ÖZLEM SABUNCU

Enhanced Unmanned Aerial Vehicle Communication Optimization in Healthcare 5.0 via Blockchain and 5G

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DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

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May, 2025

Approval

We certify that we have read the thesis submitted by Özlem SABUNCU titled "**Enhanced Unmanned Aerial Vehicle Communication Optimization in Healthcare 5.0 via Blockchain and 5G**" and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy in Electrical and Electronic Engineering.

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Declaration of Ethical Principles

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of the Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Özlem Sabuncu

19 / 05 / 2025

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In completing this thesis, I respectfully commemorate the founder of the Republic of Turkey, Mustafa Kemal Atatürk, whose words — “Hayatta en hakiki mürşit ilimdir” (“The truest guide in life is science”) — continue to inspire all pursuits of science. Fulfilling this academic work in line with his principles is a personal achievement and a reflection of my commitment to advancing science in the service of future generations.

Özlem Sabuncu

Abstract

Enhanced Unmanned Aerial Vehicle Communication Optimization in Healthcare 5.0 via Blockchain and 5G

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Healthcare 5.0 is an innovative system designed to provide fast and effective solutions, digitalized with human-centred transformation, Internet of Things (IoT) based, Fifth Generation (5G) supported network and artificial intelligence focused big data analysis in healthcare services. In this study, an advanced communication and data management infrastructure has been developed within the framework of Healthcare 5.0. The Unmanned Aerial Vehicle (UAV) application, which uses communication infrastructure in the Healthcare 5.0 system, also establishes a holistic digital structure, and operations are carried out more intelligently, efficiently, and uninterruptedly. In this study, UAVs are no longer just carrier vehicles; they become an active decision-support element within the healthcare network. The developed 5G integrated and blockchain-based system, the cyber-physical integration with Healthcare 5.0, allows UAVs to share health-based data with peripherals securely and instantly. In particular, the high data rate and low latency features offered by 5G make it possible to realize the data flow in healthcare services without delay.

The proposed system introduces two new algorithms and implements three scenarios to cover all possibilities in real applications. The system's multi-link architecture, routing directly from the UAV to another UAV, base station, or ground user device, provides a significant advantage regarding network flexibility and continuity. UAV-to-Everything (UAV2X) connectivity reduces the risk of outages; even if a node fails within the network, data transmission can be maintained through alternative means.

The simulation results of the proposed system directly improve healthcare network quality by providing a low Bit Error Rate (BER), which guarantees the accuracy of the transmitted data through the selection of an optimal transmission route. The strong Signal-to-Interference Noise Ratio (SINR) values ensure the signal remains robust, maintaining stable transmission. This guarantees connection continuity, especially during UAV2X. Furthermore, constant signal power is maintained during data transmission. Signal attenuation due to the UAV's movement, environmental factors, or network load is minimized. This stability is also crucial for energy considerations management. The constant signal level stabilizes energy consumption, extending the UAV's mission duration and enabling longer and more efficient operation across the network.

The work in this thesis improves Healthcare 5.0 by presenting a unique optimization of the integration of blockchain and UAV networks beyond 5G communication networks. Optimizing the communication system in this context is a technical improvement and directly serves the vision of Healthcare 5.0 as an element that increases healthcare availability, quality and continuity.

Keywords: healthcare 5.0, UAV to everything, wireless communication, 5G, blockchain network

Özet

Sağlık Hizmetleri 5.0 için 5G ve Blockchain Tabanlı İnsansız Hava Araçlarından Her Şeye İletişimin Gelişmiş Optimizasyonu

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Sağlık hizmetleri 5.0 sistemi, insan merkezli dönüşümü, Nesnelerin interneti (IoT) tabanlı, beşinci nesil (5G) destekli ağ ve yapay zeka odaklı büyük veri analizleri ile dijitalleşen yenilikçi bir sistemdir. Bu çalışmada, Sağlık hizmetleri 5.0 çerçevesinde sunulan ileri seviye bir haberleşme ve veri yönetimi altyapısı geliştirilmiştir. Sağlık 5.0 sisteminde İnsansız Hava Aracı (İHA) tabanlı haberleşme altyapısının da kullanılması ile bütüncül dijital yapı kurularak operasyonların daha akıllı, verimli ve kesintisiz yürütülmesini sağlanır. Bu çalışmada, İHA'lar yalnızca birer taşıyıcı araç olmaktan çıkar; sağlık ağı içinde aktif bir karar destek unsuru hâline gelir. Geliştirilen 5G entegreli ve blockchain tabanlı sistem, sağlık hizmetleri 5.0 ile birlikte gelen siber-fiziksel sistem entegrasyonu, İHA'ların sağlık verilerini çevre birimleriyle güvenli ve anlık şekilde paylaşmasına olanak tanır. Özellikle 5G'nin sunduğu yüksek veri hızı ve düşük gecikme özellikleri, sağlık hizmetlerindeki veri akışının gecikmesiz bir şekilde gerçekleşmesini mümkün kılar.

Geliştirilen sistemde iki farklı algoritma tanıtılmış ve gerçek uygulamalardaki tüm olasılıkları içerecek şekilde üç farklı senaryo uygulanmıştır. Sistemdeki çoklu bağlantı mimarisi, İHA'dan doğrudan başka bir İHA'ya, baz istasyonuna veya yer cihazlarına yönlendirme yapılması, ağ esnekliği ve sürekliliği açısından önemli bir avantaj sağlar. İHA'dan Her Şeye (İHA2X) bağlantısı, kesinti risklerini azaltılır; ağda bir düğüm arızalansa bile veri iletimi alternatif yollarla sürdürülebilir.

Geliştirilen sistemin simülasyon sonuçları, optimum rota seçilerek iletilen verilerin doğruluğunu garanti eden düşük bit hata oranı (BER) sağlayarak sağlık hizmetinin kalitesini doğrudan artırır. Yüksek sinyal-parazit gürültü oranı (SINR) değerleri sayesinde sinyalin güçlülüğü korunur ve iletim kararlılığı artar. Bu, özellikle İHA2X süresince bağlantı sürekliliğini garanti eder. Ayrıca, veri iletimi sırasında sabit sinyal gücü korunmuştur. İHA'nın hareketine, çevresel faktörlere veya ağ yüküne bağlı sinyal zayıflamalarını minimize edilmiştir. Bu kararlılık, enerji yönetimi açısından da büyük önem taşır. Sabit sinyal düzeyi, enerji tüketimini dengeleyerek İHA'nın görev süresini uzatır ve ağ genelinde daha uzun süreli ve etkili operasyon sağlanmıştır.

Genel olarak bu tez, 5G haberleşme ağlarının ötesinde blok zinciri ve İHA ağlarının entegrasyonuna ilişkin kapsamlı bir optimizasyon sunarak Sağlık hizmetleri 5.0 alanına katkıda bulunmaktadır Haberleşme sisteminin bu kapsamda optimize edilmesi, yalnızca teknik bir gelişme değil; aynı zamanda sağlık hizmetinin ulaşılabilirliğini, kalitesini ve sürekliliğini artıran bir unsur olarak Sağlık hizmetleri 5.0 vizyonuna doğrudan hizmet eder.

Anahtar kelimeler: sağlık hizmetleri 5.0, İHA'dan her şeye, kablosuz haberleşme, 5G, blockchain ağı

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List of Abbreviations

UAV:	Unmanned Aerial Vehicle
IoT:	Internet of Things
BER:	Bit Error Rate
SINR:	Signal-to-Interference Noise Ratio
QoS:	Quality of Service
QoE:	Quality of Experience
5G:	Fifth Generation
UAV2X:	UAV to Everything
AWGN:	Additive White Gaussian Noise
LOS:	Line-of-Sight
PDF:	Probability Distribution Function
MIMO:	Multiple Input Multiple Output
1G:	First Generation
2G:	Second Generation
3G:	Third Generation
4G:	Fourth Generation
LTE:	Long Term Evaluation

OFDM:	Orthogonal Frequency Division Multiplexing
MC-CDMA:	Multi-Carrier Code Division Multiple Access
LAS-CDMA:	Large-area Synchronous code Division Multiple Access
LMDS:	Local Multipoint Distribution Service
mmWave:	Millimeter Wave
SE:	Spectral Efficiency
mMIMO:	Massive Multiple Input Multiple Output
MCM:	Multi-Carrier Modulation
MEC:	Mobile Edge Computing
SDN:	Software-Defined Networking
AMC:	Adaptive Modulation and Coding
D2D:	Device-to-Device
V2X:	Vehicle-to-Everything
D2X:	Device-to-Everything
AI:	Artificial Intelligence
ML:	Machine Learning
6G:	Sixth Generation
Tbps:	Terabit per Second
THz:	Terahertz

IRS:	Intelligent Reflecting Surface
BS:	Base Station
FD:	Full-Duplex
KPI:	Key Performance Indicators
LAP:	Low-Altitude Platforms
HAP:	High-Altitude Platforms
GCS:	Ground Control Station
FANET:	Flying Ad-Hoc Networks
MANET:	Mobile Ad-Hoc Networks
CNPC:	Control Non-Payload Communication
UE:	User Equipment
ISM:	Industrial, Scientific and Medical
DoS	Denial of Service
UDN:	Ultra-Dense Networks
QPSK:	Quadrature Phase Shift Keying
QAM:	Quadrature Amplitude Modulation
PDR:	Packet Delivery Ratio

CHAPTER I

Introduction

Unmanned Aerial Vehicles (UAVs) play an integral role in modern technology, offering unmatched versatility, efficiency, and accuracy across various domains (Sun et al., 2024; Zhao et al., 2024). The development of Internet of Things (IoT) devices, associated with advancements in wireless communication, has hardened the role of UAVs as essential assets in considerable systems (Jain et al., 2024; Adil et al., 2024; Chapnevis & Bulut, 2025). These aerial platforms are now commonly used for disaster management, environmental inspection, security monitoring, and infrastructure assessment (Fang & Savkin, 2024). UAVs can operate independently or in coordinated swarms depending on the task's requirements, showcasing their adaptability and scalability (Chen et al., 2024). However, challenges such as extending flight times and ensuring stable communication links have come to the forefront as their use expands. Addressing these issues is essential to fully harness the potential of UAV technology (Clerigues et al., 2024).

The effectiveness of UAV operations is intrinsically tied to the robustness of their communication systems, particularly in dynamic settings where seamless integration with diverse devices and networks is essential (Ahmed et al., 2025, Zhan et al., 2025). Key challenges involve optimizing power consumption, improving operational range, and managing large volumes of data efficiently without compromising performance (Chang et al., 2025; Shaikh & Mouftah, 2025). Moreover, ensuring critical communication parameters—such as low bit error rate (BER), high signal-to-interference noise ratio (SINR), and stable signal quality—becomes increasingly demanding as mission requirements expand (Taştan & Ilhan, 2025; Virk & Chennupati, 2024). These issues are further exacerbated by bandwidth, latency, and data security constraints, affecting UAV-based networks' reliability and overall performance. Such challenges are especially critical in scenarios demanding real-time responses and secure data exchange, where any communication breakdown could have severe consequences (Hag et al., 2025; Banafaa et al., 2024).

Reliable communication systems are vital for UAVs to achieve their full potential (Ogunbunmi et al., 2024; Laghari et al., 2024). Traditional UAV communication frameworks often fall short of meeting the stringent demands of modern applications. For example, when UAVs operate in swarm configurations, bandwidth congestion and reduced SINR frequently result in signal degradation and higher BER. Such issues undermine mission-critical coordination and data exchange, creating vulnerabilities that could lead to significant setbacks (Aljumah, 2024; Alotaibi et al., 2024). In high-stakes applications where secure and uninterrupted communication is paramount, these challenges become even more critical, underscoring the pressing need for more robust solutions (Gupta et al., 2023; Wang et al., 2024; Sharvari et al., 2023; Liang et al., 2023).

Statement of the Problem

The limitations of existing communication systems for UAVs necessitate the development of innovative strategies to improve their reliability, adaptability, and overall performance. Advanced communication infrastructures must address critical constraints such as energy efficiency, data traffic management, and optimizing performance metrics like Quality of Service (QoS) and Quality of Experience (QoE). Striking a balance between low BER, high SINR, and stable signal strength is essential for ensuring the effective operation of UAV networks, particularly in environments characterized by high complexity and demanding conditions (Yin et al., 2024; Minh et al., 2023; Hoang et al., 2024).

Purpose of the Study

This study presents a groundbreaking communication model integrating advanced technologies such as fifth-generation (5G), blockchain, and IoT to address these challenges. By leveraging the low-latency, high-speed capabilities of 5G networks and the enhanced security and transparency offered by blockchain, the proposed model offers a comprehensive solution for optimizing UAV communication systems. In this approach, data exchanged between UAVs and ground stations is encrypted and authenticated using blockchain technology, ensuring secure and efficient data transmission. This methodology enhances data security and improves communication reliability and speed, effectively tackling the core challenges associated with UAV operations (Imam et al., 2023; Abohashish et al., 2023; Guo et al., 2023; Qazzaz et al., 2024).

In the framework of Healthcare 5.0, UAV-assisted communication systems have giant potential. However, the unpredictable and vast operational environment introduces specific challenges, such as authentication, data security, and communication reliability. This study addresses critical concerns utilizing blockchain technology, UAV-to-everything (UAV2X) communication, and 5G networks to create a secure and efficient framework for healthcare-related UAV operations. The proposed model safeguards sensitive data during transmission through blockchain-based authentication and encryption, ensuring the secure and effective delivery of medical supplies while mitigating potential breaking or communication risks (Nalini, 2024; Thakur et al., 2024; Mohsan et al., 2023; Suleiman & Adinoyi, 2023; Bhandari et al., 2024; Singh & Kaunert, 2024).

Significance of the Study

This study's significance lies in its potential to enhance the reliability and efficiency of UAV operations within healthcare 5.0. The model enables smooth data exchange in various scenarios by addressing key challenges such as low latency, high SINR, and stable signal strength. These capabilities are crucial for ensuring medical resources' safe and timely delivery, particularly in urgent and high-pressure situations. Additionally, incorporating IoT into the communication framework facilitates real-time monitoring and adaptive decision-making, further optimizing healthcare 5.0. operations (Garg et al., 2024; Jagatheesaperumal et al., 2025; Dhar et al., 2024).

Contributions

The outcomes of this study have considerable implications for advancing healthcare logistics through technological integration. Validating the proposed model with parametric measurements and simulations establishes a reliable basis for future progress in UAV-assisted healthcare systems. 5G, blockchain, and IoT within the framework address existing limitations and open the door to innovative applications that improve the reliability and quality of healthcare services. The research represents a significant step toward realizing UAV-assisted Healthcare 5.0., paving the way for broader adoption across various industries.

Several publications were produced to showcase the findings throughout the research, reflecting progressive development (Sabuncu & Bilgehan, 2024). The thesis contributions are summarized as follows.

- Reliable data transmission from UAV to all systems is achieved with a minimum BER at a consistent power level.
- Optimized UAV communication links enhance connectivity and data transmission efficiency.
- An optimized SINR ensures seamless communication in dynamic contexts and environments.
- Optimized packet delivery in UAV-to-everything transmissions ensures a high success rate with precision and speed.
- Energy-efficient data transmission strategies effectively diminish overall power consumption while preserving high-quality communication performance.

The structure of this thesis follows a systematic approach to tackling the challenges and opportunities in UAV communication systems. Chapter II offers an in-depth review of UAV-enabled communication systems, covering the principles of communication channels, wireless networks, and UAV integration into cellular systems. It also examines the challenges associated with UAV security and the incorporation of blockchain into UAV networks, emphasizing the need for enhanced frameworks. Chapter III defines the problem and presents the proposed solution, focusing on optimizing UAV communication links to overcome existing limitations. Chapter IV highlights the application of UAV-assisted communication in healthcare, demonstrating the transformative potential of the proposed model in enhancing medical logistics. By aligning technological advancements with practical applications, this research highlights the critical role of UAVs in advancing communication systems and essential healthcare services. Chapter V presents a simulation study to evaluate the performance of the proposed model quantitatively. Then, the content of the simulation and its specific contributions to this study are detailed. Chapter VI summarized the study's findings, and conclusions are drawn on how the proposed approach optimizes UAV communication for healthcare 5.0.

CHAPTER II

Background: UAV Assisted Communication Systems

General Communication System

Communication systems are systems models that provide uninterrupted and reliable transmission of information from source to destination. A typical communication system consists of three main components: transmitter, channel, and receiver, as shown in Figure 2.1 (Lathi, 1968; Coiera, 2006).

Figure 2.1. Key parts of the communication system

The information generated by the source is sent to a transmitter, which converts it into a message signal in a format suitable for the transmission medium using various techniques. The transmitter modulates the message using a carrier set to a specific frequency suitable for secure and reliable transmission. Modulation allows the signal to transmit longer distances with less loss. The channel is the physical medium that allows transmission from the transmitter to the receiver. Channel characteristic involves randomness in transmission. Therefore, transmitted signals may be exposed to effects such as noise, attenuation, distortion, and multipath propagation along the channel. The receiver detects the signal from the channel and decodes it to obtain the original message (Smith, 2012; Reiser, 1982).

The transmitted signal is represented by $x(t)$ as a function of time and modulated with a carrier frequency, and its representation is as follows:

$$x(t) = A \cdot m(t) \cdot cos(2\pi f_c t + \phi) \quad (2.1)$$

where:

- A: the amplitude of the signal,
- $m(t)$: the modulated message signal,

- f_c: the carrier frequency,
- ϕ: the phase angle.

Equation 2.1. can vary depending on the type of modulation (amplitude, frequency, or phase modulation).

The received information signal is represented as $y(t)$ and, depending on the effects of the channel, expressed as follows:

$$y(t) = h(t) \cdot x(t) + n(t) \tag{2.2}$$

where;

- $h(t)$: the channel response, representing the effect of the channel,
- $x(t)$: the transmitted information signal,
- $n(t)$: the noise added to the transmitted signal as it travels through the channel.

The channel effect $h(t)$ is the response to represent distortions such as attenuation, phase shifts, and multipath propagation. In an ideal time-invariant channel, $h(t)$ would be an impulse response representation considered as a system (Smyrnaios & Schön, 2013). However, in most cases, $h(t)$ is complex and alters the phase and amplitude of the signal over time. Noise $n(t)$ refers to unwanted and random signals that interfere with the message signal transmitted over the channel, often following a specific distribution (e.g., normal distribution) (Shannon, 1984). This noise can originate from the system or external factors and is typically modelled as Additive White Gaussian Noise (AWGN) (Deng et al., 2024). The received signal $y(t)$ is demodulated at the receiver, and an attempt is made to retrieve the signal closest to the original information. The demodulation process can be expressed as follows:

$$\widehat{m}(t) = f\big(y(t)\big)$$

where;

- $f\big(y(t)\big)$ is the demodulation function.

Using this function, the message signal, represented by $\widehat{m}(t)$, which is the closest approximation to the original signal. Depending on the noise and channel impairments, there may be differences between the obtained signal $\widehat{m}(t)$ and the original signal $\mathrm{m}(t)$.

In an effective communication system, the received information is expected to be as close as possible to the transmitted information. This can be expressed as follows:

$$\mathrm{m}(t) \cong \hat{m}(t)$$

Communication Channel

The communication channel is a cable or wireless medium that connects the transmitter and the receiver. These can include a wire that carries electrical signals, a coaxial cable, or an optical fiber that transmits light beams (Kumar, 2023).

Wireless communication transmits message signals through the air as electromagnetic waves. The modes of propagation of electromagnetic waves in the atmosphere and free space can be divided into three categories: ground wave propagation, sky wave propagation, and line of sight (LOS) propagation (Molisch, 2012; Goldsmith, 2005).

Ground wave propagation occurs when electromagnetic waves travel along the Earth's surface, making it suitable for long-distance communication at lower frequencies. This method is often employed in applications like AM radio broadcasting. However, the Earth's surface can cause attenuation, limiting the efficiency of this mode over extended ranges (Wiltvliet, 2015).

Ground wave propagation can be described by the formula for attenuation, where the power decreases exponentially with distance:

$$P(d) = P_0 \times e^{-ad} \tag{2.3}$$

where $P(d)$ is the power at distance d, P_0 is the initial power, and a is the attenuation constant.

Sky wave propagation involves the reflection of electromagnetic waves off the ionosphere, enabling signals to reach locations beyond the horizon. This mode is widely used in shortwave radio communication because it can cover vast distances. However, its effectiveness depends on factors such as ionospheric conditions, which vary with time of day, season, and solar activity (Wiltvliet, 2015).

Sky wave propagation involves using the reflection coefficient and the distance-dependent behavior of the signal. The reflection coefficient, R, can be expressed as:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{2.4}$$

where Z_1 and Z_2 are the impedances of the lower and upper layers (e.g., ionosphere and atmosphere).

LOS propagation is the most direct form of communication, where the transmitting and receiving antennas see each other. It is commonly used in high-frequency applications like satellite communication and microwave links. LOS propagation ensures high data rates but requires a clear, unobstructed path between communicating devices, making it less effective in scenarios with physical obstacles or adverse weather conditions (Xia, 1993).

For LOS propagation, the free-space path loss can be calculated using:

$$L_{fs} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \tag{2.5}$$

where d is the distance, f is the frequency, and c is the speed of light.

Channel Models

Transmitted message signals require channel models to mathematically describe the distortions and effects in the channel. Channel models provide a framework for understanding how various factors, such as multipath propagation, fading, noise, and interference, influence the quality and reliability of communication links (Krouk & Semenov, 2011; Kihero et al., 2021).

Various methods are used in communication systems and channel analysis. Physical-based models focus on environmental impacts, such as electromagnetic wave propagation, weather conditions, or geographic factors, and are often applied to empirical data and direct measurements. Deterministic models provide clear rules and assumptions to simulate specific events or physical phenomena, ensuring accurate results based on known factors. Machine learning and deep learning techniques are increasingly employed for advanced data analysis, handling large datasets and identifying patterns in channel behaviour. Hybrid models combine deterministic and statistical approaches, offering a more comprehensive view of complex systems. Empirical methods rely on real-world measurements and experimental data to directly analyze channel conditions. Computational modelling uses numerical methods to simulate physical and mathematical structures, helping with tasks like path loss calculations, signal distribution, and electromagnetic field analysis. These approaches provide diverse tools for understanding and optimizing communication channels and systems (Oestges et al., 2002; Poikonen, 2009; Narandžić et al., 2011; Wang et al., 2017; Erpek et al., 2020).

