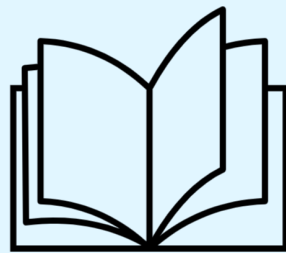


Beyond 5G: Foundations and Future of Mobile Communication

*Lecture Notes and Exercises on 5G and 6G
Technologies*

Hemant, K.





Copyright © 2025 Kumar Hemant

All rights reserved. No part of this journal may be reproduced, stored, or transmitted in any form or by any means—electronic, mechanical, photocopying, recording, scanning, or otherwise—without written permission from the author. It is illegal to copy this journal, post it to a website, or distribute it by any other means without permission.

This journal is a personal learning resource and is intended for academic and educational purposes only. Any resemblance to course content or proprietary material is coincidental and unintentional.

Licensed under a [Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License](<https://creativecommons.org/licenses/by-nc-nd/4.0/>).

First edition, 2025

Published by Kumar Hemant

</.Table of Contents >

1	Introduction to Wireless Communication	4
1.1	Cellular Network Fundamentals	4
1.2	Generations of Mobile Networks	4
1.3	The Cellular Concept	5
1.4	Visualizing Wireless Signals	5
1.5	Summary	5
1.6	Further Reading	5
1.7	Appendix A1: Signal Strength and Path Loss Notebook	6
1.8	Appendix A2: Streamlit App – Cell Coverage Planner	6
2	Spectrum and Modulation in 5G	7
2.1	Introduction	7
2.2	Spectrum Overview	7
2.3	Modulation Techniques in 5G	7
2.4	Appendix: A2 – OFDM Signal Simulation	8
2.5	References	8
3	Multiple Access and Scheduling	9
3.1	Introduction	9
3.2	Multiple Access Techniques	9
3.3	Scheduling Strategies	11
3.4	Comparative Overview	12
3.5	Conclusion	12
4	Channel Estimation and Equalization	13
4.1	Introduction	13
4.2	Channel Effects	13
4.3	Channel Models	13
4.4	Channel Estimation Techniques	14
4.5	Equalization Techniques	14
4.6	OFDM Channel Estimation	14
4.7	Conclusion	15
5	MIMO and Beamforming	16
5.1	Introduction to MIMO Systems	16
5.2	Spatial Multiplexing	16
5.3	Diversity Gain vs. Multiplexing Gain	16
5.4	Channel Capacity of MIMO	16
5.5	Beamforming Concepts	16
5.6	Antenna Arrays and Steering Vectors	17
5.7	Practical Exploration (See Appendix)	17

5.8	References and Further Reading	17
5.9	Appendix: Notebook and Streamlit App	17
6	Massive MIMO & mmWave Communication	18
6.1	Introduction to Massive MIMO	18
6.2	mmWave Communication Fundamentals	18
6.3	Propagation at mmWave Frequencies	19
6.4	Beamforming: Analog, Digital, Hybrid	19
6.5	MIMO Channel Capacity	19
6.6	Use Cases	19
6.7	Summary	20
6.8	Further Reading	20
A	Appendix: Signal Strength and Path Loss Visualization	21
a	Overview	21
b	Simulation	21
c	References	22
B	Appendix: Modulation and Spectrum Simulation	23
a	Interactive OFDM Simulation Notebook	23
C	Appendix: Multiple Access and Scheduling Simulations	25
C.1	Additional Appendix: Channel Estimation and Equalization Simulation	28
D	Appendix: MIMO & Beamforming Simulation	30
D.1	MIMO & Beamforming Simulation	30

» Lecture / 1

Introduction to Wireless Communication

1.1 Cellular Network Fundamentals

1.1.1 What is Wireless Communication?

Wireless communication refers to the transfer of information between two or more points that are not physically connected. It forms the basis for mobile networks, enabling services like voice calling, mobile data, and SMS.

1.1.2 Basic Terminology

- **Base Station (BS):** The fixed point of communication for mobile devices in a cell.
- **User Equipment (UE):** Devices such as smartphones and modems.
- **Radio Access Network (RAN):** Connects UE to the core network.
- **Frequency Band:** The range of frequencies used for wireless transmission.

1.2 Generations of Mobile Networks

1.2.1 From 1G to 5G

- **1G:** Analog voice only, poor quality and security.
- **2G:** Digital voice (GSM), SMS, and limited data (GPRS, EDGE).
- **3G:** Mobile broadband (UMTS, HSPA), video calling.
- **4G:** All-IP network (LTE), high-speed data, VoLTE.
- **5G:** Massive MIMO, mmWave, URLLC, eMBB, mMTC.

1.2.2 Key Performance Metrics

- **Latency:** Time delay in communication.
- **Throughput:** Amount of data transferred per second.

- **Spectral Efficiency:** Bits/sec/Hz — how efficiently spectrum is used.
- **Energy Efficiency:** Data transmitted per joule of energy.

1.3 The Cellular Concept

1.3.1 Cell Reuse and Frequency Planning

Cellular systems divide the service area into small regions (cells) each with a base station, and reuse frequency bands in a planned manner to avoid interference.

1.3.2 Hexagonal Cell Approximation

- Provides a geometrical model for coverage.
- Each cell uses a different set of frequencies compared to its neighbors.
- Reuse Factor $N = i^2 + ij + j^2$ where (i, j) are frequency reuse parameters.

1.3.3 Interference and SINR

The performance of wireless communication depends on the Signal to Interference plus Noise Ratio (SINR). Techniques such as sectorization, power control, and handover are used to manage interference.

1.4 Visualizing Wireless Signals

1.4.1 Path Loss Models

- **Free Space Path Loss (FSPL):**

$$\text{FSPL (dB)} = 20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10} \left(\frac{4\pi}{c} \right)$$

- **Log-distance path loss:**

$$PL(d) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right)$$

1.4.2 Interactive Visualizations (Notebook/Streamlit)

See Appendix 1.7 and Appendix 1.8 for interactive notebooks and streamlit apps.

1.5 Summary

This chapter introduced basic concepts in wireless communication including the evolution of mobile generations, the cellular concept, and essential performance metrics.

