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Theme

Performance Evaluation of UAV-Assisted Wireless Communication Systems

In front of the jury composed of:

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First and foremost, all praise is due to Allah, for granting us the strength, patience, and perseverance to carry this work through to its completion.

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Dedication

*To my father, **Mohamed Laid**,*

whose strength has always been my foundation,

*and to my mother, **Oumaima**,*

whose love and tenderness have been my shelter through every storm.

To my brothers, who stood by my side,

and to my sister, whose smile was enough to lighten my hardest days.

To my entire family — thank you for believing in me

long before I believed in myself.

This work is yours as much as it is mine.

BANE Ouejdi

Dedication

*To my father, **Mohamed Nabil**, whose wise guidance and unwavering support inspired me to move forward on this path.*

*To my mother, **Hanan**, who loved me endlessly, was there to support me through thick and thin, and never lost faith in me.*

And to everyone else in my life who offered encouragement and hope along the way — this achievement is also yours.

Cherfi Tahar Cherif

Abstract

Abstract

Unmanned Aerial Vehicles (UAVs) represent a promising technology for next-generation wireless networks, where they operate as flexible aerial base stations capable of providing reliable coverage in areas that conventional terrestrial infrastructure cannot adequately serve. Due to their elevated altitude, UAVs benefit from a high probability of line-of-sight (LoS) communication with ground users, which improves link quality and reduces path loss compared to ground-based systems. In order to further improve spectral efficiency and user fairness within UAV communication systems, Non-Orthogonal Multiple Access (NOMA) can be integrated, allowing multiple users to share the same time-frequency resources simultaneously through superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver. In our work, we analyze the performance of a downlink UAV-assisted NOMA system serving two ground users – a far user and a near user – over a Nakagami-m fading channel with a probabilistic path loss model accounting for both LoS and non-line-of-sight (NLoS) propagation conditions. We simulate the performance of the considered system in terms of capacity, Bit Error Rate (BER) and Outage Probability (OP) using MATLAB, while also investigating the effect of power allocation coefficients, modulation order, and cell radius on overall system behavior. Furthermore, we extend the analysis to examine the impact of the Nakagami fading parameter m, UAV altitude, and propagation environment type (Rural, Suburban, Urban, and Dense Urban) on system performance, providing a comprehensive characterization of the system across a wide range of realistic operating conditions. The simulation results show that the UAV-NOMA system outperforms conventional OMA in terms of outage probability and spectral efficiency, confirming that the combination of UAV communications and NOMA represents an effective and viable solution for next-generation wireless communication systems.

Keywords: UAV, NOMA, OMA, BER, OP, Capacity, Power Allocation, Nakagami-m, UAV Altitude, Propagation Environment.

Résumé

Les véhicules aériens sans pilote (UAV) représentent une technologie prometteuse pour les réseaux sans fil de nouvelle génération, où ils opèrent en tant que stations de base aériennes flexibles capables de fournir une couverture fiable dans les zones que l'infrastructure terrestre conventionnelle ne peut pas desservir de manière adéquate. Grâce à leur altitude élevée, les UAV bénéficient d'une forte probabilité de communication en visibilité directe (LoS) avec les utilisateurs terrestres, ce qui améliore la qualité de la liaison et réduit les pertes de propagation par rapport aux systèmes au sol. Afin d'améliorer davantage l'efficacité spectrale et l'équité entre les utilisateurs au sein des systèmes de communication UAV, l'accès multiple non orthogonal (NOMA) peut être intégré, permettant à plusieurs utilisateurs de partager les mêmes ressources temps-fréquence simultanément grâce au codage par superposition à l'émetteur et à l'annulation successive des interférences (SIC) au récepteur. Dans notre travail, nous analysons les performances d'un système NOMA en liaison descendante assisté par UAV desservant deux utilisateurs terrestres – un utilisateur éloigné et un utilisateur proche – sur un canal à évanouissements de Nakagami-m avec un modèle de perte de trajet probabiliste tenant compte des conditions de propagation LoS et NLoS. Nous simulons les performances du système considéré en termes de capacité, de taux d'erreur binaire (BER) et de probabilité de coupure (OP) à l'aide de MATLAB, tout en étudiant l'effet des coefficients d'allocation de puissance, de l'ordre de modulation et du rayon de cellule sur le comportement global du système. De plus, nous étendons l'analyse à l'étude de l'impact du paramètre d'évanouissement de Nakagami m, de l'altitude de l'UAV et du type d'environnement de propagation (Rural, Suburbain, Urbain et Urbain Dense) sur les performances du système, offrant ainsi une caractérisation complète dans une large gamme de conditions réalistes. Les résultats de simulation montrent que le système UAV-NOMA surpasse l'OMA conventionnel en termes de probabilité de coupure et d'efficacité spectrale, confirmant que la combinaison des communications UAV et de NOMA représente une solution efficace et viable pour les systèmes de communication sans fil de nouvelle génération.

Mots-clés: UAV, NOMA, OMA, BER, OP, Capacité, Allocation de puissance, Nakagami-m, Altitude UAV, Environnement de propagation.

ملخص

الطائرات بدون طيار (UAV) هي تقنية واعدة لشبكات الجيل القادم، إذ تعمل كمحطات قاعدة جوية متنقلة قادرة على توفير تغطية لاسلكية مرنة وموثوقة في المناطق التي تعجز عنها البنية التحتية الأرضية التقليدية. بفضل ارتفاعها، تتمتع هذه الطائرات باحتمالية رؤية مباشرة عالية مع المستخدمين الأرضيين، مما يُحسِّن جودة الرابط ويُقلِّل من خسائر الانتشار. ومن أجل تعزيز الكفاءة الطيفية وعدالة المستخدمين داخل هذه الأنظمة، يُدمَج تقنية الوصول المتعدد غير المتعامد (NOMA) مع الطائرات بدون طيار، حيث تتيح هذه التقنية لعدة مستخدمين مشاركة نفس الموارد الترددية في آنٍ واحد عبر الترميز التراكبي وإلغاء التداخل المتتالي (SIC). في عملنا هذا، ندرس أداء نظام NOMA التنازلي الذي يخدم مستخدمَين أرضيَين، مستخدم بعيد ومستخدم قريب، بمساعدة UAV عبر قناة ذات تلاشٍ من نوع Nakagami-m مع نموذج خسارة مسار احتمالي يأخذ في الحسبان حالتَي الرؤية المباشرة (LoS) وغير المباشرة (NLoS). نقوم بمحاكاة أداء النظام المدروس من حيث السعة ومعدل خطأ البت (BER) واحتمالية الانقطاع (OP) باستخدام برنامج MATLAB، مع دراسة تأثير عدة معاملات على الأداء الكلي كمعاملات توزيع القدرة ورتبة التضمين ونصف قطر الخلية. علاوة على ذلك، وسعنا نطاق الدراسة لتشمل تأثير معامل التلاشي Nakagami-m وارتفاع الطائرة ونوع بيئة الانتشار (ريفية، ضاحية، حضرية، حضرية كثيفة) على أداء النظام، مما يوفر توصيفًا شاملاً لسلوك النظام في طيف واسع من ظروف التشغيل الواقعية. تُظهر نتائج المحاكاة أن نظام NOMA-UAV يتفوق على نظام OMA التقليدي من حيث احتمالية الانقطاع والكفاءة الطيفية، مما يؤكد أن الجمع بين تقنية الطائرات بدون طيار و NOMA يُمَثِّل حلاً فعّالاً وواعدًا لأنظمة الاتصالات اللاسلكية من الجيل القادم.

الكلمات المفتاحية: UAV، NOMA، OMA، BER، OP، السعة، توزيع القدرة، Nakagami-m، ارتفاع الطائرة، بيئة الانتشار.

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1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth Generation
A2A	Air-to-Air
A2G	Air-to-Ground
A2S	Air-to-Space
AF	Amplify-and-Forward
AI	Artificial Intelligence
AMPS	Advanced Mobile Phone System
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDMA	Code Division Multiple Access
CS	Circuit-Switched
DA2GC	Direct Air-to-Ground Communication
DF	Decode-and-Forward
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
FANET	Flying Ad Hoc Network
FDMA	Frequency Division Multiple Access
GEO	Geostationary Earth Orbit
GSM	Global System for Mobile Communications
HAPS	High Altitude Platform Station
HSPA	High-Speed Packet Access
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISAC	Integrated Sensing and Communication
LEO	Low Earth Orbit
LoS	Line-of-Sight
LTE	Long-Term Evolution
MEO	Medium Earth Orbit

MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mmWave	Millimeter Wave
mMTC	Massive Machine-Type Communication
NLoS	Non-Line-of-Sight
NMT	Nordic Mobile Telephone
NOMA	Non-Orthogonal Multiple Access
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Orthogonal Multiple Access
P-GW	Packet Data Network Gateway
PS	Packet-Switched
PSTN	Public Switched Telephone Network
QAM	Quadrature Amplitude Modulation
QKD	Quantum Key Distribution
QPSK	Quadrature Phase Shift Keying
RIS	Reconfigurable Intelligent Surface
RNC	Radio Network Controller
SAGIN	Space-Air-Ground Integrated Network
SC	Superposition Coding
S-GW	Serving Gateway
SIC	Successive Interference Cancellation
SIM	Subscriber Identity Module
SINR	Signal-to-Interference-plus-Noise Ratio
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
TACS	Total Access Communication System
TDMA	Time Division Multiple Access
THz	Terahertz
UAV	Unmanned Aerial Vehicle
UAV-BS	UAV Base Station
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-Reliable Low-Latency Communication
VLC	Visible Light Communication
VTOL	Vertical Take-Off and Landing
W-CDMA	Wideband Code Division Multiple Access

Symbols List

$\boldsymbol{a, b}$	Environment-dependent constants.
$\boldsymbol{\alpha_i}$	The power allocation coefficient/factor for user i (includes α_1, α_2).
$\boldsymbol{\alpha_L, \alpha_{NL}}$	Path loss exponents for LoS and NLoS.
$\boldsymbol{B}$	The channel bandwidth (Hz).
$\boldsymbol{BER}$	Bit Error Rate.
$\boldsymbol{C_i}$	The achievable capacity for user i (includes C, C_{U1}, C_{U2}).
$\boldsymbol{C_{sum}}$	The sum-rate (total capacity of both users).
$\boldsymbol{c}$	The speed of light (3×10^8 m/s).
$\boldsymbol{d_i}$	The propagation distance between the UAV and user i (includes d).
$\boldsymbol{f_c}$	The carrier frequency (Hz).
$\boldsymbol{f_D}$	The Doppler shift.
$\boldsymbol{\Gamma(m)}$	The Gamma function.
$\boldsymbol{\gamma_i/SINR_i}$	The SINR at user i.
$\boldsymbol{\gamma/SNR}$	The signal-to-noise ratio or transmit SNR.
$\boldsymbol{\gamma_{th}}$	The minimum SNR threshold for acceptable communication quality.
$\boldsymbol{H/h}$	The UAV altitude (m).
$\boldsymbol{h_i}$	The channel coefficient for user i.
$\boldsymbol{\|h_i\|}$	The channel power gain for user i (includes $\|h\|$).
$\boldsymbol{\eta_L, \eta_{NL}}$	Additional attenuation factors for LoS and NLoS.
$\boldsymbol{K}$	The total number of users.
$\boldsymbol{L_{MIX}/PL_{avg}}$	Average or mixed path loss.
$\boldsymbol{L_{LOS}/PL_{LoS}}$	Path loss under LoS conditions.
$\boldsymbol{L_{NLOS}/PL_{NLoS}}$	Path loss under NLoS conditions.
$\boldsymbol{PL_{FS}(d)}$	Free-space path loss.
$\boldsymbol{\lambda}$	The wavelength of the carrier signal (m).
$\boldsymbol{m}$	The Nakagami fading parameter.
$\boldsymbol{N_e, N_t}$	The number of erroneous bits detected, and total transmitted bits.
$\boldsymbol{P_{LoS}, P_{NLoS}}$	The probability of LoS and NLoS propagation.
$\boldsymbol{P_{out,i}}$	Outage probability for user i (includes $P_{out}, P_{out}^{U1}, P_{out}^{U2}$).
$\boldsymbol{P_t/P_{total}}$	The total transmit power (W).
$\boldsymbol{R_i}$	The target data rate for user i (includes R_t, R_1, R_2).
$\boldsymbol{r_i}$	The horizontal distance from the UAV to user i (includes r).
$\boldsymbol{s_i/x_i}$	The message/modulated signal for user i.
$\boldsymbol{\sigma^2}$	Additive white Gaussian noise (AWGN) variance.

$\boldsymbol{U_i}$	The effective channel gain for user i.
$\boldsymbol{v}$	The relative speed between the UAV and the receiver (m/s).
$\boldsymbol{w_i}$	Additive white Gaussian noise (AWGN) with variance σ^2.
$\boldsymbol{x}$	The total transmitted signal.
$\boldsymbol{y_i}$	The received signal at user i.
$\boldsymbol{\theta}$	The elevation angle.
$\boldsymbol{\phi}$	The angle between the direction of motion and the propagation path.
$\boldsymbol{\rho_L, \rho_{NL}}$	Reference path loss for LoS and NLoS.

General Introduction

General Introduction

The rapid proliferation of connected devices and the explosive growth of data traffic have driven the evolution of mobile networks through successive generations. While 5G introduced enhanced mobile broadband, ultra-reliable low-latency communications, and massive machine-type connectivity, it still falls short in coverage and spectral efficiency — particularly in remote or disaster-affected areas. These limitations motivate the ongoing research toward sixth-generation (6G) wireless networks.

Among the most promising solutions for 6G are Non-Terrestrial Networks (NTN) and Non-Orthogonal Multiple Access (NOMA). UAVs, as a key NTN component, attract considerable attention due to their mobility, flexible deployment, and strong line-of-sight propagation at altitude, making them well-suited as aerial base stations. NOMA complements this by allowing multiple users to share the same time-frequency resource through power-domain multiplexing and successive interference cancellation (SIC), achieving higher spectral efficiency and improved user fairness over classical orthogonal schemes.

The combination of UAV communications and NOMA represents a compelling paradigm for next-generation networks. However, its performance depends critically on the air-to-ground channel model, the fading statistics, the power allocation strategy, the cell geometry, and the modulation scheme. A rigorous simulation-based evaluation of these interdependencies is essential for validating theoretical models and guiding practical system design.

Motivation

Most existing studies treat the air-to-ground channel in a simplified manner or focus on a single performance metric in isolation. In practice, the channel transitions probabilistically between LoS and NLoS conditions depending on altitude, distance, and environment, with fading behavior better captured by the Nakagami-m distribution. System-level parameters such as power allocation, cell radius, modulation order, UAV altitude, and propagation environment interact in non-trivial ways that are difficult to anticipate without careful simulation. Understanding these interactions directly informs how engineers should configure and deploy UAV-assisted NOMA networks in real environments, and this gap between theoretical promise and practical characterization is the central motivation for the present work.

Objectives of the Thesis

The primary objective of this thesis is to analyze and evaluate the performance of a UAV-assisted downlink NOMA system under realistic channel conditions. Specifically, the work aims to:

- Model the air-to-ground channel using the ITU/Al-Hourani probabilistic LoS framework combined with Nakagami-m small-scale fading.
- Simulate key performance metrics — BER, outage probability, and achievable sum rate — for both NOMA users and the overall system.

- Benchmark NOMA against OMA and investigate the influence of power allocation, modulation order, and cell radius.
- Analyze the impact of the Nakagami fading parameter m, UAV altitude, and propagation environment (Rural, Suburban, Urban, Dense Urban) on system performance.

Structure of the Thesis

This thesis is organized into four chapters.

Chapter 1 traces the evolution of mobile networks from 1G to 6G and introduces the OMA/NOMA multiple access landscape.

Chapter 2 examines Non-Terrestrial Networks as a foundational 6G component, covering satellite, HAPS, and UAV platforms and their integration into a space–air–ground architecture.

Chapter 3 focuses on UAV-assisted wireless systems, covering the A2G channel model, UAV classification, communication roles, and key performance metrics.

Chapter 4 presents the core contribution: a comprehensive MATLAB-based simulation of a UAV-assisted downlink NOMA system. Results for BER, outage probability, capacity, and LoS probability are analyzed under varying SNR, power allocation, modulation order, cell radius, Nakagami fading parameter, UAV altitude, and propagation environment, with systematic comparison against OMA.

Chapter 1:

Evolution of Mobile Networks

1.1 Introduction

Mobile communication networks have rapidly evolved from 1G to 5G to meet the growing demand for higher data rates and massive connectivity [1]. While 5G provides significant enhancements, it still faces limitations in global coverage and spectral efficiency using Orthogonal Multiple Access (OMA) [2]. Consequently, sixth-generation (6G) research envisions integrating terrestrial and non-terrestrial networks with Non-Orthogonal Multiple Access (NOMA) to achieve ubiquitous, intelligent connectivity [3].

In this chapter, we will present the evolution of mobile networks from 1G to 6G, highlighting key technological leaps. We will systematically examine the transition from OMA to NOMA, detailing NOMA's fundamental principles, benefits, and challenges as a crucial enabler for massive connectivity in future 6G networks.

1.2 Evolution of Mobile Networks

The evolution of mobile communication systems can be charted through distinct generations, each marked by specific technological breakthroughs.Figure 1.1 depicts this progression from 1G to 6G.

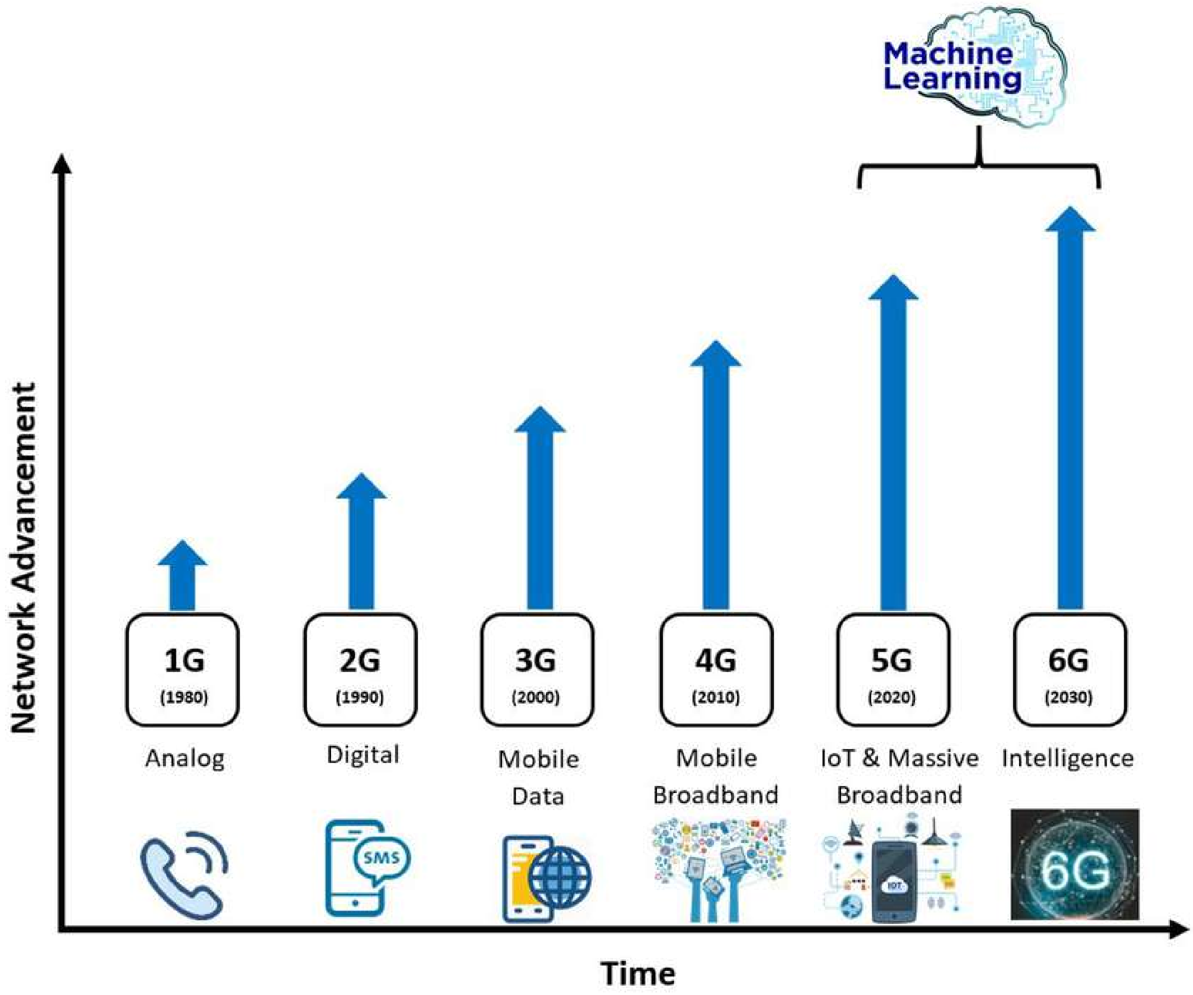

Figure 1.1: Evolution of mobile communication systems from 1G to 6G [4]

First Generation (1G): The first generation emerged in the early 1980s, employing analog transmission and Frequency Division Multiple Access (FDMA). Systems such as the Advanced Mobile Phone System (AMPS) in the United States, Nordic Mobile Telephone (NMT) in Scandinavia, and Total Access Communication System (TACS) in the United Kingdom represented the earliest cellular networks. These networks divided the available spectrum into 30 kHz channels (in AMPS) and assigned one channel per call. Voice quality was often degraded by interference and noise; moreover, analog signals lacked encryption, making eavesdropping relatively easy. The core network relied on the public switched telephone network (PSTN), and no data services were supported. Figure 1.2 illustrates the simplified architecture. Despite their limitations, 1G systems introduced the cellular concept and basic handoff mechanisms, paving the way for digital evolution [1].

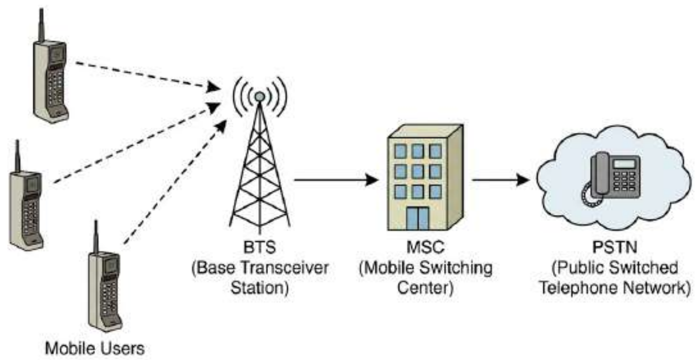

Figure 1.2: Simplified architecture of early 1G cellular systems (AMPS/NMT)

Second Generation (2G): The transition to digital in the 1990s was spearheaded by the Global System for Mobile Communications (GSM). 2G systems introduced Time Division Multiple Access (TDMA) and later Code Division Multiple Access (CDMA) as access techniques. Digitizing voice not only improved quality but also enabled encryption, authentication through SIM cards, and efficient use of spectrum. GSM operated in frequency bands around 900 MHz and 1800 MHz, with channel bandwidths of 200 kHz. Data rates up to 64 kbps were achievable, and the Short Message Service (SMS) became a global success. CDMA (IS-95) further increased capacity by allowing users to share the same frequency via unique spreading codes. Figure 1.3 shows the GSM architecture. The enhanced security and introduction of basic data services marked a significant leap over 1G [1].

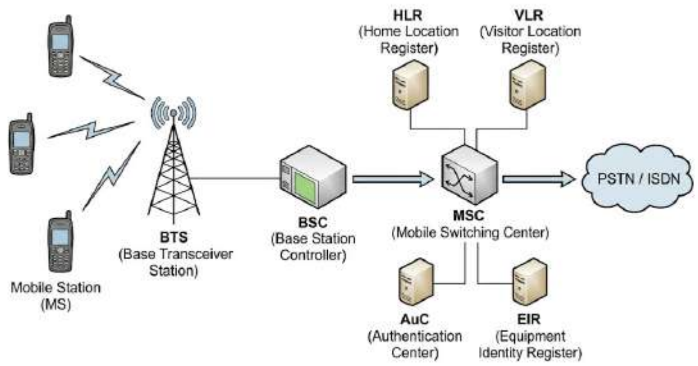

Figure 1.3: Simplified GSM digital cellular architecture

Third Generation (3G): 3G networks were standardized under the International Mobile Telecommunications-2000 (IMT-2000) requirements. The main technologies were Universal Mobile Telecommunications System (UMTS), based on Wideband CDMA (W-CDMA), and CDMA2000. 3G provided data rates up to 2 Mbps in indoor environments, enabling mobile internet access, video calling, multimedia messaging, and location-based services. Architecturally, 3G separated the circuit-switched (CS) domain for voice and the packet-switched (PS) domain for data, as depicted in Figure 1.4. The Radio Network Controller (RNC) managed radio resources, while the core network handled both CS and PS traffic. Later enhancements via High-Speed Packet Access (HSPA) pushed peak rates to tens of Mbps [2].