In addition to these various methods, statistical models play a vital role in capturing the complexities of communication channels. Statistical models like Rayleigh, Rician, and Gaussian are designed to address uncertainties and variability in wireless environments. These models help analyze channel behavior by representing the effects of fading, noise, and interference, which are common in real-world communication systems. By offering a mathematical framework, statistical models enable system performance assessment across diverse conditions, helping optimize system design and resource management (Sadıkoğlu et al., 2022).

Statistical methods effectively manage uncertainties by modeling distributions, probabilities, and relationships between variables. These methods facilitate system performance analysis under various conditions and enhance system reliability and efficiency.

Rayleigh Model**:** The Rayleigh distribution model often represents fading in wireless channels with no clear, dominant line-of-sight path. In urban or dense multipath environments, Rayleigh fading assumes that multiple scattered paths contribute to signal attenuation and random phase shifts, leading to unpredictable signal strength and quality variations (Gómez-Déniz & Gómez-Déniz, 2013).

The Rayleigh random variable's probability distribution function (PDF) can be stated as follows.

$$p(x) = \frac{x}{\sigma^2} e^{\left(-\frac{x^2}{2\sigma^2}\right)}, \text{ for x} > 0 \tag{2.6}$$

where, x is the instantaneous signal amplitude, the variable σ^2 denotes the time average power of the received signal and e is the base of the natural logarithm.

Rician Model**:** The Rician distribution is suitable when a strong LOS path exists alongside scattered paths. It applies to scenarios where a dominant LOS component provides a stable signal quality (Kang & Alouini, 2006).

The Rician distribution is expressed as;

$$p(x) = \frac{x}{\sigma^2} e^{\left(-\frac{(x^2-A^2)}{|2\sigma^2}\right)} I_0\left(\frac{Ar}{\sigma^2}\right) \text{ for } (A \geq 0, x \geq 0) \tag{2.7}$$

The variable A denotes the amplitude of a signal. I_0 is the result of the Bessel function.

These models are essential for assessing communication system performance and guiding system design and optimization across varying channel conditions.

Wireless Communication Systems

Transmission in a wireless communication system is enabled through an electromagnetic wave. The information is transmitted through various frequency bands, such as microwaves, radio waves, infrared, or satellite communication. The system has many advantages, such as ease of installation, flexibility, and mobility, and provides fast and effective data exchange with portable devices. It is also widely used in applications such as the IoT, mobile internet, and intelligent systems (Crane, 2003; Souri et al., 2022).

Wireless communication systems face channel problems such as multipath propagation, noise, and fading. These problems reduce the signal quality and increase the error rate (Saunders & Aragón-Zavala, 2024). The signal-to-noise ratio (SNR) is a fundamental metric for evaluating signal quality. A high SNR value indicates that communication is of high quality and error-free. SNR provides the ratio of signal power to noise.

$$\text{SNR(dB)} = 10 \log\left(\frac{P_{signal}}{P_{noise}}\right) \tag{2.8}$$

where;

P_{signal} : Power of signal

P_{noise} : Power of noise

The SNR value reflects the communication link's quality by comparing the desired signal's strength to the noise level (Arpali et al., 2008).

In wireless communication systems, BER measures errors that occur during data transmission. It shows the proportion of incorrect bits compared to the total number of bits sent, helping to evaluate the reliability of the communication link. A lower BER indicates more accurate data transmission, while a higher BER suggests more errors, which can result from factors like noise, interference, and signal loss.

BER is calculated as the ratio of incorrect bits to the total number of bits sent.

$$\text{BER} = \frac{\text{Number of Bit Errors}}{\text{Total Number of Bits Transmitted}}$$

Number of Bit Errors refers to the number of bits received incorrectly during data transmission. Total Number of Bits Transmitted represents the total number of bits sent from the sender to the receiver. BER is offering an assessment of communication reliability.

Channel capacity is another measure of system performance (Medard, 2000). The data transmission capacity of the communication channel is defined by the Shannon Capacity theorem and the maximum data transmission rate (bits/second) that can be realized in the channel is calculated and formulated as follows;

$$C = B\log_2(1 + \text{SNR})$$

where;

C: Capacity of the channel (bps),

B: Bandwidth (Hz).

According to the equation, channel capacity proportionally increases with SNR, but the logarithmic relationship in this ratio indicates that the increase slows down logarithmically after a point. Therefore, the communication system approaches its maximum capacity at a specific SNR value. System performance can be optimized using bandwidth, channel, and specific antenna design (Tsoulos, 2018).

Cellular Mobile Networks

The wireless communication industry has witnessed staggering growth in subscribers and mobile technology. The first generation (1G) is analog cellular technology. The second generation (2G) started the digital era and continues to develop, with each generation providing higher data speeds and more efficient spectrum usage than the previous generation. The mobile internet era began with the third generation (3G), and the next generation, the fourth generation (4G), introduced the Long-Term Evolution (LTE) standard and provided broadband, high-speed internet, and low-latency services. In 4G technology, various existing and future wireless technologies such as Orthogonal Frequency Division Multiplexing (OFDM), Multi-Carrier Code Division Multiple Access (MC-CDMA), Large-area Synchronous code Division Multiple Access (LAS-CDMA), and Local Multipoint Distribution Service (Mesh-LMDS) are assimilated, thus achieving freedom of movement and continuous roaming among heterogeneous technologies (Malini & Chandrakala, 2022; Zeqiri et al., 2019; Hajlaoui, 2020). Table 2.1. shows the main differences between cellular generations, from 1G to 4G.

Table 2.1 Key distinctions among cellular generations

Technology	**1G**	**2G**	**3G**	**4G**
Year	1979	1991	2001	2009
Frequency	30 kHz	1.8 GHz	1.6-2 GHz	2.8 GHz
Bandwidth	2 kbps	364 kbps	3 Mbps	100 Mbps
Avg Speeds	2 kbps	40 kbps	300 Mbps	25 Mbps
Range	N/A	50 mi	35 miles	10 miles
Use cases	Analog System, Giant Cell Phones, Dropped Calls	Texting (SMS), MMS, Long Distance Call Tracking, Conference Calls	Cheap data transmission, Web Browsing, GPS, SD Video Streaming	HD Video, Wearable Devices, Streaming, High Speed Applications

With the increasing demand for advanced services and connected devices, expanding communication systems have become necessary to establish comprehensive, uninterrupted communication and meet user needs.

Fifth Generation (5G) technology ushers in a new era for cellular networks, offering high transfer speeds, vast connection capacity, and a flexible and expandable network scheme to connect everything and everyone everywhere (Agival et al., 2016).

5G technology uses Millimeter Waves (mmWave) with wavelengths ranging from 1 mm to 10 mm. Using high-frequency wavelengths means more bandwidth and a broader spectrum range. The 10 to 20 Gbps speed is achieved by utilizing radio frequency spectrums ranging from 30 to 300 GHz provided by mmWave (Hussain, 2021; Sabuncu & Bilgehan, 2023).

The objectives of the 5G network are to provide high-capacity gain, high bit rate, low latency, effective QoS, high coverage, and high spectral efficiency (SE), connect through heterogeneous and ultra-dense networks, and provide broadband access everywhere, as seen in Figure 2.2 (Rachakonda et al., 2024; Lessi et al., 2024).

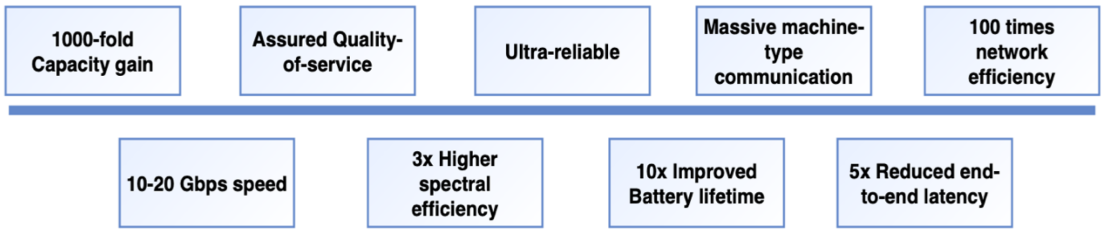


Figure 2.2. The prime objective of 5G

Among the innovations brought by 5G is low latency. The data transmitted and the response time are named latency. Benefitting from low latency, the execution of user commands is reduced to a few milliseconds, thus providing a digital revolution. The improvement in 5G is a revolutionary technology for many innovative systems such as virtual reality, digital twins, autonomous vehicles, advanced healthcare, and IoT as shown in Figure 2.3 (Biswas & Wang, 2023; Nguyen et al., 2021; Sufyan et al., 2023).

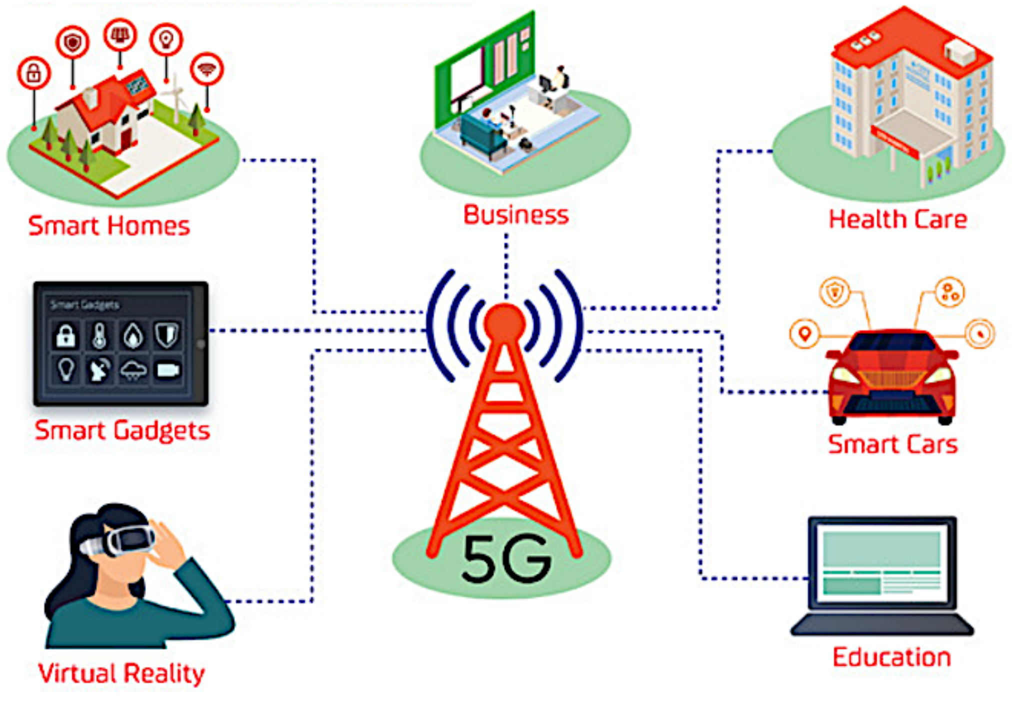


Figure 2.3. 5G connecting the community

There are some challenges using mmWave frequency in 5G: signal attenuation in the high-frequency spectrum and signal penetration with high loss. The main challenge of mmWave frequency is path loss. Path loss reduces the strength of the transmitted signal in the channel due to the obstacles. Reducing the high path loss requires a limited cell radius (Brata & Zakia, 2024; Khan et al., 2025). The high path loss in mmWave compared to microwave bands below 3 GHz is considered a key challenge, which is given by,

$$L_{\text{Freespace (dB)}} = 32.4 + 20\log_{10} f + 20\log_{10} R \tag{2.9}$$

where,

L: free space path-loss (dB)

f: carrier frequency (Hz)

R: distance between tx and rx (m)

The ongoing challenge of mobile networks is the massive demand for data traffic. To achieve the required throughput, the network depends on expanding the spectrum or densifying into cells (Islam et al., 2024; Okyere, 2024).

Several techniques have been proposed to overcome the challenges in 5G networks, establish an extensive data network, use the spectrum more efficiently, lower costs, and connect more devices, as detailed in Figure 2.4.; Massive multiple input multiple outputs (mMIMO), multi-carrier modulation (MCM) such as OFDM, network slicing, beamforming, Mobile Edge Computing (MEC), Software-Defined Networking (SDN), Adaptive Modulation and Coding (AMC), Ultra-dense and Heterogeneous networks, Channel equalization, Device-to-Device communication (D2D), Vehicle-to-Everything communication (V2X), Artificial Intelligence (AI) and Machine Learning (ML) (Sufyan et al., 2023). The techniques are used in communication systems to improve signal quality, increase data speeds, and use the available bandwidth more efficiently (Tarafder et al., 2025; Fadel & Jamel, 2024; Bahramisirat et al., 2024; Chiti et al., 2024; Manikandan et al., 2025; Bilgehan & Sabuncu, 2023; Zhang et al., 2025; Sufyan et al., 2023).

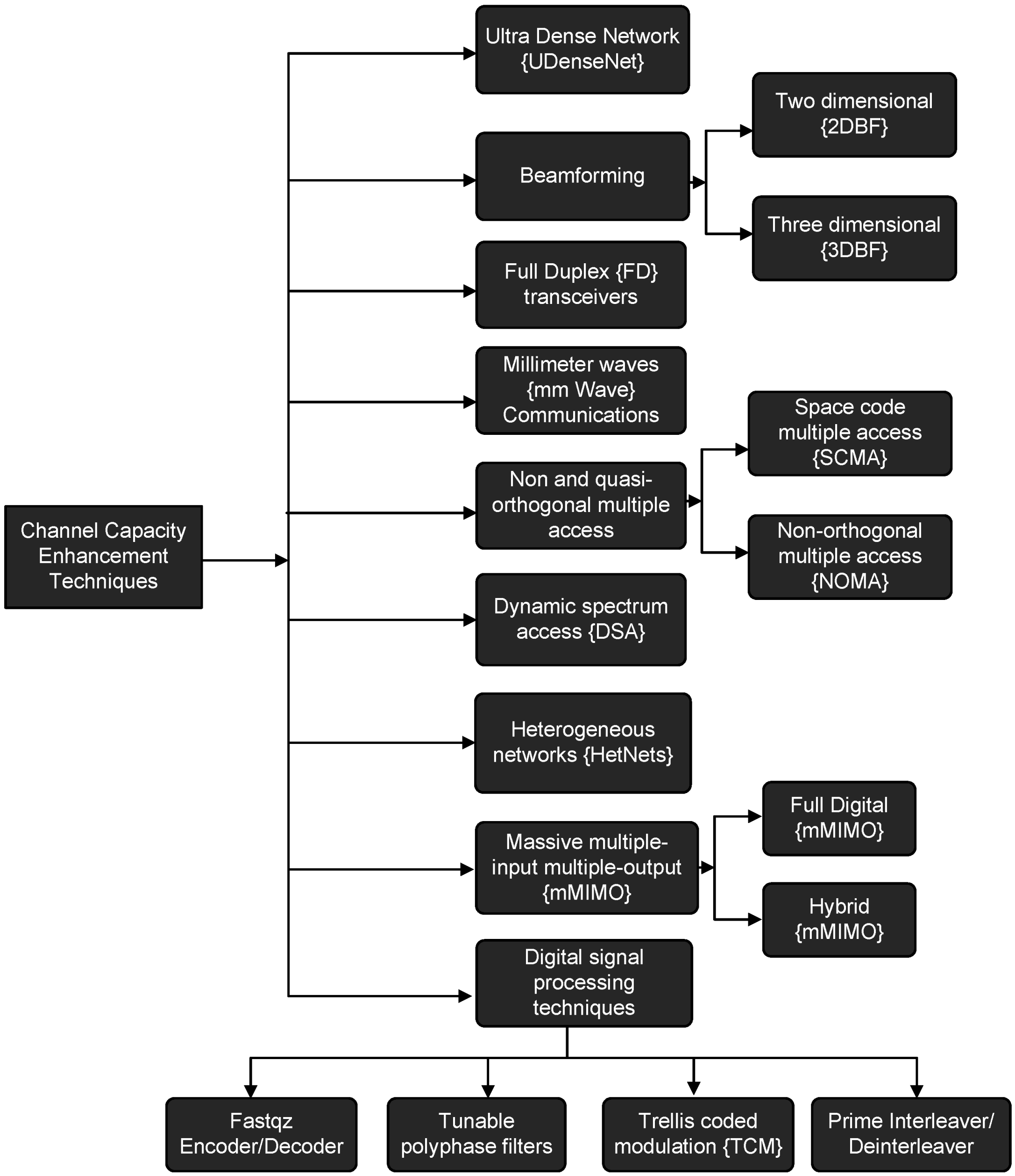


Figure 2.4. Key techniques to enhance channel capacity and spectral efficiency

As shown in Figure 2.5, integrating several techniques is expected to achieve higher performance than their individual performance (Sufyan et al., 2023).

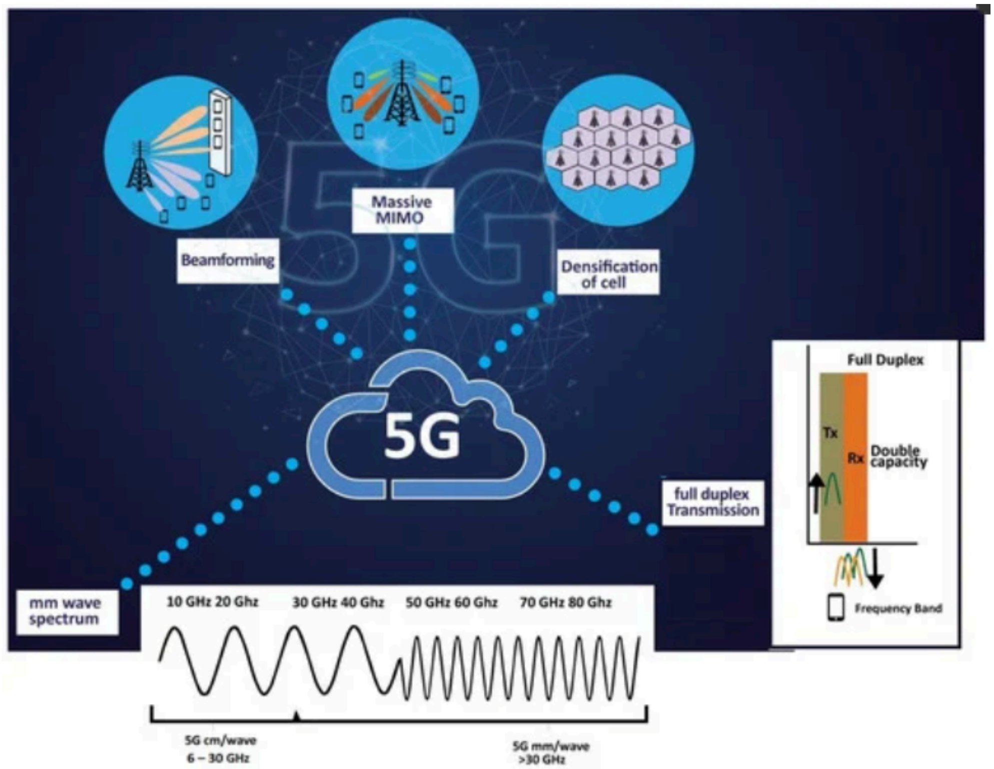


Figure 2.5. Key enabling technologies of 5G

The opportunities provided by 5G and the available areas are shown in Figure 2.6.

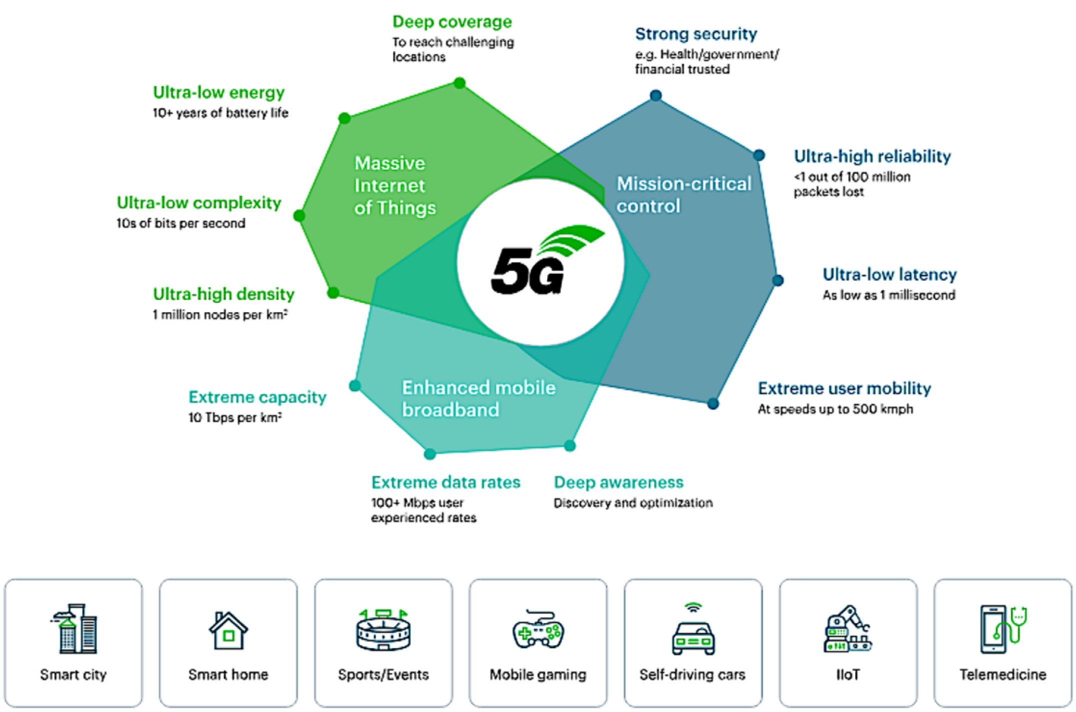


Figure 2.6. 5G opportunities and accessibility

As a consequence of the rapid expansion of IoT networks and the considerable increase in smart devices and big data, 5G networks may have to compromise on some technology requirements, such as latency, energy efficiency, hardware cost, and end-to-end reliability (Salameh & El Tarhuni, 2022).

Sixth Generation (6G) and beyond technologies aim to provide connectivity services and hyper-mobile connectivity worldwide. To address the requirements of future intelligent communication systems, 6G communication systems offering data rates at the terabit per second (Tbps) level are candidates to be activated. Communication in the terahertz (THz) frequency bands used in 6G has heralded a new era in wireless communication. New frequency bands between 0.1 THz and 10 THz, as shown in Figure 2.7, are considered potential spectrum resources that provide high bandwidth, sub-millisecond latencies, and promise speeds of up to 100 Gbps (Bilgehan & Sabuncu, 2023; Jiang et al., 2024; Dhandapani et al., 2024; Siddiky et al., 2025).