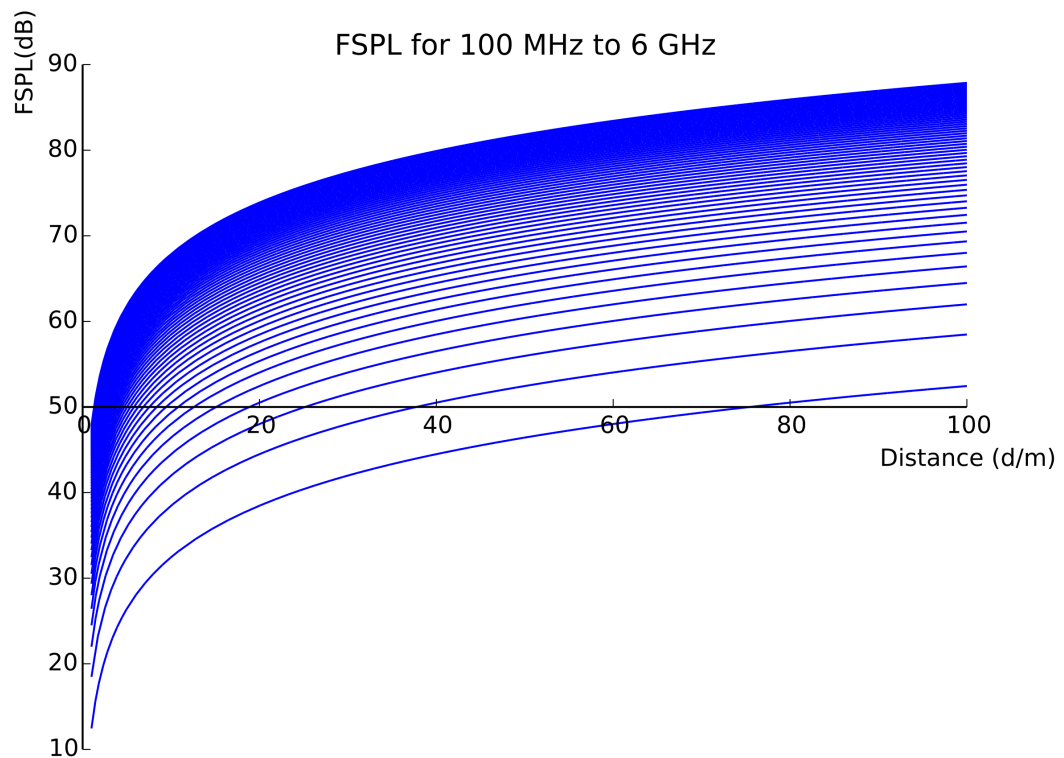
1.6 Further Reading

- T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall.
- Andreas F. Molisch, *Wireless Communications*, Wiley.
- 3GPP TS 38.300: 5G NR Overall Architecture.

1.7 Appendix A1: Signal Strength and Path Loss Notebook

Download: `notebooks/A1-signal_strength.ipynb`

Topics Covered: Free space path loss, signal visualization in dBm vs distance.



Preview:

1.8 Appendix A2: Streamlit App – Cell Coverage Planner

URL: <http://localhost:8501/CellCoverage>

Features:

- Adjust cell radius and visualize overlapping coverage.
- Frequency reuse simulation with color-coded hex cells.
- Path loss visualization with user-tunable exponent n .

» Lecture / 2

Spectrum and Modulation in 5G

2.1 Introduction

In wireless communication, the **spectrum** is the range of electromagnetic frequencies over which communication signals are transmitted. Efficient use of the spectrum is critical for the high-speed and reliable operation of 5G networks.

2.2 Spectrum Overview

2.2.1 Licensed vs Unlicensed Bands

- **Licensed Spectrum:** Controlled by national regulatory bodies. Examples: 3.5 GHz, 28 GHz.
- **Unlicensed Spectrum:** Open access bands like 2.4 GHz (used by Wi-Fi).

2.2.2 5G Spectrum Ranges

- **FR1 (Sub-6 GHz):** 410 MHz to 7125 MHz
- **FR2 (mmWave):** 24.25 GHz to 52.6 GHz

2.3 Modulation Techniques in 5G

2.3.1 Why Modulate?

Modulation encodes digital information onto analog carriers for transmission. 5G uses advanced modulation to support massive data throughput.

2.3.2 OFDM – Orthogonal Frequency Division Multiplexing

- Splits spectrum into many orthogonal subcarriers
- Robust to multipath fading
- Basis for both LTE and 5G

2.3.3 Other Modulation Techniques

- QPSK, 16-QAM, 64-QAM, 256-QAM
- Tradeoff: Higher order = more bits per symbol = more susceptible to noise

2.4 Appendix: A2 – OFDM Signal Simulation

A detailed hands-on simulation of OFDM signals in both time and frequency domains is provided in Appendix A2.

2.5 References

1. Dahlman, E., Parkvall, S., and Skold, J. (2020). *5G NR: The Next Generation Wireless Access Technology*.
2. 3GPP TS 38.211 v16.4.0
3. IEEE Spectrum: Understanding Modulation and OFDM

» Lecture / 3

Multiple Access and Scheduling

3.1 Introduction

Modern cellular networks support simultaneous access for a large number of users. Efficient multiple access techniques and intelligent scheduling algorithms are essential for maximizing throughput and ensuring fairness. This chapter explores various access schemes including FDMA, TDMA, OFDMA, and NOMA, and introduces key scheduling strategies.

3.2 Multiple Access Techniques

3.2.1 Frequency Division Multiple Access (FDMA)

In FDMA, the available frequency spectrum is divided into multiple frequency bands, and each user is assigned a distinct band.

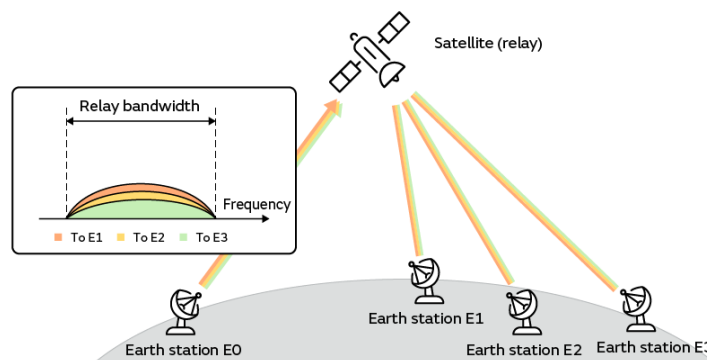


Figure 3.1: FDMA resource allocation example.

3.2.2 Time Division Multiple Access (TDMA)

TDMA divides time into slots. Each user is given a dedicated time slot in a cyclic manner.