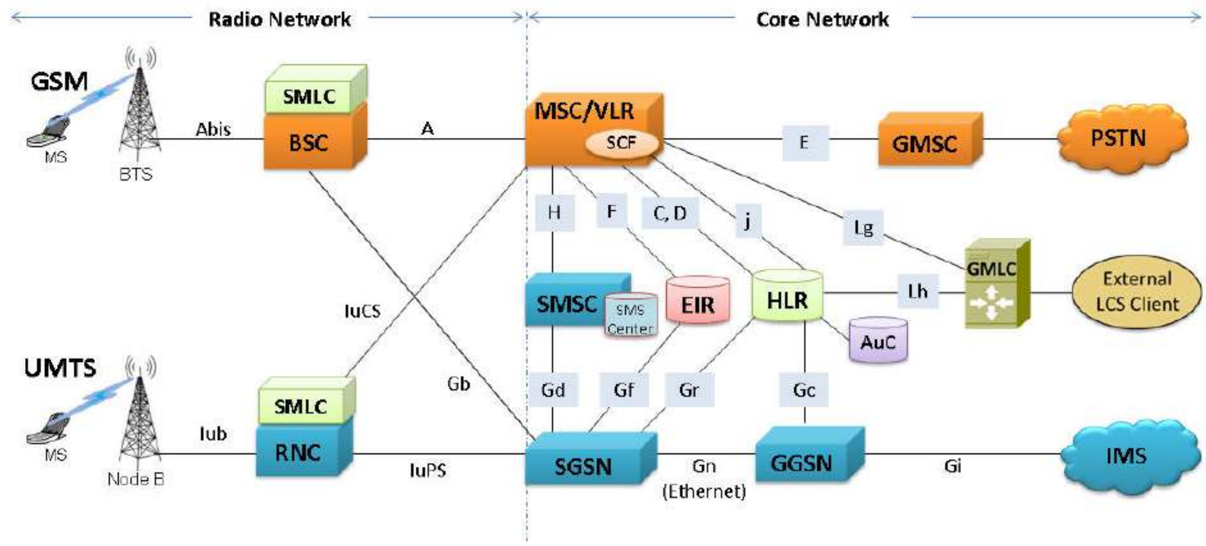

Figure 1.4: General architecture of a 3G UMTS network [5]

Fourth Generation (4G – LTE): 4G systems, designed under the IMT-Advanced framework, adopted an all-IP architecture, eliminating legacy circuit-switched components. Long-Term Evolution (LTE) employs Orthogonal Frequency Division Multiplexing (OFDM) for downlink and Single-Carrier FDMA for uplink, combined with Multiple-Input Multiple-Output (MIMO) antenna systems. MIMO uses multiple antennas at both transmitter and receiver to exploit spatial diversity and multiplexing, significantly improving spectral efficiency and throughput. Peak data rates exceed 1 Gbps in ideal conditions. The Evolved Packet Core (EPC) provides a flat, IP-based core network, with nodes such as the Mobility Management Entity (MME), Serving Gateway (S-GW), and Packet Data Network Gateway (P-GW). Figure 1.5 illustrates the simplified LTE architecture. 4G enabled rich mobile broadband services, including high-definition video streaming, online gaming, and cloud applications, making mobile internet a ubiquitous experience [1, 6].

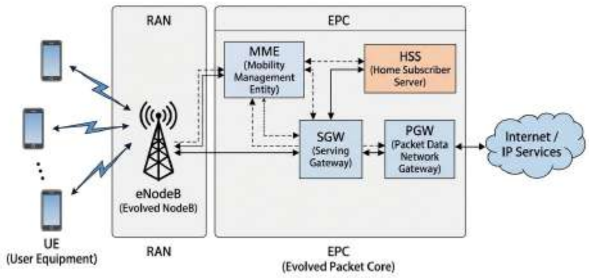

Figure 1.5: Simplified 4G LTE All-IP architecture

1.3 Fifth Generation (5G)

5G networks are designed to meet the demanding requirements of IMT-2020, focusing on three main service categories [2]:

- **Enhanced Mobile Broadband (eMBB)**: aims for peak data rates up to 20 Gbps and a consistent user experience of 100 Mbps in wide coverage areas, supporting applications such as virtual reality, 4K/8K video streaming, and immersive media.
- **Ultra-Reliable Low-Latency Communication (URLLC)**: targets end-to-end latency as low as 1 ms with reliability of 99.999%, enabling mission-critical services like autonomous driving, remote surgery, and industrial automation.
- **Massive Machine-Type Communication (mMTC)**: accommodates up to one million devices per square kilometre, serving massive Internet of Things (IoT) deployments with low power and low complexity.

To realize these diverse requirements, 5G employs several advanced technologies. Massive MIMO uses arrays of hundreds of antennas to form narrow beams, improving spectral efficiency and user throughput. Millimeter-wave (mmWave) bands (above 24 GHz) offer wide bandwidths, but suffer from high propagation loss and limited penetration [7]. Network slicing enables operators to create multiple virtual networks on a shared physical infrastructure, each optimized for a specific service type [8]. Figure 1.6 illustrates the three service categories.

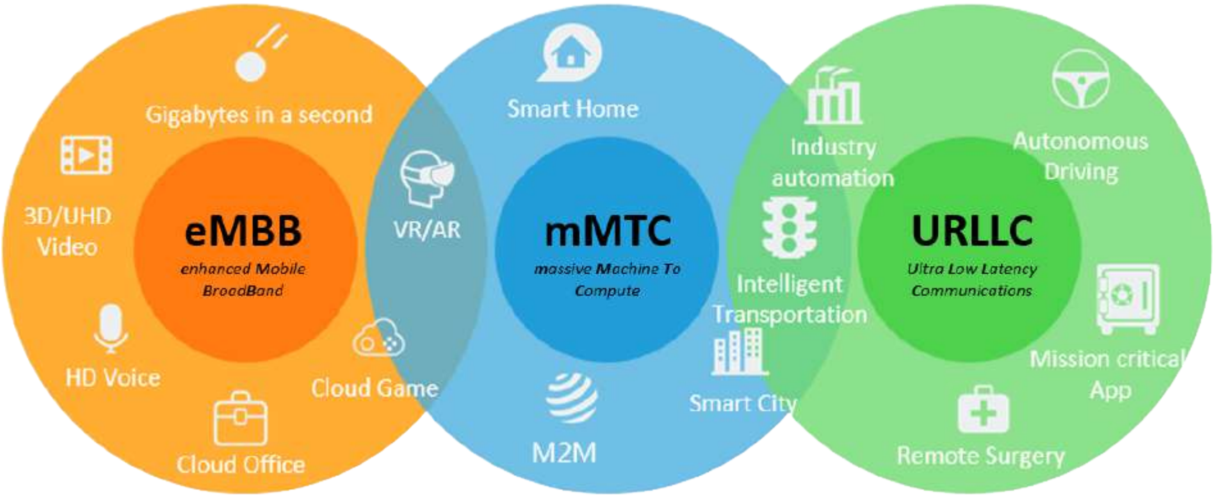

Figure 1.6: Main service categories defined in 5G networks [9]

1.3.1 Challenges in 5G

While 5G represents a major leap forward, it faces several obstacles [2, 3, 7]:

- **Coverage and propagation:** mmWave signals are highly susceptible to blockage by buildings, foliage, and even the human body. This necessitates dense deployments of small cells, increasing infrastructure cost.
- **High deployment cost:** The required fiber backhaul, massive antenna arrays, and network densification significantly raise capital and operational expenditures, making it economically challenging to provide uniform coverage in rural and remote areas.
- **Orthogonal multiple access limitations:** 5G primarily uses OFDMA, an orthogonal multiple access (OMA) scheme. OMA assigns dedicated time-frequency resources to individual users, which limits the number of simultaneous users and cannot fully exploit the available degrees of freedom, especially in massive connectivity scenarios.
- **Energy consumption:** The increased number of base stations and active antenna elements leads to higher network energy consumption, which is a growing concern.
- **Global coverage gaps:** Terrestrial infrastructure alone cannot cover oceans, polar regions, or sparsely populated areas, leaving significant gaps in connectivity.

These challenges are driving the research toward 6G, which aims to integrate non-terrestrial networks and adopt spectral-efficient non-orthogonal multiple access techniques [3].

1.4 Sixth Generation (6G)

6G is envisioned as an intelligent, deeply integrated communication system that combines terrestrial, aerial, and satellite networks with advanced computing and artificial intelligence. It is expected to be standardized around 2030 under the IMT-2030 framework [10]. The following subsections detail its requirements, usage scenarios, key technologies, and the role of non-terrestrial networks.

1.4.1 Requirements for 6G

The IMT-2030 vision outlines extremely ambitious targets [3, 10]. In terms of data rate, 6G aims to achieve peak throughput of up to 1 Tbps, enabling holographic and multi-sensory communications. End-to-end latency is targeted below 0.1 ms, essential for real-time haptic interactions and critical automation applications. Network reliability is set at 99.99999% (seven-nines) to guarantee near-perfect packet delivery. Connection density is expected to reach 10^7 devices per km^2, supporting the massive scale of future IoT and smart environments, while mobility support must extend up to 1000 km/h for high-speed trains and aerial vehicles. Furthermore, spectrum and energy efficiency must improve by a factor of 10–100 compared to 5G to ensure sustainable network growth, and global coverage must be achieved through seamless integration of terrestrial and non-terrestrial networks.

1.4.2 Usage Scenarios

6G will expand the range of applications far beyond what 5G can support [3, 11]. Among the most transformative use cases is **holographic telepresence**, which requires real-time, three-dimensional holographic projection demanding terabits per second and sub-millisecond latency. **Fully autonomous systems** — including cooperative autonomous driving, drone swarms, and robotic surgery — rely on ultra-reliable low-latency communication to function safely. **Pervasive intelligence** envisions AI embedded in every device, enabling ambient sensing, personalized healthcare, and smart infrastructure. **Global broadband connectivity** aims to deliver high-speed internet to remote, rural, maritime, and aeronautical users through integrated satellite-aerial-terrestrial networks. The **Tactile Internet and haptic communications** paradigm will enable transmission of touch, force, and motion feedback in real time for immersive teleoperation. Finally, a **space-air-ground-sea integrated network** will unify all communication domains to provide ubiquitous connectivity for scientific exploration, disaster response, and global logistics.

1.4.3 Key Technologies for 6G

6G will leverage a wide array of emerging technologies [3, 12–17]. **Artificial Intelligence (AI) and Machine Learning** will be natively integrated into the network architecture, enabling self-organizing networks, intelligent beamforming, predictive resource allocation, and semantic communication — where only the meaning of information is transmitted to save bandwidth. **Quantum Communication** through quantum key distribution (QKD) offers theoretically unbreakable encryption, while quantum repeaters and entanglement-based networks could provide ultra-secure backbone links. **Blockchain** decentralized ledgers will enable trusted authentication, spectrum sharing, and resource trading among heterogeneous operators without a central authority. **Visible Light Communication (VLC)**, using LED or laser sources, provides extremely high data rates in indoor and vehicular environments, complementing traditional RF bands. **Terahertz (THz) Communication**, operating between 0.1 and 10 THz, offers vast contiguous bandwidth enabling peak rates of 1 Tbps or more, though challenges remain in path loss and beam tracking. **Reconfigurable Intelligent Surfaces (RIS)** use large arrays of passive elements to dynamically control the propagation environment, improving coverage and capacity with minimal energy consumption. **Integrated Sensing**

and Communication (ISAC) will allow 6G base stations to simultaneously perform high-resolution radar-like sensing and data communication. Finally, **Non-Terrestrial Networks (NTN)**, integrating LEO satellites, HAPS, and UAVs, will extend global coverage and ensure network resilience.

1.4.4 Role of NTN in 6G Networks

Non-terrestrial networks are fundamental to the 6G vision of ubiquitous connectivity [3, 17]. LEO satellite constellations can offer low-latency broadband access even in remote areas, while HAPS and UAVs serve as on-demand relays to boost capacity and coverage. NTNs ensure **continuity of service** through seamless handover between terrestrial and satellite cells for users on the move. They also provide **backhaul for remote base stations**, offering cost-effective connectivity where fiber deployment is not feasible. In terms of **resilience**, NTNs maintain network operation during natural disasters when terrestrial infrastructure is damaged. Additionally, they support **global synchronization and positioning** by leveraging satellite signals for precise timing and navigation. Figure 1.7 illustrates the integrated terrestrial/non-terrestrial architecture. The integration of NTNs into 6G will require solving challenges such as high Doppler shifts, long propagation delays, and inter-satellite link management.

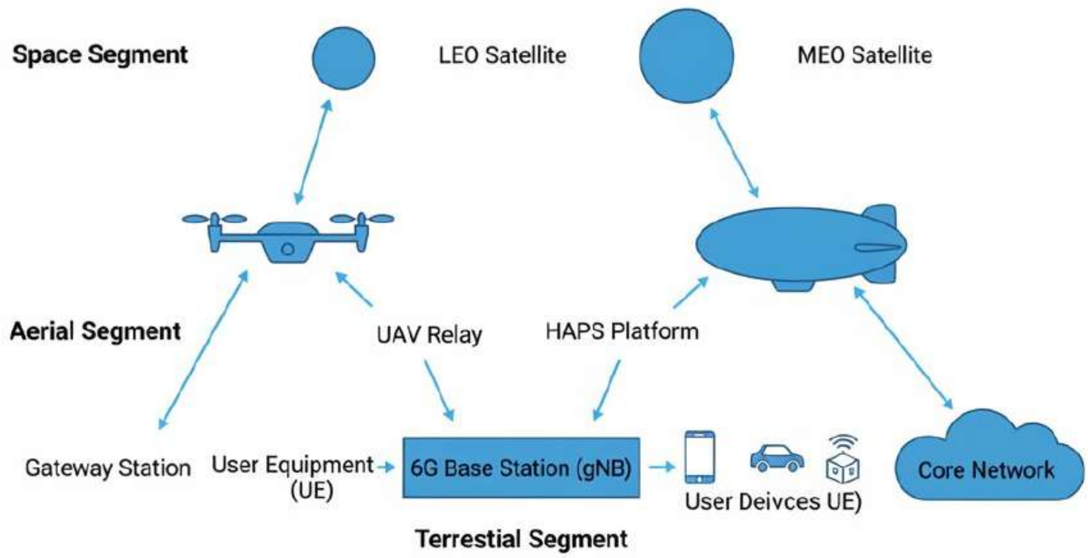

Figure 1.7: Integrated terrestrial and non-terrestrial architecture in 6G networks

1.5 Multiple Accesses: OMA and NOMA

Multiple accesses determine how radio resources are shared among users. They are a fundamental aspect of each generation, directly impacting spectral efficiency and connectivity.

1.5.1 Orthogonal Multiple Access (OMA)

OMA assigns non-overlapping resource units to different users, thereby avoiding interference at the cost of resource utilization. Each generation adopted a specific OMA scheme [18]:

- **FDMA (1G)**: The frequency band is split into channels, each assigned to one call.
- **TDMA (2G)**: Time is divided into slots; users transmit in a round-robin fashion over the same frequency.
- **CDMA (3G)**: Orthogonal spreading codes allow simultaneous transmission, but codes are interferers absent in non-orthogonal domains.
- **OFDMA (4G/5G)**: The bandwidth is divided into orthogonal subcarriers grouped into resource blocks, each allocated to one user.

OMA's main advantage is simplicity: receivers do not need to cancel interference from other users. However, OMA suffers from limited spectral efficiency because each resource element can serve at most one user, which is particularly restrictive in massive connectivity scenarios envisioned for 6G.Figure 1.8 represents the different types of Orthogonal Multiple Access (OMA) techniques. It illustrates how resources such as frequency, time, and code are orthogonally divided among users to prevent interference.

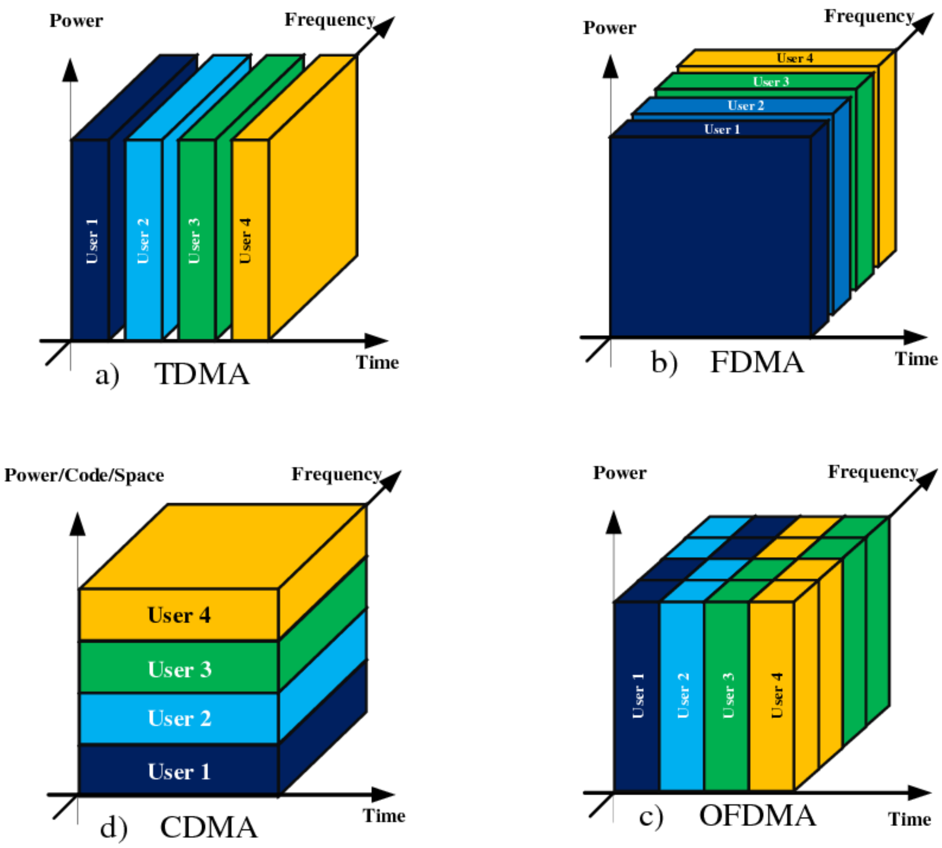

Figure 1.8: Orthogonal Multiple Access (OMA) techniques [19].

1.5.2 Non-Orthogonal Multiple Access (NOMA)

NOMA intentionally introduces non-orthogonality, allowing multiple users to overlap in time, frequency, or code domain. Separation is achieved through power-domain or code-domain multiplexing and advanced receivers such as successive interference cancellation (SIC) [20]. NOMA provides significant advantages:

- **Higher spectral efficiency**: Multiple users share the same resource block, increasing the overall sum rate.
- **User fairness**: Weak-channel users (e.g., at the cell edge) are allocated more power, improving their throughput compared to OMA where they would receive only a fraction of resources.
- **Massive connectivity**: By allowing overlapping transmissions, NOMA can accommodate far more devices in the same bandwidth, which is crucial for mMTC.
- **Low latency**: NOMA enables grant-free transmission, reducing scheduling latency because users can transmit without waiting for orthogonal resource allocation.

These benefits make NOMA a strong candidate for 6G multiple access, particularly when combined with massive MIMO and mmWave/THz frequencies [3, 18].

1.5.3 Principle of NOMA

The core idea of power-domain NOMA is superposition coding at the transmitter and SIC at the receiver. In the downlink, the base station superposes the signals of K users, each with a distinct power level. The transmitted signal is

$$x = \sum_{i=1}^{K} \sqrt{\alpha_i P_{\text{total}}}\, s_i, \tag{1.1}$$

where:

- s_i: the message signal for user i,
- α_i: the power allocation factor for user i, with $\sum \alpha_i = 1$,
- P_{total}: the total transmit power,
- K: the total number of users.

Users with poorer channel conditions receive a larger share of power (higher α_i) to ensure reliable decoding. Figure 1.9 illustrates the concept of superposition coding.

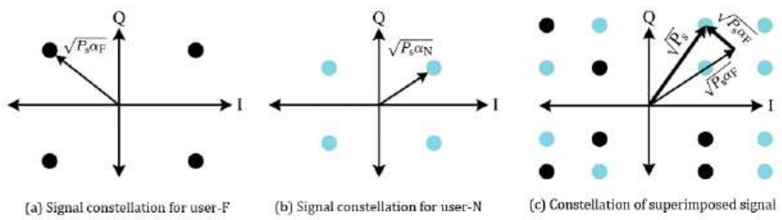

Figure 1.9: Superposition coding concept.

At the receiver, each user employs SIC. The user with the strongest channel (lowest α) decodes its signal first, treating the stronger signals of other users as interference.

After successful decoding, it subtracts the decoded signal from the received waveform, allowing the next user to process its signal without interference from the already cancelled users. This iterative process continues until the weakest user decodes its intended message without interference. The SIC process, while increasing receiver complexity, enables the recovery of superimposed signals and achieves the capacity region of the broadcast channel [20].

In uplink NOMA, multiple users transmit simultaneously to the base station using appropriately controlled power levels. The base station performs SIC in descending order of received power, decoding the strongest signal first and subtracting it, then proceeding to the next strongest. Proper power control is essential to ensure the SIC chain works effectively and to avoid near-far effects [18, 20]. Uplink NOMA improves spectral efficiency and reduces latency compared to orthogonal scheduling, as users can transmit asynchronously.

Figure 1.10 represents a typical NOMA downlink scenario with two users. It demonstrates how the base station superimposes multiple signals in the power domain to serve both the near and far users simultaneously.

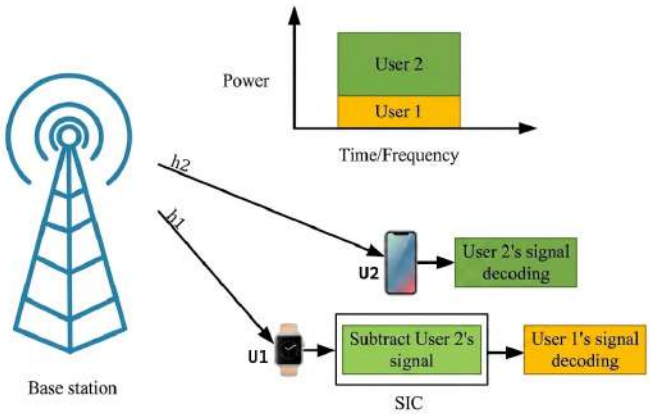

Figure 1.10: NOMA downlink with 2 users [21].

1.5.4 Benefits and Drawbacks of NOMA

NOMA offers several compelling advantages that position it as a strong candidate for future wireless systems. In terms of **spectral efficiency**, NOMA achieves higher sum rates by multiplexing users in the power domain within the same resource block, thereby making more effective use of available bandwidth. Regarding **massive connectivity**, the number of simultaneously served users is not bounded by the number of orthogonal resource units, a property that is critical for IoT and smart city applications. NOMA also promotes **user fairness**, as power allocation can be optimized to guarantee a target data rate for cell-edge users while still delivering high rates to users with favorable channel conditions. Furthermore, **low latency** is achieved through grant-free transmission, which reduces signaling overhead and connection setup time, thereby facilitating URLLC services. Finally, NOMA exhibits strong **compatibility** with existing MIMO and OFDM frameworks, enabling a smooth and incremental evolution path toward 6G.

Nevertheless, NOMA is not without limitations. Its primary drawback lies in **receiver complexity**: SIC requires accurate channel estimation and complex signal processing, and it is susceptible to error propagation — a decoding error at one stage degrades the performance of all subsequent stages. The **power domain optimization** problem is inherently non-convex and typically relies on instantaneous channel state information, which increases feedback overhead and computational burden. Additionally, **inter-user interference** persists even after SIC, due to imperfect channel estimation and residual cancellation errors, which can limit the achievable performance gains. Finally, the superposition of signals raises **security concerns**, as individual messages may be more vulnerable to eavesdropping if appropriate physical-layer or cryptographic protections are not in place.

Ongoing research focuses on robust SIC algorithms, joint resource allocation, and machine learning-based optimization to overcome these limitations and fully realize NOMA's potential in 6G [18, 20].

1.5.5 Comparison of Mobile Network Generations (1G–6G)

Table 1.1 provides a comparative summary of the evolution from 1G to 6G, highlighting key parameters and trends, based on [1–3, 10].