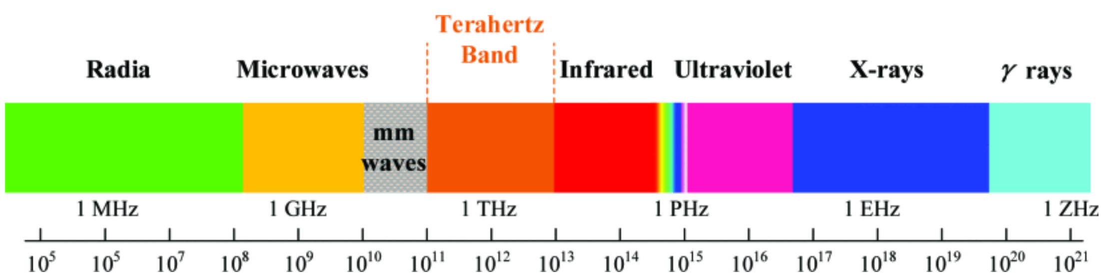


Figure 2.7. Illustration of THz

Human-centric and environmentally friendly communication solutions are targeted in 6G to increase energy efficiency, support greater data density, and minimize environmental impacts. 6G is expected to enable autonomous, highly dynamic, fully intelligent, and ultra-large-scale services with a high QoE. Ultra-high-speed connectivity enables faster data sharing. Extremely low latency, data is shared with zero latency tolerance, enabling support for accurate data services. Ubiquitous connectivity ensures uninterrupted communication (Shamsabadi et al., 2025; Chaudhari, 2025).

A series of enabling main technology techniques have been introduced to address the restrictions of 5G. In addition to THz in 6G, one of the fundamental techniques is Intelligent Reflecting Surface (IRS) technology, which controls signal reflections and can communicate beyond the LOS. IRS is a surface consisting of many passive reflective elements between many high-frequency Base Stations (BSs) and users, as shown in

Figure 2.8. IRS operates in Full-Duplex (FD) mode and is expected to change the wireless channel dynamically to improve communication quality (Ning et al., 2025; Umer et al., 2025; Khan et al., 2024; Wu et al., 2023; Wang et al., 2023).

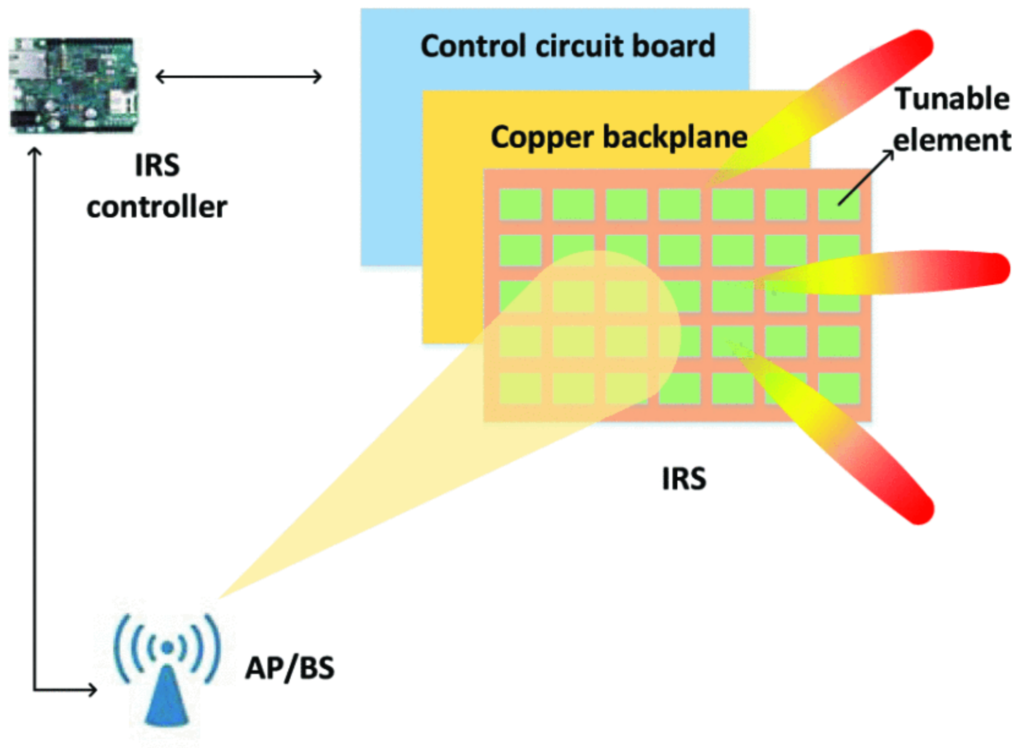


Figure 2.8 Illustration of IRS

The comparison of 5G and 6G Key Performance Indicators (KPI) is given in Table 2.2 (Wang et al., 2023; et al., 2023).

Table 2.2 Comparing 5G and 6G KPI

KPI		5G	6G	Enhancement
Data rate &Delay	Peak data rate	20 Gbps	1 Tbps	50×
	User experienced data rate	100 Mbps	10 Gbps	100×
	Latency	1 ms	0.1 ms	10×
	Delay jitter	1 ms	1 µs	1000×
Capacity& Coverage	Area traffic capacity	10 Mbps/m²	10 Gbps/m²	1000×
	Connection density	10^6 devices/km²	10^8 devices/km²	100×
	Coverage	10%	100%	10×
Service efficiency	Spectrum efficiency	30 bps/Hz	≥90 bps/Hz	≥3×
	Network energy efficiency	10^7 bit/J	10^9 bit/J	100×
	Cost efficiency	10 Gb/$	500 Gb/$	50×
Diversified service evaluation	Mobility	500 km/h	1000 km/h	2×
	Battery life	10 years	20 years	2×
	Reliability	99.999%	≥99.9999%	≥100×
	Positioning	1 m & 10 cm	10 cm & 1 cm	10×
	Sensing/Imaging resolution	1 m	1 mm	1000×
	Security capacity	Low	High	-
	Intelligence level	Low	High	-

Next-generation networks (xG) are expected to enhance connectivity, enabling information exchange anytime, anywhere, with anyone, while ensuring unrestricted access. These networks support emerging use cases, innovative architectures, enhanced services, and automated and adaptable security strategies that meet increasing demands and evolving security functionalities (Aboumahmoud et al., 2024).

Emerging-generation communication technologies' advantages, such as low latency, high data rate, and broad coverage, allow unmanned aerial vehicles to be used effectively in communication infrastructures.

Unmanned Aerial Vehicles in Communication

Unmanned aerial vehicles (UAVs), commonly referred to as drones, have garnered increasing research interest in recent years due to their mobility, flexibility, adaptability, and wide range of application areas (Chen et al., 2025; Adam et al., 2025; Fang et al., 2025). UAVs have been integrated as potential enablers and data sources in various fields, including tracking and surveillance, military operations, telecommunications, logistics, medical deliveries, search and rescue missions, and more (Sabuncu & Bilgehan, 2024; Dağaşan & Karaşan, 2025; Alqudsi & Makaraci, 2025; Gaffar et al., 2024). The selection of UAV types must be based on assessing their suitability to meet the requirements imposed by environmental and civil aviation regulations. The effectiveness of UAVs in applications relies on the appropriate flight altitude and air platform; they are generally categorized as low-altitude platforms (LAPs) and high-altitude platforms (HAPs). LAPs are capable of moving quickly and are preferred for time-critical applications. HAPs offer longer endurance, reach greater altitudes, and are suited for long-term operations compared to LAPs (Ning et al., 2024; Rzig et al., 2024). Based on their structure, UAVs are classified into different types, including rotary-wing and fixed-wing designs (Özbek et al., 2025). The characteristics of these UAV types are detailed in Table 2.3.

Table 2.3 Attributes of Different UAV Types

Model	Spreading Wings S1000 (DJI)	H520E/520 (Yuneec)	Parrot Disco	MQ-9 Reaper (Predator B)
UAV type	rotary-wing (octocopter)	rotary-wing (hexacopter)	fixed-wing	fixed-wing
Weight	4.2 kg	1.86 kg	750 g	2223 kg
Payload	6.8 kg	500 g	N/A	1746 kg
Range	N/A	up to 3.5–7 km	2 km	1852 km
Endurance	15 minutes (@ 15000 mAh & 9.5 kg take-off weight)	25-30 minutes	45 minutes	27 hours
Altitude	N/A	500 m	N/A	15.24 km
Speed	N/A	72 kph	80 kph	445 kph
Power supply	LiPo (6S, 10000mAh–20000mAh)	LiPo (4S, 6200 mAh)	LiPo (2700 mAh 3-cells)	Honeywell TPE331-10 turboprop engine
Power consumption	Maximum: 4 kw, Hover: 1.5 kw (@ 9.5 kg take-off weight)	N/A	N/A	Engine: 712 kw
Applications	Aerial photography, appropriate to transport packages, and to support cellular BSs and UEs	Aerial photography, and suitable to carry sensors	Recreation	Airborne surveillance, armed reconnaissance, and target acquisition

Although UAVs were initially designed for military applications, they are now widely used in several civilian applications, including health care, search and rescue operations, data communications, and weather monitoring (Bóveda et al., 2024; Sziroczak et al., 2022; Pattepu et al., 2024). Figure 2.9 shows UAV applications (Gupta et al., 2021).

Figure 2.9. UAV applications

UAV Communication Networks

A UAV network consists of several sub-systems, including the UAVs, ground control station (GCS), satellites, and multi-level communication links such as UAV-UAV, GCS-UAV, and satellite-UAV. UAV communication networks are grouped into flying ad-hoc networks (FANETs) and mobile ad-hoc networks (MANETs) (Ghamari et al., 2022).

FANET architecture eliminates the need for infrastructure for UAVs and provides real-time communication that can overcome communication range limitations. FANET communication makes UAV-UAV communication possible. However, communication between the main UAV and the GCS can be established, and if this connection is interrupted, the network can become dysfunctional (Sharma & Mehra et al., 2023).

In a MANET architecture, communication is decentralized. UAV-UAV communication and UAV-GCS communication are possible with MANET, and if this connection is interrupted, the network is still functional.

UAV Control and Links Requirements

UAV communication can be divided into two primary operations: control non-payload communication (CNPC) and payload communication. The CNPC allows updates during the mission to ensure secure and reliable operation. The communication link requirement is to provide a secure and reliable connection at low data rates, usually around 100 kb/s. The packet error rate for the CNPC communication link should not be more than 10^{-3} (Wang et al., 2024; Mishra & Natalizio, 2020).

Payload communication encompasses all information dissemination activities a UAV performs during its specific operations. When the UAV transmits data to the ground station through payload communication, the transmission medium can support high data rates.

The latency and speed requirements for CNPC and payload communication types are summarized in Table 2.4.

Table 2.4 UAV control and link requirements

Type	Payload	CNPC Uplink	CNPC Downlink
Rate	~50 Mbps	~100 Kbps	~100 Kbps
Latency	Identical to ground user devices	-	~50 ms

Integration Process of UAV and Cellular System

In the various application domains of UAVs, a reliable communication infrastructure is demanded for efficient information dissemination to the ground control station (Mozaffari et al., 2019; Nawaz et al., 2021). The structural design of UAVs functions as inherently mobile, and mobility necessitates wireless connectivity solutions (Zeng et al., 2016; Zolanvari et al., 2019). Shrink-sized wireless network equipment, introduced in microelectronic technology developments and mounted on UAVs, provides flexibility in terms of communication and offers cost advantages. Especially in telecommunications, using UAVs with wireless equipment is a creative solution to satisfy the increasing demand for communication systems.

The wireless communication requirement is fulfilled through licensed or unlicensed spectrum. Unlicensed spectrum is shared among many users and devices simultaneously, making it more susceptible to signal collisions and interference issues. Licensed spectrum offers more dependable channel allocation in UAV communication, as specific users operate within a designated frequency band. UAV communication can utilize various methods such as satellite communication, cellular bands, or dedicated licensed spectrum explicitly allocated for UAVs. While satellite communication offers extensive coverage ideal for UAVs, it has drawbacks like high cost, high latency, and low throughput. Dedicated licensed spectrums are expensive and require building a system supporting UAV operations (Hosseini et al., 2019). The broad coverage, high throughput, low latency, and continuous connectivity capabilities of wireless cellular networks serve as essential technologies for supporting UAVs.

Figure 2.10 shows three fundamental scenarios for integrating UAVs into cellular communications (Mishra & Natalizio, 2020).

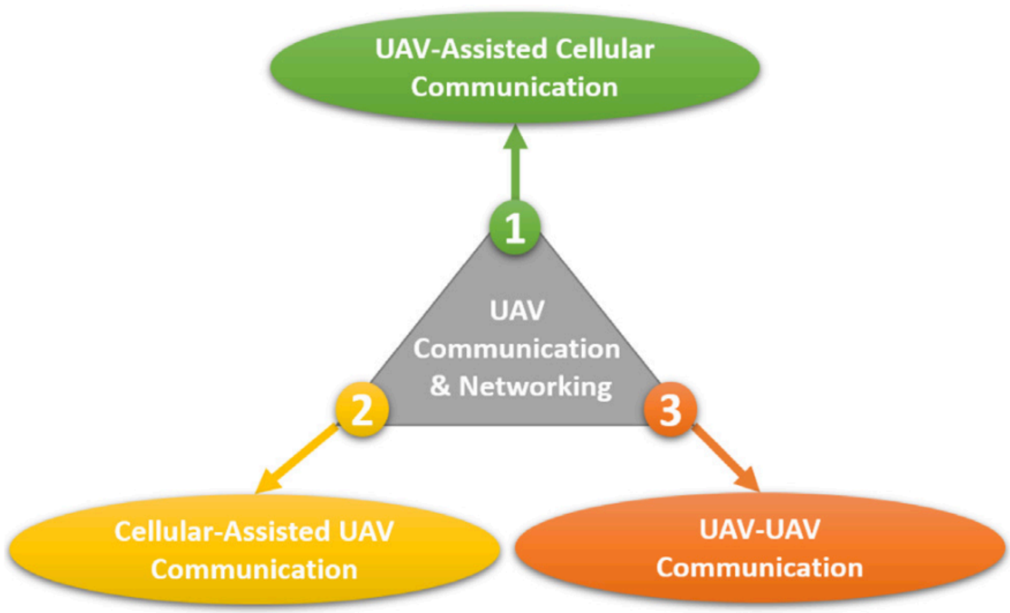


Figure 2.10. UAV and cellular network integration opportunities

Figure 2.11 provides a detailed representation of the three basic scenarios for integrating UAVs into cellular communication (Mishra & Natalizio, 2020).

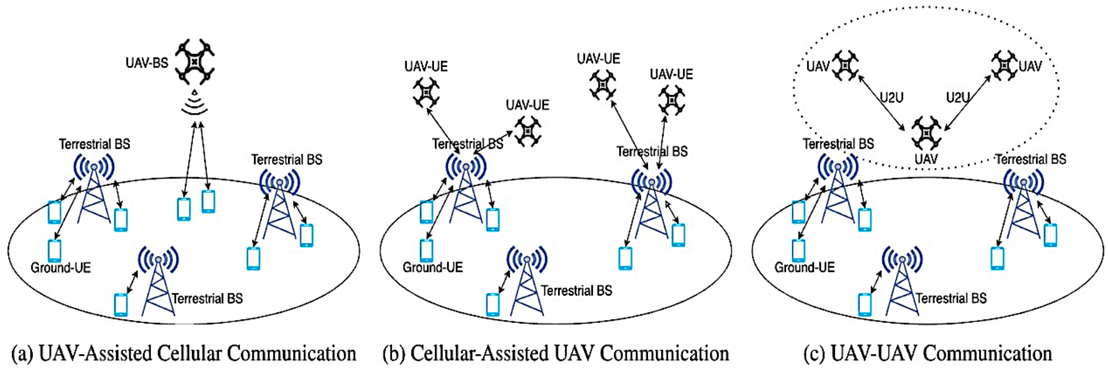


Figure 2.11. Integration of UAV opportunities with cellular networks

UAV-Assisted Cellular Communication: Establishing a terrestrial infrastructure that provides a network may not be feasible during temporary situations, emergencies or unexpected circumstances. UAVs can support the network in various ways, such as serving as a BS, relaying in emergencies, or collecting data for IoT devices. Base stations affixed to UAVs can support the existing terrestrial wireless communication system as aerial BSs. These can be used as aerial relays to overcome the difficulties in positioning terrestrial relays and improve the user experience. This scenario architecture is shown in Figure 2.11(a), where the aerial BSs are featured as intelligently repositioned, have dynamic movements, stand out with the LOS connection, and can facilitate wireless coverage. Advantages of overcoming the limitations of communication services include more effective QoE, coverage gain, spectral efficiency and creating an uninterrupted communication network (Chakraborty et al., 2018; Sundaresan et al., 2018). These benefits solve various, dynamic and increasing data demands in 5G/B5G cellular systems. The collaborative utilization of 5G technology, distinguished by its capacity enhancement features in active settings and mobility-controlled aerial BSs, improves communication performance. The UAVs' altitude as aerial BSs can be reduced to transmit more data, achieve higher data rates, and maintain better wireless connectivity with the ground user. An aerial BS has the potential to act as an independent communication platform in UAV-enabled networks, providing on-demand communication and responding to the needs of wireless networks. The network's benefits and challenges are listed in Figure 2.12 (Mozaffari et all., 2019).

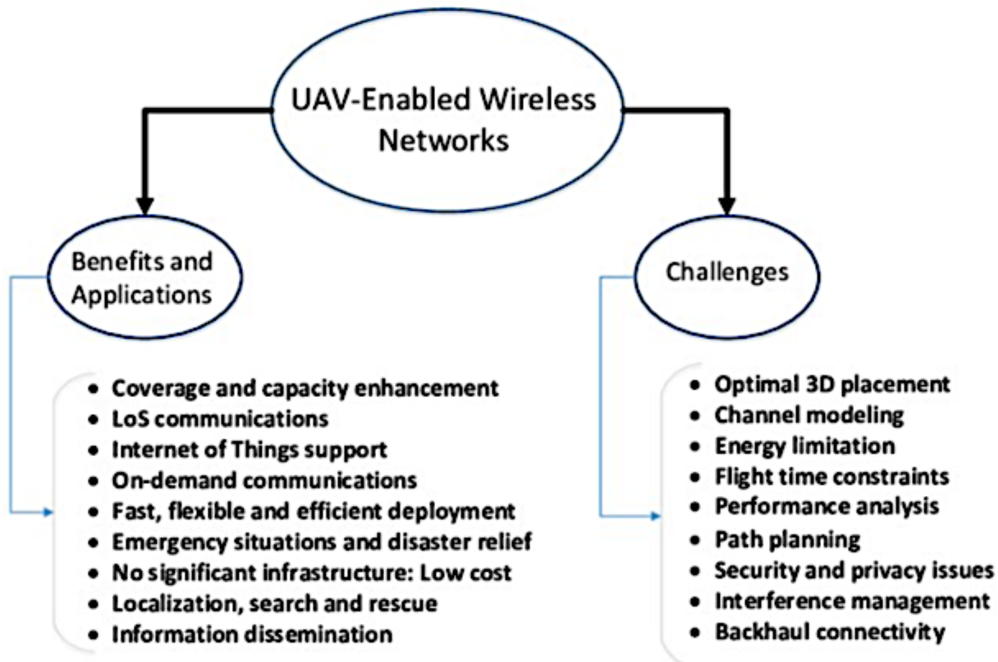


Figure 2.12. Opportunities of wireless networks enabled by UAVs

Cellular-Assisted UAV Communication: UAVs function as enablers of communication networks, acting as new aerial User Equipment (UE) in the sky. In this scenario, UAVs work with terrestrial UEs on the ground for their operations and are provided access to the cellular network infrastructure from the sky. This scenario architecture is shown in Figure 2.11(b). UAVs have the potential to be used as base stations or relays to connect devices in areas without communication infrastructure (point-to-point networks, rural areas, after hazardous events). UAVs acting as aerial UEs provide data communication in broad areas, enabling the potential provided by cellular networks, and can use licensed mobile spectrum for payload communications. Advanced authentication mechanisms of cellular networks make it possible to protect cellular-connected UAVs from unauthorized access control. This scenario has an effective solution for establishing reliable wireless connectivity with ground cellular stations (Zeng & Zhang, 2018).

UAV to UAV Communication: The UAV-to-UAV communication system has been developed to establish a reliable and uninterrupted link between UAVs via a central network or directly, as shown in Figure 2.11(c). A mesh or ad-hoc network is used to communicate. The mesh network is used as an intermediate point in UAV communication, the network's coverage area is expanded, and security is increased. An ad-hoc network is a temporary and dynamic network where data is transmitted when UAVs are close to each other. In UAV-to-UAV communication, different communication networks are used, considering the speed and capacity of the network, such as Wi-Fi, LTE, and 5G. The communication coverage area relies on data transmission speed and signal durability, depending on the channel band. The 2.4 GHz and 5 GHz channel bands are used for industrial, scientific and medical (ISM) applications. Some reserved frequency bands provide higher data rates and more secure communication. Since UAVs or signal sources using the same channel band are likely to cause interference. Techniques such as frequency hopping spread spectrum and adaptive frequency selection are used to overcome such problems. When selecting the channel band, the Doppler shift occurring due to UAVs' dynamic and fast movement may affect the signal quality. UAV-to-UAV communication data security, end-to-end secure connection and a defensive structure against attacks are possible with authentication and encryption protocols. QoS protocols increase the network's performance, reduce delays, and manage bandwidth (Han, 2022; Godugu et al., 2025; Ajakwe et al., 2024).

UAV Security Challenges: UAVs with cellular connectivity are equipped with numerous sensors to collect and disseminate data. UAVs use wireless communication networks to share sensor data with other UAVs or GCSs. Sensitive data sent over a communication channel is prone to cyber and physical attacks. As UAV networks grow in size, their communication poses serious cybersecurity challenges. Therefore, it is essential to ensure the security and confidentiality of UAV communication, especially for critical missions. In addition to data sharing, it is essential to protect sensitive information of the flight mission, such as telemetry data and control commands, from unauthorized access to prevent information leakage. Maintaining data integrity that may change the behaviour of the UAV system is of utmost importance. For this, the communication network should be protected and authenticated.

