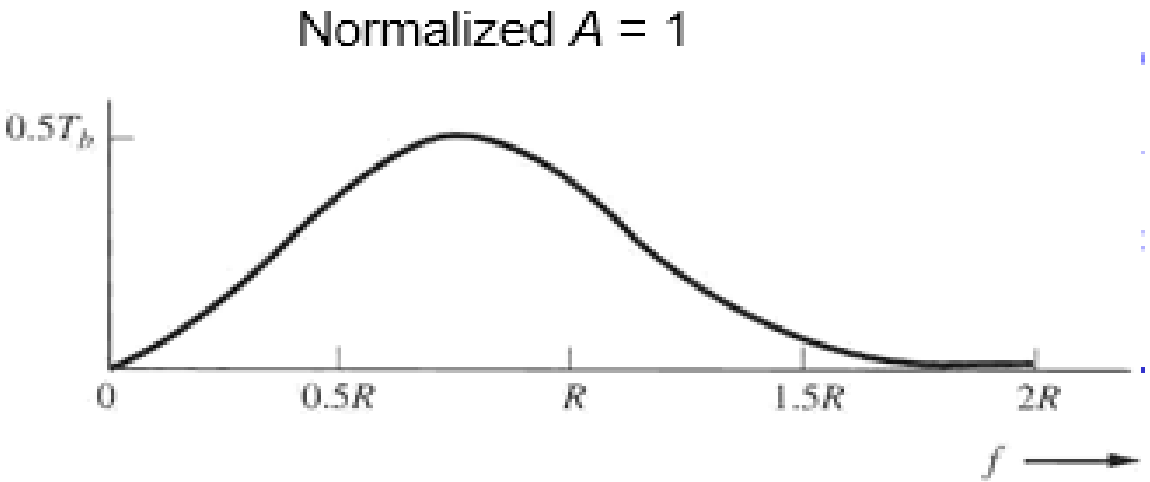
Manchester RZ

Advantages:

- One zero crossing per bit provides good recovery of clock signal
- Excellent synchronization since string of 0's won't cause loss of clock
- Good in case of heavy interference on band edges.

- Disadvantages:
- Double BW relative to NRZ codes
- Dual power supply for ±V





Encoding into Digital Signal:

Consider the given stream of Digital data: 1 1 1 0 0 0 1 0 1 0

Draw the waveforms of this sequence using:

- On-off (RZ)
- Polar (RZ)
- Bipolar (RZ)-AMI
- On-off (NRZ)
- Polar (NRZ)
- Manchester RZ

Thanks!