Table 1.1: Comparison of Mobile Network Generations

Parameter	**1G**	**2G**	**3G**	**4G**	**5G**	**6G**
Deployment Period	1980s	1990s	2000s	2010s	2020 onwards	2030 onwards
Peak Data Rate	2.4 Kbps	64 Kbps	Up to 2 Mbps	200 Mbps–1 Gbps	Up to 20 Gbps	Up to Tbps (expected)
Access Technology	FDMA	TDMA / CDMA	WCDMA / CDMA2000	OFDM / LTE	Massive MIMO, mmWave	NOMA
Switching Type	Circuit	Circuit + Packet	Packet (with CS support)	All-IP Packet	Service-based / Packet	Fully IP + Integrated NTN
Core Network	PSTN	PSTN + Packet Core	Packet Network	Internet / All-IP Core	Internet (evolved core)	Integrated terrestrial and non-terrestrial core
Main Services	Voice Only	Digital Voice + SMS	Mobile Internet + Multimedia	Mobile Broadband + HD Streaming	eMBB, URLLC, mMTC	Intelligent communication, global connectivity
ITU Requirement	No official standard	No official requirement	IMT-2000 (144 kbps–2 Mbps)	IMT-Advanced (up to 1 Gbps)	Ultra-low latency and multi-Gbps	IMT-2030 (Tbps, global connectivity)

1.6 Conclusion

The anticipated 6G networks aim to overcome current limitations by integrating advanced technologies, notably Non-Orthogonal Multiple Access (NOMA). As discussed, NOMA offers significant gains in spectral efficiency and massive connectivity, making it a fundamental enabler for ultra-reliable, high-density future networks.

The next chapter explores Non-Terrestrial Networks (NTN) and aerial platforms as the architectural backbone for ubiquitous 6G connectivity.

Chapter 2:

Non-Terrestrial Networks in 6G

2.1 Introduction

The evolution toward 6G introduces unprecedented requirements for massive, ubiquitous connectivity. Traditional terrestrial networks face physical and economic limitations in serving remote and disaster-stricken areas [22, 23]. To achieve truly global coverage, Non-Terrestrial Networks (NTN) have emerged as a critical architectural component. By integrating space and aerial platforms—such as satellites, HAPS, and UAVs—NTN establishes a three-dimensional (3D) network that guarantees enhanced Line-of-Sight (LoS) conditions and seamless service continuity [24, 25].

In this chapter, we will present the core concepts of Non-Terrestrial Networks as a fundamental pillar of 6G. We will classify the primary NTN platforms, detail the Space-Air-Ground Integrated Network (SAGIN) architecture, and establish the key performance metrics. Finally, we will analyze the technical challenges and practical applications of these advanced 3D networks.

2.2 NTN Platforms and System Components

Non-Terrestrial Networks (NTN) utilize multiple types of spaceborne and airborne platforms to provide wireless communication beyond conventional ground-based infrastructure. These platforms include satellites operating at different orbital altitudes, High Altitude Platform Stations (HAPS), and Unmanned Aerial Vehicles (UAVs). Each platform contributes to extending network coverage, improving communication reliability, and enabling global connectivity in 6G communication systems [22, 23].

2.2.1 Satellite Communication Systems

Satellite systems represent the primary component of NTN and provide wide-area communication coverage across large geographical regions. Satellites operate at different orbital altitudes, including Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO), each offering different characteristics in terms of coverage area, latency, and communication performance [24].

Low Earth Orbit (LEO) satellites typically operate at altitudes between approximately 400 km and 2,000 km above the Earth's surface. Due to their lower altitude, LEO satellites provide reduced propagation delay and improved communication performance compared to higher orbit satellites. Medium Earth Orbit (MEO) satellites operate at altitudes between approximately 2,000 km and 35,786 km and provide a balance between coverage area and latency. Geostationary Earth Orbit (GEO) satellites operate at approximately 35,786 km above the Earth's equator and remain fixed relative to the Earth's surface, enabling continuous coverage of specific geographical regions [26].

Satellite-based communication plays a critical role in enabling global connectivity in 6G networks by providing communication services in remote, rural, and underserved areas where terrestrial infrastructure is unavailable. Satellite systems significantly extend network coverage and support continuous communication over wide geographical regions [23, 26].

2.2.2 High Altitude Platform Stations (HAPS)

High Altitude Platform Stations (HAPS) are aerial communication platforms operating in the stratosphere at altitudes typically ranging from approximately 20 km to 50 km above the Earth's surface. These platforms function as quasi-stationary aerial base stations capable of providing wireless communication services over large geographical areas [24].

Due to their high altitude and quasi-stationary operation, HAPS platforms provide improved Line-of-Sight communication conditions and enhanced signal coverage compared to terrestrial base stations. HAPS platforms offer advantages such as wide coverage area, flexible deployment, and improved communication reliability, making them suitable for integration into 6G NTN architectures [22, 23].

2.2.3 UAV-Based Communication Platforms

Unmanned Aerial Vehicles (UAVs) represent flexible aerial communication platforms that can operate at lower altitudes compared to satellites and HAPS. UAVs can function as aerial base stations, relay nodes, or mobile communication platforms, depending on network requirements [27].

UAVs can provide direct communication services to ground users, extend network coverage, and support communication between different network segments. Their mobility and flexible deployment capability make UAV platforms particularly suitable for dynamic communication scenarios, temporary network deployment, and coverage enhancement in 6G NTN environments [23].

Figure 2.1 shows the different NTN platform types and their integration with the ground segment.

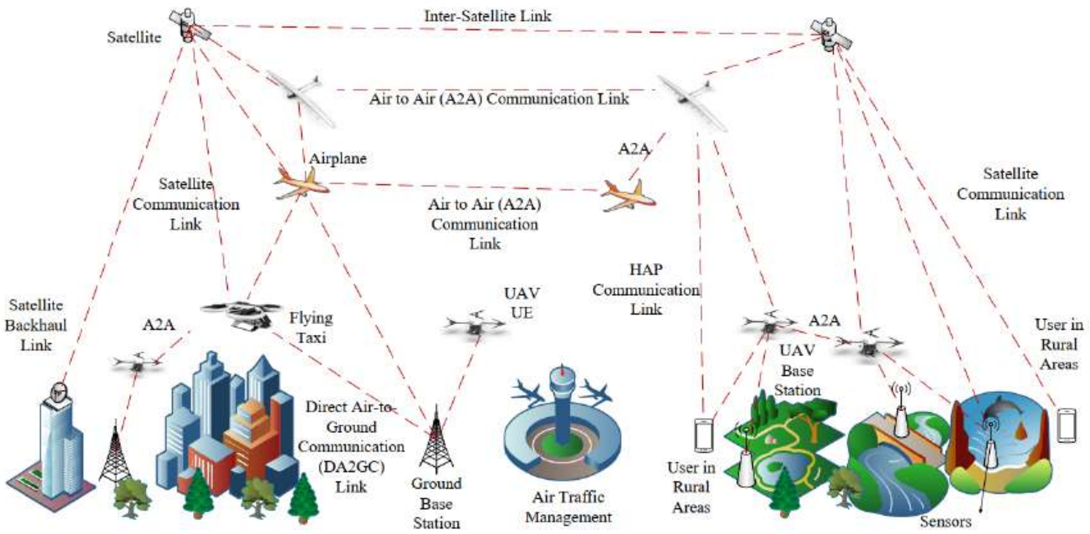

Figure 2.1: Non-Terrestrial Network platforms integrated with the ground segment [28].

2.3 NTN Performance Metrics in 6G

The performance of Non-Terrestrial Networks (NTN) in 6G systems is evaluated based on several key performance metrics that determine the effectiveness, efficiency, and reliability of communication. These metrics include coverage, latency, reliability, energy efficiency, and system capacity. These performance indicators are essential for assessing the ability of NTN to provide global connectivity and support next-generation communication services [22, 29].

2.3.1 Coverage

Coverage represents one of the most significant advantages of NTN in 6G systems. Satellite and aerial communication platforms provide wide-area coverage that extends beyond the limitations of terrestrial infrastructure. Satellites, especially those operating in LEO, MEO, and GEO orbits, enable global communication coverage across large geographical areas, including oceans, rural regions, and remote locations [22, 25].

NTN significantly improves communication availability in underserved and remote areas where terrestrial network deployment is limited or economically impractical. This extended coverage capability ensures continuous connectivity and supports the 6G objective of providing ubiquitous communication services worldwide [29].

2.3.2 Latency

Latency is a critical performance metric in NTN systems and is primarily influenced by signal propagation delay between communication nodes. Due to the large distances between satellites and ground stations, NTN communication may experience higher propagation delays compared to terrestrial networks. The altitude of satellites plays a significant role in determining latency, with LEO satellites providing lower latency compared to MEO and GEO satellites due to their closer proximity to the Earth [24, 26].

The use of aerial platforms such as UAVs and HAPS can help reduce communication latency by providing intermediate communication nodes and improving signal transmission efficiency [22].

2.3.3 Reliability

Reliability refers to the ability of NTN systems to maintain stable and consistent communication links. Satellite and aerial communication platforms often benefit from improved Line-of-Sight (LoS) communication conditions due to their elevated positions, which reduces signal obstruction and improves communication stability [23, 30].

The use of multiple satellites and aerial platforms also improves network redundancy and ensures continuous communication availability, enhancing overall system reliability in 6G NTN environments [22].

2.4 Advantages of NTN in 6G

Non-Terrestrial Networks (NTN) provide several significant advantages that make them a key component of 6G communication systems. By utilizing satellite and aerial communication platforms, NTN enables enhanced connectivity, improved network performance, and expanded communication capabilities beyond the limitations of terrestrial infrastructure [22, 29].

2.4.1 Global Seamless Coverage

One of the most important advantages of NTN is its ability to provide global seamless coverage. Satellite communication systems operating at different orbital altitudes can cover large geographical areas, including oceans, deserts, mountainous regions, and remote locations where terrestrial networks are not available. This enables continuous communication and supports the 6G objective of providing ubiquitous global connectivity [22, 25].

2.4.2 Rapid Deployment Capability

NTN platforms such as UAVs and HAPS can be deployed rapidly compared to terrestrial infrastructure, which requires extensive physical installation. This rapid deployment capability enables quick network setup in emergency situations, temporary communication scenarios, and disaster recovery operations [23, 29].

2.4.3 Support for Remote and Isolated Areas

NTN enables communication services in remote and isolated areas where terrestrial network deployment is difficult or economically inefficient. Satellite and aerial platforms provide connectivity to underserved regions, improving communication accessibility and supporting digital inclusion in rural and remote areas [25].

2.4.4 Improved Network Resilience

The integration of NTN with terrestrial communication systems improves overall network resilience. Multiple communication platforms provide redundancy and alternative communication paths, ensuring service continuity even in cases of terrestrial network failure or infrastructure damage [22, 29].

2.4.5 Enhanced Flexibility

NTN provides enhanced flexibility due to the mobility and adaptability of aerial communication platforms. UAVs and HAPS can dynamically adjust their position based on communication requirements, allowing flexible network deployment and efficient resource utilization. This flexibility improves network performance and supports diverse communication scenarios in 6G systems [23].

2.5 Applications of NTN in 6G

Non-Terrestrial Networks (NTN) enable a wide range of applications in 6G communication systems by providing connectivity in environments where terrestrial networks alone cannot ensure reliable communication. Satellite and aerial communication platforms enable global connectivity, support emerging technologies, and improve communication availability across diverse application scenarios [22, 29].

2.5.1 Remote Area Connectivity

One of the primary applications of NTN is providing connectivity in remote and underserved areas. Satellite communication systems enable network access in rural regions, deserts, mountainous areas, and isolated locations where terrestrial infrastructure is unavailable or difficult to deploy. This improves communication accessibility and supports global connectivity objectives in 6G systems [22, 25].

2.5.2 UAV Communication Systems

NTN supports communication with Unmanned Aerial Vehicles (UAVs), enabling reliable communication for aerial operations. Satellite and aerial communication platforms provide connectivity for UAV control, monitoring, and data transmission, supporting applications such as aerial surveillance, environmental monitoring, and communication relay services [23, 29].

2.5.3 Internet of Things (IoT)

NTN enables connectivity for Internet of Things (IoT) devices deployed in remote and geographically distributed environments. Satellite-based communication supports large-scale IoT deployment in applications such as environmental monitoring, smart agriculture, and industrial systems, enabling data collection and communication in areas without terrestrial network coverage [25].

2.5.4 Disaster Recovery Communications

NTN plays a critical role in disaster recovery scenarios by providing communication services when terrestrial infrastructure is damaged or unavailable. UAVs and satellite communication platforms can be rapidly deployed to restore connectivity, enabling emergency communication, coordination, and response operations [22, 29].

2.5.5 Maritime Communications

Satellite-based NTN enables communication services in maritime environments where terrestrial networks are not available. Ships and offshore platforms rely on satellite communication for navigation, monitoring, and communication, ensuring reliable connectivity across oceans and remote marine regions [25].

2.5.6 Emergency Networks

NTN supports emergency communication networks by providing reliable connectivity during critical situations. Satellite and aerial communication platforms ensure communication availability for emergency responders, public safety operations, and mission-critical communication scenarios, improving response efficiency and operational coordination [23, 29].

2.6 Technical Challenges of NTN in 6G

Despite the significant advantages of Non-Terrestrial Networks (NTN) in 6G systems, several technical challenges must be addressed to ensure efficient and reliable communication. These challenges arise due to the high mobility of communication platforms, long transmission distances, dynamic network topology, and unique propagation characteristics of space and aerial communication environments [22, 29].

2.6.1 Doppler Effect

The Doppler effect represents a major challenge in NTN systems due to the high relative velocity between communication platforms and user equipment. Satellites, particularly those operating in Low Earth Orbit (LEO), move at high speeds relative to ground users, resulting in frequency shifts that can significantly affect signal transmission and reception [24].

These Doppler-induced frequency variations can impact synchronization, signal detection, and communication reliability, requiring advanced compensation techniques and adaptive communication mechanisms to ensure proper system performance [22].

2.6.2 Propagation Delay

Propagation delay is another critical challenge in NTN systems caused by the large distances between communication nodes. Signals transmitted between satellites and ground stations must travel long distances, which introduces communication delay. This delay is particularly significant in higher orbit satellites such as Geostationary Earth Orbit (GEO) systems [24].

Propagation delay affects communication latency, synchronization, and overall network performance, requiring efficient communication protocols and system optimization to minimize its impact on 6G services [29].

2.6.3 Mobility Management

Mobility management in NTN systems is more complex than in terrestrial networks due to the continuous movement of satellites and aerial platforms. The dynamic topology of NTN requires frequent handovers between communication nodes to maintain continuous connectivity [25].

Efficient handover mechanisms and mobility management strategies are required to ensure seamless communication as user equipment moves between different satellite beams, aerial platforms, or ground stations [22].

2.6.4 Power and Energy Constraints

Power and energy constraints represent a significant challenge, particularly for aerial communication platforms such as UAVs and HAPS, which operate with limited onboard energy resources. Efficient energy management is essential to ensure continuous operation and maintain communication performance [30].

Energy-efficient communication techniques and optimized transmission strategies are required to minimize power consumption while maintaining reliable communication in NTN systems [29].

2.6.5 Channel Modeling Challenges

Accurate channel modeling is essential for the design and evaluation of NTN communication systems. Unlike terrestrial communication, NTN systems operate in complex propagation environments that include air-to-ground and space-to-ground communication channels [24].

These communication channels are affected by various factors such as atmospheric conditions, signal attenuation, Doppler effects, and mobility, requiring specialized channel models to accurately represent NTN communication environments [22].

2.6.6 Interference Management

Interference management is another critical challenge in NTN systems due to the coexistence of multiple communication platforms operating in shared frequency bands. Interference may occur between satellites, aerial platforms, and terrestrial networks, affecting communication quality and system performance [29].

Efficient spectrum management, interference mitigation techniques, and coordination mechanisms are required to ensure reliable communication and optimize overall network performance in 6G NTN environments [25].

2.7 Conclusion

This chapter presented a comprehensive overview of Non-Terrestrial Networks (NTN) and their integration into the Space-Air-Ground Integrated Network (SAGIN) architecture. We detailed the diverse space and aerial platforms that enable 3D ubiquitous coverage and examined the significant technical challenges—such as Doppler effects and propagation delays—that must be mitigated for efficient operation.

The next chapter focuses on Unmanned Aerial Vehicles (UAVs), detailing their unique air-to-ground channel models and characteristics essential for accurate network simulation.

Chapter 3:

UAV-Assisted Wireless Communication Systems

3.1 Introduction

Terrestrial cellular networks often encounter critical limitations when providing continuous coverage in remote regions, rural areas, or disaster zones due to the high cost and technical difficulty of deploying fixed infrastructure [31, 32]. To address these challenges, Unmanned Aerial Vehicles (UAVs) have emerged as highly flexible aerial communication platforms. Due to their exceptional mobility and ability to establish strong line-of-sight (LoS) links, UAVs enable rapid network deployment and dynamic reconfiguration, making them indispensable for next-generation wireless systems [33, 34].

In this chapter, we will present the theoretical foundations of UAV-assisted wireless communications. We will analyze the air-to-ground (A2G) propagation channel, explore the operational roles of UAVs, and mathematically define the key performance metrics required for practical system evaluation.

3.1.1 Motivation for UAV-Assisted Communications

The motivation for integrating UAVs into wireless communication networks arises from several technological and practical challenges faced by conventional terrestrial systems. Despite the extensive deployment of cellular infrastructure worldwide, many regions still suffer from limited network coverage due to geographical obstacles, sparse population distribution, or the absence of communication infrastructure. UAV-assisted communication provides a flexible and cost-effective approach to address these challenges by enabling the rapid deployment of aerial communication nodes capable of extending wireless coverage to underserved areas [31, 32].

Another important motivation is related to emergency and disaster recovery scenarios. Natural disasters such as earthquakes, floods, and hurricanes can severely damage terrestrial communication infrastructure, resulting in the loss of connectivity when communication services are most critical. In such situations, UAVs can be quickly deployed to restore communication links and support rescue operations by providing temporary wireless coverage and data connectivity for affected regions [33]. Their ability to hover at specific locations and dynamically adjust their positions allows UAVs to maintain communication services even in highly dynamic environments.

Moreover, the increasing proliferation of Internet of Things (IoT) devices has further strengthened the motivation for UAV-assisted communications. Large-scale IoT deployments often involve sensor nodes distributed over wide geographical areas where direct communication with terrestrial base stations may not be efficient. UAVs can act as mobile data collectors that periodically gather data from distributed sensors and relay the collected information to centralized processing units, thereby improving network scalability and reducing the energy consumption of IoT devices [34].

3.1.2 Role of UAVs in Next-Generation Networks

Next-generation wireless communication systems aim to support massive connectivity, ultra-low latency, and extremely high data rates. To achieve these ambitious performance targets, future networks must adopt flexible and adaptive architectures capable of dynamically responding to varying traffic demands and user distributions. In this context, UAVs are expected to play an important role in enhancing network flexibility and extending coverage beyond the limitations of conventional terrestrial infrastructures.

One of the primary roles of UAVs in wireless communication networks is their use as aerial base stations. In this configuration, UAVs are equipped with communication transceivers that allow them to provide wireless connectivity directly to ground users, similarly to traditional cellular base stations. Due to their elevated positions, UAV-based base stations often experience improved line-of-sight conditions, which can significantly enhance signal quality and expand coverage areas [31].

In addition to functioning as aerial base stations, UAVs can also operate as relay nodes within the network. In relay-assisted communication scenarios, UAVs can forward data between distant users or between users and ground base stations when direct communication links are weak or unavailable. This relay functionality is particularly beneficial in complex environments such as mountainous regions, dense urban areas with significant signal blockage, or disaster zones where communication infrastructure may be partially destroyed [33].

Furthermore, UAVs can serve as mobile data collectors in wireless sensor networks and Internet of Things (IoT) systems. By flying over large sensor deployments, UAVs can efficiently collect data from distributed devices and transmit the collected information to base stations or cloud servers. This approach reduces the communication burden on sensor nodes and improves the overall efficiency of large-scale IoT networks [34].

3.1.3 UAVs in the Context of NTN and 6G

The vision of sixth-generation (6G) wireless communication systems extends beyond traditional terrestrial networks toward integrated three-dimensional communication architectures. In this paradigm, communication infrastructure is no longer limited to ground-based stations but also includes aerial and space-based platforms working together to provide seamless global connectivity. These integrated architectures are commonly referred to as Non-Terrestrial Networks (NTN) [35].

Within the NTN framework, UAVs represent an intermediate layer between terrestrial communication systems and satellite networks. This layered architecture forms what is often referred to as a Space–Air–Ground Integrated Network (SAGIN), in which satellites, high-altitude platforms, and UAVs cooperate to provide continuous and reliable communication coverage.

Compared with satellite communication systems, UAVs operate at much lower altitudes, which significantly reduces signal propagation delays and improves communication reliability. At the same time, their mobility allows them to dynamically reposition themselves according to network requirements, enabling adaptive coverage and capacity where it is most needed.

In the context of 6G networks, UAV-assisted communication systems are expected to support a wide range of emerging applications, including intelligent transportation systems, large-scale Internet of Things deployments, disaster recovery communications, and immersive multimedia services. By integrating UAV platforms with advanced technologies such as millimeter-wave communication, intelligent reflecting surfaces (RIS), and artificial intelligence-based network optimization, future wireless networks will achieve unprecedented levels of flexibility, coverage, and performance [35].

In this chapter, we will present the theoretical foundations of UAV-assisted wireless communications. We will analyze the air-to-ground (A2G) propagation channel, explore the operational roles of UAVs, and mathematically define the key performance metrics required for practical system evaluation.

3.2 UAV Fundamentals

Unmanned Aerial Vehicles (UAVs) have evolved from specialized military platforms into versatile systems widely used in civilian, industrial, and communication applications. Their ability to operate without an onboard human pilot while carrying communication equipment makes them particularly attractive for modern wireless communication systems. In UAV-assisted communication networks, these aerial platforms can provide connectivity, extend coverage, and assist existing terrestrial infrastructures.

Due to their mobility and flexible deployment, UAVs can dynamically adapt their positions to improve communication performance and coverage in complex environments. As a result, UAV-assisted communication has become an important research topic in recent years, especially in the context of next-generation wireless networks and non-terrestrial communication systems.

3.2.1 Definition and Historical Background

An Unmanned Aerial Vehicle (UAV) is generally defined as an aircraft that operates without a human pilot onboard and is controlled either remotely by an operator or autonomously through onboard control systems. UAVs are typically equipped with navigation systems, sensors, communication modules, and payload equipment that allow them to perform various missions such as surveillance, monitoring, data collection, and wireless communication support.

Historically, UAV technology was initially developed for military reconnaissance missions, where unmanned platforms offered strategic advantages by reducing the risk to human pilots. Over time, rapid advancements in electronics, navigation systems, and wireless communication technologies significantly expanded the capabilities of UAV systems.

Today, UAVs are widely used in numerous civilian applications, including environmental monitoring, disaster management, aerial photography, agriculture, logistics, and communication networking. Their capability to rapidly reach inaccessible areas and provide temporary communication infrastructure has made them particularly valuable in wireless communication systems.

3.2.2 UAV Classification

UAV platforms can be classified according to several design characteristics, including aerodynamic structure, operational altitude, and mission requirements.

- **Classification by Aerodynamic Structure:** One of the most widely used classification approaches is based on the aerodynamic design of the aircraft. From this perspective, UAVs are generally divided into fixed-wing UAVs and rotary-wing UAVs. Fixed-wing UAVs generate lift through forward motion using their wings, similar to conventional airplanes. These platforms typically provide longer flight endurance and are capable of covering large geographical areas. In contrast, rotary-wing UAVs use rotating propellers to generate lift, allowing them to hover in place and perform vertical take-off and landing (VTOL). This capability provides high maneuverability and precise positioning, which makes rotary-wing UAVs particularly suitable for communication applications where stable positioning is required.

- **Classification by Size and Altitude:** Another important classification of UAV systems is based on their physical size and operational altitude. Depending on their flight capabilities and mission profiles, UAVs can be categorized into low-altitude platforms and high-altitude platforms. Low-altitude UAV platforms typically operate at relatively low heights and are commonly used for short-range missions such as surveillance, environmental monitoring, and communication coverage extension. These UAVs are usually lightweight, energy-efficient, and relatively inexpensive to deploy. High-altitude UAV platforms, on the other hand, operate at significantly higher altitudes and can provide wider communication coverage areas. These platforms are often considered as complementary solutions to satellite systems because they can remain airborne for extended periods while supporting wide-area communication services.

Figure 3.1 presents the main categories of UAVs based on their aerodynamic design and operational altitude.