Secure communication between UAVs through various possible links is essential for maintaining data confidentiality and integrity. The communication network involves multiple stakeholders, including service providers, regulators, and UAV operators. Data exchanged in the UAV communication system should only be shared with authorized users, and third-party access must be prevented. A viable solution for providing a secure, scalable communication mechanism is integrating Blockchain, an immutable, distributed, and decentralized technology, into peer-to-peer UAV networks (Hafeez et al., 2023; Shah, 2024; Ghribi et al., 2024).

Blockchain-Assisted UAV Communication Networks

The blockchain network is a decentralized technology featuring key components such as immutability, smart contracts, encryption, and a distributed ledger. Its decentralization and absence of third-party involvement facilitate secure and transparent record tracking, ensuring data security and privacy. Moreover, it allows multiple entities to communicate securely in a decentralized and collaborative manner.

Traditional communication methods used by UAVs equipped with many sensors in various fields are insufficient to keep UAV data secure. Wireless channels used in communication are prone to security vulnerabilities. UAVs' existing centralized communication and control systems are constantly vulnerable to external attacks, and security vulnerabilities are suitable for information theft. Therefore, there is always a need for a secure UAV network. Blockchain technology significantly contributes to UAV networks due to various security concerns of UAV communication networks (Hafeez et al., 2024).

Blockchain is a chain technology that ensures UAV data is secure and immutable through cryptographic hashing techniques. Cryptography provides a robust security framework used as a barrier to encrypt data against cyberattacks on UAV networks (Khan et al., 2024). Using distributed ledgers provided by Blockchain in UAV communication eliminates the need for a central authority. It enables agreements between UAV and network stakeholders to be automated without any intermediaries through smart contracts, preventing retroactive transactions. Distributed ledgers use public-private key pairs, and peer nodes verify the operation before adding it to the block. Operations recorded and verified by all participants in the network encourage trust and transparency among stakeholders. Blockchain uses consensus mechanisms to ensure that all nodes in the network agree on the state of communication between UAVs. UAVs have unique digital identities. Blockchain provides authentication of the UAV and ensures that only authorized UAVs can access the network (Xiong et al., 2024; Ivascu & Jahankhani, 2024).

Figure 2.13 represents the blockchain layer, data sensing layer, communication layer, and UAV application and control environment for blockchain-assisted UAV networks (Hafez, 2024).

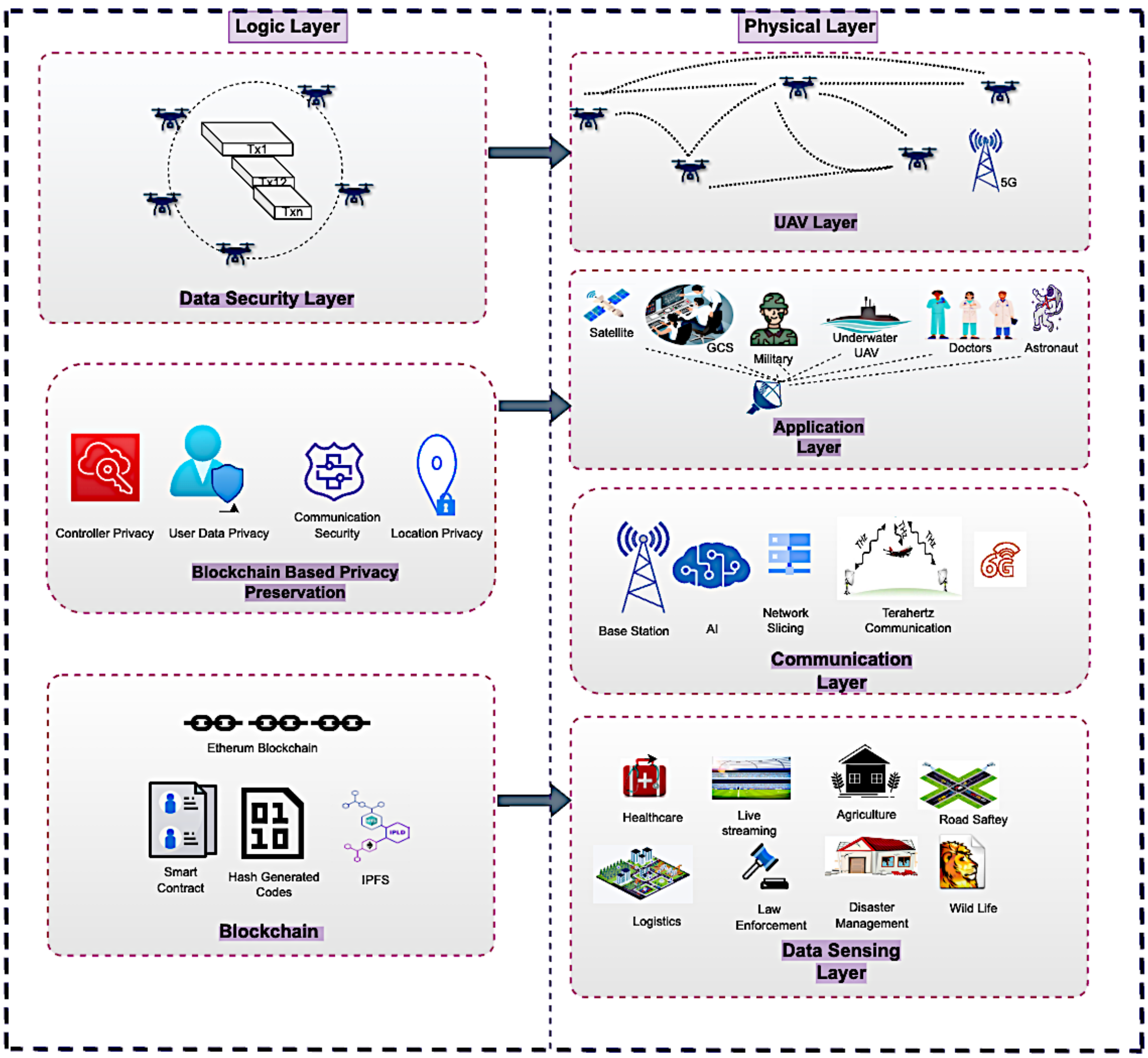


Figure 2.13 UAV communication powered by blockchain

Figure 2.14 illustrates the preservation of privacy in UAV communications based on blockchain technology (Wu et al., 2024).

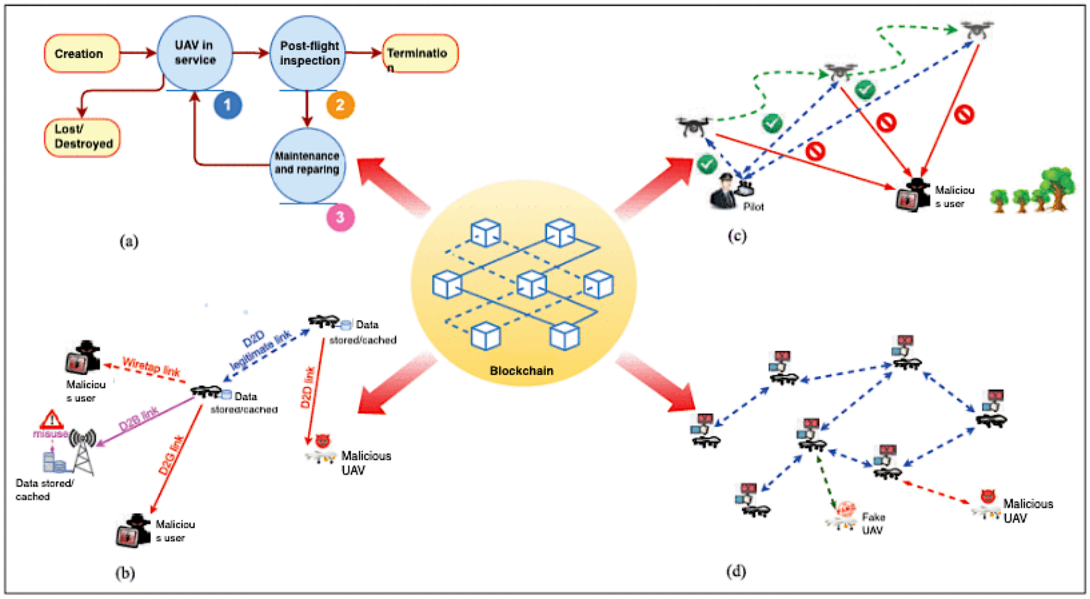


Figure 2.14. Privacy protection using blockchain for UAV communication

Figure 2.14(a) shows the six main stages of blockchain-based identity management for UAVs. Through the decentralized consensus feature, a UAV's identity is securely registered in the decentralized blockchain-based identity management system from its production. The system updates all UAV operation processes during and after service. Thus, the entire life cycle of a UAV is tracked through the system. Smart contracts automate the UAV ID management process.

Data obtained from UAV sensors is of interest to malicious attackers, as shown in Figure 2.14(b). UAVs with high storage capacity collect, temporarily store, and transmit data. In addition to data storage, bandwidth and latency limitations are associated with big data. Therefore, authentication mechanisms should be fully integrated with blockchain-based identity management systems to protect the security and confidentiality of data in UAV communications.

Trajectory planning is crucial for UAV navigation, route planning, and control. The trajectory information of UAVs is vulnerable to malicious attacks, as illustrated in Figure 2.14(c). Centralized management of trajectory information is susceptible to privacy violations, denial of service (DoS), and single-point attacks. These attacks can lead to UAVs being stopped, tracked, and hijacked, while user data may be compromised. Blockchain-based access control mechanisms and authentication help protect trajectory privacy. The decentralization feature of Blockchain reduces the risk of single-point attacks (Venkatasivarambabu & Agrawal, 2024; Anagnostis et al., 2025).

According to many real-world scenarios, multiple UAVs work together, dividing tasks into subtasks. A reliable UAV network requiring coordination must be established for UAV swarms. The dynamic nature of UAVs and the wireless communications used between them make it challenging to maintain a dependable network (Meng et al., 2023). Figure 2.14(d) shows that legitimate UAVs may join the network and disguise themselves to access other UAVs and data. To mitigate potential risks, operations are transferred to the blockchain network. Blockchain's identity management system and consensus mechanisms enhance the network's resilience to these risks.

Blockchain and 5G Integrated UAV Communication Network

5G networks offer low latency and high data rates while enhancing QoS requirements. However, the continuous rise in IoT devices leads to challenges such as unpredictable and irregular loading in 5G networks. This rapid growth in communication traffic results in ultra-dense networks (UDN). When the available network capacity fails to meet the required throughput, QoS standards are compromised. UAVs, serving as mobile service stations, present a solution to UDN. UAV base stations extend coverage and boost network capacity, thus enhancing the QoS of wireless networks. Traditional centralized systems, like cloud and fog computing, are often vulnerable to security and privacy attacks. Conversely, a blockchain-integrated 5G UAV network ensures low latency and provides fast, secure communication between network participants through a decentralized service delivery and routing approach for end users (Aloqaily et al., 2023; Gupta et al., 2021).

Table 2.5 summarizes the blockchain-based solutions for 5G UAV communications.

Table 2.5 Utilizing blockchain technology in UAV communication

No.	UAV Communications	Blockchain Solutions
1	UAV ID management	Transparency, tamper-proof, traceability
2	Data privacy protection	Asymmetric encryption algorithms
3	Trajectory privacy	Authentication and access control schemes
4	Consensus of UAV networks	Fault-tolerance, traceability, anti-falsification

Figure 2.15 presents the blockchain UAV networking architecture utilizing 5G communications across various application scenarios, including healthcare, smart grid, smart city, and border surveillance (Gupta et al., 2021).

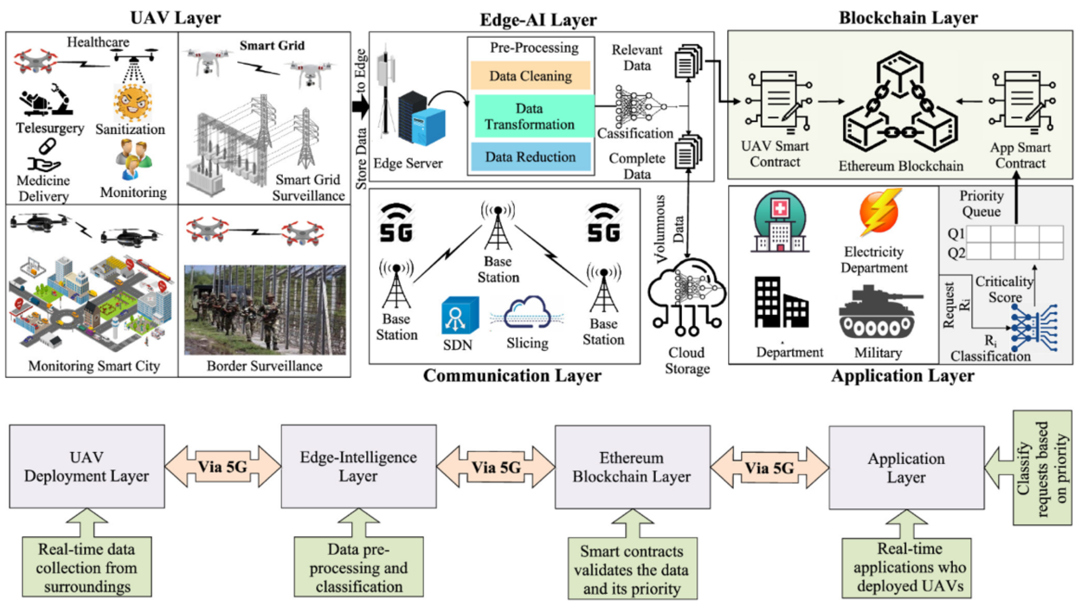


Figure 2.15. Blockchain and AI-based UAV network

The challenges and deployment scenarios of blockchain-assisted UAVs are explained in Figure 2.16 (Hafeez, 2024).

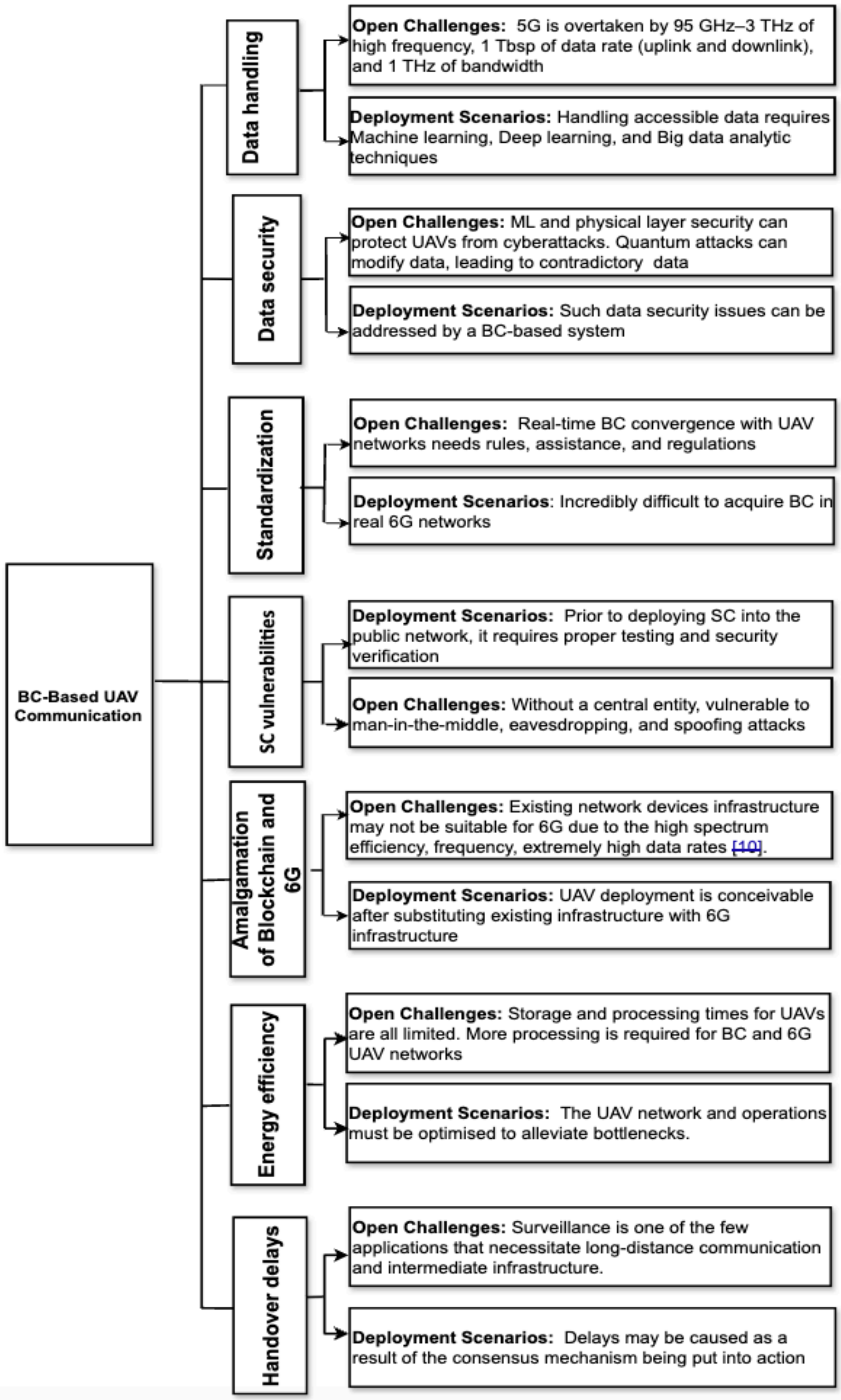


Figure 2.16 The challenges of deploying blockchain-assisted UAV scenarios

CHAPTER III

Problem Definition and Proposed Solution: Optimized UAV Communication

Problem Definition

In recent years, UAVs have gained popularity with their advantages in various fields. UAVs offer a fast and reliable solution, opportunities for modern applications based on the increasing use of IoT devices and rapid developments in wireless communication technologies. Applications are very diverse and require different requirements or features. Current UAV trends are focused on operations such as collecting and transmitting data from sensors, providing information processing services, surveillance, search and rescue, etc., in various communication networks. Depending on the operation, a single UAV or UAV swarm deployment is required. However, while UAVs are used in multiple operations, it should be kept in mind that they are devices with various limitations in terms of staying in the air and establishing communication (Sabouti et al., 2024; Wan et al., 2024; Pandey et al., 2024; Eskandari et al., 2024).

The proven success of UAVs is based on a reliable and efficient communication infrastructure. Wireless communication technologies allow UAVs to participate in dynamic networks. Many challenges need to be addressed to make UAVs more efficient and effective. Crucial limitations, such as energy consumption, flight time, trajectory, amount of data to be received and sent, BER in data transmission, signal quality, SINR, and uninterrupted network provision, create difficulties in the early stages (MahmoudZadeh et al., 2024; Demir et al., 2024; Shakhatreh et al., 2024).

Reliable communication of UAVs is essential in applications where fast, urgent and dependable data communication is required. However, there are some fundamental challenges in UAV communication.

- Communication distance and coverage can be limited, impacting how far signals can travel effectively.
- Bandwidth limitations and managing high data traffic can pose challenges in maintaining efficient communication.

- Reliability and error rates are important to ensure data accuracy and minimize transmission issues.
- Energy consumption and battery life are key concerns, especially for devices operating on limited power sources.
- Issues with metrics like latency and communication speed can affect the responsiveness and efficiency of wireless systems.
- QoS and QoE focus on enhancing communication systems' overall experience and performance.

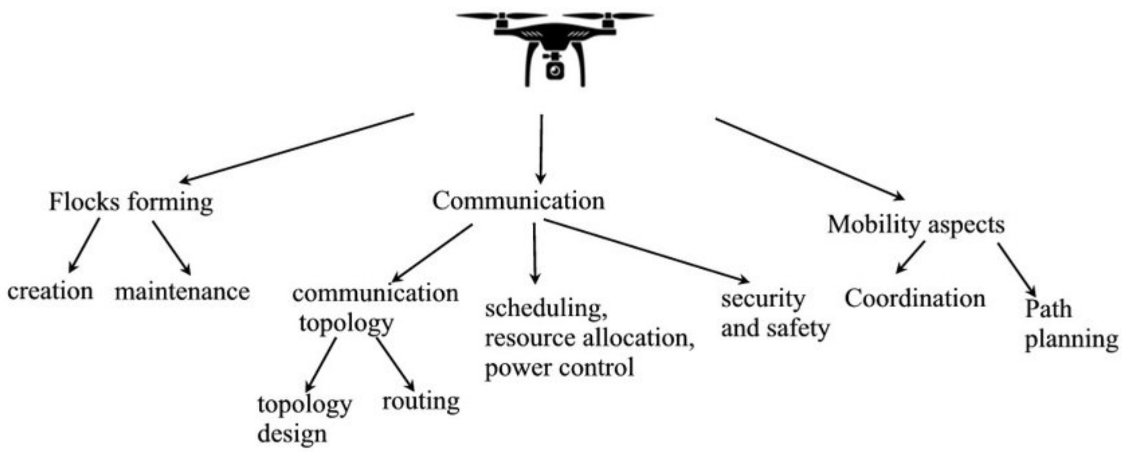


Figure 3.1. UAV flocking challenges

In a successful UAV communication system, low latency, reliable and fast data transmission are expected. The communication infrastructures used in UAV networks require high bandwidth and contain large data traffic, limiting factors for UAV communication. The deficiencies of the topologies proposed and designed for UAV communication create potential obstacles regarding reliable data transmission and signal strength. In cases where signal strength, stability, and a reliable end-to-end link cannot be provided (Garcia-Gil et al., 2024; Mao et al., 2024; Zhang et al., 2024).

Traditional UAV communication solutions are inadequate regarding reliability, flexibility, and efficiency. Signal stability cannot be provided in cases where UAV swarms use the same communication network while the SINR decreases and BER increases. There are operations where UAVs work in coordination with each other. In the continuation of operations, data security between UAVs may be vulnerable to threats and data transmission may be limited. Interruption of operations as a result of such situations creates serious risks in applications where data flow and security are critical.

Optimization challenges often contribute to the achievements of many successful UAV-supported applications. Several optimization methods are needed to make UAVs more reliable and effective and to provide higher-performance communication infrastructures (Jajala & Buduri, 2024; Thantharate et al., 2024; Kumar & Chaudhary; Li et al., 2024).