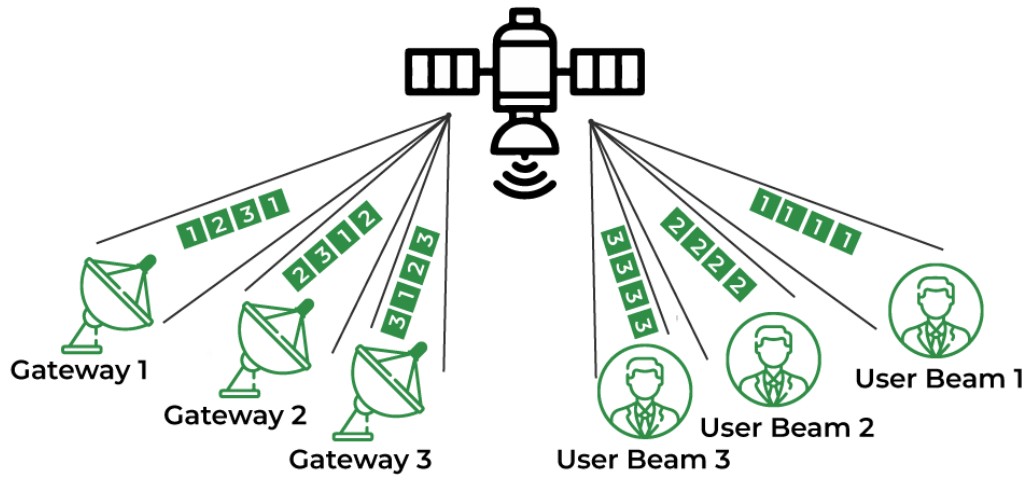


Figure 3.2: TDMA time-slot allocation.

3.2.3 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is widely used in 4G and 5G systems. It divides the spectrum into many subcarriers and assigns them orthogonally to users.

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi kn/N} \quad (3.1)$$

Where:

- X_k is the k -th subcarrier symbol
- x_n is the data on subcarrier n
- N is the total number of subcarriers

3.2.4 Non-Orthogonal Multiple Access (NOMA)

NOMA allows multiple users to share the same time-frequency resources by using power-domain multiplexing and successive interference cancellation (SIC).

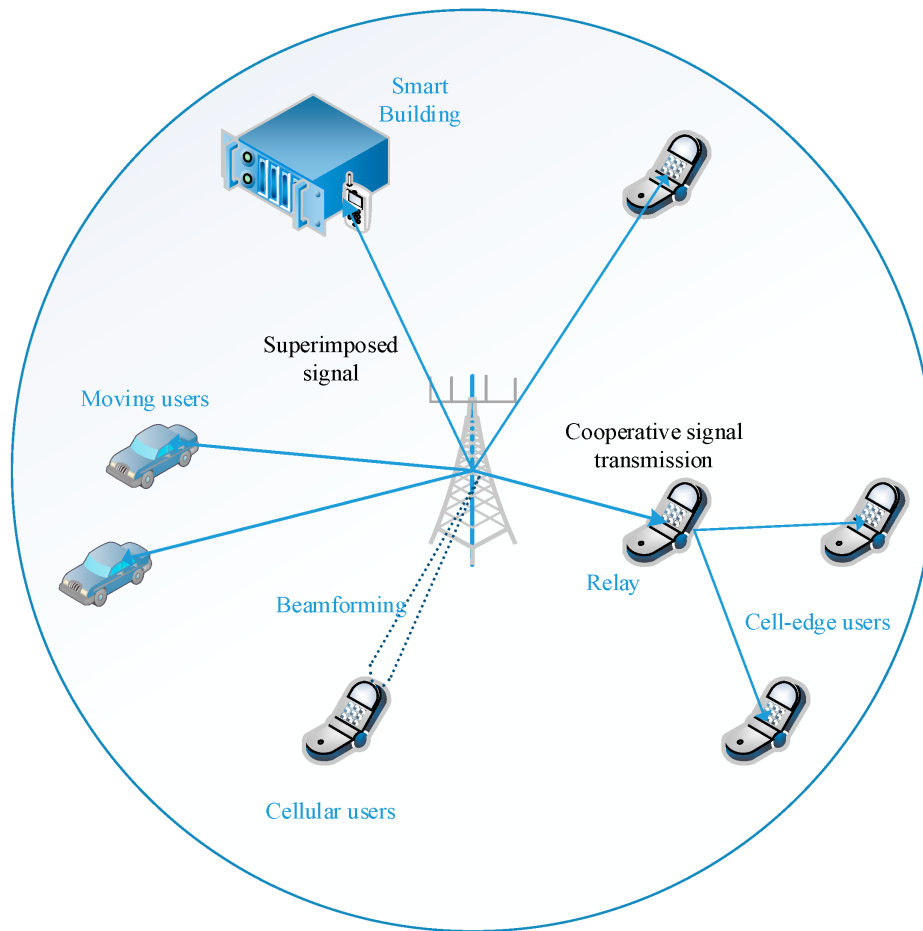


Figure 3.3: NOMA with successive interference cancellation.

3.3 Scheduling Strategies

3.3.1 Round Robin (RR) Scheduler

This scheduler allocates time slots to users in a cyclic order, ensuring fairness but not necessarily optimizing throughput.

3.3.2 Proportional Fair (PF) Scheduler

PF scheduler attempts to balance fairness and throughput. The metric is defined as:

$$M_i = \frac{R_i(t)}{\bar{R}_i(t)} \quad (3.2)$$

Where:

- $R_i(t)$ is the instantaneous rate of user i
- $\bar{R}_i(t)$ is the historical average rate

3.4 Comparative Overview

Scheme	Orthogonal	Used In
FDMA	Yes	1G
TDMA	Yes	2G
OFDMA	Yes	4G, 5G
NOMA	No	5G, 6G

Table 3.1: Comparison of multiple access techniques.

3.5 Conclusion

Multiple access and scheduling techniques form the backbone of cellular systems. Understanding their principles allows for better network optimization and user experience.

Next: Appendix section includes hands-on simulations using Jupyter notebooks and Streamlit apps.

» Lecture / 4

Channel Estimation and Equalization

4.1 Introduction

In a wireless communication system, signals propagate through a channel that introduces distortion due to multipath fading, noise, and Doppler shifts. To reliably decode the transmitted data, the receiver must estimate the channel and apply equalization techniques to mitigate these effects.

4.2 Channel Effects

4.2.1 Multipath Fading

A transmitted signal reaches the receiver through multiple paths, causing constructive and destructive interference.

- Delay spread leads to Inter-Symbol Interference (ISI)
- Coherence bandwidth determines frequency selectivity

4.2.2 Noise and Doppler Effects

The wireless channel also adds additive white Gaussian noise (AWGN) and may cause Doppler shift due to user mobility.