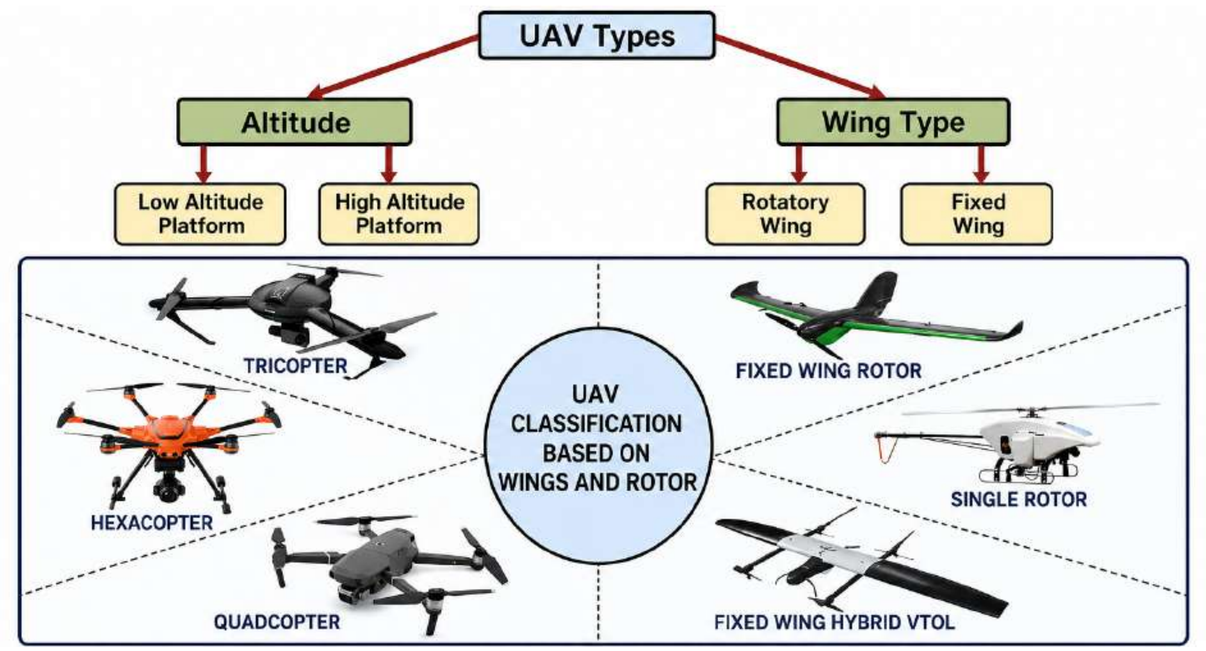

Figure 3.1: Classification of unmanned aerial vehicles according to altitude and aerodynamic structure [36].

3.2.3 Key Operational Parameters

The performance of UAV-assisted communication systems depends on several operational parameters related to the UAV platform and its flight characteristics. Among the most important parameters are flight altitude, velocity, endurance, payload capacity, and communication range.

Flight altitude directly affects the quality of the communication link between UAVs and ground users. Higher altitudes typically increase the probability of line-of-sight communication and expand coverage areas, while lower altitudes may reduce propagation losses in certain environments.

Another important parameter is UAV velocity, which influences the stability of wireless links and may introduce mobility-related effects such as Doppler shifts and rapid channel variations. In addition, the endurance of the UAV, defined as the maximum flight duration before battery depletion, plays a critical role in determining the feasibility of long-duration communication missions.

Payload capacity is also a key factor because UAV communication platforms must carry communication hardware, antennas, sensors, and onboard processing units. These components increase the overall weight of the UAV and may affect its flight performance and energy consumption.

3.2.4 UAVs vs Terrestrial Base Stations

Although UAV-based communication platforms share certain functional similarities with terrestrial base stations, they differ significantly in terms of deployment flexibility, coverage characteristics, and operational constraints.

Terrestrial base stations are installed at fixed locations and provide stable long-term communication coverage. Their infrastructure allows high transmission power and continuous operation. However, the deployment of terrestrial infrastructure often requires significant investment and may be limited by geographical or regulatory constraints.

In contrast, UAV-based communication platforms offer much greater flexibility. UAVs can be rapidly deployed and repositioned according to network requirements, allowing them to provide temporary communication coverage in areas where terrestrial infrastructure is unavailable or insufficient.

Despite these advantages, UAV systems also face several limitations compared with terrestrial base stations. UAVs have limited onboard energy resources, restricted payload capacity, and shorter operational durations. Therefore, efficient resource management and careful system design are necessary to ensure reliable UAV-assisted communication services.

3.3 UAV Air-to-Ground Channel Model

The air-to-ground (A2G) channel is one of the most important elements in UAV-assisted wireless communication systems because it directly determines the quality of the link between the aerial platform and ground users. Unlike conventional terrestrial channels, the UAV channel is inherently three-dimensional and is strongly affected by the UAV altitude, elevation angle, mobility, and surrounding environment. For this reason, channel modeling in UAV communications cannot be treated as a simple extension of classical ground communication models. Instead, it requires dedicated formulations that capture the specific propagation characteristics of aerial links [37, 38].

A typical UAV A2G channel contains both large-scale and small-scale effects. The large-scale component is mainly related to path loss and shadowing, whereas the small-scale component is related to multipath fading. In practice, the quality of the UAV communication link depends on whether the propagation condition is line-of-sight (LoS) or non-line-of-sight (NLoS), since the received signal strength and fading statistics differ significantly between these two cases [37, 39]. As a result, most UAV channel models are built by combining path-loss expressions with probabilistic LoS/NLoS characterization and suitable fading distributions.

3.3.1 Introduction to UAV Channel Modeling

Channel modeling for UAV systems aims to describe how the transmitted signal propagates from the UAV to the ground receiver under realistic environmental conditions. In general, UAV communication links are divided into air-to-ground (A2G), air-to-air (A2A), and air-to-space (A2S) channels. Among these, the A2G channel is the most widely studied because it forms the basis of UAV-assisted wireless access, aerial relaying, and data collection applications [38].

The main difference between UAV A2G channels and terrestrial channels lies in the stronger dependence on elevation geometry. In terrestrial networks, propagation is often dominated by buildings, terrain blockage, and scattering close to the ground. In contrast, UAV links frequently benefit from a higher probability of direct visibility between the transmitter and receiver, especially when the UAV flies at moderate or high altitude. However, this advantage does not eliminate channel impairments completely. The wireless link may still experience additional losses due to reflections, shadowing from buildings or mountains, atmospheric effects, and motion-induced channel variations [37, 38].

For this reason, UAV channel modeling usually considers the following main aspects:

- distance-dependent path loss,
- probabilistic LoS and NLoS propagation,
- small-scale fading behavior,
- altitude-dependent channel quality,
- mobility effects such as Doppler shift.

These elements together provide a sufficiently accurate representation of practical UAV communication scenarios without requiring overly complicated mathematical treatment.

3.3.2 Path Loss Model

Path loss describes the attenuation of the transmitted signal power as the propagation distance increases. In UAV communications, the simplest starting point is the free-space path-loss model, which is appropriate when a dominant direct path exists between the UAV and the ground receiver. It can be written as [37]:

$$PL_{\mathrm{FS}}(d) = 20\log_{10}\left(\frac{4\pi d f_c}{c}\right), \tag{3.1}$$

where:

- d: the propagation distance between the UAV and the receiver (m),
- f_c: the carrier frequency (Hz),
- c: the speed of light (3×10^8 m/s).

Although (3.1) is useful as a baseline, practical UAV links are rarely purely free-space links. In real deployments, additional attenuation appears due to environmental blockage, terrain irregularities, foliage, urban clutter, or weather conditions. Therefore, a more practical representation is often expressed as a combination of LoS and NLoS losses [37, 39]:

$$PL_{\mathrm{avg}} = P_{\mathrm{LoS}}\, PL_{\mathrm{LoS}} + (1 - P_{\mathrm{LoS}})\, PL_{\mathrm{NLoS}}, \tag{3.2}$$

where:

- P_{LoS}: the probability of LoS propagation,
- PL_{LoS}: the path loss under LoS conditions,
- PL_{NLoS}: the path loss under NLoS conditions.

This formulation is particularly useful because it captures the fact that UAV links are not always strictly LoS or strictly NLoS. Instead, the average channel behavior depends on the operating environment and on the UAV geometry relative to the ground terminal. In urban areas, for example, tall buildings reduce the direct visibility of the UAV at low elevation angles, whereas in open or rural areas the propagation is often closer to free-space conditions [37, 38].

3.3.3 LoS and NLoS Propagation

One of the defining features of UAV communication channels is the importance of LoS probability. In many UAV-assisted systems, the received signal quality improves substantially when a direct path exists between the UAV and the user. Because UAVs operate above the ground, the probability of LoS generally increases with altitude and with elevation angle. This is one of the main reasons why aerial platforms can provide more favorable propagation conditions than conventional ground transmitters [39, 40].

A commonly used expression models the LoS probability as a function of the elevation angle θ [37]:

$$P_{\mathrm{LoS}}(\theta) = \frac{1}{1 + a \exp\left[-b\left(\theta - a\right)\right]}, \tag{3.3}$$

where:

- $\theta = \arctan(h/r)$: the elevation angle,
- h: the UAV altitude,
- r: the horizontal distance between the UAV and the ground user,
- a, b: environment-dependent constants.

This equation reflects a simple but important idea: when the UAV is observed under a larger elevation angle, the chance of having an unobstructed propagation path becomes higher.

Under LoS conditions, the path loss is generally lower and the received signal is more stable. Under NLoS conditions, the signal experiences additional attenuation due to diffraction, scattering, and blockage by surrounding objects. Consequently, NLoS links typically suffer from weaker received power and more severe fading [37, 38]. In mountainous or dense urban scenarios, this distinction becomes even more critical because terrain and obstacles may strongly affect the availability of the direct path.

3.3.4 Small-Scale Fading (Rician / Rayleigh)

In addition to large-scale path loss, UAV links are also affected by small-scale fading, which describes rapid fluctuations in the received signal amplitude due to multipath propagation. The fading distribution depends mainly on whether a dominant direct component is present.

When a strong direct path exists, the UAV channel is often modeled using Rician fading. In this case, the received signal contains one dominant component in addition to several weaker scattered components. Rician fading is therefore considered appropriate for many LoS-dominated UAV scenarios [37, 38]. The strength of the dominant component is usually quantified by the Rician K-factor, which measures the ratio between the power of the direct path and the power of the scattered components.

On the other hand, when the direct path is blocked and the received signal is composed mainly of many scattered components, Rayleigh fading becomes a more suitable model. Rayleigh fading is therefore more relevant for NLoS UAV links, especially in environments with severe blockage or rich scattering [39].

In practical channel modeling, this distinction is important because it affects system performance metrics such as bit error rate, outage probability, and achievable data rate. LoS-dominated channels with Rician fading generally lead to more stable communication performance than NLoS channels characterized by Rayleigh fading.

Table 3.1: Typical propagation characteristics in UAV A2G links.

Channel condition	**Typical model**	**Main characteristic**
LoS link	Free-space / Rician	Strong direct path, lower attenuation
NLoS link	Excess loss / Rayleigh	Blockage, stronger fading, weaker signal
High elevation angle	Higher P_{LoS}	Better visibility and coverage
Low elevation angle	Higher NLoS probability	More blockage and shadowing

3.3.5 Effect of UAV Altitude on Channel Quality

UAV altitude has a direct and sometimes non-linear impact on channel quality. When the UAV altitude increases, the elevation angle seen by the ground user also tends to increase, which improves the probability of LoS propagation. This generally enhances coverage and reduces the chance of blockage [38, 39]. However, the benefit of higher altitude is not unlimited.

At very high altitudes, although LoS conditions become more likely, the propagation distance between the UAV and the receiver also increases. This larger distance can lead to greater path loss, which may offset part of the LoS advantage. Therefore, there is often an altitude trade-off in UAV communications: a low altitude may suffer from blockage and weak LoS probability, whereas an excessively high altitude may introduce unnecessary path-loss increase [39].

This trade-off explains why many studies report the existence of an optimal UAV altitude for communication performance. At that operating point, the UAV is high enough to benefit from favorable visibility, but not so high that distance-related attenuation dominates the link budget. In practical network planning, altitude must therefore be selected according to the propagation environment, service area size, and communication objective.

3.3.6 Doppler Effect and Mobility Impact

Because UAVs are mobile platforms, their motion introduces additional channel dynamics that are absent or less pronounced in many static terrestrial systems. One of the most important mobility-related effects is the Doppler shift, which represents the frequency variation caused by relative motion between the transmitter and receiver. It is commonly expressed as:

$$f_D = \frac{v}{\lambda}\cos(\phi), \tag{3.4}$$

where:

- v: the relative speed between the UAV and the receiver (m/s),
- λ: the wavelength of the carrier signal (m),
- ϕ: the angle between the direction of motion and the propagation path.

In UAV-assisted communication systems, Doppler effects may become significant when the UAV moves at high speed or when the carrier frequency is high, such as in mmWave or

THz systems [38, 41]. The resulting frequency shift may degrade synchronization, increase channel estimation difficulty, and reduce link reliability if it is not properly compensated.

Mobility also affects the channel in another way: the propagation geometry changes continuously as the UAV moves. This means that the communication link is inherently time-varying, with changing path loss, fading statistics, and LoS probability. In practical terms, the UAV trajectory, speed, and hovering stability all influence the quality of the communication link. For this reason, mobility-aware channel models are essential for realistic evaluation of UAV-assisted wireless systems [37, 38].

Overall, the UAV air-to-ground channel is shaped by a combination of geometry, environment, and mobility. Even when the mathematical models remain relatively simple, they provide important insight into the design trade-offs of UAV-assisted wireless communication systems.

3.4 UAV Communication Roles

One of the main reasons behind the increasing interest in UAV-assisted wireless communication is the versatility of UAV platforms. Unlike traditional fixed infrastructure, UAVs can dynamically adapt their position, altitude, and trajectory according to network requirements. This flexibility allows UAVs to perform several communication roles depending on the application scenario, including acting as aerial base stations, relay nodes, data collectors, or cooperative communication agents within aerial networks [31, 33, 37].

In modern wireless networks, UAVs are no longer considered only as flying devices but rather as intelligent network components capable of enhancing coverage, improving connectivity, and supporting emerging technologies such as non-terrestrial networks (NTN), Internet of Things (IoT), and reconfigurable intelligent surfaces (RIS). The following subsections discuss the main communication roles that UAVs can perform in UAV-assisted wireless systems.

3.4.1 UAV as Aerial Base Station (UAV-BS)

One of the most widely studied applications of UAVs in wireless communication is their use as aerial base stations. In this configuration, a UAV is equipped with wireless communication hardware and operates similarly to a terrestrial base station by providing direct connectivity to ground users. Because the UAV operates at an elevated position, it often benefits from improved line-of-sight (LoS) propagation conditions, which can significantly enhance signal coverage and link quality [31, 32].

The UAV-BS concept is particularly useful in scenarios where terrestrial infrastructure is unavailable, damaged, or temporarily overloaded. For instance, UAV base stations can be rapidly deployed during natural disasters to restore communication services in affected areas. Similarly, UAV-BS platforms can be used to support temporary high-traffic events such as concerts, festivals, or large public gatherings where existing cellular infrastructure may not be sufficient to handle the increased demand.

Another important advantage of UAV-BS systems is their ability to dynamically reposition themselves to optimize network coverage. By adjusting their altitude and location, UAV base stations can adapt to the spatial distribution of users and improve communication performance in real time [32]. This capability makes UAV-BS systems an attractive solution for flexible and on-demand wireless network deployment.

Figure 3.2 illustrates a UAV operating as an aerial base station serving ground users.

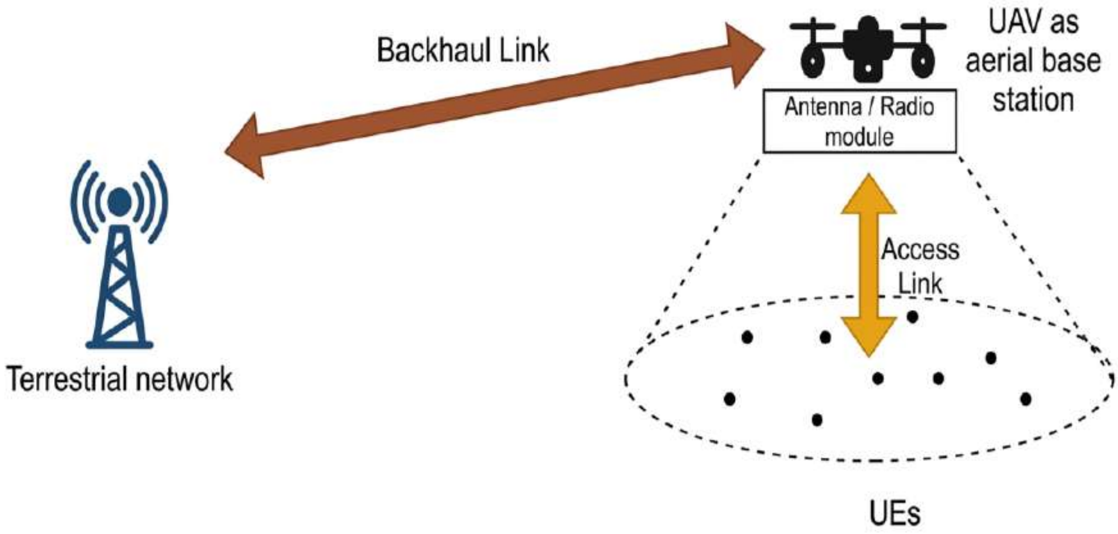

Figure 3.2: UAV as an aerial base station [42].

3.4.2 UAV as Relay Node (UAV-Relay)

In many wireless communication scenarios, direct communication between a transmitter and a receiver may be limited due to distance, obstacles, or unfavorable propagation conditions. In such cases, UAVs can act as relay nodes that assist in forwarding data between communication endpoints. Relay-assisted UAV communication improves link reliability and extends communication coverage beyond the limits of direct transmission [39, 41].

In a typical UAV relay system, the UAV receives signals from a ground transmitter and then forwards them to the destination receiver using techniques such as amplify-and-forward (AF) or decode-and-forward (DF) relaying. Because UAVs operate above ground level, they can often establish stronger LoS links with both communication endpoints, which significantly improves the reliability of the communication channel.

UAV relay systems are particularly useful in challenging environments such as mountainous regions, dense urban areas, or rural zones where terrestrial infrastructure may be limited. In addition, relay-based UAV communication has been investigated in emerging high-frequency systems such as millimeter-wave and terahertz communications, where blockage and path loss are more severe [41].

Figure 3.3 depicts a UAV acting as a relay node between the terrestrial network and end users.

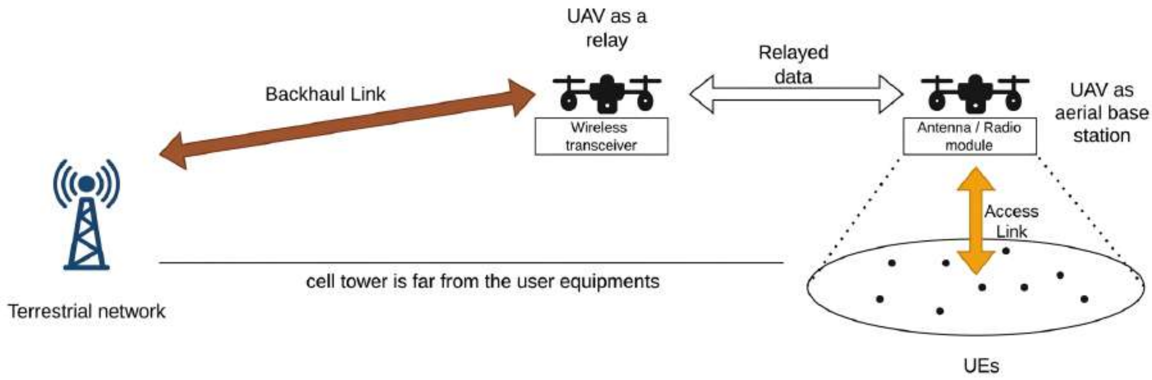

Figure 3.3: UAV as a relay node [42].

3.4.3 UAV as Data Collector

Another important role of UAVs in wireless communication networks is data collection from distributed devices. This role is especially relevant in Internet of Things (IoT) applications where large numbers of sensors are deployed over wide geographic areas. Instead of requiring each sensor to maintain a direct long-distance communication link with a base station, a UAV can periodically fly over the sensing region and collect data from nearby devices [33, 43].

In such systems, UAVs act as mobile gateways that gather information from ground sensors and transmit the collected data to centralized servers or cloud platforms. This approach offers several advantages. First, it significantly reduces the communication burden on individual sensor nodes, which often operate with limited energy resources. Second, UAV mobility allows the system to scale to large sensor deployments without requiring extensive terrestrial infrastructure.

Data collection using UAVs has been widely studied in applications such as environmental monitoring, precision agriculture, disaster management, and smart city systems. By optimizing UAV flight trajectories and communication schedules, it is possible to significantly improve data collection efficiency and reduce energy consumption in wireless sensor networks.

Figure 3.4 shows a UAV collecting data from distributed ground sensors along its flight path.

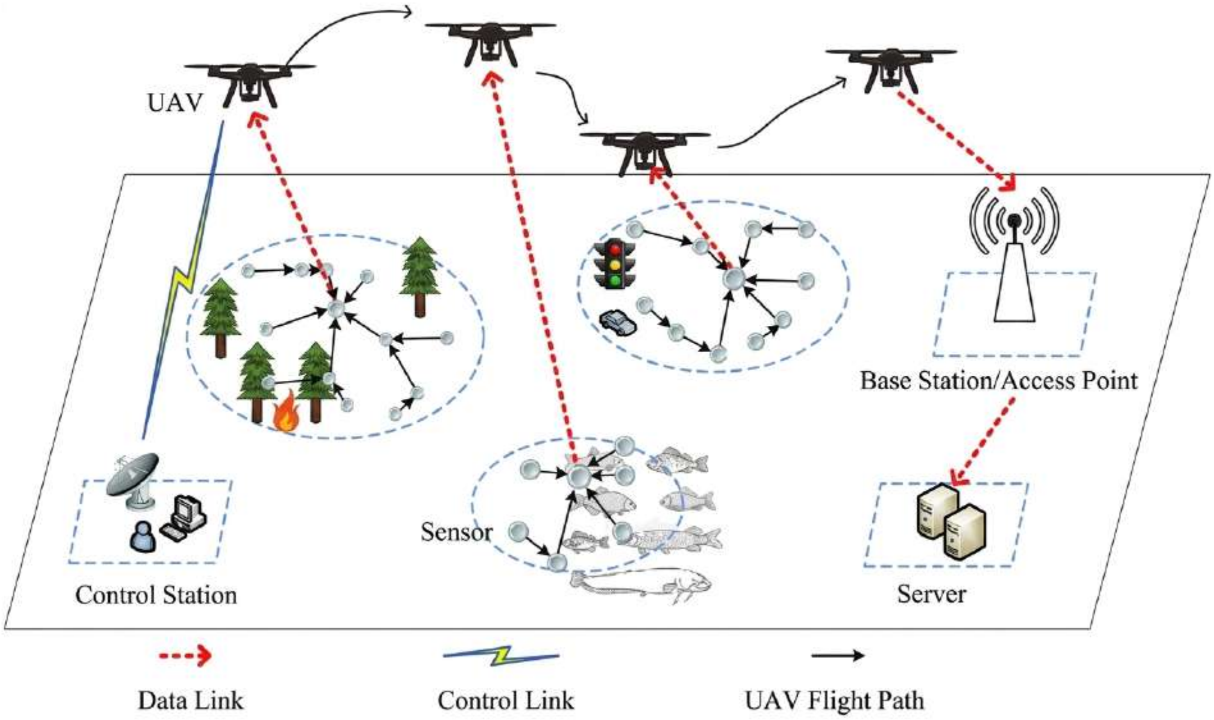

Figure 3.4: UAV as a mobile data collector [44].

3.4.4 UAV Swarm and Cooperative Communication

In advanced communication scenarios, multiple UAVs can cooperate with each other to form aerial networks known as UAV swarms or Flying Ad Hoc Networks (FANETs). In such systems, UAVs communicate with one another and coordinate their actions in order to improve network performance, coverage, and reliability [33, 38].

Cooperative UAV communication provides several advantages compared with single-UAV systems. First, multiple UAVs can collectively cover larger geographical areas. Second, cooperative communication enables load balancing and redundancy, which improves network resilience in case of node failure. Third, swarm-based UAV systems can support complex communication tasks such as distributed sensing, coordinated surveillance, and collaborative data processing.

However, UAV swarm communication also introduces several challenges. Maintaining stable communication links between moving aerial nodes requires efficient routing protocols, synchronization mechanisms, and interference management techniques. Additionally, coordination among multiple UAVs must be carefully designed to avoid collisions and ensure efficient utilization of network resources.

Figure 3.5 presents a cooperative UAV swarm system performing coordinated communication and sensing.

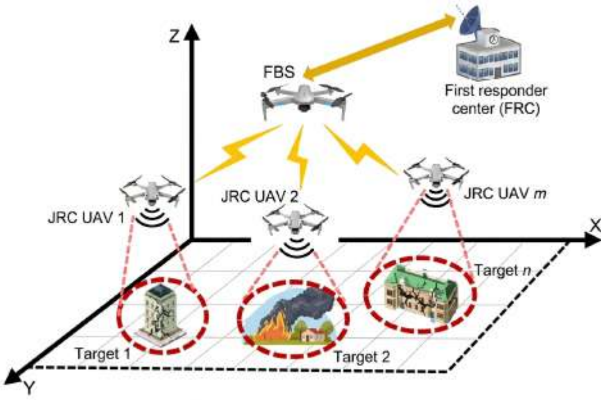

Figure 3.5: Cooperative UAV swarm communication system [45].