Low BER, high SINR, and constant signal strength during data transmission increase the system's overall performance. Achieving all these goals together requires optimization suggestions.

The proposed model is to overcome the existing limitations by providing high-performance and reliable communication links.

Proposed Model

A proposal model aims to optimize the UAV communication infrastructure by leveraging the benefits offered by integrated technologies such as 5G, blockchain, and IoT to overcome the limitations encountered in UAV communication. While data transfer occurs with UAVs, each data packet is transmitted over the 5G infrastructure and enters the verification process in the blockchain layer.

A blockchain network is employed to ensure the integrity and confidentiality of transmitted data; when data is transmitted from one UAV to another or a ground station, the blockchain system encrypts the data, organizes it into verified blocks, and securely delivers it to the intended recipient. This approach optimizes the data flow, balancing both security and transmission efficiency. At the same time, the data can be integrated with a cloud platform, addressing the UAV’s limited capacity and enhancing accessibility and scalability. This method ensures an efficient data flow while maintaining a balance between security, transmission speed, and effective use of cloud resources.

The proposed model introduces various communication scenarios, using newly introduced optimization algorithms to enhance communication links to their most efficient levels.

Data Communication Scenarios

Data communication involves transferring and handling large amounts of information, including business records, personal data, and other digital content. Systems or devices responsible for managing these transactions often face processing power and storage capacity limitations, making it difficult to manage such extensive data efficiently. To address this challenge, cloud computing has emerged as a key solution, offering the infrastructure to store and process large datasets securely.

Cloud computing facilitates smooth data processing and analysis, enabling systems to handle significant volumes of information through various communication methods like wireless, cellular, and internet connections. UAVs transmit data to the cloud using various communication methods, ensuring reliable and efficient data transfer. This enables users to access and analyze data in real-time, facilitating prompt and accurate decision-making during critical situations.

The data communication layer provides transmission from source to destination via UAVs using a 5G network. 5G supports ultra-low end-to-end latency (less than 1 ms), ultra-high reliability (normally 99.9%), fast delivery and reliable communication channel. UAVs in operation constantly share information. UAVs are limited by flight time to ensure safe delivery. Delivery information is securely stored as transactions within a blockchain, each identified by a distinct hash value. The transactions encompass essential data, including package weight, transmitter and receiver addresses, the distance between the source and destination, and real-time location tracking. Due to the high costs and limitations of storage within blockchain systems, cloud computing solutions are employed to manage and store the data efficiently, ensuring scalability and seamless operation.

Three unique scenarios were developed to enhance communication efficiency and create dependable, effective service connections. Each scenario utilizes transmission pathways to optimize performance and satisfy specific operational needs.

UAV-to-UAV Communication Scenario: The first scenario depends on the UAV-to-UAV communication link to process the data on the cloud.

Direct communication between UAVs enables them to exchange data and coordinate UAVs actions without relying on a central ground station. This capability enhances real-time information sharing, boosting both operational efficiency and autonomy. Setting up communication between UAVs demands a reliable wireless link that supports high-speed data transfer, minimal delays, and secure transmissions. This setup enhances operational efficiency, boosts situational awareness, and enables advanced tasks like search and rescue, surveillance, and collaborative data gathering. Additionally, this approach minimizes dependence on external infrastructure, making it suitable for remote and isolated missions. However, UAVs have limited data processing and storage capabilities, making cloud computing essential for managing large volumes of data. Cloud services provide the infrastructure required to store, process, and analyze the significant data generated during UAV operations. Incorporating blockchain technology strengthens data security by using decentralized verification and encryption. This ensures the integrity of data and safeguards sensitive information, providing a more reliable and trustworthy communication environment. This enables efficient and smooth data flow between UAVs and other systems, supporting real-time decision-making and enhancing overall system performance.

The UAV-to-UAV communication link is shown in Figure 3.2.

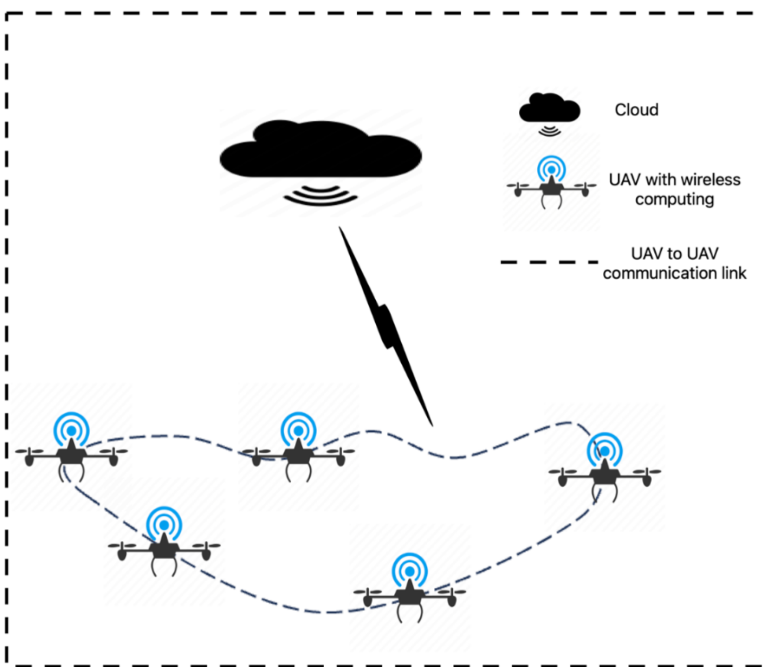


Figure 3.2. UAV to blockchain network connection through the neighborhood UAV

In the UAV-to-UAV communication scenario, priority is given to establishing a connection with nearby UAVs. The setup assumes a possible connection between UAVs and smart contracts within the blockchain network. The aim is to transmit data to the cloud securely via a UAV. The multiple UAVs in the network require an optimal link to ensure reliable, low-latency, and secure communication using 5G services. To achieve this setup, Algorithms 1 and 2 are employed to meet these criteria.

UAV-to-Everything Communication Scenario: The UAV-to-everything (UAV2X) communication link enables seamless interaction between UAVs and other entities, such as UAVs, ground stations, sensors, ground devices, and cloud platforms. It integrates edge computing for real-time processing and utilizes cloud services for scalable data management. Security measures like encryption, authentication, and secure data transmission ensure reliable communication. These components serve the UAV2X communication link to enhance data flow and system reliability.

In cases where no UAV is nearby, the UAV2X communication link is given second priority, as seen in Figure 3.3.

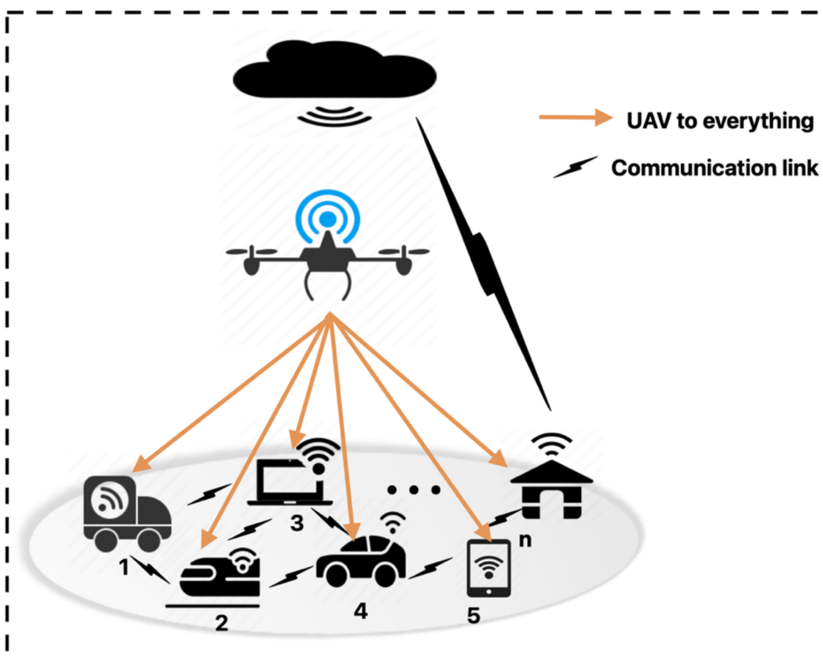


Figure 3.3. UAV to blockchain network connection through the ground devices

The UAV2X scenario considers a flat ground surface with a base station providing cellular 5G service and having a smart contract within a blockchain network. The goal is to form an optimal link with the maximum SINR value and path selection using fixed power algorithms for the UAV relay.

UAV2X has bi-directional communication between UAVs and ground user devices to send commands, receive telemetry data, and ensure real-time control. The obtained big data are transmitted to ground user devices for processing. Big data processing is performed through cloud-based solutions. Cloud platforms allow devices to process data locally, reducing latency and dependence on centralized servers. This is particularly important for time-sensitive applications.

The UAV2X scenario involves device-to-device communication, where devices autonomously exchange data and execute tasks. This is critical for the proposed system's automation and efficiency.

The UAV2X scenario is a dynamic ecosystem that relies on a 5G network, standardized protocols, cloud computing, and blockchain to enable UAVs to communicate with everything from other devices to decentralized servers and cloud platforms.

UAV-to-Base Station Communication Scenario: The UAV-to-base station communication link integrates hardware and technologies to ensure smooth data transfer. The UAV may use advanced communication systems such as RF, cellular networks, or satellite communication, depending on the range and reliability needs. A ground-based base station should have compatible hardware to receive and process the data. To improve the performance, edge computing can be used near the base station for real-time data processing, while cloud services provide scalable storage and analytics capabilities. Secure protocols help maintain the integrity and confidentiality of the transmitted data, ensuring the communication link is efficient and reliable for various applications.

UAVs strategically communicate with a designated base station when finding another UAV or a suitable ground user device for direct connection. The third scenario is a UAV-to-base station connection, as shown in Figure 3.4.

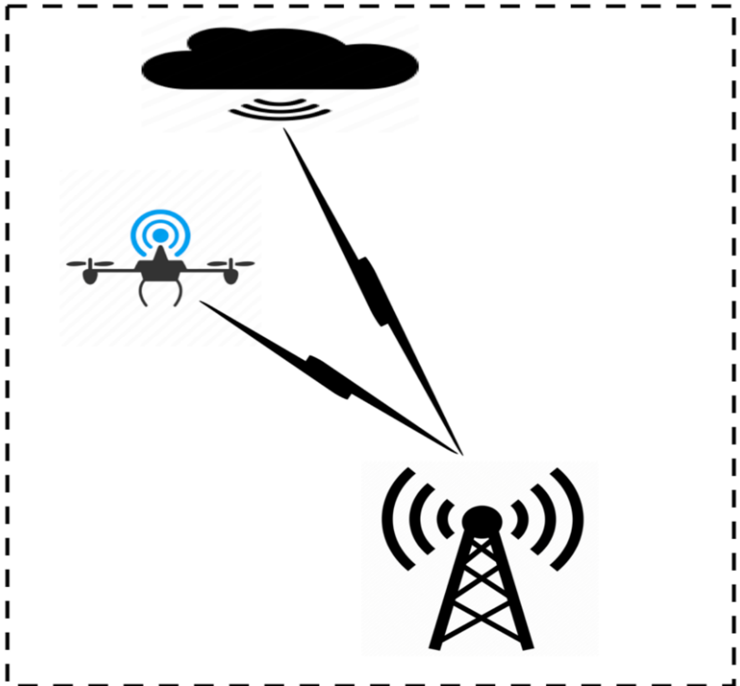


Figure 3.4. UAV to blockchain network connection through the base station

In UAV-to-base station scenarios where UAVs are not directly connected to another UAV or a suitable ground user device, they rely on UAV-to-base station communication to maintain connectivity and enable efficient operations. The base station is a central point of communication, serving as a key connection for UAVs within its coverage area. Communication is established using a 5G cellular network, allowing UAVs to send important data to the base station and receive real-time instructions in return. The base station has advanced communication technology and acts as a relay point, maintaining a seamless connection between the individual UAV and the more extensive network.

The base station collects data from the UAV and establishes a connection with cloud platforms, initiating the transfer of valuable information for processing and analysis. Cloud integration supports the management of large datasets generated by UAVs, facilitating advanced analytics, real-time decision-making, and extracting meaningful insights.

This is particularly crucial in remote or challenging terrains with limited direct UAV-to-UAV or UAV-to-ground communication. The base station serves as a communication bridge and facilitates data exchange, command transmission and link to the cloud.

The base station then uses blockchain technology to enhance the security and transparency of the processed data. Tracking the processed data on a blockchain network ensures an immutable and decentralized ledger, strengthening the integrity and traceability of information. This intricate dance of UAV-to-base station communication, cloud processing, and blockchain tracking represents a sophisticated ecosystem that addresses immediate connectivity challenges and incorporates advanced data management and security measures, showcasing the multi-faceted capabilities of modern UAV technologies.

The UAV-to-base station communication link contributes significantly to UAV operations' overall performance and independence across various, ever-changing environments.

Communication Channel

The channel's characteristics and details need to be optimized for the system's reliability, performance, and efficiency. A more detailed analysis of the different components is necessary for an optimal channel design.

Channel Features

1. **Low Latency:**
   - Low latency is especially important for real-time applications. In a UAV2X connection, remote control commands and data transmission must be timely.
   - Latency should minimize delays in sending and receiving data packets.
2. **High Reliability:**
   - Reliability in UAV2X communication systems means the system can provide uninterrupted communication, especially depending on wind, weather changes and geographical conditions. The channel must be resistant to signal attenuation and noise.
   - Error detection and correction mechanisms (such as ARQ - Automatic Repeat reQuest) help make the channel more resilient.

3. **High Capacity and Efficiency:**
    - In a UAV2X communication link, data transmission usually must be high in quantity and fast. Therefore, a high-capacity channel is necessary to transmit large data packets smoothly.
    - Efficient channel use allows more effective spectrum management and the ability to connect multiple devices simultaneously.
4. **Spectrum Efficiency and Bandwidth:**
    - The channel to be used in UAV2X communication must provide a wide spectrum range to provide more bandwidth and less interference.
    - Bands such as 2.4 and 5.8 GHz offer better performance and wide coverage. In addition, sufficient bandwidth on the channel effectively optimizes data transmission speeds.
5. **Coverage and Mobility:**
    - The channel needs to provide wide coverage since the UAV2X connection is used in fixed or mobile environments. This is especially important for connections with a wide geographic area or mobile drones.
    - The channel, being compatible with mobility, provides a stable connection in communication with vehicles moving at different speeds.
6. **Resistance to Motion and Acoustic/Visual Channels:**
    - The channel must be designed to provide accurate data transfer even in motion to minimize the effect of environmental factors during the drone's flight.
    - Acoustic or visual channels can be used as alternative data transmission methods to increase the reliability of the UAV2X link, especially in challenging environments.

Possible Channel Details:

1. **Frequency Bands:**
    - 2.4 GHz: Generally, provides wide coverage but carries more risk of interference.
    - 5.8 GHz: Has less interference and offers higher data rates, but is effective over a more limited distance.

2. **Modulation and Coding:**
    - High modulation techniques such as Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM), and 64-QAM can be preferred to provide higher data rates and lower error rates.
3. **Spectrum Management:**
    - Methods such as dynamic spectrum access or channel sharing can make the channel more efficient.
4. **Advanced Discovery and Adaptation:**
    - Channel status should be constantly monitored, and the channel that provides the best performance should be selected using adaptive algorithms.

Node and Cell Selection

In the context of UAV2X, establishing a solid communication link is essential for the UAV to maintain continuous and reliable communication with the devices in its environment. Ensuring this connection requires the UAV to evaluate the SINR values around it continuously. The UAV carefully scans the devices in its operating cell, selecting the node that exhibits the highest SINR value to establish the most effective communication with these devices. This process actively enhances communication quality and maximizes data transmission speed.

In addition, in cases where the SINR falls below a predetermined threshold value, the UAV is designed to explore adjacent cells autonomously to provide an optimal connection. This cell-to-cell exploration mechanism allows the UAV to search continuously for the most suitable communication conditions. In this process, the UAV adapts to environmental variables and optimizes signal strength, maximizing communication reliability.

Considering cell and node-based factors, this adaptive strategy is important in modern UAV communication systems. This system provides a more dynamic and intelligent communication infrastructure, performing well in different environmental conditions. Mechanisms in place to continuously assess the UAV’s environment and provide the most effective communication link will provide more advanced and sustainable solutions for future communication systems.

Optimized Communication Link

Communication systems have become one of the fundamental components of technology-based applications in the modern age. The need for effective and reliable communication links, from embedded systems such as UAVs to smartphones and satellite communications to IoT devices, is increasing. Optimizing communication links is very important for these systems to operate effectively.

Establishing communication links presents many challenges, especially for mobile platforms like UAV-based systems. These systems aim to provide fast, reliable, and uninterrupted communication between devices. However, factors such as limited energy resources, dynamic environmental conditions, bandwidth restrictions, and signal weakness in remote areas can negatively affect the continuity and performance of communication links.

Energy consumption is one of the most significant limiting factors in UAV-based systems. Due to limited battery capacities, communication protocols must be carefully designed to conserve energy. Moreover, weather conditions, geographical obstacles, and electromagnetic interference can disrupt the stability of communication links. Insufficient bandwidth is another crucial issue that diminishes communication performance in networks with high data flow. Establishing connections in rural or hard-to-reach areas presents a significant technical challenge due to weak signal strength.

Various optimization methods are used to overcome these challenges. Dynamic link adaptation analyzes the movement of devices and environmental conditions to optimize data transfer rates. Energy-efficient protocols are used especially in UAV networks that require low power consumption, extending battery life. Network topology management optimizes distances and data flows between devices, increasing connection continuity. Frequency management strategies prevent interference by ensuring more efficient use of the radio spectrum.

AI-supported algorithms provide a revolutionary method for optimizing communication links. These algorithms can take proactive measures by predicting connection quality and directing data flow to more efficient routes. At the same time, they offer effective solutions in energy management, ensuring that UAV batteries have an extended lifespan. The capacity to swiftly adapt to dynamic changes enhances the effectiveness of AI in such systems.

Optimization methods are crucial for enhancing communication network performance across a wide range of systems, from UAV-based systems to IoT devices. These approaches, developed for energy efficiency, reducing error rates, and increasing connection continuity, are of great importance for the future development of communication systems. This study discusses theoretical and practical approaches to optimizing communication systems from UAV2X.

Determining the link quality and optimizing the communication performance for UAV2X communication systems is critical for signal strength. SINR expresses the applicable signal strength ratio to the background noise in a communication channel, and high SINR values ensure faster and more error-free data transfer. Especially in communication with mobile devices such as UAVs, the balance between signal strength and interference level directly affects the continuity of the connection. Poor SINR values can lead to data loss, low connection speeds, and increased error rates. Therefore, methods such as adaptive modulation techniques, more powerful antenna systems, and noise reduction algorithms should be used to optimize SINR in communication systems. Increasing SINR positively affects the connection quality and the system's energy efficiency, extending the devices' operating time.

UAV2X connection can provide real-time data flow, supporting rapid decision-making processes in emergencies or sudden changes. The shortest and most efficient connection path is necessary to optimize the communication; low latency and high data transfer rates increase the application's performance and consume less energy. This connection between UAVs, the cloud, and modern technologies provides reliable communication even in all weather conditions and complex environments.

The optimized communication link aims to achieve fast and low bit error rate data transfer within the UAV2X communication network. The optimization uses two different methods.

- The first optimization method prioritizes connections based on SINR, thus creating strong, low-error-rate communication channels. This method aims to reduce errors and signal distortions in the connections between the UAV and the intermediate devices.

- The second optimization method aims to determine the shortest and most efficient path between the UAV and the cloud. This reduces data transmission delays and speeds up transaction completion.

The dual optimization method processes coordinates to improve signal quality and use data paths most efficiently, creating an agile, reliable, and energy-efficient UAV communication network.

The communication link is essential for data transmission, as shared values play a key role. Interference significantly affects the threshold value, making careful consideration crucial. One critical factor to consider is the signal power. In most cases, the signal power between UAV2X is relatively low, making it vulnerable to interference overshadowing.

The first optimization method's UAV2X link uses a fixed rate for data transmission, which is important in minimizing errors during transmission. The basic strategy is to minimize the channel's interference. The communication links in UAV2X scenarios can exhibit various SINRs. The goal is to determine the optimal path between nodes. Carrying out this task requires a comprehensive optimization process. Algorithm 1 carefully determines a path by providing a consistent signal strength.

Algorithm 1: Path selection using fixed power

1. initialize $\boldsymbol{\gamma}, \boldsymbol{\alpha}$; Establish threshold values for the SINR to determine viable link conditions.
2. $\boldsymbol{P_{d_T}^{d_R} \leftarrow P_{int}^{d_R} + \gamma + 10\alpha\, log\left(D_{d_T}^{d_R}\right)}$; Compute the dB equivalent of the transmitter power needed for a specified UAV to Everything (UAV2X) transmitter distance $\mathbf{d_T}$**,** and transmit to the destination $\mathbf{d_R}$.
3. $\boldsymbol{D_{max} \leftarrow 10^{\left(\frac{P-\gamma_b}{10\alpha}\right)}}$; Determine the radius originating from the base station, encompassing cellular users with a SINR shown as $\boldsymbol{\gamma_b}$.
4. For UAV2X do
5. If the UAV2X distance $\leq \boldsymbol{D_{max}}$
6. then declare UAV2X as infeasible
7. Else if
8. $\boldsymbol{P_{d_T}^{max}, BS_k \leftarrow \gamma_d + 10\alpha\, log\left(D_{d_T,BS_k} - D_{max}\right)}$; Compute the power level $\boldsymbol{D_T}$ outside the $\boldsymbol{D_{max}}$ region, ensuring that the maximum interference is below $\boldsymbol{\gamma_d}$ for each UAV2X.
9. $\boldsymbol{P_{d_T}^{max} \leftarrow min_{1\leq i\leq N} P_{d_T,S_i}^{max}, BS_k}$; Met the interference constraint for all $\boldsymbol{BS_k}$.
10. Else if
11. $\boldsymbol{P_{d_T}^{d_R} > P_{d_T}^{max}}$
12. $\boldsymbol{d_T \rightarrow d_R}$ is infeasible
13. Else
14. $\boldsymbol{d_T \rightarrow d_R}$ is feasible
15. End if
16. End for

The first proposed optimization algorithm is to achieve low BER while maintaining a constant power level. The algorithm manages a balance between error reduction and power efficiency, increasing communication reliability without requiring upgraded power transmission. This dual focus demonstrates the algorithm's commitment to providing effective and robust communication performance. The algorithm establishes a UAV2X connection based on a certain SINR threshold value. This threshold should be within the specified limits to ensure secure communication. If this condition is not met, the algorithm works theoretically, and improvements are needed for real-world applications. The algorithm can be better explained using a flowchart technique. The flowchart in Figure 3.5 shows the optimization process to determine the maximum possible power between two nodes that yields a feasible link. The optimum signal strength between nodes is targeted to ensure secure data transmission speed.