4.3 Channel Models

4.3.1 Flat Fading vs. Frequency Selective Fading

- Flat fading: Channel gain is constant across bandwidth
- Frequency selective fading: Channel varies across subcarriers

4.3.2 Mathematical Model

For a baseband channel:

$$r(t) = h(t) * s(t) + n(t)$$

Where:

- $r(t)$ is the received signal
- $h(t)$ is the channel impulse response
- $s(t)$ is the transmitted signal
- $n(t)$ is additive noise

4.4 Channel Estimation Techniques

4.4.1 Pilot-Based Estimation

Transmit known pilot symbols at predefined locations. Estimate channel response based on received pilot values.

$$\hat{h} = \frac{y_p}{x_p}$$

4.4.2 Least Squares (LS) Estimation

Minimizes the squared error between received and estimated values.

$$\hat{h}_{LS} = (X^H X)^{-1} X^H y$$

4.4.3 Minimum Mean Squared Error (MMSE) Estimation

Takes noise and channel statistics into account.

$$\hat{h}_{MMSE} = R_{hy} R_{yy}^{-1} y$$

4.5 Equalization Techniques

4.5.1 Zero Forcing Equalizer (ZF)

Inverts the channel matrix assuming no noise.

$$\hat{x} = (H^H H)^{-1} H^H y$$

4.5.2 MMSE Equalizer

Balances inversion and noise suppression.

$$\hat{x}_{MMSE} = (H^H H + \sigma^2 I)^{-1} H^H y$$

4.6 OFDM Channel Estimation

OFDM uses pilot subcarriers across time and frequency.

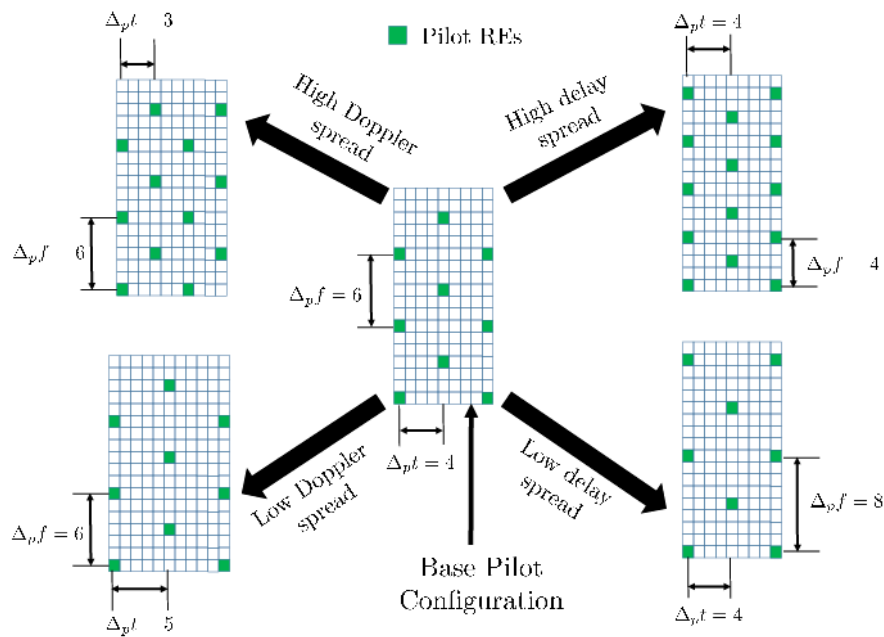


Figure 4.1: Pilot placement in time-frequency grid of OFDM.

4.7 Conclusion

Accurate channel estimation and equalization are crucial for reliable communication in fading environments. In modern systems like 5G, advanced equalizers are paired with MIMO and OFDM to enhance performance.

Further Reading

- Rappaport, T. S. (2010). *Wireless Communications: Principles and Practice*.
- Tse, D., & Viswanath, P. (2005). *Fundamentals of Wireless Communication*.

» Lecture / 5

MIMO and Beamforming

5.1 Introduction to MIMO Systems

Multiple-Input Multiple-Output (MIMO) is a fundamental technology in modern wireless communication systems, enabling high data rates and improved reliability. By using multiple antennas at both the transmitter and receiver, MIMO exploits multipath propagation to improve link capacity and robustness.

5.2 Spatial Multiplexing

Spatial multiplexing allows multiple data streams to be transmitted simultaneously over the same frequency band, effectively increasing the spectral efficiency. Each stream is transmitted from a different antenna and ideally received without interference.

5.3 Diversity Gain vs. Multiplexing Gain

5.3.1 Diversity Gain

Improves reliability by sending the same data across multiple antennas.

5.3.2 Multiplexing Gain

Increases capacity by transmitting independent data streams.

The diversity-multiplexing tradeoff must be carefully considered during system design.

5.4 Channel Capacity of MIMO

For an $N_t \times N_r$ MIMO system, the channel capacity is given by:

$$C = \log_2 \det \left(I + \frac{\rho}{N_t} H H^H \right) \text{ bits/s/Hz}$$

where H is the channel matrix, ρ is the SNR, and H^H is the Hermitian transpose.

5.5 Beamforming Concepts

5.5.1 Analog Beamforming

Single RF chain, phase shifters applied in analog domain.

5.5.2 Digital Beamforming

Each antenna has its own RF chain, allowing full spatial control.

5.5.3 Hybrid Beamforming

Combines analog and digital techniques to reduce hardware complexity while maintaining performance.

5.6 Antenna Arrays and Steering Vectors

Beamforming is implemented by adjusting the phases across antenna elements. For a Uniform Linear Array (ULA), the steering vector for angle θ is:

$$\mathbf{a}(\theta) = \left[1, e^{-jkd \sin(\theta)}, \dots, e^{-jkd(N-1) \sin(\theta)} \right]^T$$

5.7 Practical Exploration (See Appendix)

A detailed simulation and visualization of MIMO and beamforming concepts is provided in the accompanying Jupyter notebook and optional Streamlit app.

5.8 References and Further Reading

- Goldsmith, A. (2005). *Wireless Communications*. Cambridge University Press.
- Tse, D., & Viswanath, P. (2005). *Fundamentals of Wireless Communication*.
- Heath, R. W., & Lozano, A. (2018). *Foundations of MIMO Communication*.
- <https://web.mit.edu/6.450/www/> – Advanced Digital Communication resources.

5.9 Appendix: Notebook and Streamlit App

- **Notebook:** `A5_mimo_beamforming_simulation.ipynb` includes MIMO capacity simulations, beam pattern visualizations, and interactive antenna exploration.
- **Streamlit App:** `BeamPatternVisualizer.py` (optional) enables real-time exploration of beamforming patterns under different configurations.