3.4.5 UAV as RIS Platform

Recent research has also explored the integration of UAV platforms with reconfigurable intelligent surfaces (RIS), which are considered a promising technology for future wireless networks. RIS consists of programmable meta-surfaces capable of dynamically controlling the reflection of electromagnetic waves, thereby improving signal propagation and communication performance [43].

In RIS-assisted UAV communication systems, UAVs can carry or support RIS devices that manipulate radio signals to enhance wireless connectivity between transmitters and receivers. This approach is particularly beneficial in environments where direct communication links are blocked by obstacles. By intelligently reflecting signals toward intended receivers, RIS-equipped UAV platforms can improve coverage, increase signal strength, and reduce interference.

The combination of UAV mobility with RIS beamforming capabilities opens new possibilities for adaptive wireless communication architectures in next-generation networks. Such systems can dynamically adjust both the UAV position and the RIS reflection parameters to optimize communication performance in real time. Consequently, UAV-RIS integration is expected to play an important role in future 6G and non-terrestrial network architectures [38, 43].

Figure 3.6 illustrates a RIS-assisted UAV communication scenario where reflected signals bypass obstacles to reach ground users.

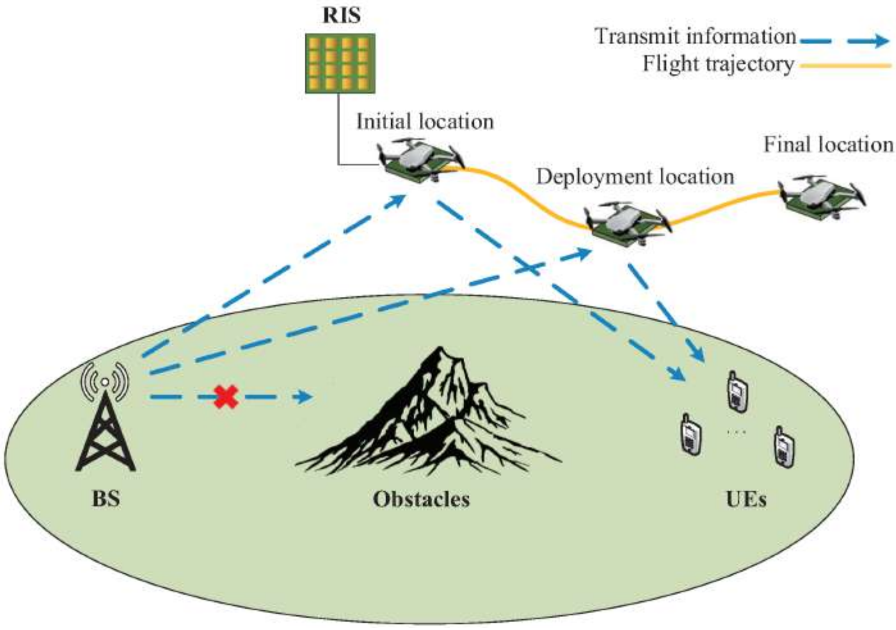

Figure 3.6: RIS-assisted UAV communication system [46].

3.5 Performance Metrics for UAV Communication Systems

Evaluating the performance of UAV-assisted wireless communication systems requires the use of well-defined metrics that reflect the reliability, efficiency, and robustness of the communication link. Since UAV platforms operate in dynamic environments and experience varying propagation conditions, performance analysis becomes essential in order to assess the effectiveness of UAV-assisted communication architectures.

Several performance metrics are commonly used in the analysis of UAV communication systems. Among the most important metrics are Bit Error Rate (BER), system capacity, and outage probability. These metrics provide complementary perspectives on system performance. While BER evaluates the reliability of data transmission, capacity measures the maximum achievable data rate of the communication channel, and outage probability quantifies the likelihood that the communication link fails to meet a required quality threshold [34, 37, 38].

3.5.1 Bit Error Rate (BER)

Bit Error Rate (BER) is one of the most widely used metrics for evaluating the reliability of digital communication systems. It represents the probability that a transmitted bit is incorrectly received due to channel impairments such as noise, interference, or fading.

Mathematically, BER can be defined as

$$BER = \frac{N_e}{N_t}, \tag{3.5}$$

where:

- N_e: the number of erroneous bits detected at the receiver,
- N_t: the total number of transmitted bits.

In UAV-assisted communication systems, BER performance is influenced by several factors including signal-to-noise ratio (SNR), propagation distance, channel fading conditions, and UAV mobility. For instance, when a strong line-of-sight (LoS) component exists between the UAV and the ground user, the communication link generally experiences lower BER compared with non-line-of-sight (NLoS) scenarios where multipath fading is more severe [37].

Furthermore, modulation schemes and coding techniques also play a significant role in determining BER performance. Advanced modulation techniques and error correction mechanisms can significantly reduce the error probability even under challenging propagation conditions.

3.5.2 System Capacity (Shannon Capacity)

System capacity is another fundamental metric used to evaluate wireless communication performance. It represents the maximum achievable data rate that can be transmitted over a communication channel without error under ideal conditions.

According to Shannon's channel capacity theorem, the maximum achievable data rate can be expressed as

$$C = B \log_2(1 + SNR), \tag{3.6}$$

where:

- C: the channel capacity (bits/s),
- B: the channel bandwidth (Hz),
- SNR: the signal-to-noise ratio.

In UAV communication systems, capacity is strongly affected by several parameters such as UAV altitude, transmission power, channel bandwidth, and propagation conditions. Because UAV platforms often experience improved LoS propagation compared with terrestrial systems, they can potentially achieve higher data rates and improved spectral efficiency [31, 32].

However, mobility and channel variability may introduce fluctuations in the received SNR, which directly impacts the achievable capacity. As a result, adaptive communication strategies are often required to maintain stable data rates in UAV-assisted networks.

3.5.3 Outage Probability (OP)

Outage probability is another important performance metric widely used in wireless communication analysis. It measures the probability that the instantaneous signal-to-noise ratio falls below a predefined threshold required for reliable communication.

Formally, outage probability can be expressed as

$$P_{out} = P(SNR < \gamma_{th}), \tag{3.7}$$

where:

- γ_{th}: the minimum SNR threshold required to maintain acceptable communication quality.

In UAV communication scenarios, outage probability is affected by channel fading, UAV position, propagation distance, and environmental conditions. For example, when the UAV is positioned at an optimal altitude with a strong LoS link to the receiver, the outage probability can be significantly reduced [39, 41].

Outage probability analysis is particularly important in UAV-assisted networks because UAV mobility allows the communication link quality to change rapidly. Therefore, evaluating outage probability helps determine whether the communication system can maintain reliable connectivity under dynamic operating conditions.

3.5.4 Trade-offs Between Metrics

Although BER, capacity, and outage probability are all essential indicators of communication performance, they are often interrelated and involve inherent trade-offs. Improving one metric may sometimes negatively affect another.

For instance, increasing transmission power can reduce BER and outage probability by improving the received SNR. However, higher transmission power may also increase interference levels and energy consumption, which is particularly important for UAV platforms with limited onboard energy resources.

Similarly, increasing data transmission rates can improve system capacity but may lead to higher BER if the channel conditions are not sufficiently strong. In dynamic UAV environments where channel quality fluctuates due to mobility and altitude changes, balancing these performance metrics becomes a critical design consideration.

Consequently, the design of UAV-assisted wireless communication systems typically requires optimization strategies that jointly consider multiple performance metrics. By carefully balancing reliability, data rate, and connectivity requirements, it is possible to achieve efficient and robust UAV communication networks suitable for next-generation wireless applications [38, 43].

3.6 Advantages and Challenges

Despite the rapid development of terrestrial cellular infrastructure, UAV-assisted wireless communication systems have emerged as a promising complement to conventional networks. The mobility and flexibility of UAV platforms enable new deployment strategies that are difficult to achieve using fixed ground infrastructure alone. However, while UAV-assisted communication offers several advantages, it also introduces a number of technical challenges that must be carefully addressed when designing reliable aerial communication systems [31–33].

3.6.1 Advantages over Terrestrial Systems

UAV-assisted communication systems provide several advantages compared with traditional terrestrial wireless networks. One of the most important advantages is deployment flexibility. Unlike fixed base stations, UAV platforms can be rapidly deployed and repositioned according to network requirements. This makes them particularly useful in temporary communication scenarios such as disaster recovery, emergency operations, or large public events where existing infrastructure may not be sufficient [31].

Another significant advantage is the improved probability of line-of-sight (LoS) communication. Because UAVs operate at elevated positions above the ground, the likelihood of signal blockage caused by buildings, vegetation, or terrain obstacles is generally reduced. As a result, UAV-assisted communication links often experience better propagation conditions compared with conventional terrestrial links [37].

UAV platforms also provide enhanced coverage capabilities. By adjusting their altitude and position, UAVs can dynamically adapt their coverage area to match the spatial distribution of users. This adaptability enables more efficient network resource utilization and improves connectivity in sparsely populated or geographically challenging regions [32].

Furthermore, UAV-assisted communication can support emerging applications such as Internet of Things (IoT) data collection, aerial surveillance, environmental monitoring, and intelligent transportation systems. These applications benefit from the mobility and rapid deployment capabilities of UAV platforms, which allow communication infrastructure to be temporarily established in areas where traditional networks are unavailable [33].

3.6.2 Technical Challenges

Despite their advantages, UAV-assisted communication systems also face several technical challenges that must be addressed to ensure reliable and efficient network operation. One of the most significant challenges is the limited onboard energy capacity of UAV platforms. Since most UAVs rely on battery-powered propulsion systems, their operational time is inherently limited. This constraint directly affects communication duration, flight range, and mission planning [32].

Another important challenge is related to mobility management. Because UAVs are constantly moving platforms, maintaining stable communication links with ground users can be difficult. UAV mobility introduces time-varying channel conditions, Doppler shifts, and dynamic network topology changes, all of which complicate system design and resource allocation [37].

Interference management also represents a major challenge in UAV-assisted networks. When UAVs operate as aerial base stations within existing cellular systems, they may introduce additional interference to terrestrial users or neighboring cells. Proper interference mitigation techniques and intelligent resource allocation strategies are therefore required to maintain acceptable network performance [33].

Finally, regulatory and safety considerations must also be taken into account. UAV operations are subject to aviation regulations that may restrict flight altitude, operational zones, and communication frequencies. Ensuring safe and compliant UAV deployment is therefore an essential aspect of practical UAV-assisted communication systems.

3.6.3 Comparison Table: UAV Roles

UAV platforms can perform multiple roles in wireless communication systems depending on the specific application scenario. Table 3.2 summarizes the main characteristics and typical use cases of different UAV communication roles.

Table 3.2: Comparison of UAV communication roles in wireless networks.

UAV Role	Main Function	Typical Applications
UAV Base Station (UAV-BS)	Provides direct connectivity to ground users	Temporary cellular coverage, disaster recovery
UAV Relay	Forwards data between communication nodes	Extending communication range, overcoming blockage
UAV Data Collector	Gathers data from distributed sensors	IoT monitoring, environmental sensing
UAV Swarm	Cooperative communication among multiple UAVs	Surveillance, coordinated sensing
UAV with RIS	Enhances signal reflection and coverage	Smart radio environments, 6G networks

The comparison highlights the versatility of UAV platforms in wireless communication networks. Depending on system requirements, UAVs can either operate independently or cooperate with other aerial or terrestrial nodes to improve network performance. As research in UAV-assisted communication continues to evolve, these roles are expected to become increasingly integrated within future 6G and non-terrestrial network architectures [38, 43].

3.7 Conclusion

This chapter established the theoretical foundations of UAV-assisted wireless communications. We examined the unique characteristics of the air-to-ground (A2G) propagation channel, including line-of-sight probabilities and fading effects. Furthermore, we detailed the versatile roles of UAV platforms and mathematically defined critical performance metrics such as bit error rate (BER), capacity, and outage probability.

The next chapter presents a practical MATLAB simulation of a UAV-assisted NOMA system to evaluate its performance and validate its advantages over conventional OMA.

Chapter 4:

Performance Evaluation of UAV-Assisted Wireless Communication Systems

4.1 Introduction

Unmanned Aerial Vehicles (UAVs) acting as aerial base stations are crucial for extending coverage and enhancing connectivity in 6G networks [47]. Concurrently, Non-Orthogonal Multiple Access (NOMA) significantly improves spectral efficiency by serving multiple users simultaneously using superposition coding and successive interference cancellation [48]. The integration of UAVs with NOMA leverages the mobility of aerial platforms and the high capacity of non-orthogonal transmissions.

In this chapter, we will present a comprehensive MATLAB-based simulation to evaluate the performance of a UAV-assisted downlink NOMA system. We will generate and discuss empirical curves for the Bit Error Rate (BER), outage probability, and sum-rate to systematically prove NOMA's advantage over conventional OMA across varying system parameters.

4.2 System Model

We consider a downlink NOMA system consisting of a UAV serving two ground users: a far user (U1) and a near user (U2), as illustrated in Fig. 4.1. The UAV is at a fixed height H. The horizontal distances from the UAV to the far user and near user are denoted by r_1 and r_2, respectively.

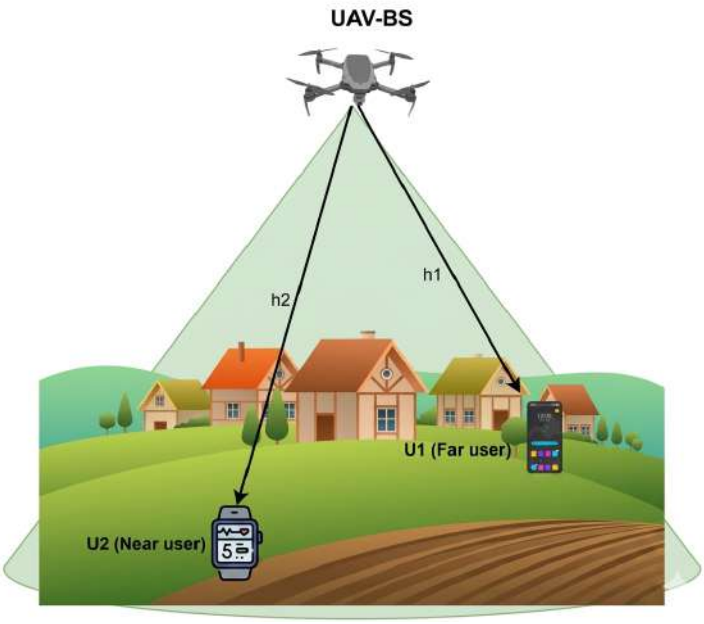

Figure 4.1: UAV-assisted NOMA downlink system model.

4.2.1 Channel Model

The distance between the UAV and a user is given by

$$d_i = \sqrt{H^2 + r_i^2}, \quad i = 1, 2, \tag{4.1}$$

where:

- H: the UAV altitude (m),

- r_i: the horizontal distance from the UAV to user i (m).

The mixed path loss for LoS and NLoS is expressed as

$$L_{\text{MIX}} = P_{\text{LoS}} L_{\text{LOS}} + P_{\text{NLoS}} L_{\text{NLOS}}, \tag{4.2}$$

with

$$L_{\text{LOS}} = \rho_L \eta_L d^{-\alpha_L}, \quad L_{\text{NLOS}} = \rho_{\text{NL}} \eta_{\text{NL}} d^{-\alpha_{\text{NL}}}. \tag{4.3}$$

where:

- ρ_L, ρ_{NL}: reference path loss for LoS and NLoS,
- η_L, η_{NL}: additional attenuation factors for LoS and NLoS,
- $\alpha_L, \alpha_{\text{NL}}$: path loss exponents for LoS and NLoS,
- d: the propagation distance (m).

The LoS probability is given by

$$P_{\text{LoS}} = \frac{1}{1 + a \exp\left(-b\left(\theta - a\right)\right)}, \tag{4.4}$$

where:

- $\theta = \arctan(H/d) \times 180/\pi$: the elevation angle in degrees,
- a, b: environment-dependent constants,
- $P_{\text{NLoS}} = 1 - P_{\text{LoS}}$: the NLoS probability.

For small-scale fading, we adopt Nakagami-m fading with fading parameter $m = 2$. The probability density function of the channel gain $|h|^2$ is

$$f_{|h|^2}(x) = \frac{m^m x^{m-1}}{\Gamma(m)} e^{-mx}, \quad x \geq 0. \tag{4.5}$$

where:

- m: the Nakagami fading parameter,
- $|h|^2$: the channel power gain,
- $\Gamma(m)$: the Gamma function.

4.2.2 NOMA Transmission Protocol

The transmitted signal is

$$x = \sqrt{P_t}\left(\sqrt{\alpha_1} x_1 + \sqrt{\alpha_2} x_2\right), \tag{4.6}$$

where:

- P_t: the total transmit power (W),
- α_1, α_2: the power allocation coefficients for users 1 and 2,

- x_1, x_2: the modulated signals of users 1 and 2.

The received signal at user i is

$$y_i = h_i x + w_i, \quad i = 1, 2, \tag{4.7}$$

where:

- h_i: the channel coefficient for user i,
- w_i: additive white Gaussian noise (AWGN) with variance σ^2.

4.2.3 SINR, Capacity, and Outage

The SINR at the far user (which treats the near user's signal as interference) is

$$\mathrm{SINR}_1 = \frac{\alpha_1 \gamma |h_1|^2}{\alpha_2 \gamma |h_1|^2 + 1}. \tag{4.8}$$

The near user performs perfect SIC to remove the far user's signal. So, the $SINR$ of near user is given by

$$\mathrm{SINR}_2 = \alpha_2 \gamma |h_2|^2. \tag{4.9}$$

where:

- α_1, α_2: power allocation coefficients,
- $\gamma = P_t/\sigma^2$: the transmit SNR,
- $|h_i|^2$: the channel power gain for user i.

The achievable capacity for user i is

$$C_i = \frac{1}{2} \log_2 (1 + \mathrm{SINR}_i), \quad i = 1, 2. \tag{4.10}$$

Outage occurs when $C_i < R_t$, with target rate R_t. The outage probability is

$$P_{\mathrm{out},i} = \Pr (C_i < R_t), \quad i = 1, 2. \tag{4.11}$$

4.3 Simulation Results and Discussion

The simulation parameters are summarized in Table 4.1.

Table 4.1: Simulation parameters

Parameter	**Value**	**Parameter**	**Value**
Height of UAV H	100 m	Noise power σ^2	10^{-3}
Far user horizontal distance	$\approx$ 286 m	Power allocation (far/near)	$\alpha_1 = 0.8, \ \alpha_2 = 0.2$
Near user horizontal distance	$\approx$ 135 m	Target rate R_t	0.5 bps/Hz
Path loss exponent α	2	Number of channel realizations	10^6
Nakagami fading parameter m	2	LoS probability parameters a, b	9.61, 0.16

4.3.1 Basic Performance Comparison

We evaluate the fundamental performance of the proposed UAV-NOMA system compared to conventional OMA under standard parameters. We analyze the system across three primary metrics: Bit Error Rate (BER), Outage Probability, and Capacity.

- **Bit Error Rate (BER)**

BER is a key metric used to evaluate the reliability of a transmission system. It is defined as the ratio of erroneous bits to the total number of transmitted bits:

$$\text{BER} = \frac{\text{Number of erroneous bits}}{\text{Total number of transmitted bits}} \tag{4.12}$$

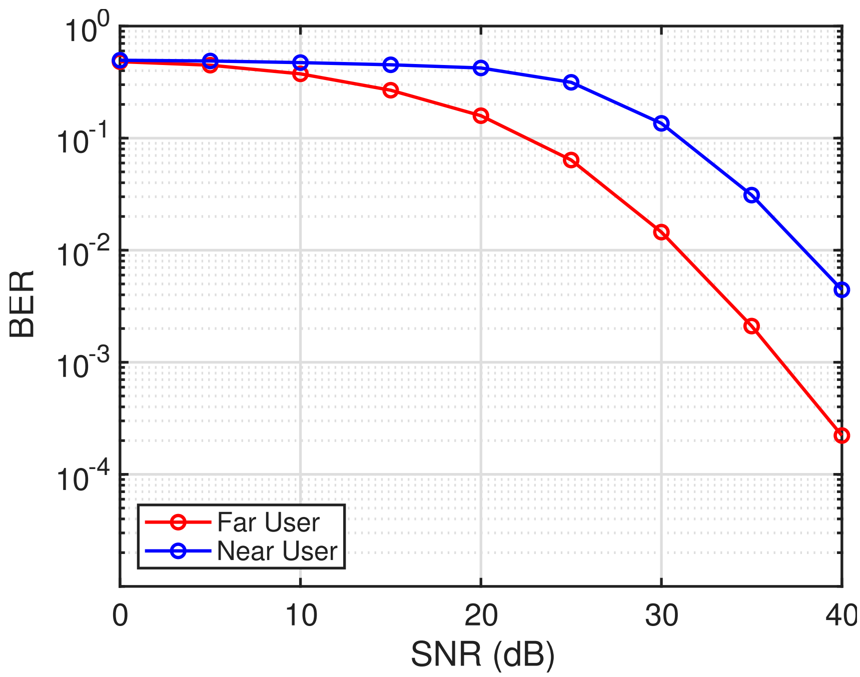

Figure 4.2: BER of NOMA users versus SNR

Figure 4.2 shows BER of NOMA users versus SNR. We observe that the far user consistently achieves a lower BER than the near user across the entire SNR range. Both curves start near 0.5 at 0 dB, then the far user declines much faster: it reaches about 2.5×10^{-4} at 40 dB, whereas the near user only reaches 4×10^{-3}. This difference can be explained by the power allocation strategy — the far user receives 80% of the total power ($\alpha_1 = 0.8$) to compensate for its larger path loss, while the near user operates with only 20% ($\alpha_2 = 0.2$) and also suffers from residual interference after SIC.

The system BER gives an overall view of the error performance of the entire system regardless of individual users.

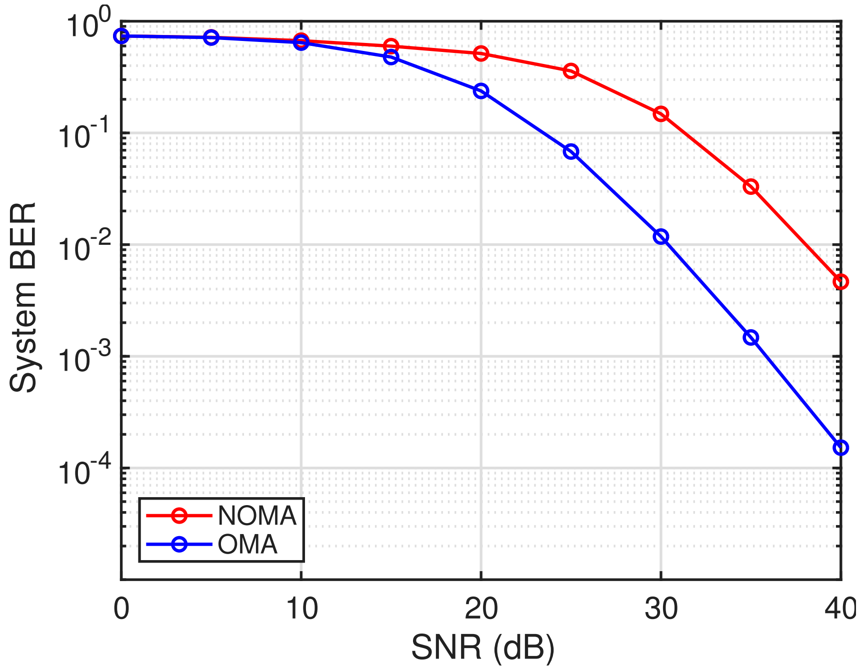

Figure 4.3: System BER comparison between NOMA and OMA

Figure 4.3 shows the system BER of NOMA and OMA versus SNR. We note that OMA achieves a much lower BER than NOMA across the whole SNR range, with the gap growing at high SNR. Both curves start near 0.7 at 0 dB; at 40 dB, OMA reaches about 1.5×10^{-4}, while NOMA only reaches 4×10^{-3}. This is because each user in OMA gets its own separate channel with no interference from other users, while in NOMA the near user always has some residual interference after SIC that prevents the BER from dropping as fast.

- **Outage Probability**

Outage probability is defined as the probability that the channel capacity falls below a required transmission rate. For user 1, the outage probability is given by:

$$P_{\text{out}}^{U1} = P(C_{U1} < R_1) \tag{4.13}$$

where C_{U1} is the achievable capacity of user 1, and R_1 is the target data rate for user 1.

For user 2, outage occurs when both users cannot be decoded successfully:

$$P_{\text{out}}^{U2} = P(C_{U2} < R_2) \tag{4.14}$$

where C_{U2} is the achievable capacity of user 2, and R_2 is the target data rate for user 2.