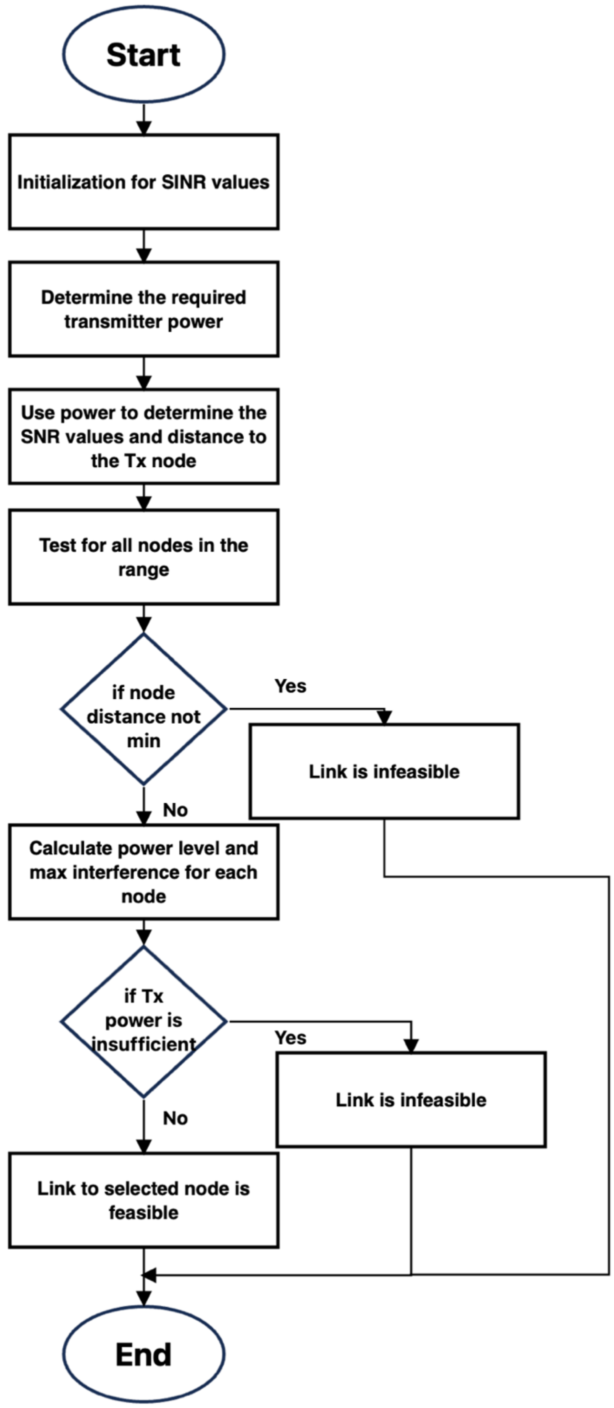


Figure 3.5. Optimized SINR power selection between the nodes

The second proposed optimization algorithm aims to determine the optimal path between nodes.

The optimization method is based on a fixed data transmission rate. The difficulty in the method is directly related to the channel capacity. The process maintains the power at a constant level to keep the data transmission rate constant and ensures that small changes in the channel have minimal impact on the operation. This approach facilitates fast and efficient operation. The overall data transmission is calculated by dividing the number of link hops. This process includes the SINR for the minimum relay nodes. As a result, it selects the optimal path aiming at continuous operation at a single frequency.

The total effective transmission rate R_{eff} calculates and can be expressed as:

$$R_{eff}(\gamma) = \frac{log(1+\gamma)}{Number\ of\ hops} bps\ per\ Hz. \quad (3.1)$$

In Equation 3.1, as the value of the SINR parameter γ increases, the speed of the network, R_{eff}, also increases. The important point is to optimize γ, so that the transmission speed can be increased as much as possible. The objective function can be expressed as follows:

$$\gamma_{opt} = arg_{\gamma^{max}} R_{eff}(\gamma) \quad (3.2)$$

The objective function in Equation 3.2 aims to improve the link performance by limiting the fixed power option. During transmission, the UAV only considers nearby receivers that meet these criteria and excludes the others. This selective transmission reduces the number of hops, increases the channel rate, and provides a shorter transmission time. Reducing hops allows for more efficient communication by considering the power levels at varying distances.

Algorithm 2 describes the optimization procedure for Equation 3.2.

Algorithm 2: Selection of the optimal SINR

1. Initialization $\left(P_{d_S}^{max}\right) \leftarrow d_S$; The highest allowable transmitting power for the source d_S.

2. Repeat the process until the destination node.

3. Choose any three nodes d_K within the coverage area.

4. calculate $\gamma_{d_S}^{d_D} \leftarrow d_D$; Identify the possible SINR. The initial maximum value is observed as (γ_1).

5. $\gamma_2 \leftarrow \max_{k \neq D,S}\left(min\left(\gamma_{d_S}^{d_k}, \gamma_{d_k}^{d_D}\right)\right)$; It calculates the highest possible SINR

6. If $\gamma_1 > \gamma_2$; Greater value does not exist

7. the link is not feasible

8. Else

9. Set possible link $\leftarrow \gamma_2$; the winner is the node with max γ_2 value.

10. step 4 to 9 is repeated for next node γ_3 ; the process for all pathways that involve a three-hop configuration is repeated.

11. end for

12. Test if $\gamma_3 > \gamma_2$ then ; The maximum value of γ_3 encountered if a value greater than the previous one exists.

13. Set possible link $\leftarrow \gamma_3 = \max_{k \neq D,S,j \neq D,S,k}\left(min\left(\gamma_{d_S}^{d_k}, \gamma_{d_k}^{d_j}, \gamma_{d_j}^{d_D}\right)\right)$

14. Else

15. γ feasible link $\leftarrow \gamma_3$

16. End if

17. End repeat

18. $\gamma_{opt} \leftarrow \arg max_{1\le k\le M, \gamma_k\ exists} R_{eff}(\gamma_k)$; the optimum value determined.

The flowchart in Figure 3.6 shows the optimization process performed to determine the maximum usable SINR value.

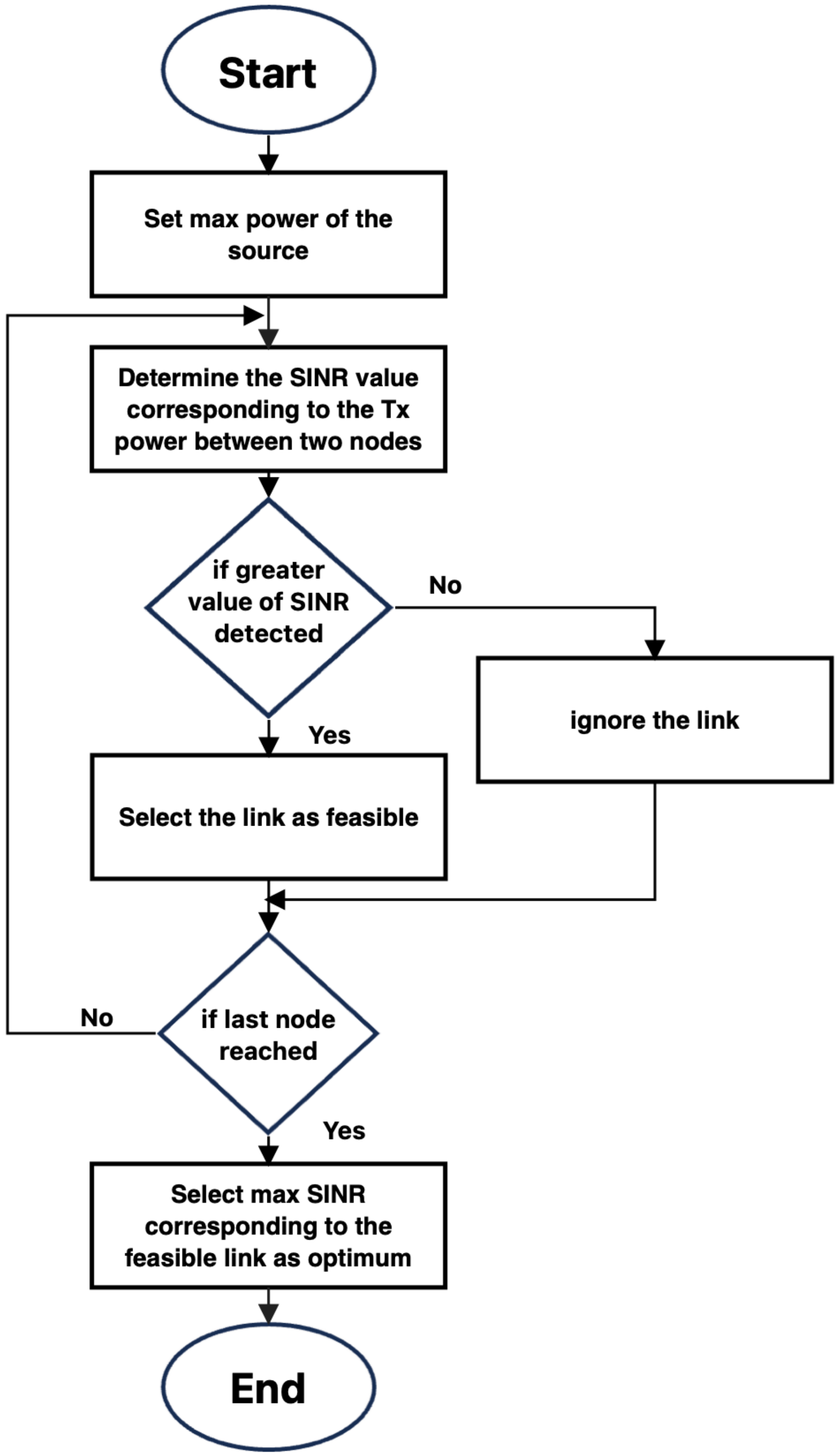


Figure 3.6. Optimized SINR selection for applicable connections

The proposed method enables a UAV to establish links with the nodes by jointly maximizing the SINR and minimizing the distance, under a fixed transmission power constraint. Node selection prioritizes the highest SINR within an acceptable region; if not, the nearest node with SINR above a threshold is chosen. The process iteratively minimizes BER while advancing toward the destination.

Primary objective:

$$\min \text{BER}(\text{SINR})$$

Secondary condition:

- If the nearest node has an acceptable SINR (≥ threshold), prefer the nearest node.

The distance affects selection, however BER (or SINR) is still the driving optimization goal.

$$\min_i \text{BER}_i(\text{SINR}_i)$$

subject to $d_i \leq d_{max}$ (within acceptable region)

If $i \neq$ nearest node: $\text{SINR}_{\text{nearest}} \geq \text{SINR}_{\text{threshold}}$; select the nearest node

$Power_{\text{UAV}} =$ constant

Multi-objective optimization considers four main parameters in the process; distance, fixed power, SINR, and BER. The proposed method combines the two objectives (maximize SINR and minimize distance) into one objective function using weighting factors.

$$\min_i (w_1 \times \text{BER}_i(\text{SINR}_i) + w_2 \times d_i) \tag{3.3}$$

where;

- w_1 and w_2 are positive weighting factors.
- w_1 puts importance on minimizing BER (maximize SINR).
- w_2 puts importance on minimizing distance.

The general optimization objective can be expressed as:

$$\min_i (w_1 \times \mathrm{BER}_i(\mathrm{SINR}_i) + w_2 \times d_i) \tag{3.4}$$

Subject to $d_i \leq d_{max}$

$\mathrm{SINR}_i \geq \mathrm{SINR}_{\mathrm{threshold}}$ (for selected node)

$Power_{\mathrm{UAV}} = \mathrm{constant}$

The weights control the trade-off between SINR (for better BER) and distance (for shorter hops).

- If the prioritize SINR (low BER) over distance**;**

$$w_1 \gg w_2 \text{ (e.g., w1=1, w2=0.1)}$$

The optimization will mostly select nodes with the best SINR, even if they are slightly farther.

- If the prioritize minimizing path length (shorter hops);

$$w_2 \gg w_1 \text{(e.g., w1=0.1, w2=1)}$$

The optimization will favour nearby nodes, as long as the SINR is still above the threshold.

- To establish balance;

$$w_1 \approx w_2 \text{ (e.g., w1=1, w2=1)}$$

The optimization method provides a fair balance between SINR and distance equally.

The UAV operates in a dynamic environment, and network conditions must be changed accordingly. The proposed method dynamically maintains a balance between multiple affecting parameters.

If the UAV is experiencing a depletion of energy resources, it is advisable to implement a strategy such as increase w_2 that prioritizes shorter hops.

If channel conditions deteriorate, such as increased interference, a strategy that prioritizes higher SINR should be adopted.

$$w_1 = \frac{1}{1 + \alpha d_i}, w_2 = \frac{\alpha d_i}{1 + \alpha d_i} \tag{3.5}$$

where α is the tuning parameter controlling the sensitivity of weight change with distance:

- If distance d_i increases, w_2 increases, meaning shorter hops are preferred.
- If distance is small, w_1 dominates, meaning SINR is more critical.

The weighting factors' behaviour and meaning can be explicitly defined as follows.

The weights sum to 1 and can be expressed as:

$$w_1 + w_2 = \frac{1 + \alpha d_i}{1 + \alpha d_i} = 1$$

w_1 is inversely related to distance, as distance increases, the SINR weight decreases.
w_2 is directly related to distance, as distance increases, the distance penalty increases.
α controls the rate of transition:

Small α → smoother weighting, less distance sensitivity.

Large α → steeper change, more aggressive distance penalty.

The process enables advantages as follows.
Automatically adapts weights based on real-time distance.
It avoids hard switching and smoothly interpolates between SINR priority and distance efficiency.
Particularly useful in dynamic environments like UAV communication.
The affecting parameter of α can be shown in Figure 3.7.

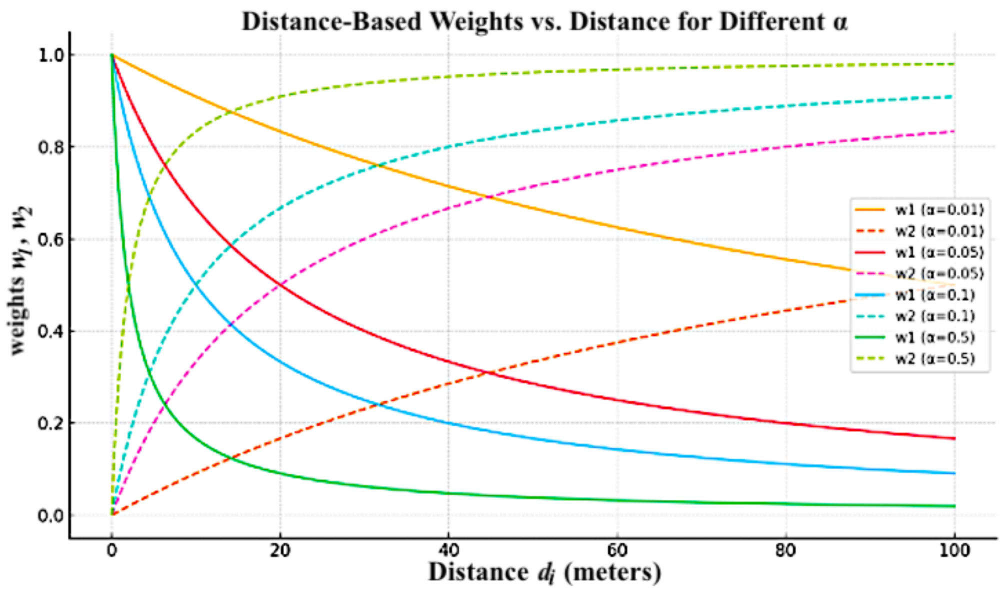


Figure 3.7. Dynamic behavior of the tuning parameter α

The plot showing how the weights w_1 and w_2 vary with distance for different values of α. As d_i increases, w_1 (SINR weight) decreases, w_2 (distance weight) increases. Larger α values cause a steeper transition, making the system more sensitive to distance changes.

The tuning parameter α plays a pivotal role in balancing the influence of distance and SINR during the link selection process. Several selection strategies can be employed to determine its value:

- Empirical Tuning via Simulation: α may initially be selected based on simulation results. A range of α values are tested under varying network scenarios to observe their effect on key performance indicators such as BER, SINR, transmission delay, and overall link stability. The optimal α is chosen to minimize BER while ensuring reliable and consistent communication performance.
- Context-Aware Determination: The value of α can be defined according to the operational environment. In urban or interference-dense scenarios, it is advisable to assign a smaller α to prioritize SINR over distance. Conversely, in sparsely populated or long-range transmission settings, a higher α is more suitable as it emphasizes shorter communication paths.

- Dynamic or Adaptive α Adjustment: To reflect environmental dynamics, α can be defined as a time-varying function:

$$\alpha(t) = \alpha_0 + \beta \cdot I(t) \tag{3.6}$$

where:

α_0 is the baseline weight factor,

$I(t)$ represents a real-time indicator of channel conditions, such as interference level or SINR variability,

β is a sensitivity coefficient determining the rate of adaptation.

This formulation enables the UAV to adjust its decision-making criteria in response to real-time network conditions. The goal is to dynamically shift the balance between SINR and distance as the network environment changes.

The parameters can be determined as follows.

To define the range of $I(t)$ in Equation 3.6, a function that reflects current channel conditions and is calculated using normalized SINR can be used. For example, if the SINR varies between 0 and 20 dB, the interference indicator may be defined as:

$$I(t) = \frac{20 - \text{SINR}\ (t)}{20}$$

In this form, $I(t) = 0$ means excellent SINR, while $I(t) = 1$ indicates lower signal quality.

The setting α_0 defines the influence of distance under ideal conditions. Typically, small values are chosen, such as:

$$\alpha_0 \in [0.01, 0.05]$$

Smaller values make the system more SINR-focused, while slightly higher values allow distance to have a moderate effect even when SINR is strong.

The coefficient β controls how aggressively α changes in response to interference. It is computed based on a chosen maximum value of α:

$$\beta = \alpha_{max} - \alpha_0$$

For instance, if $\alpha_0 = 0.02$ and $\alpha_{max} = 0.2$, then $\beta = 0.18$, this configuration allows $\alpha(t)$ to increase as SINR degrades, shifting the selection strategy toward favoring closer nodes.

This dynamic approach enables the algorithm to remain adaptive, ensuring that link selection continues to balance communication reliability and path efficiency in real time.

To ensure adaptability in dynamic communication conditions, the weighting parameter α is adjusted in real time as a function of network interference or SINR degradation. The formulation can be defined as;

$$\alpha(t) = \alpha_0 + (\alpha_{max} - \alpha_0) \cdot I(t)$$

allows α to scale smoothly between value α_0 and an upper bound α_{max}based on a normalized interference indicator $I(t) \in [0,1$. This ensures that under low interference, SINR is prioritized (lower α), while in high-interference environments, greater emphasis is placed on minimizing distance (higher α). This dynamic adjustment helps maintain link quality while managing energy efficiency and reliability.

The method automatically balances SINR and distance depending on the UAV's position and node locations. The proposed optimization method is subject to several constraints to ensure safe and secure communication, distance limitations, and constant transmission power.

- SINR constraint:
  $SINR_i \geq SINR_{threshold}$, ensuring reliable communication quality.
- Distance constraint:
  $d_i \leq d_{max}$, limiting the maximum transmission range.
- Transmission power constraint:
  $P_{tx} = P_0$, where P_0 is the fixed transmission power.

The general objective function can be expressed as:

$$\min_{i \in \mathcal{N}} w_1 \times \text{BER}_i(\text{SINR}_i) + w_2 \times d_i \tag{3.6}$$

Subject to $d_i \leq d_{max}$

$\text{SINR}_i \geq \text{SINR}_{\text{threshold}}$

$P_{tx} = P_0$

The distance from the UAV to a node was calculated using the 3D Euclidean distance formula. The UAV has an altitude (z-axis) and the node is located in a 2D plane (x, y).

The UAV position defined as $(x_{\mathrm{UAV}}, y_{\mathrm{UAV}}, h)$ (where h is the fixed altitude of the UAV) and ground node position defined as $(x_i, y_i, 0)$. Then the distance d_i between the UAV and node i is:

$$d_i = \sqrt{(x_{\mathrm{UAV}} - x_i)^2 + (y_{\mathrm{UAV}} - y_i)^2 + h^2} \tag{3.7}$$

The proposed optimization method was implemented in a healthcare application directly impacting human life.

CHAPTER IV

UAV Communication Assisted Healthcare 5.0 Industry

UAVs have increasingly become invaluable across various fields in recent years, providing innovative solutions for the healthcare sector. They offer numerous practical advantages, such as delivering medical supplies to remote locations and establishing communication networks during emergencies. In scenarios involving natural disasters, epidemics, or conflict zones where traditional methods fall short, UAVs enable healthcare services to expand their reach by delivering quicker, more affordable, and easily accessible options. These technologies have transformed the sector through logistical services, improved data transmission, patient monitoring, and the digitalization of the healthcare industry (Nalini, 2024; Campbell et al., 2024; Akhai, 2024; Thakur et al., 2024; Mohsan et al., 2023; Suleiman & Adinoyi, 2023; Bhandari & Sharath, 2024; Singh & Kaunert, 2024).

The healthcare industry is radically transforming by integrating digital advancements and cutting-edge technologies. Healthcare 5.0 is a concept that defines an integrated healthcare system driven by data, centred on individuals, and supported by advanced technologies. Communication-based applications of UAVs enhance the effectiveness of healthcare services and play a crucial role in this transformation. Utilizing UAVs in line with the Healthcare 5.0 vision offers significant benefits regarding the accessibility, speed, and efficiency of healthcare services (Wu et al., 2024; Maguluri et al., 2024; Kolasa, 2023; Malviya et al., 2024; Basulo-Ribeiro & Twixeria).