» Lecture / 6

Massive MIMO & mmWave Communication

Massive MIMO and millimeter-wave (mmWave) technologies form the backbone of modern 5G and future 6G wireless systems. This chapter introduces the fundamentals of these technologies, explores the associated mathematical models, and demonstrates their benefits and limitations through examples.

6.1 Introduction to Massive MIMO

Massive MIMO refers to wireless communication systems with an extremely large number of antennas (typically tens to hundreds) at the base station. The primary goals are:

- Increased spectral efficiency through spatial multiplexing.
- Improved energy efficiency by focusing transmission energy.
- Reduced interference via beamforming and spatial separation.

6.1.1 Key Benefits

- **Channel hardening:** With more antennas, small-scale fading averages out.
- **Favorable propagation:** Orthogonality between channels of different users.
- **High capacity:** Significant data rate improvements under line-of-sight (LoS) and rich scattering.

6.2 mmWave Communication Fundamentals

Millimeter-wave (mmWave) bands typically refer to the frequency range between 24 GHz and 100 GHz. They are critical for high-bandwidth communication, enabling:

- Multi-gigabit-per-second data rates.
- Dense spectrum reuse due to narrow beams.
- Compact antenna arrays because of small wavelengths.

6.2.1 Challenges

- Severe free-space path loss (FSPL).
- High susceptibility to blockages and weather.
- Hardware complexity in RF chains and beamforming.

6.3 Propagation at mmWave Frequencies

Propagation characteristics at mmWave include:

- High reflection and scattering.
- Poor diffraction around obstacles.
- Shorter range compared to sub-6GHz.

Despite these, mmWave communication benefits from the ability to use large antenna arrays to steer beams and concentrate energy.

6.4 Beamforming: Analog, Digital, Hybrid

- **Analog beamforming:** Uses phase shifters at RF level.
- **Digital beamforming:** Baseband processing with each antenna connected to its own RF chain.
- **Hybrid beamforming:** Combination of both to reduce hardware complexity while retaining flexibility.

6.5 MIMO Channel Capacity

The capacity of a MIMO system increases with the number of antennas and SNR. For a MIMO system with N_t transmit and N_r receive antennas:

$$C = \log_2 \det \left(I + \frac{P}{N_t N_0} H H^H \right)$$

Where H is the channel matrix and P is the transmit power.

6.6 Use Cases

- Fixed Wireless Access (FWA)
- Ultra-HD video streaming
- Wireless backhaul
- Vehicle-to-Everything (V2X)

6.7 Summary

- Massive MIMO provides large gains in throughput and reliability by leveraging large antenna arrays.
- mmWave frequencies offer huge bandwidths but face path loss and blockage issues.
- Hybrid beamforming and smart antenna design are essential to realize these systems.

6.8 Further Reading

- Marzetta, T. L., et al. “Fundamentals of Massive MIMO.”
- Heath, R. W., et al. “Millimeter Wave Wireless Communications.”
- 3GPP TR 38.900: Study on channel model for frequencies above 6 GHz.

Appendix A

Appendix: Signal Strength and Path Loss Visualization

a Overview

This appendix introduces practical visualization of signal strength decay over distance using:

- Free Space Path Loss (FSPL)
- Log-distance Path Loss model

b Simulation

We provide both a Jupyter notebook and an interactive Streamlit app for hands-on exploration.

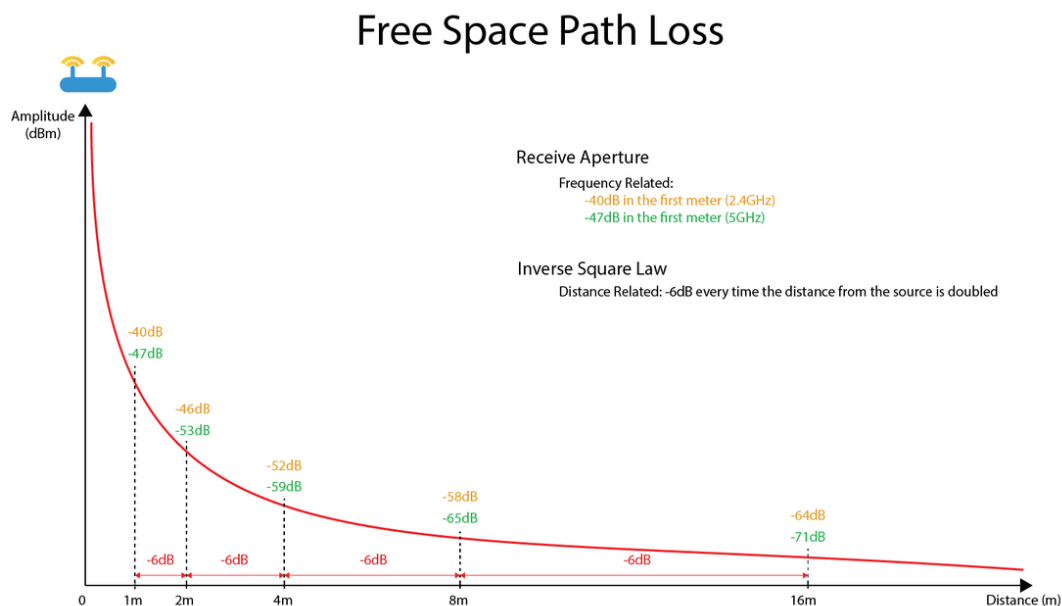


Figure A.1: Free Space and Log-distance Path Loss vs. Distance

b.1 Notebook

The notebook visualizes path loss vs. distance.

Download:

- [Jupyter Notebook \(A1\)](#)
- [Generated Path Loss Plot](#)

b.2 Interactive Streamlit App

The following app allows real-time manipulation of key parameters:

- Frequency (GHz)
- Maximum Distance
- Path Loss Exponent

Link: [Open Signal Visualizer App](#)

c References

1. Rappaport, T. S. (2014). *Wireless Communications: Principles and Practice*.
2. 3GPP Technical Specification TS 36.942.
3. Fundamentals of 5G Mobile Networks – Wiley.

Appendix B

Appendix: Modulation and Spectrum Simulation

a Interactive OFDM Simulation Notebook

To solidify the understanding of OFDM signal structure and spectral characteristics, an interactive Python notebook titled `A2-ofdm_simulation.ipynb` is provided. This notebook allows learners to:

- Visualize subcarriers of OFDM symbols.
- Explore Inverse Fast Fourier Transform (IFFT) as a modulation mechanism.
- Understand the effect of symbol length and guard intervals.
- Plot time and frequency domain representations.