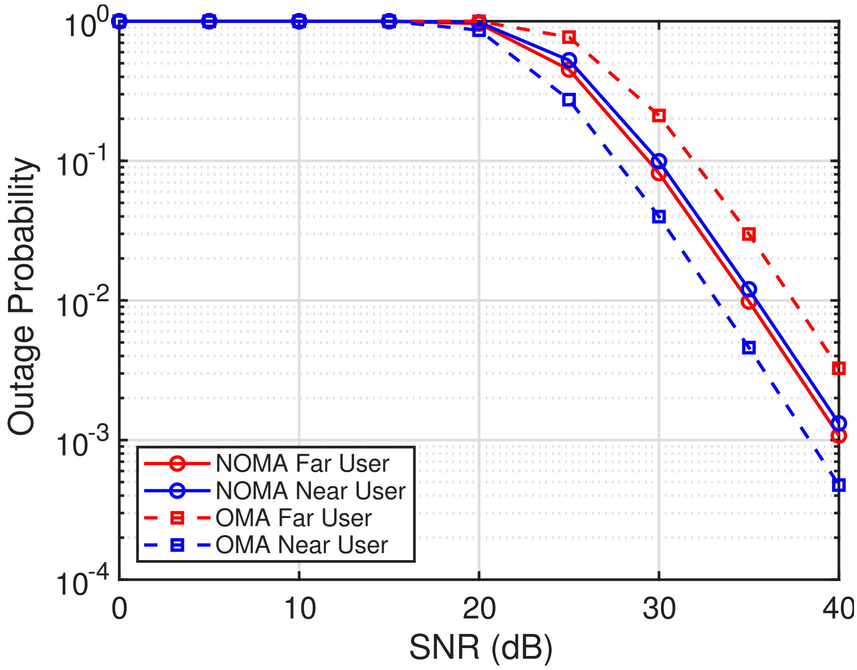

Figure 4.4: User outage probability for NOMA and OMA

Figure 4.4 illustrates the outage probability of the far user (U1) and the near user (U2) for both NOMA and OMA versus SNR. It can be seen that both NOMA users (solid curves) perform nearly the same and achieve lower outage than their OMA counterparts (dashed curves) at high SNR. All curves stay at 1 below 20 dB; at 40 dB, both NOMA users reach about 10^{-3}, the OMA near user reaches 5×10^{-4}, and the OMA far user only reaches 3×10^{-3}. The similar performance of the two NOMA users shows that the power allocation successfully balances reliability between them, while the gap between OMA users shows that OMA naturally favors the near user and leaves the far user at a disadvantage.

Figure 4.5 depicts the system outage probability of NOMA and OMA versus SNR. We observe that both systems stay in full outage below 20 dB, after which NOMA drops faster than OMA. At 40 dB, NOMA reaches about 2×10^{-3}, while OMA reaches about 4×10^{-3}. This is because NOMA gives more power to the far user, which helps it reach the required data rate threshold at a lower SNR than OMA, making NOMA better at keeping cell-edge users connected.

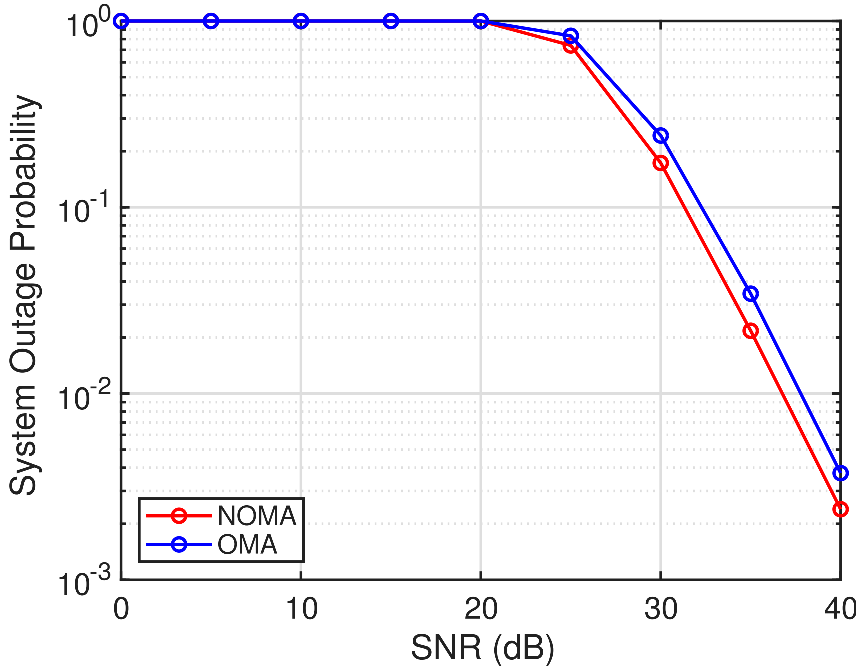

Figure 4.5: System outage probability comparison between NOMA and OMA

- **System Capacity**

Capacity is the maximum rate at which information can be transmitted reliably over a channel. For the downlink cooperative NOMA system, the capacities of U1 and U2 are given by:

$$C_{U1} = \log_2(1 + \gamma_1 U_1) \tag{4.15}$$

$$C_{U2} = \log_2(1 + \gamma_2 U_2) \tag{4.16}$$

where γ_1, γ_2 are the SINR at users 1 and 2, and U_1, U_2 are the effective channel gains for users 1 and 2.

Figure 4.6 displays the individual user capacity of NOMA and OMA versus SNR for the far user (U1) and the near user (U2). We remark that the NOMA near user achieves the highest capacity among all four curves, while the NOMA far user gives the lowest. All curves start near zero at 0 dB; at 40 dB, the NOMA near user reaches about 2.4 bits/s/Hz, the NOMA far user reaches only 1.1 bits/s/Hz, and the OMA users reach 1.75 and 1.45 bits/s/Hz for the near and far users respectively. This is because the NOMA near user, after removing the far user's signal via SIC, uses the full system bandwidth with no interference, while OMA users each get only half the bandwidth.

The sum-rate is the total capacity of both users added together:

$$C_{\text{sum}} = C_{U1} + C_{U2} \tag{4.17}$$

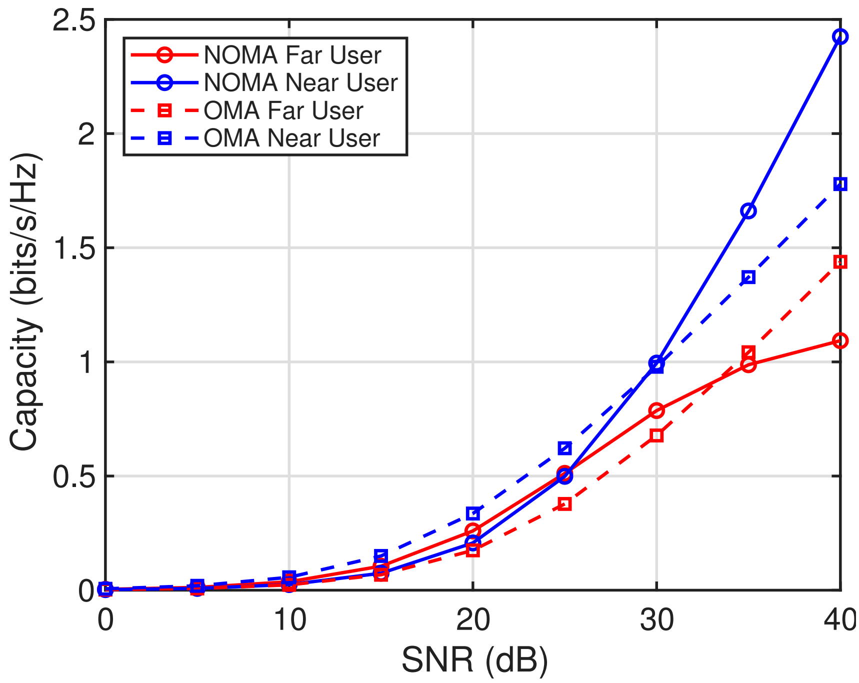

Figure 4.6: User capacity for NOMA and OMA

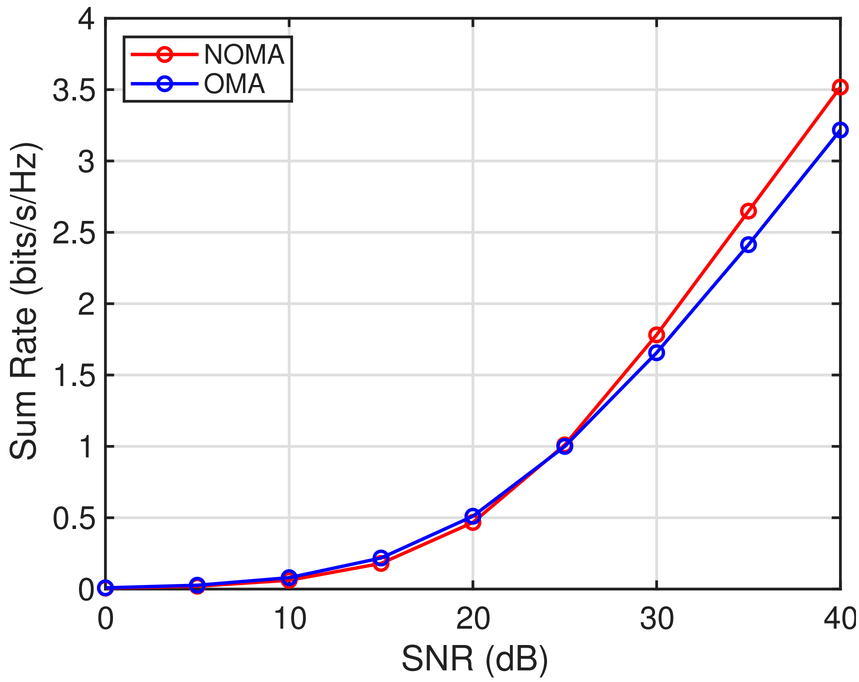

Figure 4.7: Sum-rate comparison between NOMA and OMA

Figure 4.7 shows the system sum rate of NOMA and OMA versus SNR. The results indicate that NOMA achieves a higher sum rate than OMA across the full SNR range, with the gap growing beyond 25 dB. Both curves start near zero at 0 dB and are close to each other up to 20 dB; at 40 dB, NOMA reaches about 3.5 bits/s/Hz while OMA reaches 3.2 bits/s/Hz. This is because NOMA lets all users share the same frequency band at the same time, while OMA splits the band between users and limits how much each one can achieve.

4.3.2 Impact of Modulation Order

- **Bit Error Rate (BER)**

Different modulation orders have different levels of resilience to noise and interference. Lower-order modulations like BPSK are more robust but have lower spectral efficiency.

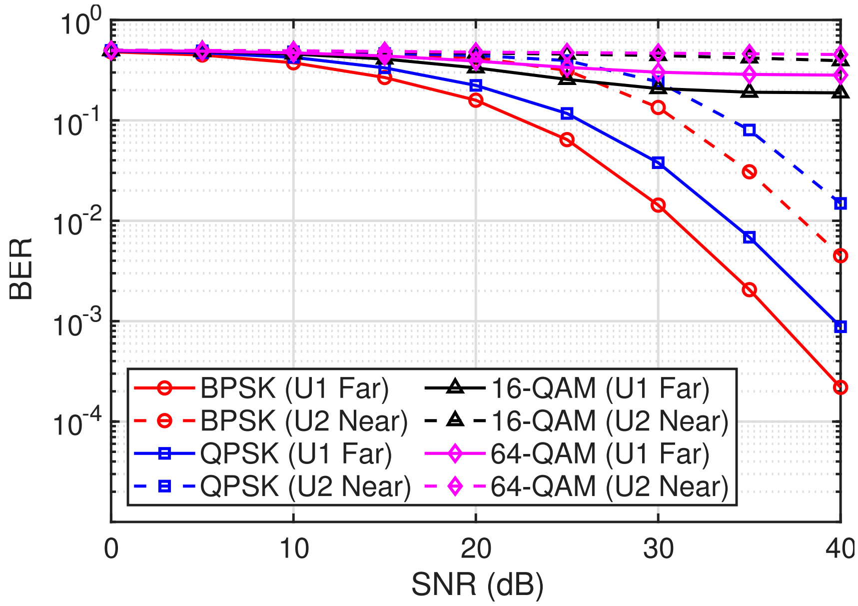

Figure 4.8: BER for different modulation orders

Figure 4.8 presents the BER of the far user (U1, solid curves) and the near user (U2, dashed curves) in NOMA versus SNR for four modulation schemes. We observe that lower-order modulations give much better BER, and that the far user always outperforms the near user under every scheme. Both users with BPSK start near 0.5 at 0 dB; at 40 dB the far user reaches about 3×10^{-4}, while the near user reaches 4×10^{-3}. In contrast, 64-QAM shows almost no improvement for the near user across the full SNR range, staying above 2×10^{-1}. This is because higher-order modulations pack more bits into each symbol, making them much more sensitive to the interference that remains after SIC in NOMA.

4.3.3 Impact of Cell Radius

- **Bit Error Rate (BER)**

The cell radius R affects the distance between the UAV and the users, which in turn affects the received signal quality.

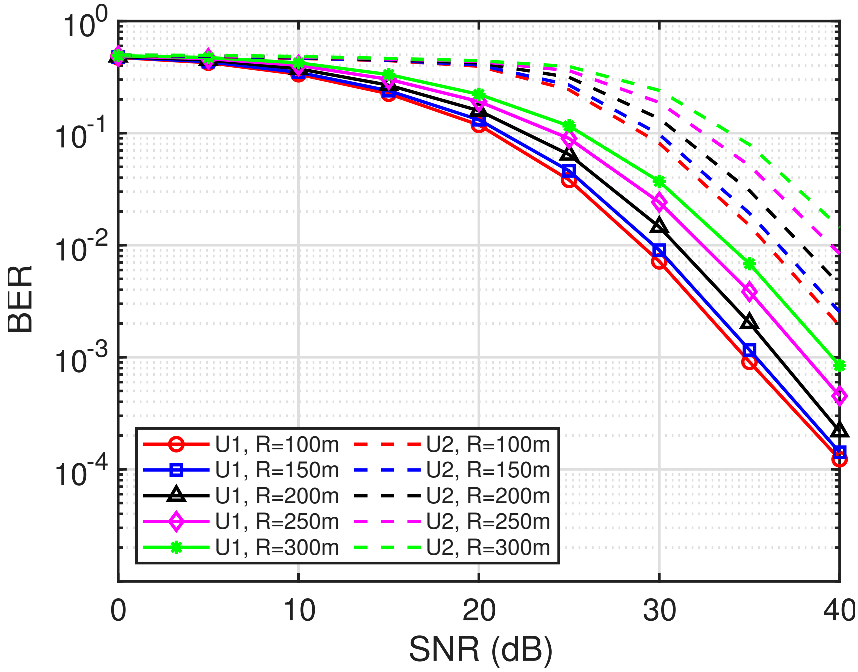

Figure 4.9: User BER under different cell radiuses

Figure 4.9 plots the BER of the far user (U1, solid curves) and the near user (U2, dashed curves) in NOMA versus SNR for cell radiuses from $R = 100\,\text{m}$ to $R = 300\,\text{m}$. It is clear that the far user always achieves lower BER than the near user at every radius, and that smaller radiuses give better results for both users. At 40 dB, the far user with $R = 100\,\text{m}$ reaches about 10^{-4}, while the near user with $R = 300\,\text{m}$ barely falls below 10^{-2}. This is because at larger radiuses the far user's signal becomes weaker, which makes SIC less effective at the near user and leaves more interference that raises its BER.

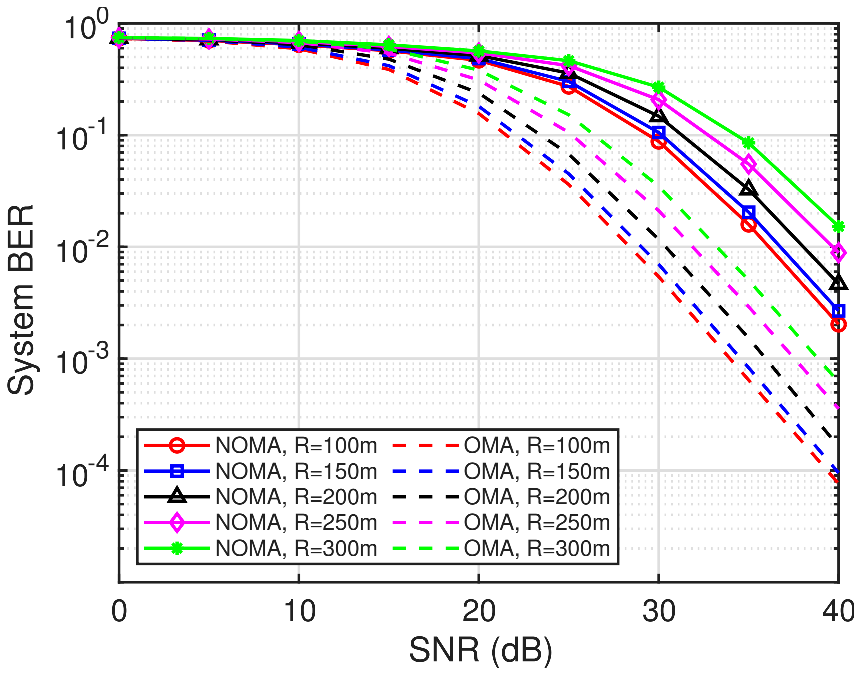

Figure 4.10: System BER under different cell radiuses

Figure 4.10 illustrates the system BER of NOMA and OMA versus SNR for cell radiuses from $R = 100\,\text{m}$ to $R = 300\,\text{m}$. We observe that OMA (dashed curves) always achieves lower BER than NOMA (solid curves), and that smaller radiuses give better results for both. All curves start near 0.7 at 0 dB; at 40 dB, OMA with $R = 100\,\text{m}$ reaches about 10^{-4}, while NOMA with $R = 300\,\text{m}$ only reaches 1.2×10^{-2}. This is because larger radiuses increase the path loss of the far user, which weakens the SIC process at the near user and leaves more interference, raising the overall system BER.

- **Outage Probability**

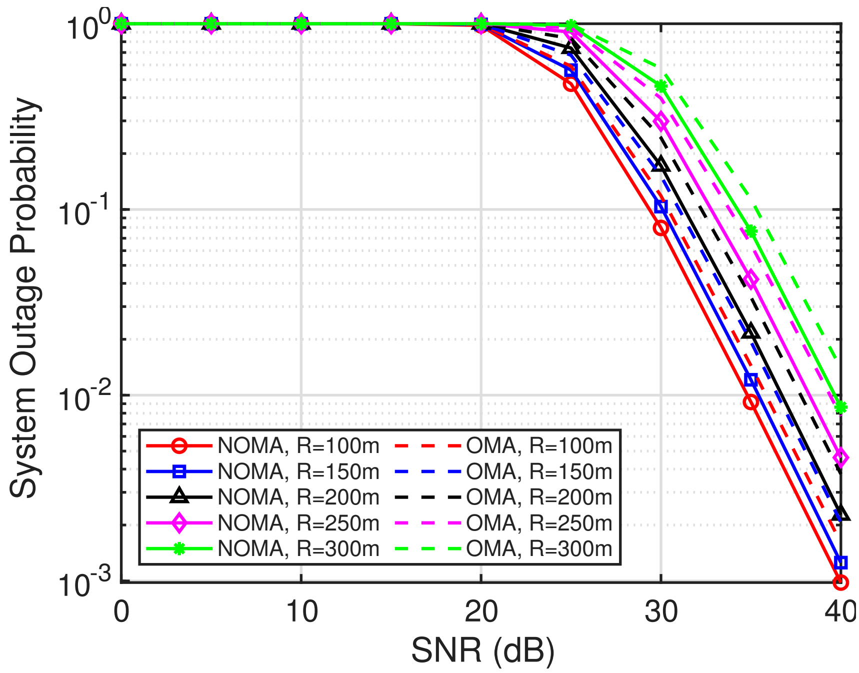

Figure 4.11: System outage under different cell radiuses

Figure 4.11 depicts the system outage probability of NOMA and OMA versus SNR for cell radiuses from $R = 100\,\text{m}$ to $R = 300\,\text{m}$. One can note that NOMA (solid curves) achieves lower outage probability than OMA (dashed curves) at every radius once SNR exceeds about 20 dB. At 40 dB, NOMA with $R = 100\,\text{m}$ reaches 10^{-3}, while OMA at the same radius reaches about 1.2×10^{-3}; at $R = 300\,\text{m}$ both systems reach near 9×10^{-3}, with NOMA still slightly better. This advantage comes from NOMA giving more power to the far user, which helps it maintain a reliable link even at larger distances where OMA would struggle.

- **System Capacity**

Figure 4.12 shows the system sum rate of NOMA and OMA versus SNR for different cell radiuses. We observe that NOMA consistently outperforms OMA across all radiuses, and that smaller radiuses give better performance for both schemes. Both families of curves start near zero at 0 dB and grow monotonically; at 40 dB, NOMA with $R = 100\,\text{m}$ reaches about 3.8 bits/s/Hz, whereas NOMA with $R = 300\,\text{m}$ reaches only 3.0 bits/s/Hz. This is because a smaller cell radius means shorter distances between the UAV and users, which reduces path loss and improves the received signal quality, while NOMA gains its extra advantage by allowing all users to share the same frequency band at the same time.

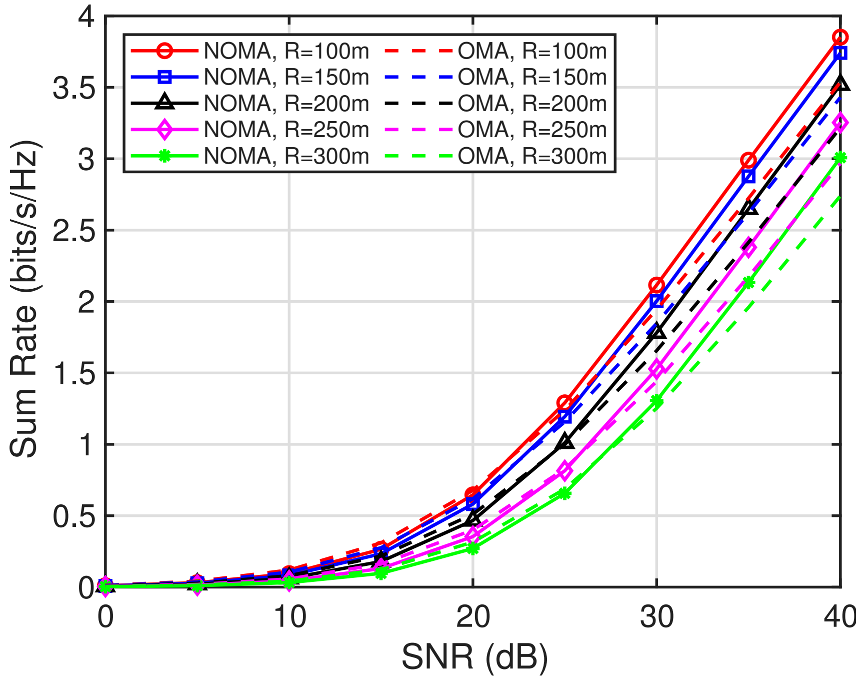

Figure 4.12: Sum-rate under different cell radiuses

- **Line-of-Sight (LoS) Probability**

Cell radius has a direct impact on line-of-sight probability. As the cell radius increases, the LoS probability decreases due to more obstacles and longer distances.

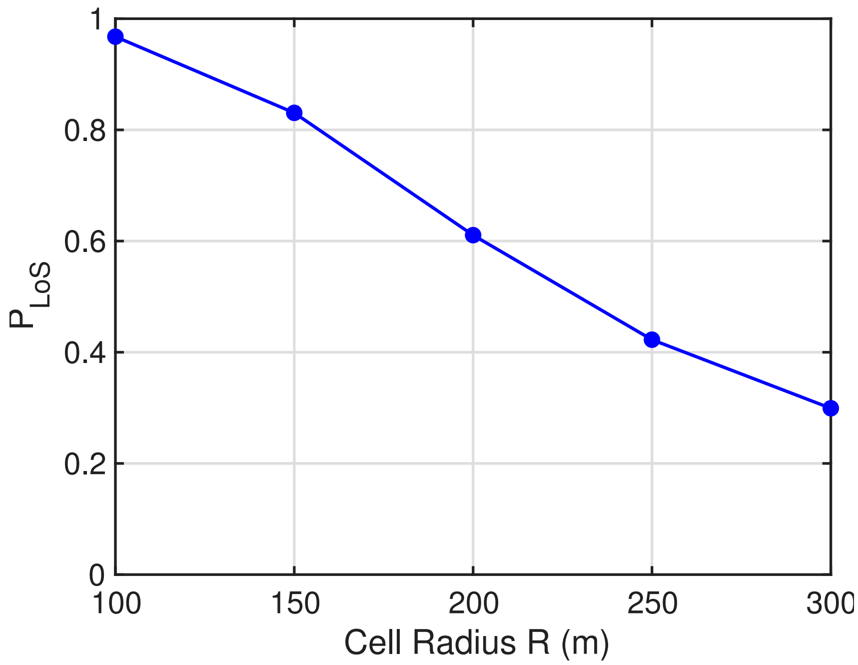

Figure 4.13: Line-of-sight probability as a function of cell radius

Figure 4.13 illustrates the Line-of-Sight probability P_{LoS} as a function of cell radius R. We remark that P_{LoS} drops steadily as the radius increases, starting at about 0.96 at $R = 100\,\text{m}$ and falling to 0.30 at $R = 300\,\text{m}$. This is because as the distance between the UAV and the ground user grows, there are more obstacles like buildings in the way that block the direct signal path, which motivates keeping the cell radius small in UAV-assisted NOMA systems to maintain good channel quality.