UAV-based communication systems are regarded as essential technologies supporting the connected and personalized healthcare services envisioned by Healthcare 5.0. When traditional communication infrastructures are inadequate or damaged during crises such as natural disasters, UAVs can mitigate communication disruptions by functioning as portable base stations and facilitating emergency response operations. These systems ensure coordination among teams and also allow for the real-time transmission of patients' biometric data or medical records to health centers.

Consequently, decision-making processes are expedited, improving patient outcomes (Fotohi, 2022; Kumar, 2022; Kou et al., 2022).

Supported by artificial intelligence, UAVs offer innovative solutions in healthcare services as one of the cornerstones of the Healthcare 5.0 ecosystem. Analysis of data collected by UAVs equipped with sensors with artificial intelligence algorithms allows early diagnosis and proactive intervention mechanisms to be operated effectively. Real-time data sharing by UAVs offers a significant advantage, especially in monitoring and controlling epidemics. This approach is directly compatible with the preventive health management strategies targeted by Healthcare 5.0 (Pattepu et al., 2024; Nalini, 2024).

Data security and privacy are indispensable elements of the Healthcare 5.0 vision, and the integration of UAV communication systems with blockchain technology offers an important solution in this area. Blockchain-based systems ensure patient data is transported securely and accessed only by authorized persons. This prevents data privacy violations and increases the reliability of healthcare services (Wang et al., 2023; Son et al., 2023; Harbi et al., 2023; Li et al., 2024).

In line with Healthcare 5.0's sustainability goals, UAVs also significantly reduce environmental impacts. Unlike traditional transportation methods, UAVs provide an environmentally friendly alternative with low energy consumption and carbon emissions. This feature optimizes healthcare services within the economic and environmental sustainability framework.

The UAV-based communication systems stand out as an innovative tool that contributes to the individual-focused and technologically based healthcare ecosystem of Healthcare 5.0. With advantages such as real-time communication, artificial intelligence-supported data analysis, blockchain-based security, and environmental sustainability, UAV systems are expected to find wide-ranging applications in healthcare services. In this context, the widespread use of UAVs in the healthcare sector can potentially create a revolutionary transformation in future healthcare services.

Motivation

The study adapts the integration of UAV and blockchain technologies for the safest and most efficient transportation of medical supplies in healthcare services. Due to changing environmental or logistical parameters, medical supplies generally require fast delivery and a secure recording and tracking system. In this context, UAVs are used to meet fast delivery requirements, while blockchain technology ensures that data transactions during the transportation process are managed securely and reliably. In particular, variable environmental and logistic parameters related to the delivery of medical supplies can be effectively monitored and recorded in the integrated operation of these technologies. This approach creates fast, secure, transparent supply chain processes in Healthcare 5.0 services.

The model proposed in Figure 4.1 describes the functioning of blockchain-based drone delivery for healthcare applications.

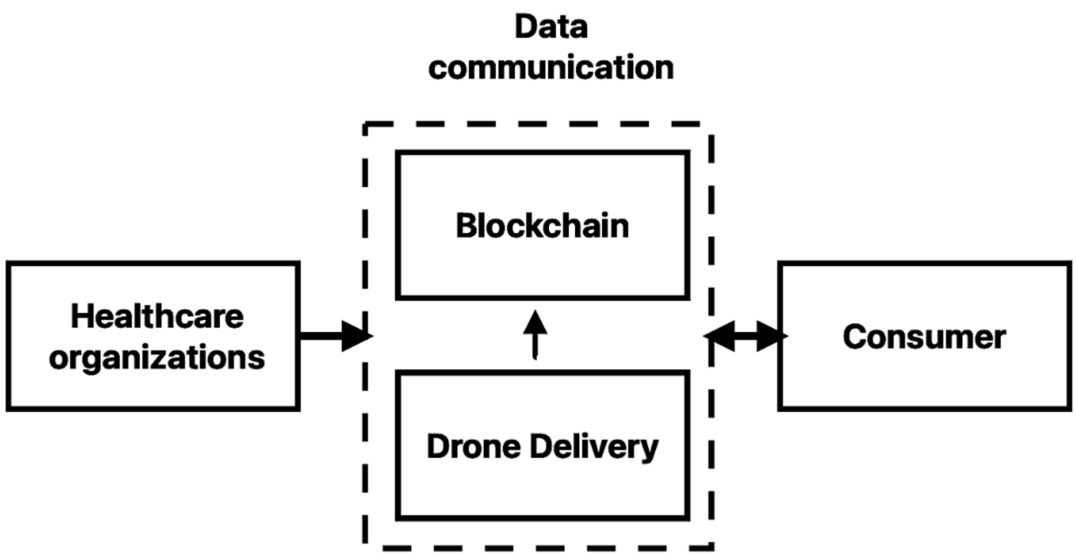


Figure 4.1. Block diagram illustrating the proposed architecture

Healthcare organizations use blockchain networks to transmit information about medical supplies or healthcare services securely. Blockchain allows data to be recorded transparently, securely, and immutably. Through this network, healthcare organizations send the necessary information to the drone delivery unit, including all the parameters related to delivering healthcare supplies or services.

The consumer unit (patient or healthcare recipient) requests a service from a healthcare institution through a data communication unit. This communication unit communicates the consumer's healthcare needs to the healthcare institution. The healthcare institution then coordinates with the UAV delivery unit to provide the medical supplies or service.

UAV delivery plays an important role in healthcare 5.0 applications because low-power open channels meet the dynamic communication requirements of high mobility. This enables the rapid and safe delivery of medical supplies or medicines. UAVs are remotely operated via ground stations and navigate through challenging terrains and environments as self-programmed systems. However, the security of these systems is at risk due to several critical threats. UAVs are vulnerable to security threats such as jamming, hijacking, and side-channel attacks by malicious entities. Jamming disrupts communication signals, negatively affecting drone and ground station data transmission. Hijacking attacks can seize control of UAVs from malicious entities, leading to system misdirection. In addition, side-channel attacks by malicious entities can threaten the security of UAVs by interfering with their electronic systems. On the other hand, the energy depletion of UAVs is also a major challenge, especially in long-distance deliveries, as rapid battery depletion can hinder operations. Additionally, changes in guidance paths, weather conditions, or obstacles can make it difficult to accurately navigate UAVs. These challenges are important hurdles to overcome before UAV technologies can be effectively used in healthcare.

Blockchain technology offers an effective solution to overcome security threats to UAVs. Blockchain networks protect against malicious attacks that gain unauthorized access to UAVs. Participants in the blockchain network share blocks with unique hashtags stored on distributed ledgers. This structure records each transaction securely and transparently, making all data transfers to UAVs traceable. One of the important advantages of this system is that miners participating in the blockchain network can access blocks using their hash information to verify transactions. All miners who complete the transaction complete the verification process, adding new blocks to the chain, and these replicated copies are shared with all miners. The chaining process prevents the modification of blocks, creating a strong firewall against potential attacks on UAVs. These decentralized structures play a critical role in ensuring the security of UAVs' communication systems and making them resistant to attacks. In addition, the decentralized structure of the blockchain improves the system's performance, improving security more efficiently and ensuring the security of data transmission with UAVs. This technological integration enables the safe and efficient use of UAVs in healthcare, providing an important security solution within the framework of Healthcare 5.0 applications.

The proposed scheme uses three interconnected parts: The Healthcare organizations layer, the UAV layer, and the consumer layer, as shown in Figure 4.2.

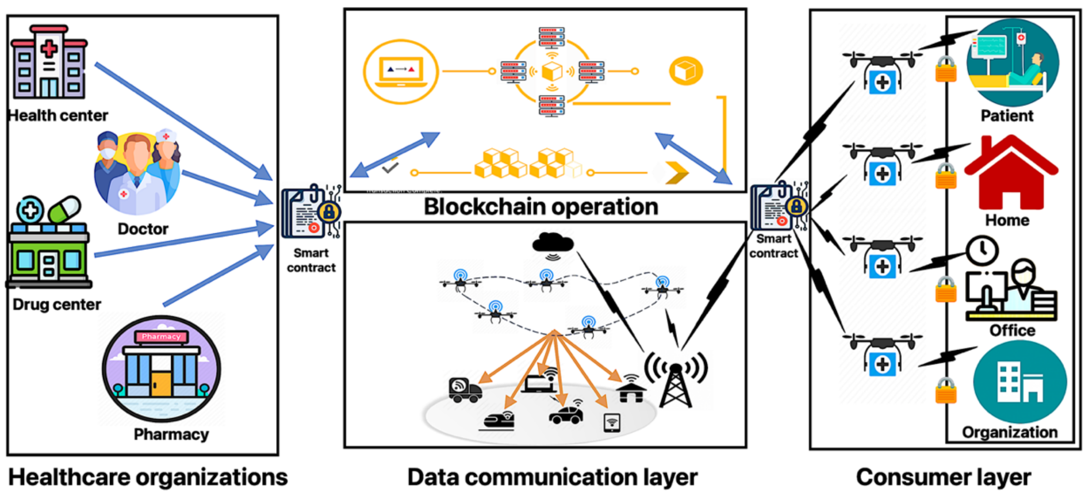


Figure 4.2. Infrastructure of the suggested approach

Figure 4.2 presents the core functionality of a secure healthcare service, operating independently of a centralized approval process. The healthcare organization's unit consists of all parties, such as a doctor, drug center, health center, pharmacy, etc. The basic operation of this unit is to receive a request from the consumer layer.

The blockchain network operates on a decentralized model, which helps lower operational costs while enhancing system throughput and latency. One key benefit is accessing patient medical records using a single hash key, enabling healthcare organizations to verify the suitability of a requested healthcare product based on the patient's medical history.

The institutions involved in the consumer layer can include patients and non-patients requesting medical supplies via a smart contract operating on a blockchain network. The consumers ' hash key values facilitate communication between the consumer layer and healthcare organizations. Additionally, the consumer layer indicates the delivery location for the supplies, ensuring it falls within the healthcare provider's service area.

The verification process prioritizes requests based on their urgent or non-urgent status by assigning a critical level to the request score. Most classification algorithms, such as the Bayesian classifier, use the status of 1 for urgent and 0 for non-urgent. It is the unit responsible for the reliability and consistency of the delivery system and the payment reconciliation between the parties using smart contracts. After reconciliation and after establishing a communication connection with the data communication layer as the following process, the delivery action begins.

The data communication layer primarily facilitates the transmission of information from source to destination through UAVs utilizing the 5G network. While in operation, UAVs continuously transmit data. Their flight time is restricted to guarantee safe delivery. The delivery details are recorded in the blockchain as transactions, each identified by a unique hash value.

The transaction consists of information such as the address of both parties, the weight of the package, the distance between the source and the destination, and tracking the location. The storage capacity in such a system is limited and costly, so cloud computing is used for these purposes.

The introduced method resolves the requirements for privacy, security, data reliability, fault tolerance, data inconsistency, and instant data access.

CHAPTER V

Simulation Setup and Results

Purpose of the Simulation

This study evaluates the use of UAV technology in medical services within the Healthcare 5.0 paradigm. This approach aims to make healthcare services more efficient, secure, and accessible using advanced technologies such as IoT, blockchain, and autonomous systems.

In this context, the main purpose of the simulation is:

- To analyze the communication and security aspects of drone-based medical supply delivery.
- To test various algorithms to increase communication efficiency.
- To increase the efficiency of the system by implementing a prioritization mechanism.

The proposed system was developed to ensure the rapid and reliable transportation of medical supplies in emergencies. Therefore, data transmission between drones, smart devices and base stations is highly significant in the simulation process.

Content of the Simulation

The simulation was created to test the optimization of data communication for UAV-based medical supply delivery. Several critical elements and algorithms have been proposed.

- The proposed algorithm has been tested to perform communication and data transfer most efficiently.
- The improved algorithm has optimized the data transmission between UAVs, ground user devices (e.g. smart devices in hospitals or ambulances) and base stations.
- It aims to prevent communication interruptions, speed up data transfer, and minimize delays in delivering medical supplies.

General Contribution

The contributions of this model are verified through the simulation as follows;

- The difficulties encountered in the communication process and their solutions are determined.
- The ability to make UAV-based medical supply delivery more efficient is tested.
- The effect of the prioritization mechanism on medical services is examined.
- A comprehensive assessment is made of the possibility of UAV technology revolutionizing the healthcare sector.

The outcome of the simulation is as follows;

- Medical delivery processes can be made more secure, ensuring the reliability of sensitive procedures such as drug and organ transplants.
- The system helps provide medical services much faster in difficult-to-access places, such as natural disasters, war zones, rural areas, or emergencies.
- Since the communication infrastructure is made more stable, delays in healthcare services can be prevented.

The simulation was carried out to test and optimize the performance of the UAV data transmission system. The data obtained guides real-world applications and contributes to the widespread and more feasible use of UAVs in healthcare 5.0.

Simulation System Settings

Table 5.1 lists the parameters of the simulation setup. These parameters clearly show the simulation with the initial values.

Table 5.1 Simulation parameters of the communication system

Parameter	Description	Value
N_a	Number of transmitter/receiver antennas	10
f_c	Carrier frequency	30 GHz
T_s	Sampling time	10^{-7} s
G	Length of the cyclic prefix	256
f_{Dmax}	Maximum Doppler shift	2 kHz
N	Number of subcarriers	1024

The purpose of the communication link is to enable all facilities from the transmitter (UAV) to the receiver at a destination. Several methods can be considered to implement such a communication link.

Chapter 3 describes the possible communication links using three scenarios: UAV-to-UAV, UAV-to-Base Station, and UAV-to-X communication links. The UAV2X communication link involves all scenarios, so the optimization process only applies to it.

Optimized Process for UAV2X Communication Link

The main criteria for the process are the UAVs' energy consumption, minimization, and the selection of the highest SINR values to minimize the error margins during the data transfer process.

The initial process is to locate the source, destination, and available nodes, as shown in Figure 5.1.

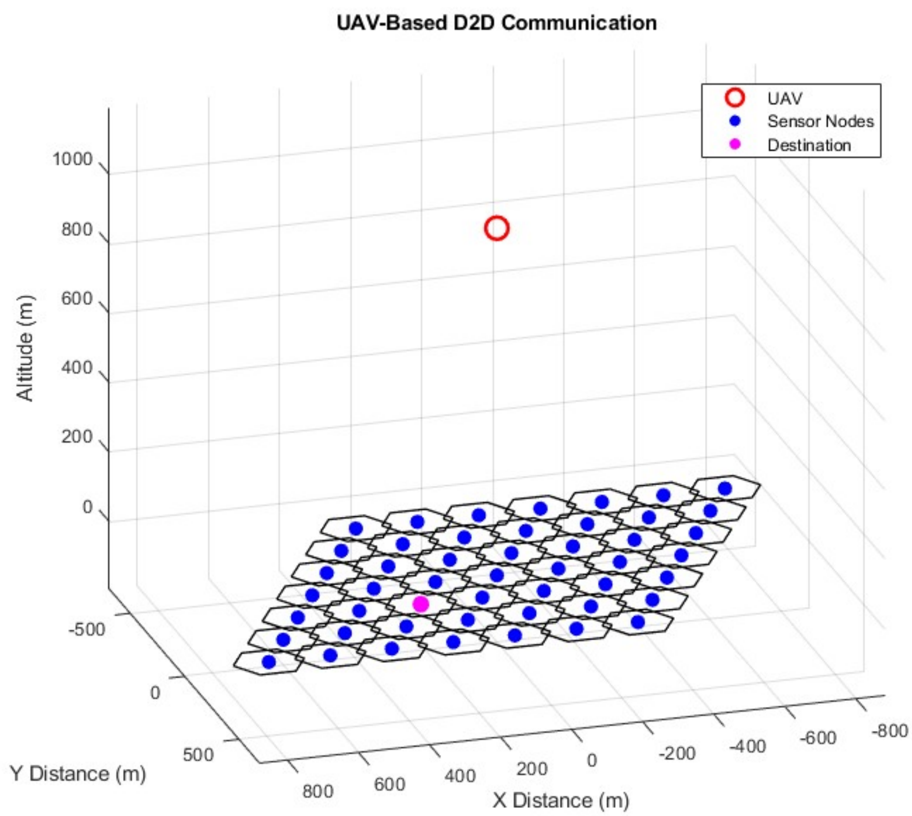


Figure 5.1. State of source, destination, and nodes arrangement

Figure 5.1. shows a UAV hovering and performing communication tasks at a certain altitude. The area is divided into multiple small cells on the ground, each containing a sensor node.

The first selection is to identify the nearest node with the highest SINR value. The optimization process prioritizes the node with the highest SINR value before searching for the shortest distance. The SINR is a key metric used to evaluate the performance of communication systems, including UAV-based communication systems. It measures the quality of a received signal in the presence of interference and noise.

For a general communication system, the SINR at the receiver can be defined as:

$$\text{SINR} = \frac{P_{\text{signal}}}{P_{\text{interference}} + P_{\text{noise}}} \tag{5.1}$$

where:

- P_{signal} is the power of the desired signal (from the source or UAV).

- $P_{\text{interference}}$ is the total power of interfering signals (from other sources or UAVs).
- P_{noise} is the noise power, which is typically modelled as AWGN.

UAV-based Communication:

The SINR was computed at the destination node, considering the signal from the UAV as the desired signal, interference from other UAVs or devices (if any), and noise. The step-by-step process is described below.

1. Signal Power P_{signal} :

The signal power received at a destination node depends on the distance between the UAV (source) and the destination and the UAV's transmission power. The path loss model can model this.

$$P_{\text{signal}} = P_{\text{tx}} \cdot \left(\frac{d_0}{d}\right)^n \tag{5.2}$$

where:

- P_{tx} is the transmission power of the UAV.
- d_0 is the reference distance (often chosen to be 1 meter for simplicity).
- d is the distance between the UAV and the destination node.
- n is the path loss exponent, typically taken between 2 (free space) to 4 (urban environments).

2. Interference Power $P_{\text{interference}}$:

In the case of multiple UAVs transmitting to different sensor nodes, interference will be caused by the UAVs transmitting signals to other destinations close to the desired destination. The interference power depends on the signal strength of these interfering UAVs.

For each interfering UAV i, the interference power is given by:

$$P_{\text{interference}} = \sum_{i \neq \text{UAV}} P_{\text{tx}} \cdot \left(\frac{d_0}{d_i}\right)^n \tag{5.3}$$

where:

- d_i is the distance between the interfering UAV i and the destination node.
- The sum accounts for all interfering UAVs.

3. Noise Power P_{noise} :

The noise power is often modelled as AWGN and is calculated based on the system's bandwidth and noise figure. The noise power is given by:

$$P_{\text{noise}} = N_0 \cdot B \tag{5.4}$$

where:

- N_0 is the noise power spectral density (typically in dBm/Hz).
- B is the bandwidth of the communication system (in Hz).

The SINR calculation procedure is defined as follows.

1. **Identify Parameters:**
    - Transmission power P_{tx} of the UAV.
    - Distance d between the UAV and the destination node.
    - Distance d_i between interfering UAVs and the destination node.
    - Path loss exponent n.
    - Noise power P_{noise} based on N_0 and bandwidth B.
2. **Calculate the Desired Signal Power P_{signal} :**
    - Use the path loss model to calculate the desired signal power the destination node receives from the UAV.
3. **Calculate the Interference Power $P_{\text{interference}}$:**
    - Sum the interference from all other UAVs based on their distances to the destination node.
4. **Calculate the Noise Power P_{noise} :**
    - Use the known noise spectral density and bandwidth to calculate the noise power.
5. **Compute the SINR:**
    - Finally, compute the SINR using the formula:

$$\text{SINR} = \frac{P_{\text{signal}}}{P_{\text{interference}} + P_{\text{noise}}} \tag{5.5}$$

Interpretation:

- A higher SINR indicates better communication quality, as the desired signal is stronger than interference and noise.
- A lower SINR may result in poor communication performance and higher bit error rates.

Furthermore, the power energy consumption optimization requires minimum path selection using the shortest distances. Calculating the distance between the node to the node and the node to the UAV follows.

The general 3D Euclidean distance formula in Equation 5.6 between two points (x_1, y_1, z_1) and (x_2, y_2, z_2) is:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{5.6}$$

where:

(x_1, y_1, z_1) are the coordinates of the first point (e.g., the UAV or the sensor node).

(x_2, y_2, z_2) are the coordinates of the second point (e.g., the destination node or other sensor nodes).

The UAV is at a fixed altitude, and the sensor nodes are on the ground (z = 0). To calculate the distance from the UAV to a sensor node or destination, the 3D Euclidean distance formula was applied.

For each sensor node at position $[x_{\text{node}}, y_{\text{node}}, 0]$, the distance to the UAV can be calculated using the formula:

$$d_{\text{UAV-node}} = \sqrt{(x_{\text{node}} - x_{\text{UAV}})^2 + (y_{\text{node}} - y_{\text{UAV}})^2 + (0 - z_{\text{UAV}})^2} \tag{5.7}$$

The resulting SINR and the distance values for each node were calculated using the formulation procedure above, and the results are plotted in Figure 5.2.