Notebook Access: You can download the notebook from the following location:
`<YOUR-LINK-TO-NOTEBOOK>`

a.1 Modulation Scheme Explorer (Optional Streamlit App)

For learners who prefer hands-on exploration, an interactive web application `ModulationExplorer.py` is also available. It allows users to experiment with:

- QPSK, 16-QAM, and 64-QAM constellations.
- Variable number of symbols and noise levels.
- Visualization of signal degradation due to noise.

App Access: Run the Streamlit app using the following command:

```
streamlit run ModulationExplorer.py
```

App Download: `<YOUR-LINK-TO-APP-CODE>`

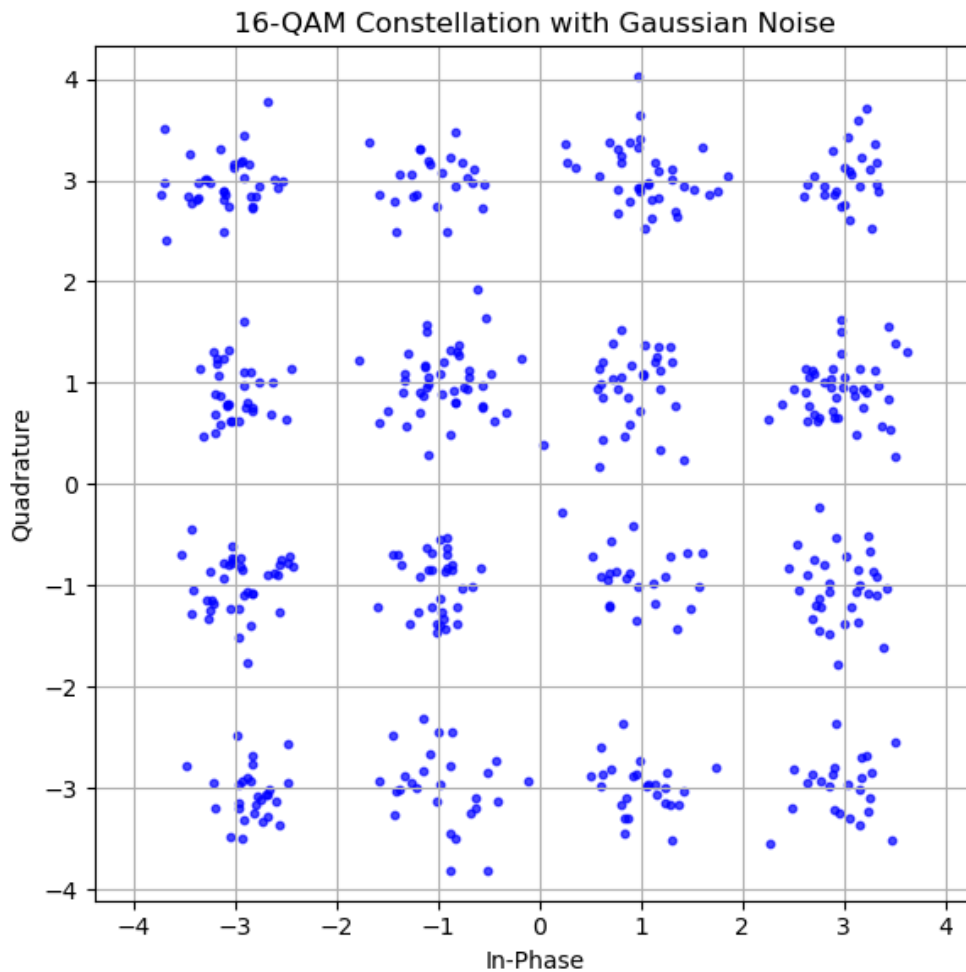


Figure B.1: Example QAM constellation with added Gaussian noise (from Streamlit app).

a.2 Learning Outcomes

- Experience the spectral efficiency of OFDM in practice.
- Understand modulation scheme differences in terms of constellation design and noise resilience.
- Gain intuition about bit-symbol mappings and symbol space in the IQ-plane.

Recommended Exercises:

1. Modify the number of subcarriers in the OFDM notebook and observe spectral changes.
2. Change modulation order in the Streamlit app and analyze BER qualitatively.

Appendix C

Appendix: Multiple Access and Scheduling Simulations

.1 A3_multiple_access_simulation.ipynb

This Jupyter notebook demonstrates various multiple access techniques such as FDMA, TDMA, OFDMA, and NOMA using interactive Python visualizations. It includes practical implementations of:

- Frequency division and time division allocation
- Subcarrier mapping in OFDMA
- Power-domain multiplexing in NOMA
- Basic scheduler logic for Round Robin and Proportional Fair algorithms

You can run and interact with the notebook directly via:

- **Notebook GitHub link:** https://github.com/your-repo/5G6G-course/blob/main/notebooks/A3_multiple_access_simulation.ipynb
- **View online (via nbviewer):** https://nbviewer.org/github/your-repo/5G6G-course/blob/main/notebooks/A3_multiple_access_simulation.ipynb

.2 SchedulerVisualizer.py (Streamlit App)

To allow real-time interaction and exploration, we have also developed a dedicated Streamlit web app for this chapter.

This app provides:

- Interactive sliders to simulate TDMA/FDMA/OFDMA with customizable users and resources
- A visual explanation of NOMA's power domain allocation
- Simulated round-robin and proportional fair scheduler behavior

Run the app locally with:

```
streamlit run SchedulerVisualizer.py
```

Or visit the hosted version here:

- **Live app:** <https://your-app-hosting-url.com/SchedulerVisualizer>

.3 Figures Used in This Chapter

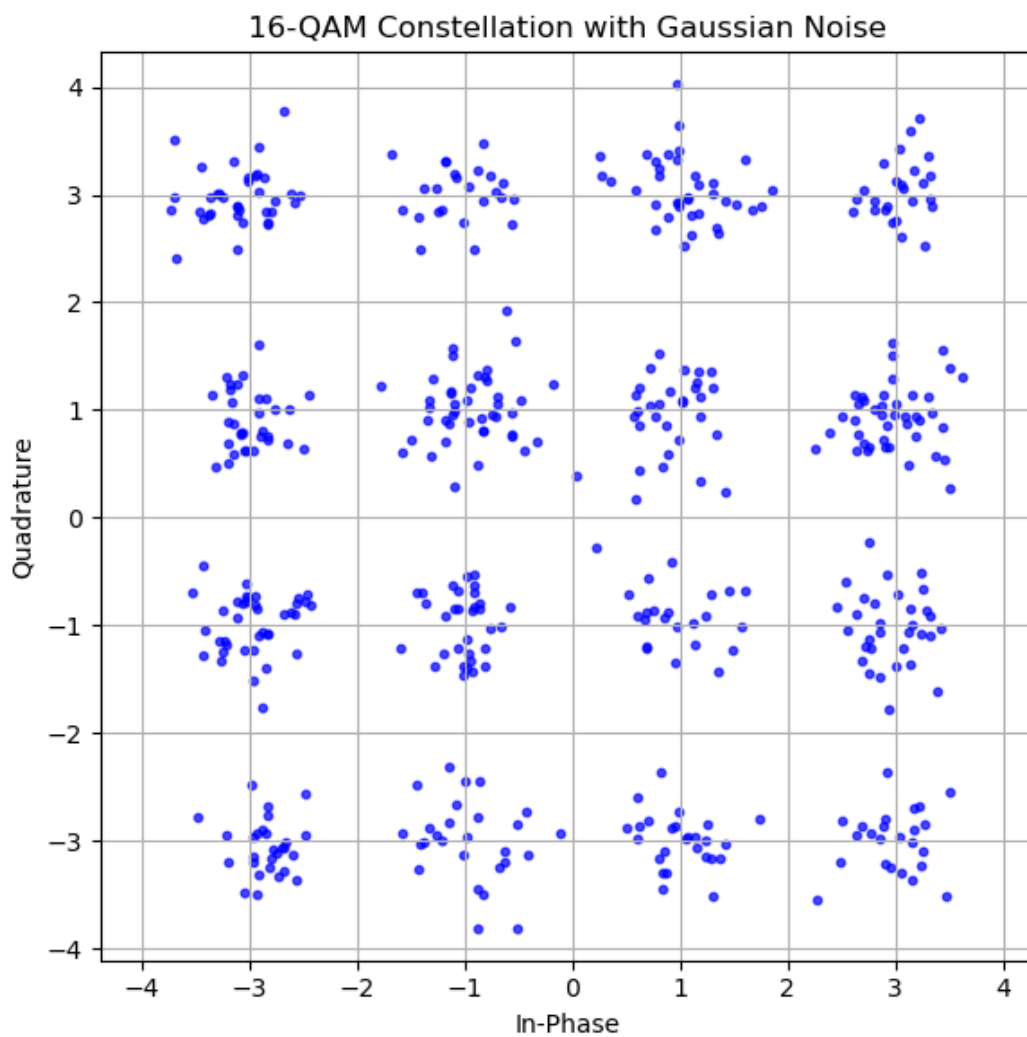


Figure C.1: Example modulation constellation diagram, used in Chapter 2 and referenced in scheduler visualizations.

: Channel Estimation and Equalization

This appendix supplements Chapter 4 by providing a practical demonstration of channel estimation and equalization techniques used in modern OFDM systems like LTE and 5G NR.

C.0.4 Notebook Simulation: `A4_channel_equalization.ipynb`

The notebook implements the following:

- QPSK modulation over 64 OFDM subcarriers.
- Addition of a cyclic prefix and multipath channel convolution.
- Complex AWGN noise addition.
- Channel estimation using Least Squares (LS) method.
- Equalization and recovery of original QPSK symbols.

The simulation assumes pilot-based LS estimation and perfect channel knowledge at the receiver for educational clarity.

C.0.5 Streamlit App (Optional)

For interactive learning, a Streamlit-based simulation page may be included in the modular app to vary parameters like channel taps, SNR, and modulation order.

C.0.6 Visualization of Equalized Symbols

Figure C.2 shows the scatter plot of the received frequency-domain symbols and the equalized output after applying channel estimation.

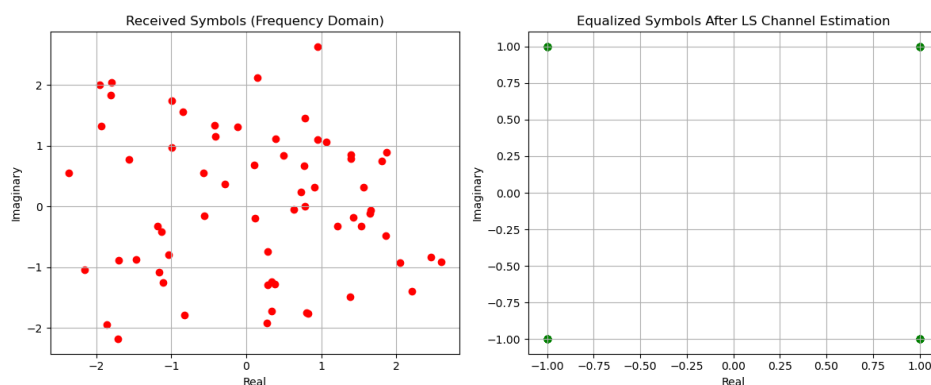


Figure C.2: Constellation plot of received vs. equalized QPSK symbols.

References

1. Rappaport, T. S. *Wireless Communications: Principles and Practice*, Pearson.
2. Goldsmith, A. *Wireless Communications*, Cambridge University Press.
3. Proakis, J. G., *Digital Communications*.
4. 3GPP TS 36.211: *Physical Channels and Modulation (LTE)*.

C.1 Additional Appendix: Channel Estimation and Equalization Simulation

C.1.1 Overview

This appendix provides a hands-on simulation of OFDM-based channel estimation and equalization using a simple multipath fading channel. The exercises are aimed at helping learners visualize the distortion introduced by the wireless channel and how equalization can recover the original signal.