4.3.4 Impact of Power Allocation

- **Bit Error Rate (BER)**

Power allocation coefficients (a_1 for the far user and a_2 for the near user) determine how much of the total power is given to each user. The sum $a_1 + a_2 = 1$.

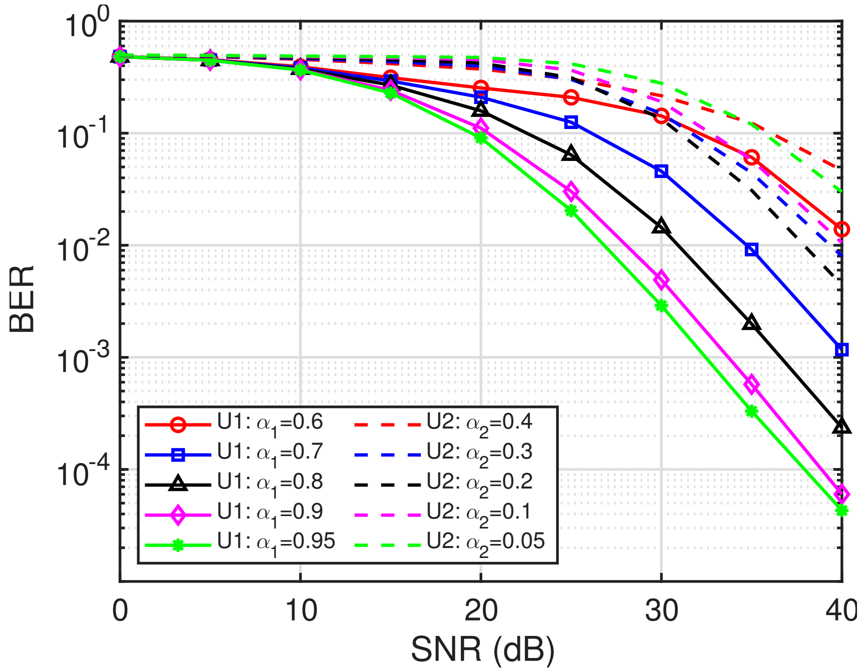

Figure 4.14: BER of both users under different power allocations

Figure 4.14 plots the BER of the far user (U1, solid curves) and the near user (U2, dashed curves) in NOMA versus SNR for five power allocation settings. We observe that giving more power to the far user improves its BER but makes the near user's BER worse, showing a clear trade-off. Both users start near 0.5 at 0 dB; at 40 dB, the far user with $\alpha_1 = 0.95$ reaches about 5×10^{-5}, while the near user with $\alpha_2 = 0.05$ stays above 5×10^{-2}. This happens because a larger α_1 boosts the far user's signal but also increases the interference that the near user must cancel via SIC, and any leftover interference directly raises the near user's BER.

Figure 4.15 shows the system BER of NOMA versus SNR for five power allocation settings, along with an OMA baseline. We note that OMA achieves the lowest BER overall, and that among NOMA cases the setting $\alpha_1 = 0.8$, $\alpha_2 = 0.2$ performs best. All curves start near 0.7 at 0 dB; at 40 dB, OMA reaches below 2×10^{-4}, the best NOMA case reaches about 4×10^{-3}, and the worst NOMA case ($\alpha_1 = 0.6$) only reaches 6×10^{-2}. This happens because NOMA always has some leftover interference between users even after SIC, which OMA avoids completely by giving each user a separate channel, and $\alpha_1 = 0.8$ is the setting that best balances the signal quality for both users.

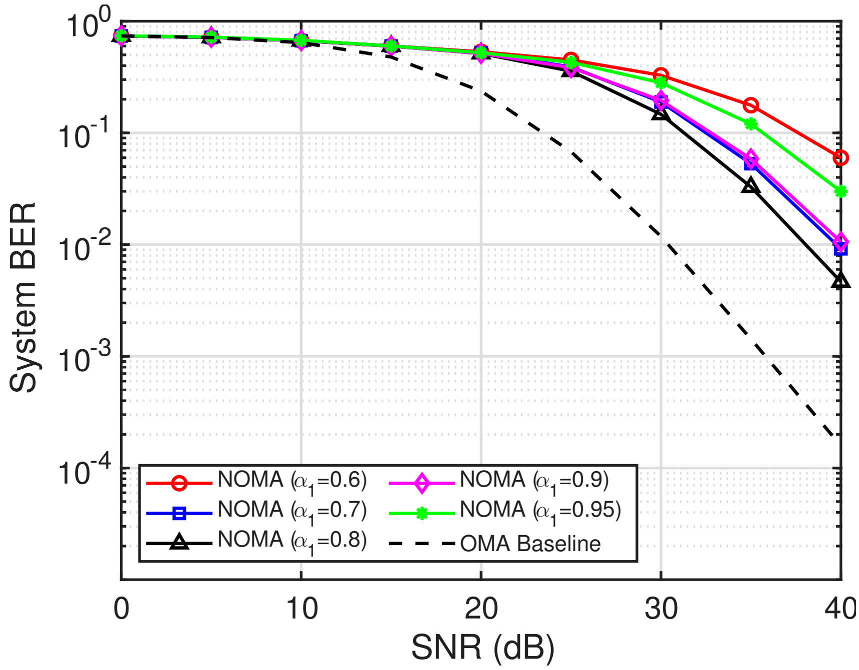

Figure 4.15: System BER under different power allocations

- **Outage Probability**

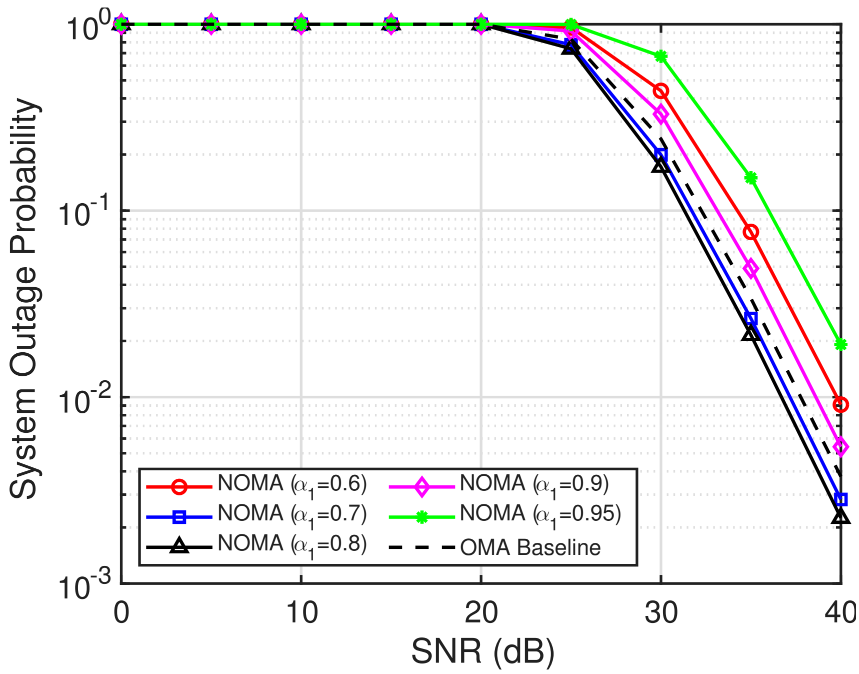

Figure 4.16: System outage under different power allocations

Figure 4.16 depicts the system outage probability of NOMA versus SNR for five power allocation settings, along with an OMA baseline. We observe that all curves stay at 1 for SNR below 20 dB, then drop at different rates. The setting $\alpha_1 = 0.8$, $\alpha_2 = 0.2$ gives the lowest outage, closely following OMA; at 40 dB it reaches about 3×10^{-3}, while the worst case $\alpha_1 = 0.95$ only reaches 2×10^{-2}. This is because giving almost all power to the far user leaves the near user with a very weak signal, making it very likely that its data rate falls below the required threshold, which confirms that $\alpha_1 = 0.8$ is the best trade-off between the two users.

- **System Capacity**

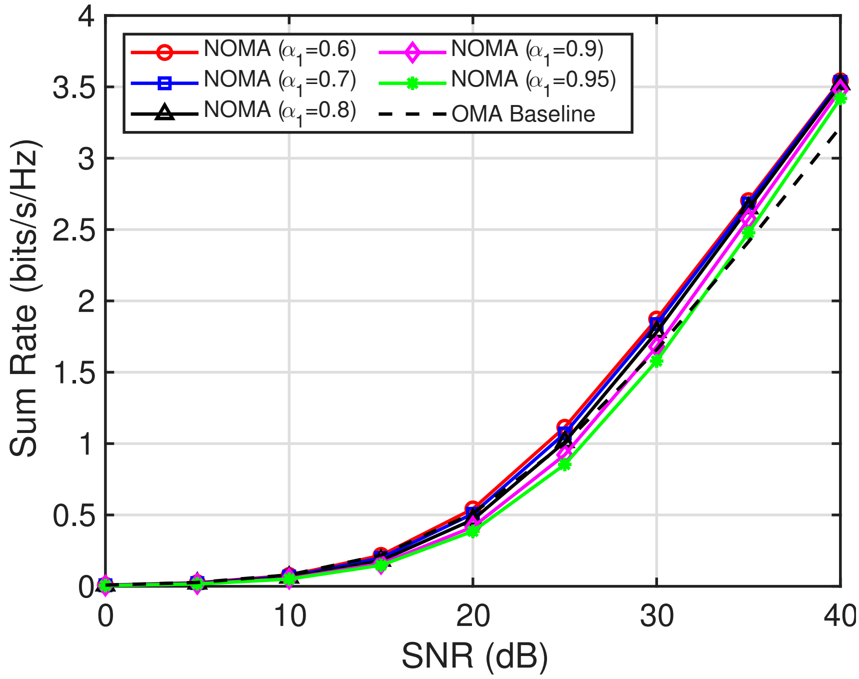

Figure 4.17: Sum-rate under different power allocations

Figure 4.17 depicts the system sum rate of NOMA versus SNR for five power allocation settings, along with an OMA baseline. As can be seen, all NOMA settings outperform OMA at high SNR, and that moderate power splits give the best results. All curves start near zero and stay close up to 20 dB; at 40 dB, the settings $\alpha_1 = 0.6$ and $\alpha_1 = 0.7$ both reach about 3.55 bits/s/Hz, while $\alpha_1 = 0.95$ gives the lowest NOMA sum rate of about 3.45 bits/s/Hz, and OMA reaches 3.2 bits/s/Hz. This is because giving almost all power to the far user greatly reduces what the near user can achieve, while a balanced split lets both users contribute well to the total system throughput.

4.3.5 Impact of Nakagami Fading Parameter

The Nakagami-m parameter dictates the severity of multipath fading, fundamentally shaping the channel's envelope distribution. So, we evaluate the system's resilience by simulating the performance under four distinct fading conditions ($m = 0.5, 1, 1.5, 2$), ranging from severe fading to strong line-of-sight propagation.

- **Bit Error Rate (BER)**

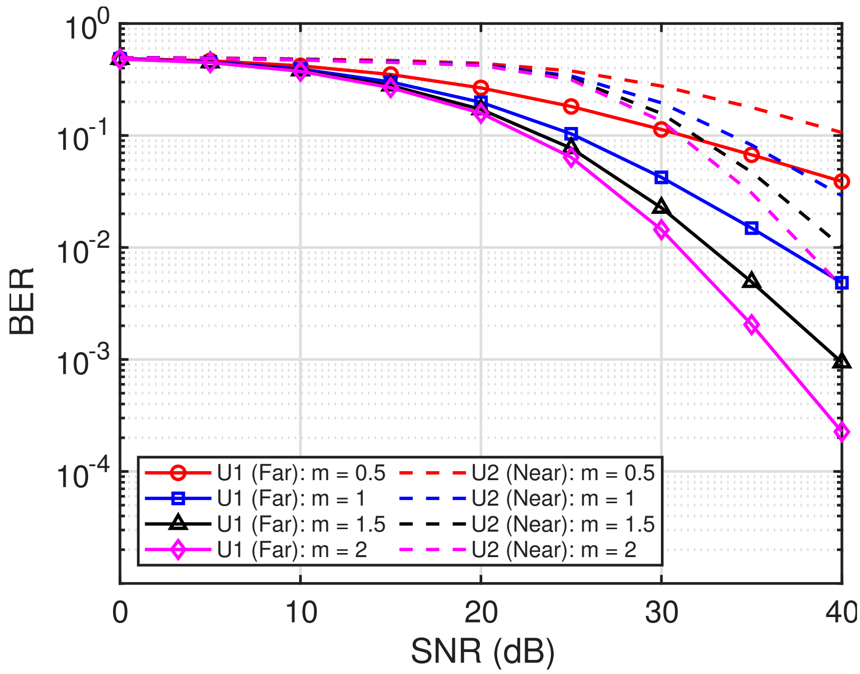

Figure 4.18: BER of both users under different Nakagami fading parameters

Figure 4.18 illustrates the BER of the far user (U1, solid lines) and near user (U2, dashed lines) versus SNR for four Nakagami-m fading parameters ($m = 0.5, 1, 1.5, 2$). We observe that higher m values yield consistently lower BER for the far user across the full SNR range, while the near user curves remain elevated and nearly flat regardless of m. All far-user curves start near 0.5 at 0 dB; at 40 dB, U1 with $m = 2$ reaches approximately 10^{-4} whereas $m = 0.5$ remains near 10^{-2}. The near user BER for all m values clusters above 0.4 throughout the sweep, showing no meaningful improvement with SNR. This is because a larger Nakagami parameter corresponds to a more deterministic channel with reduced fading severity, which raises the effective received SINR at the far user and lowers its detection error rate; the near user, however, is fundamentally limited by residual interference after SIC rather than by fading depth, making its BER insensitive to improvements in m.

Figure 4.19 shows the system BER of NOMA and OMA versus SNR for four Nakagami-m values. It can be seen that OMA achieves lower system BER than NOMA across all m values, and that both schemes improve with increasing m. All curves start near 0.7 at 0 dB; at 40 dB, OMA with $m = 2$ reaches approximately 2×10^{-4} while NOMA $m = 2$ sits near 4×10^{-3}, and OMA $m = 0.5$ reaches about 2×10^{-3} versus NOMA $m = 0.5$ at roughly 10^{-2}. This is because system BER in NOMA is dominated by the near user's residual SIC interference floor, which persists regardless of fading parameter improvements, whereas OMA assigns each user an interference-free dedicated resource, allowing both users to translate the channel quality gain from higher m directly into BER reduction.

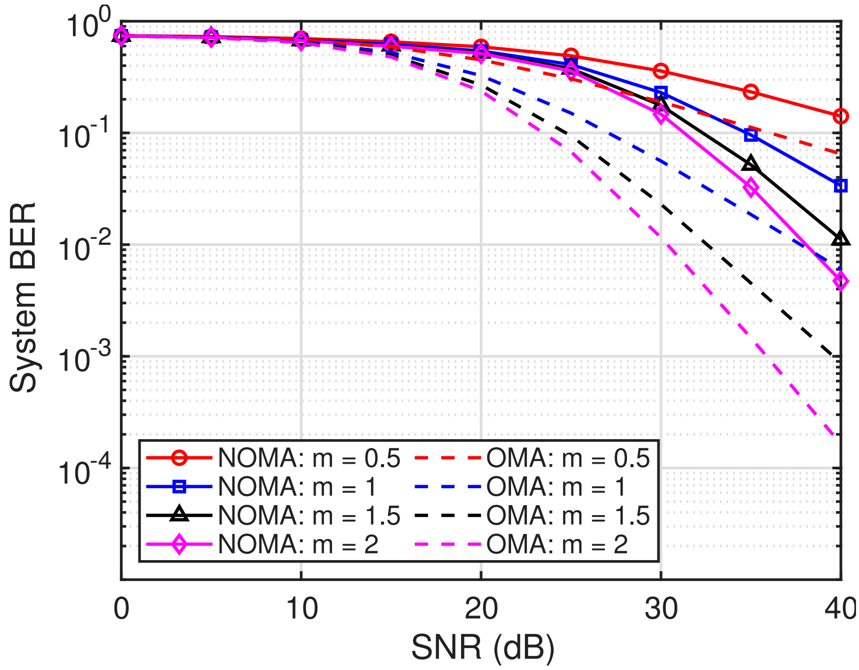

Figure 4.19: System BER under different Nakagami fading parameters

- **Outage Probability**

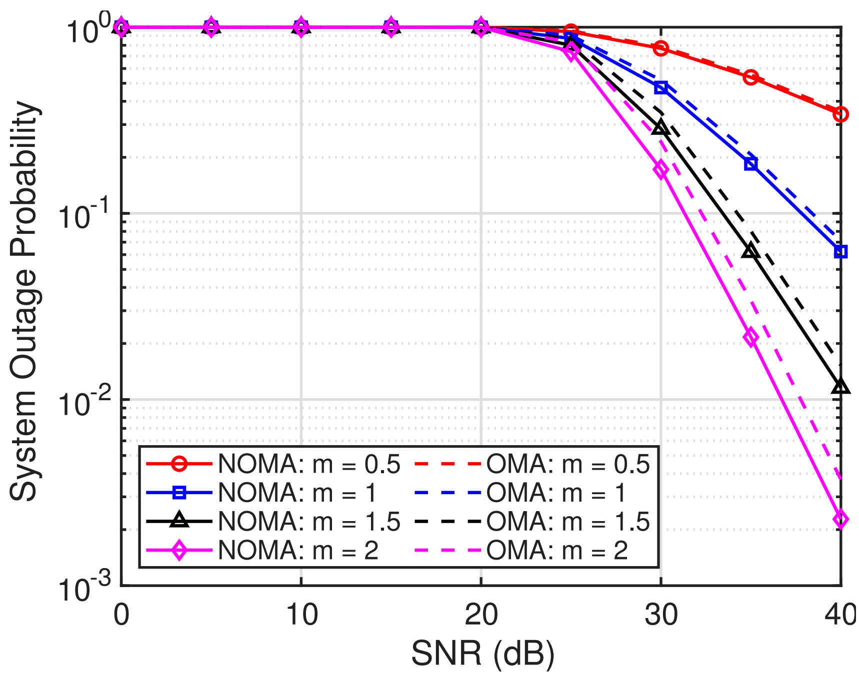

Figure 4.20: System outage under different Nakagami fading parameters

Figure 4.20 illustrates the system outage probability of NOMA and OMA versus SNR for four Nakagami-m values. We remark that NOMA achieves lower outage probability than OMA across all m values, and that higher m accelerates the outage decline. All curves remain near unity up to approximately 10 dB, then drop steeply; at 30 dB, NOMA with $m = 2$ reaches approximately 10^{-2} while OMA $m = 2$ sits near 4×10^{-2}, and at the same SNR NOMA $m = 0.5$ reaches about 8×10^{-2} compared to OMA $m = 0.5$ at roughly

2×10^{-1}. This is because a larger m parameter concentrates the fading distribution around its mean, reducing the probability that instantaneous channel realizations fall below the target rate threshold; NOMA gains an additional advantage by power-domaining the far user, allowing it to meet its rate requirement at a lower SNR than OMA's equal resource split.

- **System Capacity**

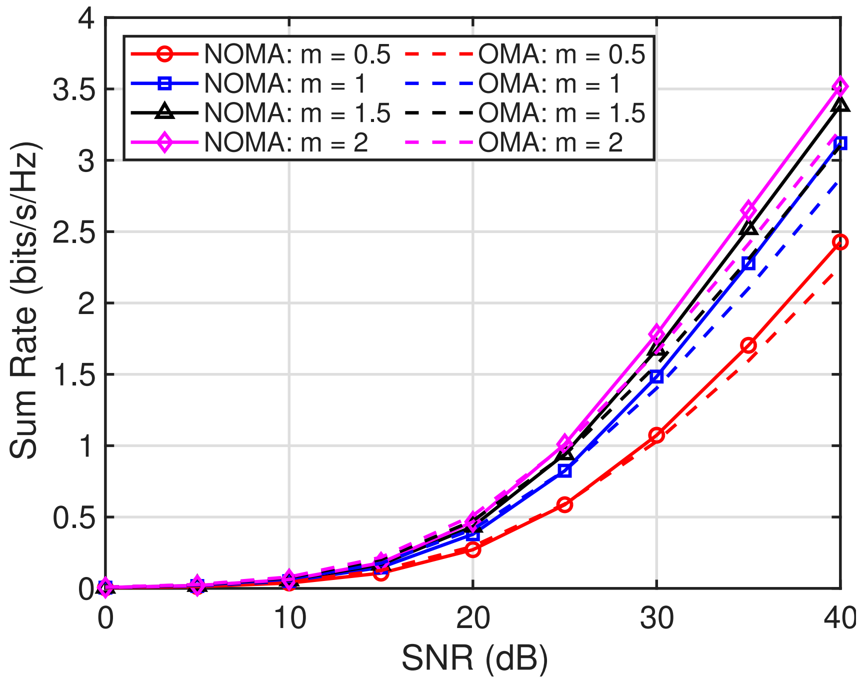

Figure 4.21: Sum-rate under different Nakagami fading parameters

Figure 4.21 shows the system sum rate of NOMA and OMA versus SNR for four Nakagami-m values. We observe that NOMA consistently outperforms OMA across all m values, and that higher m yields greater sum rate for both schemes. All curves start near zero at 0 dB and grow monotonically; at 40 dB, NOMA with $m = 2$ reaches approximately 3.8 bits/s/Hz while $m = 0.5$ reaches about 3.2 bits/s/Hz, and the corresponding OMA values are roughly 3.4 and 2.8 bits/s/Hz respectively. This is because a higher Nakagami-m parameter reduces channel randomness and raises the average received SNR for both users simultaneously, allowing each NOMA layer to contribute more to aggregate throughput, while NOMA retains its spectral efficiency advantage over OMA by enabling simultaneous user access on the same frequency band.

4.3.6 Impact of UAV Altitude

The operating altitude of the UAV plays a critical role in establishing reliable air-to-ground communication links by balancing line-of-sight probability against distance-based path loss. Therefore, we investigate this geometric trade-off by comparing the system performance across five different UAV altitudes ranging from 50 m to 500 m.

- **Bit Error Rate (BER)**

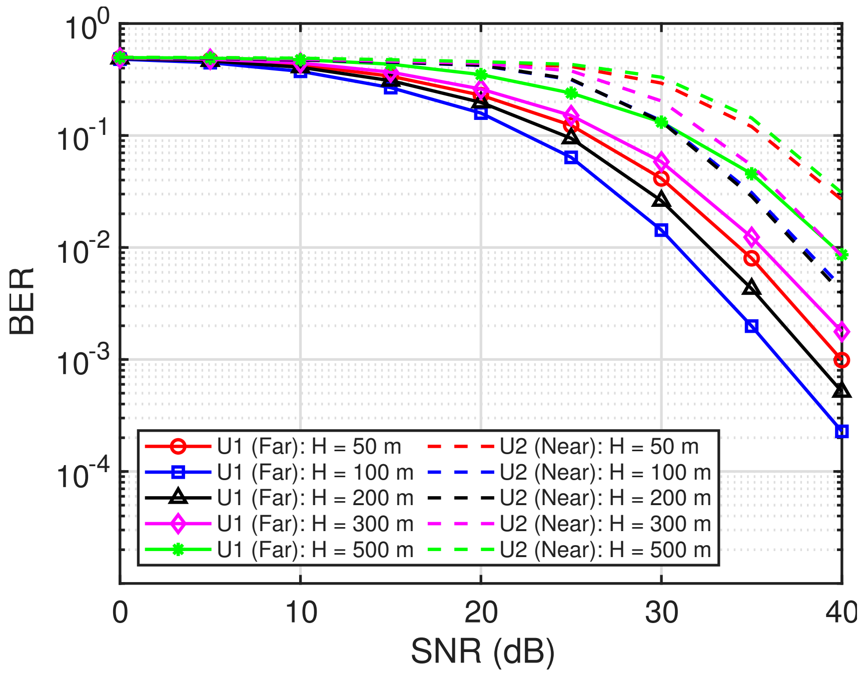

Figure 4.22: BER of both users under different UAV altitudes

Figure 4.22 presents the individual BER of the far user (U1) and near user (U2) versus SNR for five UAV altitudes ($H = 50, 100, 200, 300, 500\,\text{m}$). We observe that lower altitudes yield better BER performance for the far user, with $H = 50\,\text{m}$ achieving the steepest decline, while the near user remains near 0.5 and essentially insensitive to altitude across the entire SNR range. At 40 dB, U1 with $H = 50\,\text{m}$ reaches approximately 3×10^{-4} while $H = 500\,\text{m}$ sits near 5×10^{-2}, and all near user dashed curves remain clustered above 0.4. This is because reducing the UAV altitude shortens the 3D slant distance to the far user, which lowers path loss and raises the received SINR; the near user's BER, by contrast, is governed by SIC residual interference and is therefore unresponsive to altitude changes.

Figure 4.23 displays the system BER of NOMA and OMA versus SNR for five UAV altitudes. We note that OMA achieves lower system BER than NOMA at all altitudes, and that lower UAV altitudes benefit OMA more than NOMA. At 40 dB, OMA with $H = 50\,\text{m}$ reaches approximately 5×10^{-4} while NOMA $H = 50\,\text{m}$ sits near 6×10^{-3}, and OMA $H = 500\,\text{m}$ reaches about 10^{-2} versus NOMA $H = 500\,\text{m}$ at roughly 4×10^{-2}. This is because OMA users each occupy interference-free dedicated resources, so the path-loss reduction from lower altitude translates directly into BER improvement for both users; in NOMA, the near user's SIC residual interference constitutes a persistent error floor that caps the system BER improvement regardless of altitude, causing OMA's advantage to widen as altitude decreases.

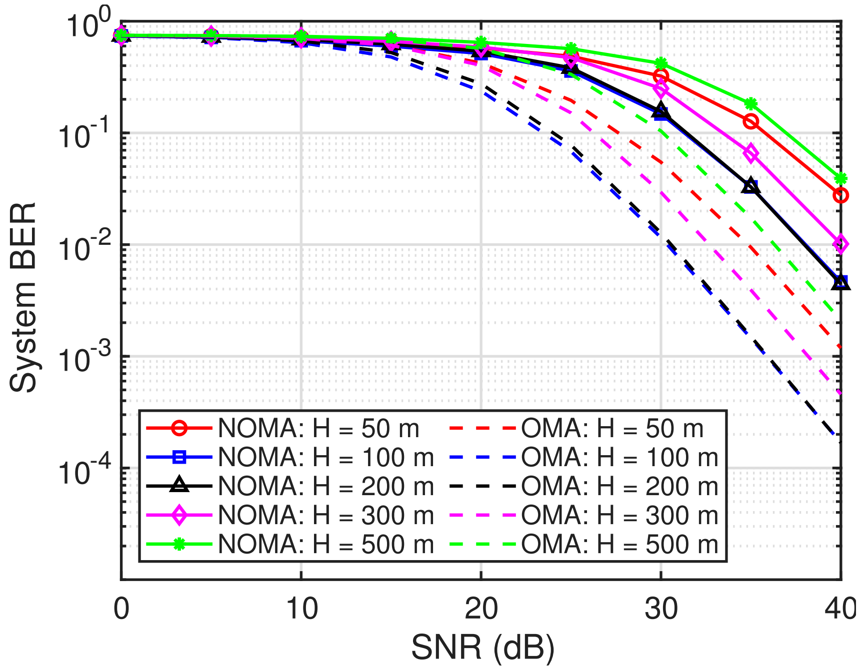

Figure 4.23: System BER under different UAV altitudes

- **Outage Probability**

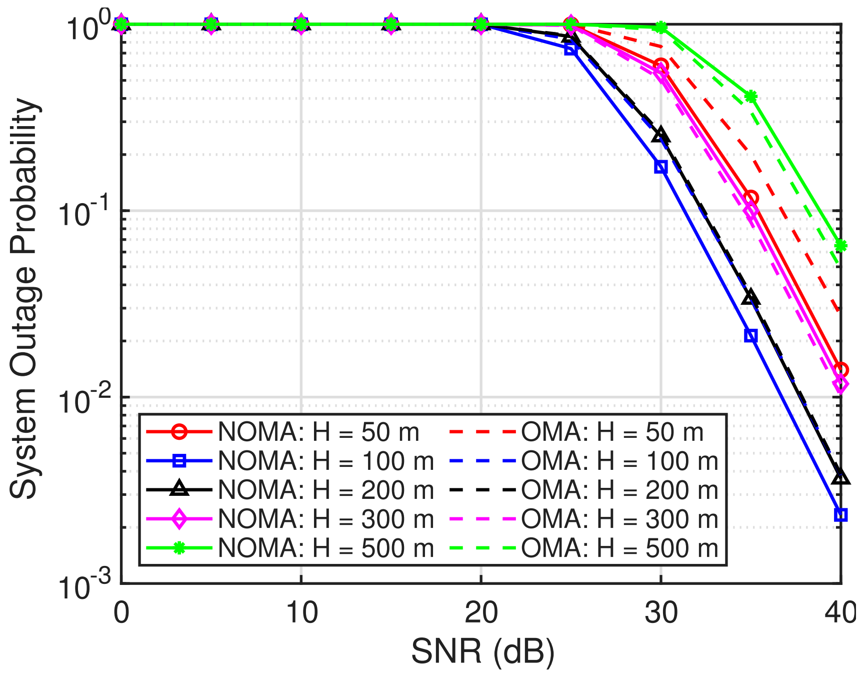

Figure 4.24: System outage under different UAV altitudes

Figure 4.24 depicts the system outage probability of NOMA and OMA versus SNR for five UAV altitudes. We observe that NOMA achieves lower outage probability than OMA across all altitudes, and that lower altitudes produce a steeper and earlier outage decline. All curves stay near unity below 10 dB then fall sharply; at 30 dB, NOMA with $H = 50\,\text{m}$ reaches approximately 8×10^{-3} while OMA $H = 50\,\text{m}$ sits near 3×10^{-2}, and NOMA $H = 500\,\text{m}$ reaches about 0.15 versus OMA $H = 500\,\text{m}$ at roughly 0.3 at the same SNR. This is because a lower UAV altitude reduces path loss and raises the instantaneous channel capacity above the target rate threshold for both users at a lower transmit SNR, causing an earlier and steeper outage probability collapse; NOMA's power allocation strategy further ensures the far user meets its rate requirement at a lower SNR than the equal-split OMA baseline.

- **System Capacity**

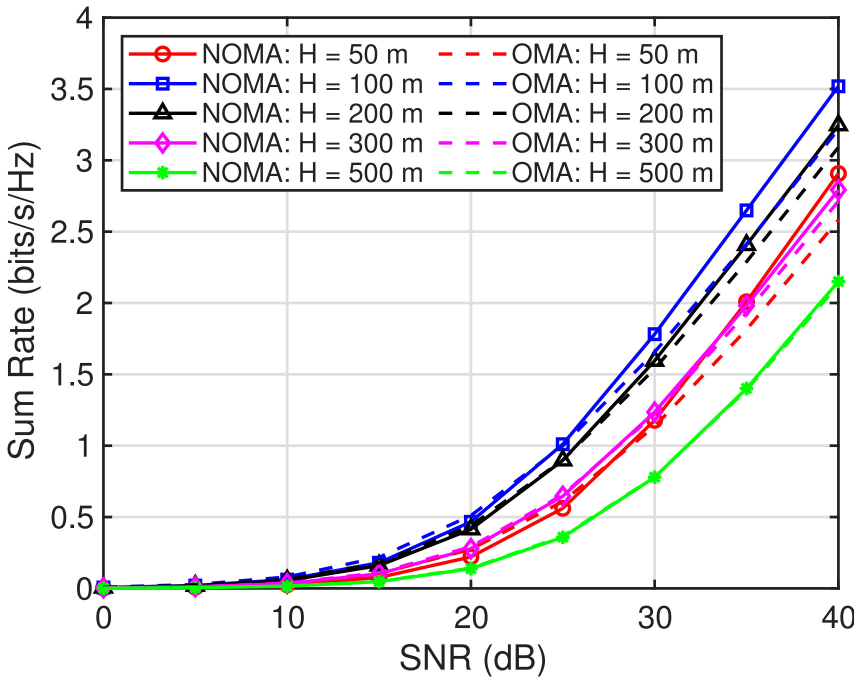

Figure 4.25: Sum-rate under different UAV altitudes

Figure 4.25 shows the system sum rate of NOMA and OMA versus SNR for five UAV altitudes. It is clear that NOMA consistently outperforms OMA at all altitudes, and that lower altitudes yield higher sum rate for both schemes. All curves begin near zero at 0 dB; at 40 dB, NOMA with $H = 50\,\text{m}$ reaches approximately 3.8 bits/s/Hz while $H = 500\,\text{m}$ achieves only about 1.8 bits/s/Hz, and the corresponding OMA values are roughly 3.3 and 1.4 bits/s/Hz respectively. This is because a lower UAV altitude reduces the slant-range path loss for both users simultaneously, increasing the effective received SNR and allowing each NOMA layer to contribute more spectral efficiency; NOMA retains its advantage over OMA at all altitudes by exploiting power-domain multiplexing on a shared frequency resource.

4.3.7 Impact of Environment

Different propagation environments inherently possess varying densities of physical obstacles, directly affecting the likelihood of signal blockage and attenuation. To understand the system's adaptability, we simulate and compare the performance across four distinct environmental profiles: Rural, Suburban, Urban, and Dense Urban.

- **Bit Error Rate (BER)**

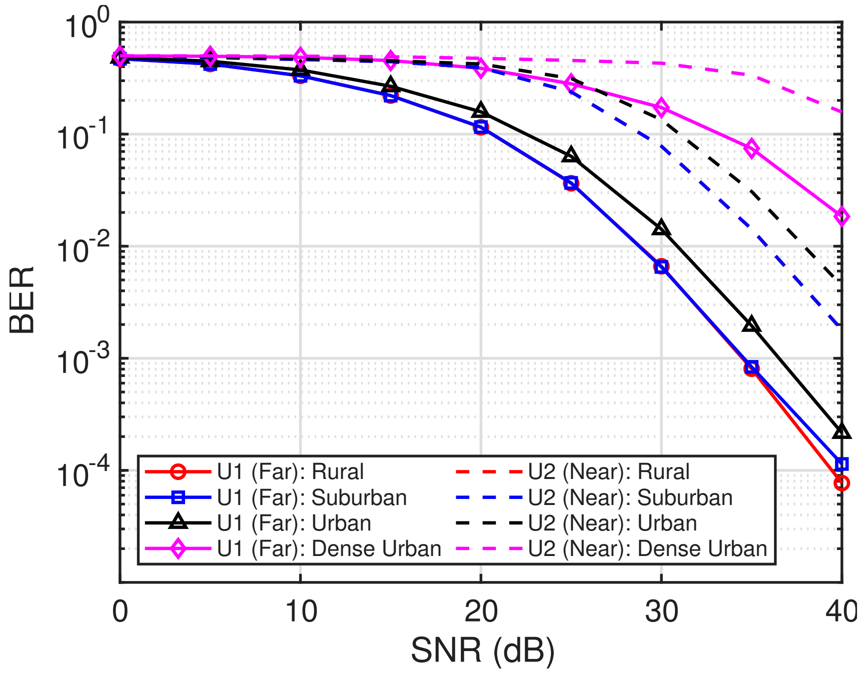

Figure 4.26: BER of both users under different environments

Figure 4.26 shows the individual BER of the far user (U1) and near user (U2) versus SNR for four propagation environments: Rural, Suburban, Urban, and Dense Urban. We observe that open environments yield significantly better performance for both users, while Dense Urban severely degrades the far user and leaves the near user at a near-constant error floor. At 40 dB, U1 in Rural reaches approximately 8×10^{-4} and Suburban about 2×10^{-3}, while Urban sits near 3×10^{-3}, and Dense Urban U1 remains above 0.08; all near user dashed curves cluster above 0.1 for Rural and Suburban but barely improve for Urban and Dense Urban. This is because open environments provide a high LoS probability between the UAV and ground users, substantially reducing effective path loss and enabling a strong channel quality differential between U1 and U2 that NOMA can exploit; in Dense Urban settings, persistent building blockage collapses the LoS probability, compresses the inter-user channel gap, and degrades the SIC cancellation quality, leaving both users with poor SINR.

Figure 4.27 illustrates the system BER of NOMA and OMA versus SNR for four propagation environments. We observe that OMA achieves lower system BER than NOMA in all environments, and that both schemes degrade substantially in Dense Urban conditions. At 40 dB, OMA Rural reaches approximately 5×10^{-5} and OMA Suburban about 2×10^{-4}, while NOMA Rural sits near 10^{-3} and NOMA Suburban near 4×10^{-3}; Urban OMA reaches roughly 8×10^{-4} versus Urban NOMA at about 2×10^{-2}, and Dense Urban keeps both schemes above 0.3 throughout. This is because OMA's interference-free resource allocation allows each user to benefit directly from the channel quality improvement offered by open propagation, while NOMA's system BER is limited by the near user's SIC residual interference floor, which is exacerbated in environments where poor LoS probability weakens the inter-user channel contrast and degrades cancellation accuracy.

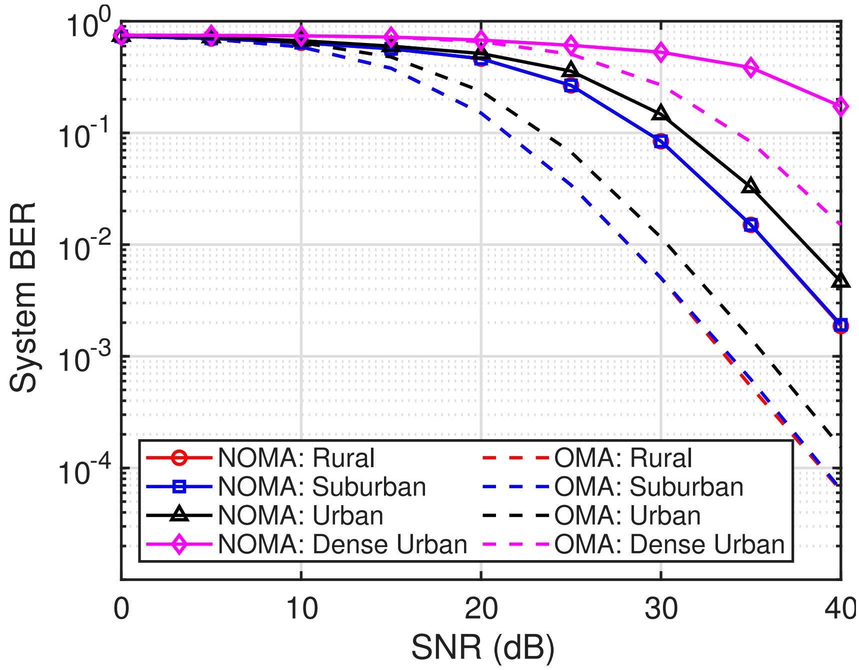

Figure 4.27: System BER under different environments

- **Outage Probability**

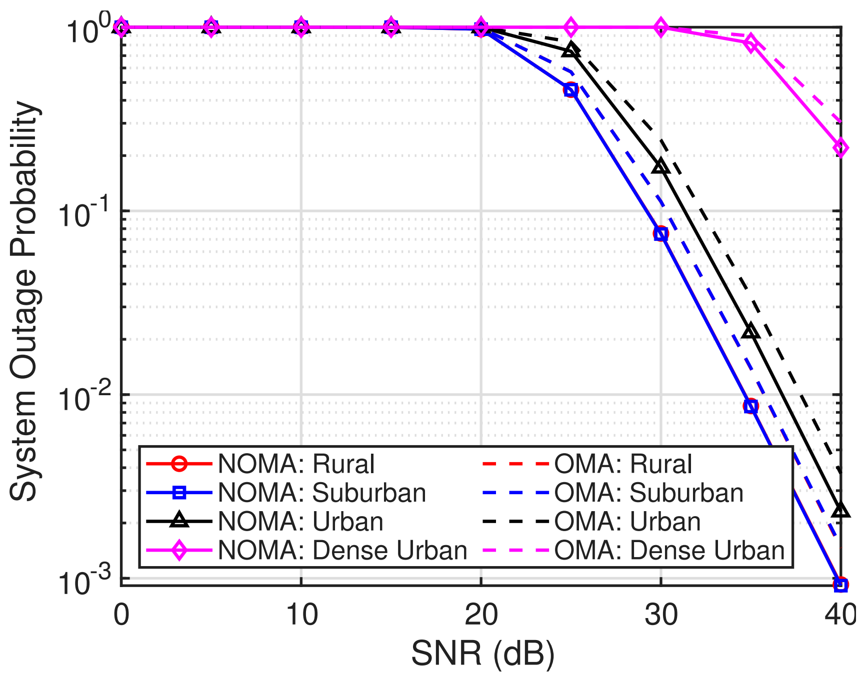

Figure 4.28: System outage under different environments

Figure 4.28 depicts the system outage probability of NOMA and OMA versus SNR for four propagation environments. The results show that NOMA achieves lower outage probability than OMA in all environments that show meaningful improvement, and that Dense Urban maintains near-unity outage for both schemes across the full SNR range. Rural and Suburban curves begin falling steeply after approximately 15 dB; at 30 dB, NOMA Rural and Suburban both reach approximately 5×10^{-3} while their

OMA counterparts sit near 2×10^{-2}, and Urban NOMA reaches roughly 8×10^{-2} versus Urban OMA at about 0.2. This is because high LoS probability in open environments raises the instantaneous channel capacity above the rate threshold at moderate SNR, triggering rapid outage collapse; in Dense Urban areas, severe blockage keeps the effective channel gain permanently below the threshold regardless of transmit power, resulting in a persistent outage floor near unity.

- **System Capacity**

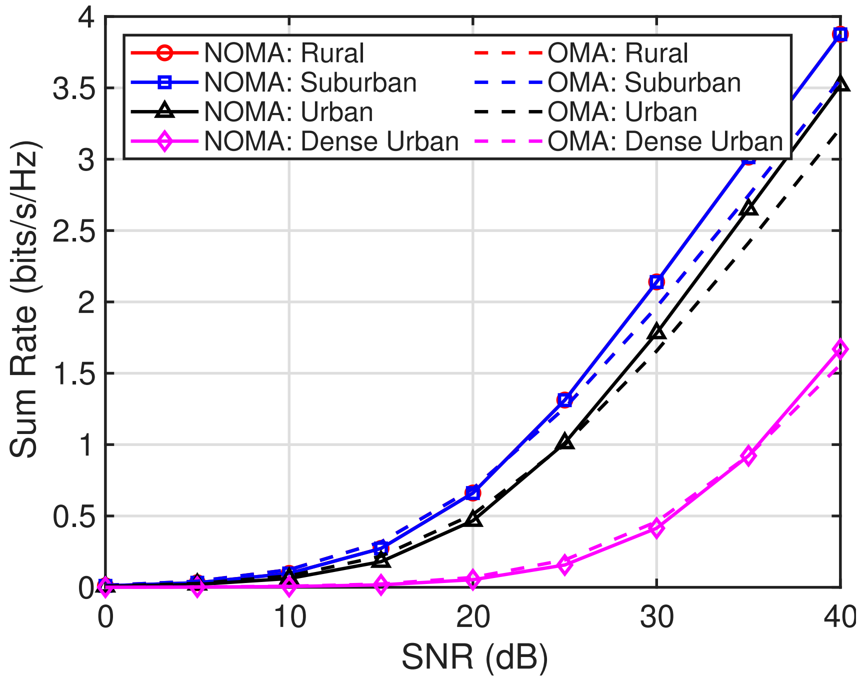

Figure 4.29: Sum-rate under different environments

Figure 4.29 displays the system sum rate of NOMA and OMA versus SNR for four propagation environments. We observe that NOMA outperforms OMA in all environments, and that the performance ordering follows Rural > Suburban > Urban > Dense Urban for both schemes. All curves begin near zero at 0 dB; at 40 dB, NOMA Rural reaches approximately 3.8 bits/s/Hz and Suburban about 3.5 bits/s/Hz, whereas Urban reaches roughly 2.8 bits/s/Hz and Dense Urban only about 1.0 bits/s/Hz, with the corresponding OMA values consistently 0.3–0.4 bits/s/Hz below their NOMA counterparts. This is because environments with high LoS probability deliver lower effective path loss and higher received SNR for both users, enabling each NOMA layer to contribute more to aggregate throughput; Dense Urban propagation severely attenuates the signal, leaving little room for NOMA's spectral efficiency gain to materialize over OMA.

4.4 Conclusion

In this chapter, we simulated a UAV-assisted downlink NOMA system and compared its performance with conventional OMA. The BER, outage probability, and system sum rate were evaluated under various conditions. The results showed that NOMA outperforms OMA in terms of outage probability and spectral efficiency. We also investigated the effect of modulation order, power allocation, cell radius, Nakagami fading parameter, UAV altitude, and propagation environments on system performance. We found that each of these parameters plays an important role in determining the overall system behavior. These results suggest that UAV-assisted NOMA is a viable and effective solution for next-generation wireless communication systems.

General Conclusion

General Conclusion

Wireless communication has come a long way. From the analog voice calls of 1G to the massive connectivity ambitions of 5G, each generation was built to solve the problems the previous one could not. Yet despite all the progress, 5G still leaves significant gaps — in coverage, in spectral efficiency, and in its ability to serve users in remote or infrastructure-poor areas. These limitations are not minor engineering details; they are fundamental constraints that push researchers toward a new paradigm, what is now being discussed as 6G.

This work was motivated by one of the more compelling combinations being explored for 6G: UAV-assisted communications paired with Non-Orthogonal Multiple Access. The reason this combination attracted attention is straightforward. UAVs can be deployed quickly, they fly above most obstacles, and they tend to maintain stronger line-of-sight links than ground-based stations. NOMA, for its part, breaks from the traditional one-resource-one-user logic of OMA by stacking multiple users on the same channel through power-domain multiplexing and successive interference cancellation. Together, they address two problems at once — coverage and capacity.

The objective of this thesis was not to prove theoretically that the combination works, but to evaluate it carefully under realistic conditions. The air-to-ground channel was modeled using the Al-Hourani probabilistic LoS framework, with Nakagami-m fading to capture the small-scale behavior of the link. Three performance metrics were examined: BER, outage probability, and sum rate. These were evaluated under varying SNR levels, different power allocation strategies, different cell sizes, and different modulation schemes — always comparing NOMA against OMA as a baseline. The analysis was further extended to investigate the influence of the Nakagami fading parameter m, the UAV operating altitude, and the propagation environment type — ranging from Rural and Suburban to Urban and Dense Urban — providing a comprehensive characterization of the system across a wide range of realistic operating conditions.

In terms of structure, the dissertation moved from the general to the specific. The first chapter reviewed the evolution of mobile networks and introduced the multiple access landscape. The second chapter covered non-terrestrial networks and their role in 6G. The third focused on UAVs — how they are classified, how their channels behave, and what roles they can play in a network. The fourth chapter brought everything together in the simulation.

The results were informative, though not entirely one-sided. NOMA clearly outperformed OMA in outage probability and sum rate. At 40 dB SNR, NOMA reached a system outage of around 2×10^{-3} compared to 4×10^{-3} for OMA, and a sum rate of approximately 3.5 bits/s/Hz versus 3.2 bits/s/Hz. This advantage comes directly from NOMA's power allocation strategy, which gives more power to the far user and keeps it connected even at distances where OMA would struggle. On BER, however, OMA performed better — each user gets its own channel, so there is no residual interference to deal with. NOMA's near user always carries some interference even after SIC, and that limits how low the BER can go. The power split $\alpha_1 = 0.8, \alpha_2 = 0.2$ consistently gave the best overall results across all three metrics. Cell radius also mattered significantly — as the radius grew from 100 m to 300 m, the LoS probability dropped from 0.96 to

0.30, and performance degraded accordingly for both schemes. Regarding the Nakagami fading parameter, higher m values reduced channel randomness and improved both outage probability and sum rate for NOMA and OMA alike, while NOMA maintained its outage advantage at every fading level. The UAV altitude analysis confirmed the expected trade-off: lower altitudes reduce path loss and improve all metrics, but NOMA's advantage in outage probability is preserved across the full altitude range from 50 m to 500 m. Finally, the environment study showed that Rural and Suburban deployments yield the best performance, while Dense Urban conditions severely degrade both schemes due to the collapse of LoS probability; NOMA nonetheless retained its sum-rate and outage superiority in every environment where meaningful improvement was observed.

In the end, the results support the conclusion that UAV-assisted NOMA is a practical and effective approach for next-generation networks. It is not a perfect solution — the near user's BER limitation and the complexity of SIC are real concerns — but the gains in outage and spectral efficiency are meaningful. Future work could look at extending this to multi-UAV deployments, incorporating RIS to improve coverage further, applying machine learning to adapt power allocation dynamically based on channel conditions, or exploring more advanced fading models and three-dimensional user distributions to capture the full complexity of real-world UAV-assisted NOMA deployments.

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