C.1.2 Interactive Notebook: `A4_channel_equalization.ipynb`

The Jupyter Notebook implements the following:

- Generation of QPSK-modulated OFDM symbols
- Simulation of a multipath channel with user-defined tap coefficients
- Addition of AWGN noise based on a tunable SNR
- Least Squares (LS) channel estimation
- Equalization of the received signal
- Scatter plots comparing received and equalized symbols

You can access and run the notebook here:

[Download or open from: `A4_channel_equalization.ipynb`]

C.1.3 Streamlit App: `EqualizerSimulator.py`

A lightweight web interface allows learners to interactively tune parameters like:

- Number of subcarriers (N)
- Cyclic prefix length
- SNR (dB)
- Complex channel tap coefficients

Launch the app locally or via cloud deployment to visualize the following:

1. Received symbols (with distortion)
2. Equalized symbols (recovered)

To launch locally:

```
streamlit run EqualizerSimulator.py
```

C.1.4 Example Constellation Plot

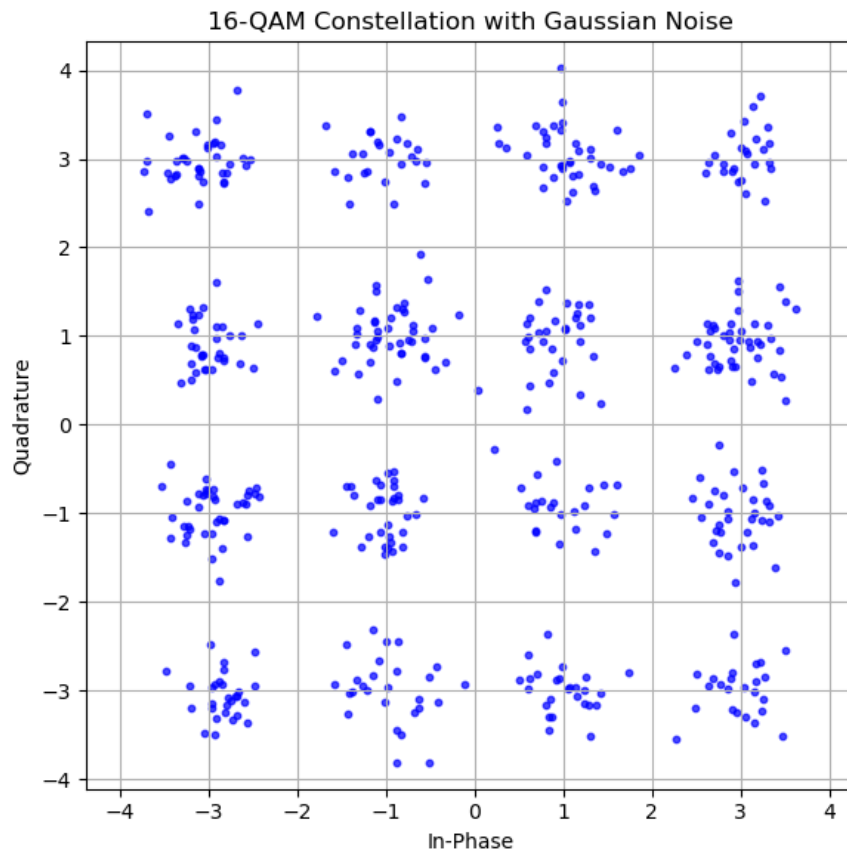


Figure C.3: Comparison of Received vs Equalized QPSK Symbols

C.1.5 References

- S. Haykin and M. Moher, *Modern Wireless Communications*, Pearson
- T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall
- 3GPP Technical Reports on OFDM and Channel Estimation
- MATLAB and Python tutorials on Least Squares Estimation

Appendix D

Appendix: MIMO & Beamforming Simulation

D.1 MIMO & Beamforming Simulation

D.1.1 Overview

This appendix supplements Chapter 5 by providing simulation code and interactive visualizations to reinforce understanding of key MIMO and beamforming concepts.

D.1.2 Jupyter Notebook: MIMO and Beamforming Simulation

The notebook `A5_mimo_beamforming_simulation.ipynb` covers the following topics:

- Simulation of a MIMO channel
- Calculation of MIMO channel capacity
- Beamforming weight computation
- Visualization of antenna beam patterns
- Exploration of capacity scaling with antenna count

Download notebook:

https://your-download-link.com/A5_mimo_beamforming_simulation.ipynb (replace with actual link)

D.1.3 Interactive Streamlit App: Beam Pattern Visualizer

An interactive app named `BeamPatternVisualizer.py` allows students to explore beamforming characteristics in real time.

- Select number of antennas and spacing
- Adjust steering direction
- Switch between analog, digital, and hybrid beamforming

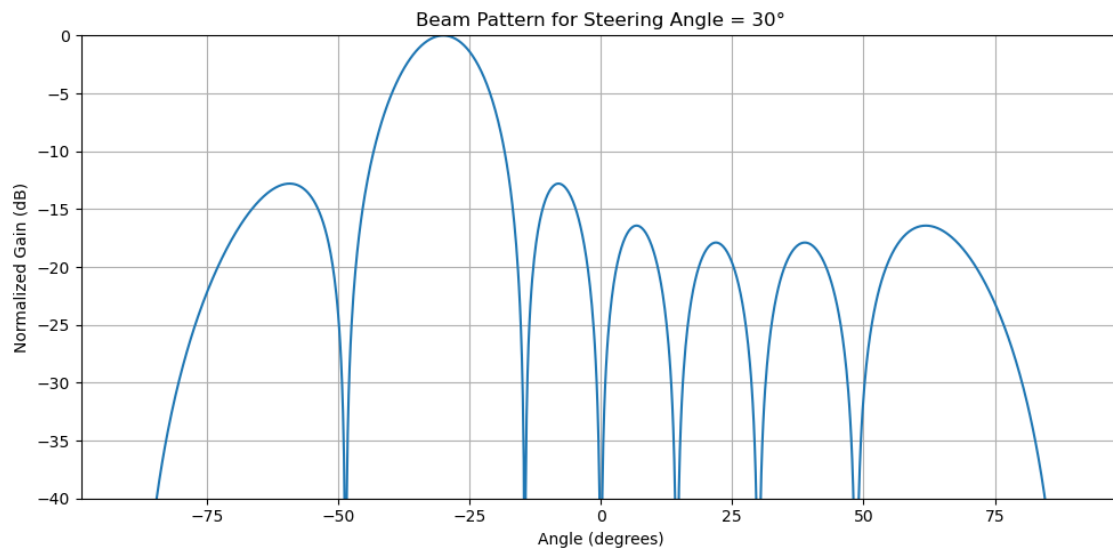


Figure D.1: Example beam pattern for an 8-element uniform linear array steering at 30°

Run app:

<https://your-streamlit-link.com/BeamPatternVisualizer> (replace with actual deployed URL)

D.1.4 Key Learnings

- Increasing the number of antennas enhances directionality and capacity
- Beamforming focuses signal energy toward desired directions
- Analog beamforming uses phase shifts only, while digital uses complex weights
- Hybrid beamforming provides a practical trade-off

D.1.5 References

- T. L. Marzetta, "Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas," IEEE Trans. Wireless Commun., 2010.
- A. Goldsmith, "Wireless Communications," Cambridge University Press, 2005.
- D. Tse and P. Viswanath, "Fundamentals of Wireless Communication," Cambridge University Press.