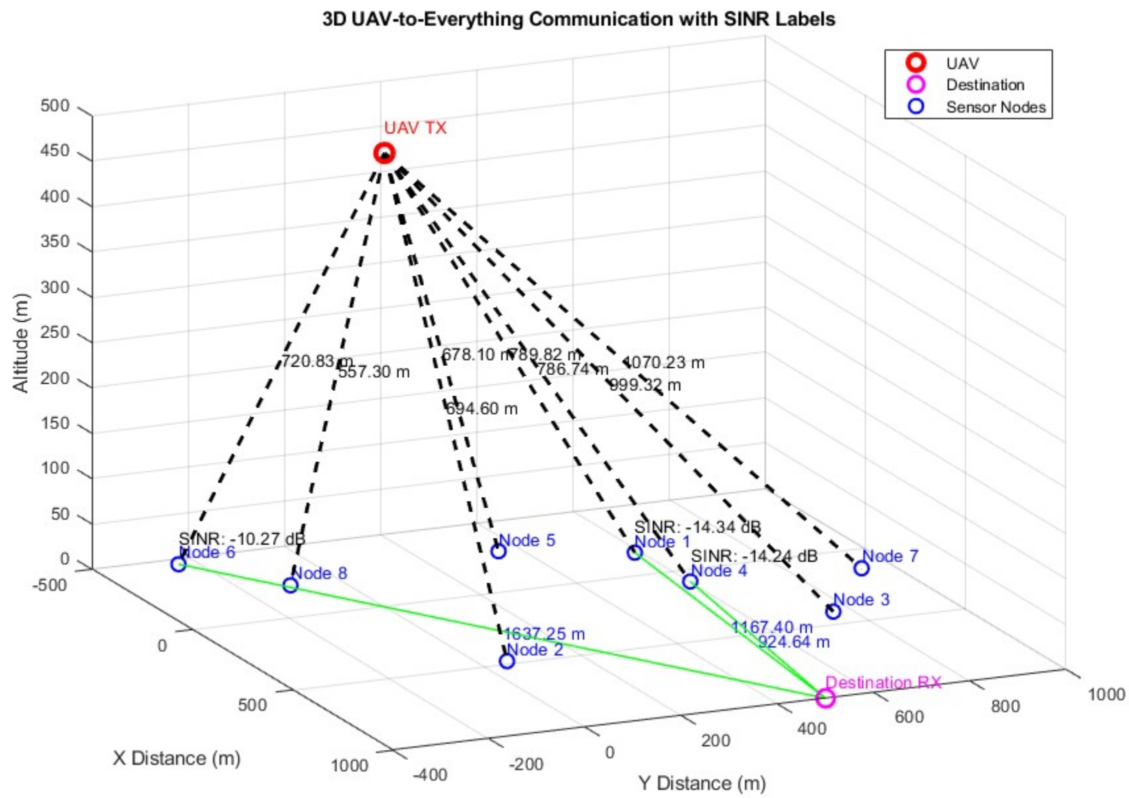


Figure 5.2. Node destination and calculated SINR values

Figure 5.2 illustrates the individual node distances and the calculated SINR values using the setup parameters. The distances are calculated and plotted as a black dotted line using the 3D Euclidean distance formula as in Equation 5.7. The formulation calculates the distance between the UAV (positioned at a height) and the sensor nodes on the ground and between any other points indicated as a green line between the UAV and the destination node.

The next step is to form a communication link from the UAV to the destination node using the intermediate sensor node. Figure 5.3 shows a typical connection for such an application.

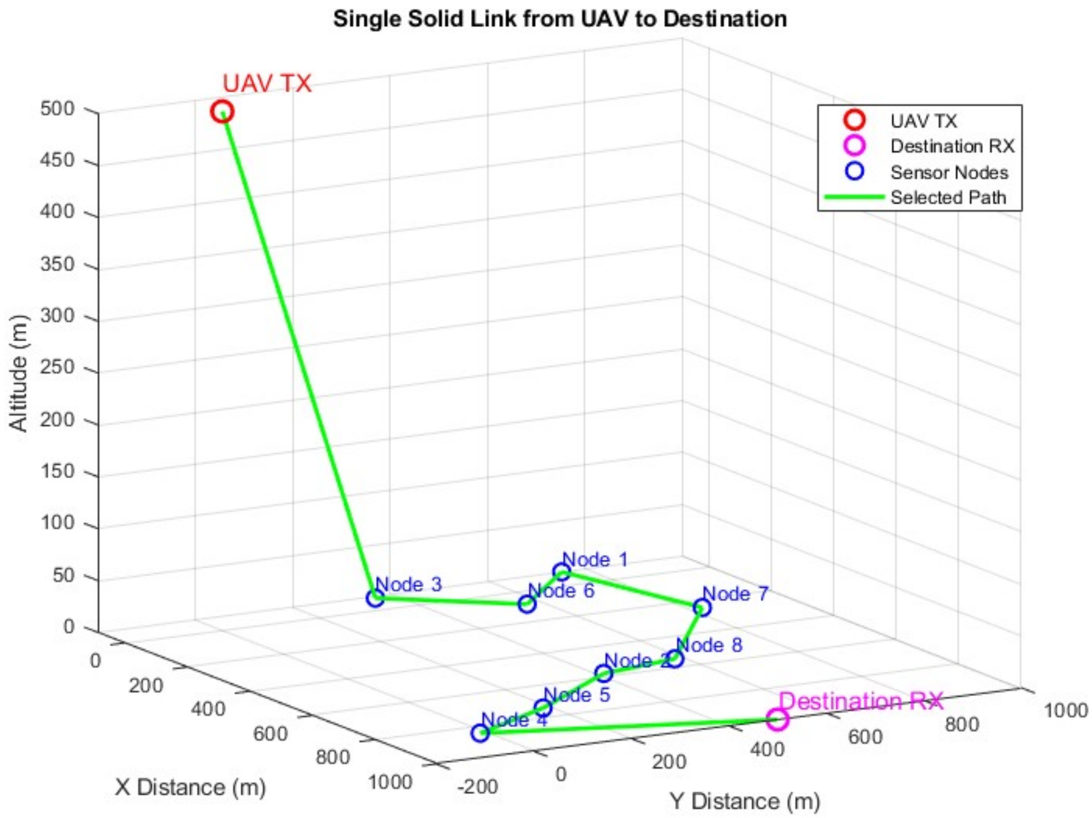


Figure 5.3. Non-optimized connection path

Figure 5.3 represents a non-optimized UAV-assisted communication link where a UAV (transmitter) relays data to a destination (receiver) through multiple intermediate sensor nodes.

The UAV, positioned at a high altitude (~500m), acts as the transmitting node. It establishes a communication path with the destination using sensor nodes. Several ground-level nodes marked in blue are relays to forward data toward the final destination. The UAV first connects to Node 3, and data is forwarded through subsequent nodes in a multi-hop manner. Each node selection is likely based on connectivity without constraints such as shortest distance, link reliability, and signal strength. The node marked in magenta, the destination, receives data after it has traversed through the sensor nodes. The chosen path appears to result from heuristic or predefined routing without an optimization approach.

Implementing path optimization algorithms or Machine Learning-based routing can enhance efficiency. Power-aware routing balances energy consumption among sensor nodes. Furthermore, adaptive UAV positioning can dynamically adjust UAV altitude and placement based on environmental and network conditions.

Since the UAV transmits data through multiple sensor nodes, total energy consumption should be considered effectively. The energy consumption calculation is below.

The UAV transmits to the first relay node (Node 5). The energy required follows:

$$E_{\mathrm{TX,UAV}} = P_{\mathrm{TX,UAV}} \cdot T \tag{5.8}$$

where:

- $P_{\mathrm{TX,UAV}}$ is the UAV's transmission power,
- T is the transmission duration.

If the UAV uses a power-controlled transmission based on distance d, then the required power follows the Friis Free-Space Path Loss Model:

$$P_{\mathrm{TX,UAV}} = P_{\mathrm{RX}} \cdot \left(\frac{4\pi d f}{c}\right)^2 \tag{5.9}$$

where:

- P_{RX} is the received power at the first node,
- f is the carrier frequency,
- c is the speed of light,
- d is the distance between the UAV and the first relay node.

Each relay node consumes energy for both receiving and transmitting:

$$E_{\text{RX, node}} = P_{\mathrm{RX}} \cdot T, E_{\text{TX, node}} = P_{\text{TX, node}} \cdot T \tag{5.10}$$

Total energy consumed in the entire communication path:

$$E_{\text{total}} = E_{\mathrm{TX,UAV}} + \sum_{i=1}^{N} \left(E_{\text{RX, node }i} + E_{\text{TX, node }i}\right) + E_{\text{RX, Dest}} \tag{5.11}$$

where N is the number of intermediate nodes.

The BER in such an application is another important constraint since the system relies on multi-hop relaying. BER is affected by multiple factors, such as path loss, interference, and noise.

The transmitted data use modulation over an AWGN channel, therefore, the BER can be expressed as:

$$P_b = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{5.12}$$

where,

$Q(\mathrm{x})$ is the Q-function,

E_b is the energy per bit,

N_0 is the noise power spectral density.

This work uses Rayleigh fading where the average BER is:

$$P_b = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma}{1+\gamma}}\right) \tag{5.13}$$

where $\gamma = \frac{E_b}{N_0}$ is the average SINR**.**

For a multi-hop link, assuming each sensor node forwards data independently, the end-to-end BER can be approximated as:

$$P_{b,\,\text{total}} \approx 1 - \prod_{i=1}^{N} \left(1 - P_{b,i}\right) \tag{5.14}$$

where $P_{b,i}$ is the BER at each sensor node.

The BER increases with more relays, leading to degraded performance without optimization.

The optimal path selection using the SINR-based algorithm, which considers two parameters, the SINR and the distance, was applied. The results are plotted in Figure 5.4.

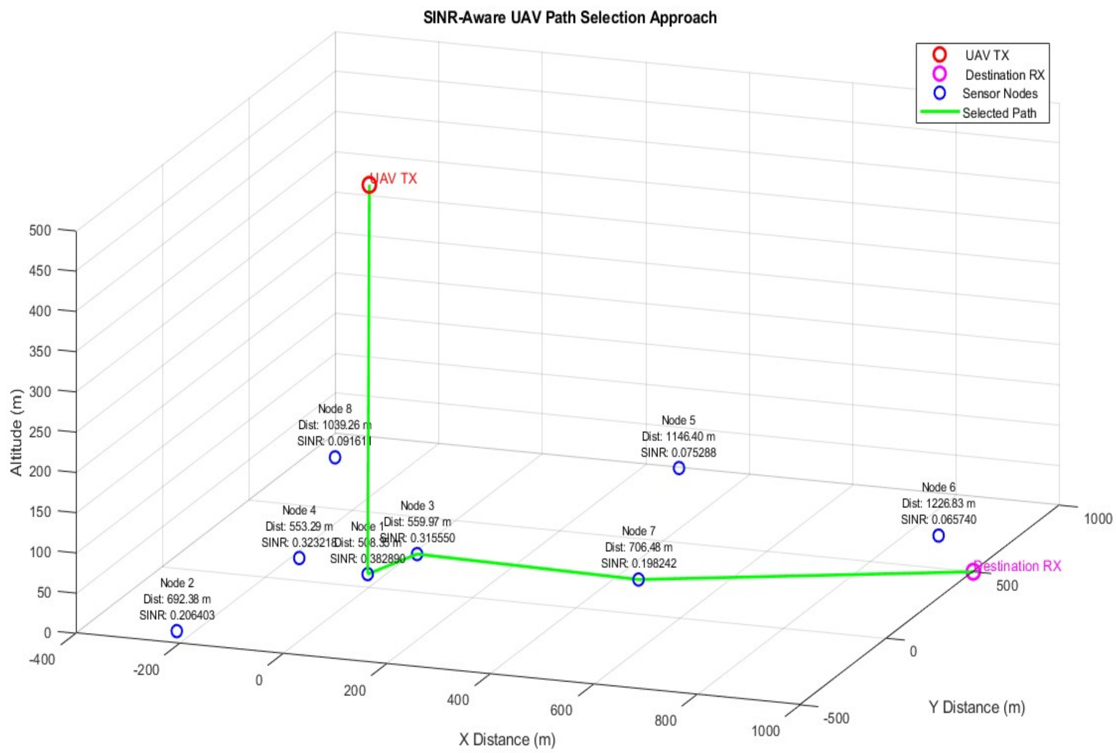


Figure 5.4. A SINR-Driven Routing Strategy for UAV Networks

Figure 5.4 illustrates a UAV-assisted communication path between a source node (UAV TX) and a destination node (RX) through intermediate sensor nodes, leveraging SINR and distance. The UAV, positioned at a higher altitude, selects relay nodes with the highest SINR values and distances to form a multi-hop communication path instead of a direct transmission, which might suffer from high path loss and low SINR. The green path in the figure represents the relay selection.

The SINR-based path selection, shown in Figure 5.4, operates on the principle that the source UAV initially evaluates the SINR values of all nodes to select a communication path. However, once the transmission begins, the method does not dynamically reassess the SINR values of the nodes throughout the communication process. This static nature can be considered a limitation, as it does not account for potential fluctuations in the SINR, which may result from mobility, interference, or environmental changes. Consequently, the communication path may not remain optimal throughout the transmission, leading to suboptimal performance in certain scenarios.

This work enhanced the algorithm by incorporating an optimization approach that dynamically controls the operation of the UAV network. These improvement factors include fixed power, highest SINR, and shortest distance as key parameters. Considering these elements, the algorithm can adapt to changing network conditions in real-time, ensuring more reliable and efficient communication. The dynamic adjustment of these parameters allows the UAV system to continuously optimize the communication path, leading to improved signal quality, coverage, and energy efficiency throughout the transmission. The proposed Algorithms 1 and 2 are executed, and the results are plotted in Figure 5.5.

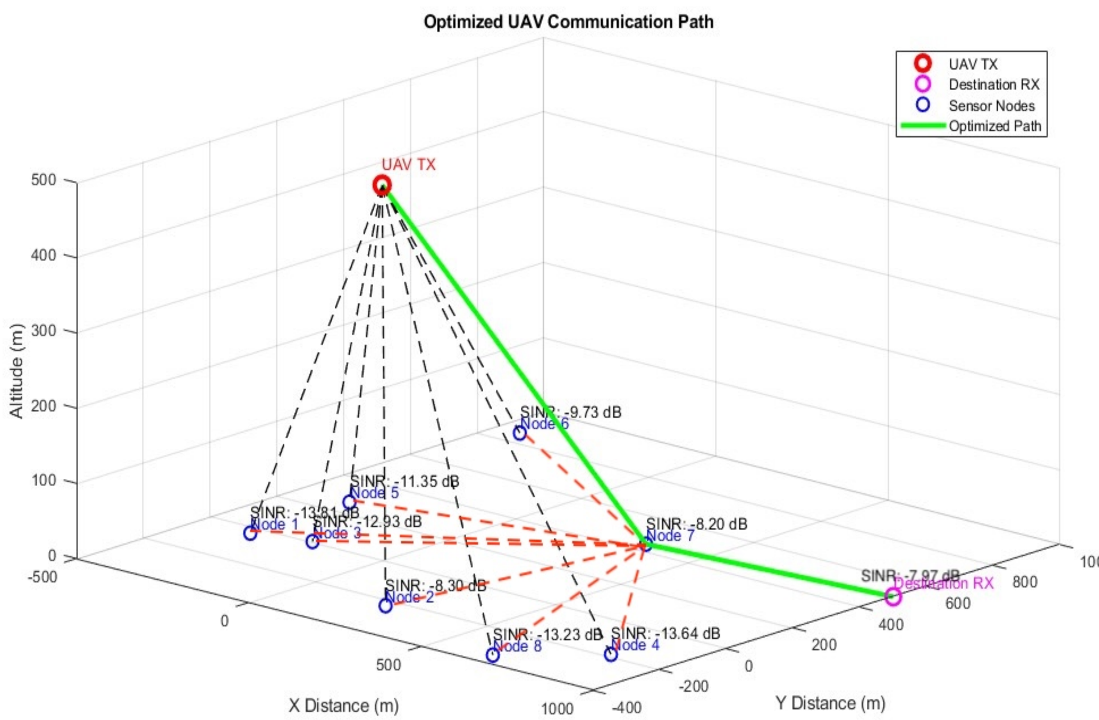


Figure 5.5. Optimized UAV communication path

Figure 5.5 shows the process of determining the optimized UAV-based communication path. In the first stage, the UAV (UAV TX) calculates the SINR and distance values of all sensor nodes in the communication network, and this evaluation is shown in the black dotted lines. As a result of the evaluation, the node with the highest SINR value is determined. As can be seen in the figure, the UAV initially selects Node 7 with a SINR of -8.20 dB to establish the first link, which is shown by the green continuous line. From the selected node, the UAV again calculates the SINR values of all nodes and the red dotted lines show this process. The algorithm dynamically repeats this iterative process to determine the optimal communication path. Finally, after evaluating all SINR values, the optimal communication path is selected and the data is transmitted to the destination receiver node (Destination RX) over the path indicated by the green continuous line. This method aims to improve signal quality, reduce latency, and ensure energy efficiency in communication. By determining the optimum communication path, data transmission time has been shortened and energy efficiency has been increased. Communication has become uninterrupted and can be done with less errors. The reliability and performance of the network have been maximized.

An optimized algorithm is used instead of the classical method to determine the optimal path for data transmission. The SINR threshold value is considered when selecting connection points. The proposed method provides more efficient data transmission by disabling unnecessary nodes. Since an optimized algorithm is used instead of the classical method, more powerful and uninterrupted communication is provided. This ensures a higher data rate and a more reliable and energy-efficient data transmission path.

Energy Consumption for Data Transmission

The energy consumed by a UAV's communication module mainly depends on:

- Transmission power (P_t): Measured in watts (W), it depends on the transmission range and data rate.
- Transmission time (T_t): The duration for which the UAV transmits data.
- Efficiency (η): Efficiency of the communication module.

The transmission energy can be calculated as:

$$E_{tx} = \frac{P_t \times T_t}{\eta} \tag{5.15}$$

To find the energy per bit (E_b), the data rate R (bits per second) should be considered as indicated in the following expression.

$$E_b = \frac{E_{tx}}{R \times T_t} \tag{5.16}$$

The setup parameters are listed in Table 5.2.

Table 5.2 Setup parameters for energy simulation

Parameter	Value
Transmission Power (P_t)	12 mW (0.012 W)
Transmission Time (T_t)	0.8 seconds
Total Transmission Energy (E_{tx})	24 mJ
Data Rate (R)	10 Gbps

Equation 5.16 applied to the proposed method to calculate the optimum energy.

$$E_b = \frac{24 \times 10^{-3}}{(10 \times 10^9) \times 0.8}$$

$$E_b = \frac{24}{8} \times 10^{-12}$$

$$E_b = 3 \times 10^{-12} \text{J/bit}$$

$$E_b = 0.003 \text{nJ/bit}$$

The optimized, non-optimized and SINR-based methods are compared and listed in Table 5.3.

Table 5.3 Comparison results

Path Selection	**BER**	**Data Rate**	**Energy per Bit**
Non-Optimized Method	0.358	Up to 10 Gbps	0.01-0.1(nJ/bit)
SINR Based Method	0.029	Up to 10 Gbps	0.008-0.01(nJ/bit)
Optimized Method	0.013	Up to 10 Gbps	0.003-0.006 (nJ/bit)

Figure 5.6 shows the BER that occurs during data transmission. BER is a performance metric to compare the change between optimized, SINR-based, and non-optimized communication methods. The plot shows the change in BER related to distance.

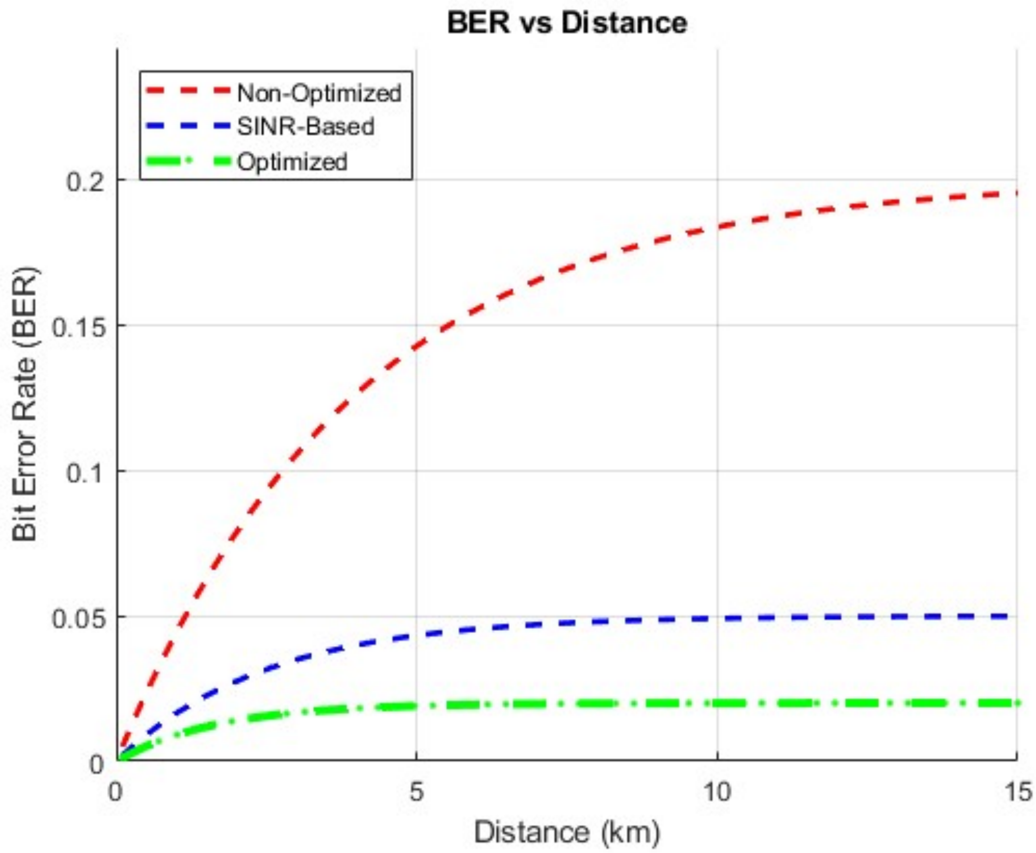


Figure 5.6. Average BER performance

Figure 5.6. shows the relationship between BER and distance. The graph compares three different communication methods, as summarized below.

1. Non-Optimized (Red, Dashed Line):
   - This method works without any optimization.
   - The BER value increases exponentially at a high rate until it reaches 10 km. After 10 km, it settles to a lower increase rate.
   - An increase in BER is undesirable since the signal may not be decoded to the original state.
   - Considering the long-distance communication path, the link with high BER is unacceptable for communication purposes.

2. SINR-Based (Blue, Dotted Line):
   - SINR-based optimization is applied.
   - In this method, the selection of the receiving node is based on the SINR value.
   - It offers lower BER than the non-optimized method but still has a certain level of error rate.
   - The BER increases as the distance increases, but it is a more balanced increase rather than a completely uncontrolled increase.
3. Optimized (Green, Dashed Dotted Line):
   - The proposed optimization technique has been applied.
   - Besides SINR, the communication route and data transmission strategy are also optimized.
   - The BER is kept at the lowest level and remains low even as the distance increases.
   - This indicates that the communication quality and error rate are optimally controlled.
   - The green curve represents the optimized results, the blue curve represents the SINR-based results, and the red curve represents the non-optimized results.

The proposed optimized method (green line) ensures reliable communication by minimizing communication errors. The SINR-based method (blue line) offers moderate performance, while the non-optimized system (red line) has a high error rate. Such optimization techniques provide significant advantages in UAV communication systems, Healthcare 5.0, 5G, and emergency communication networks.

BER increases in all methods at the beginning (around 0-5 km). The optimized method especially reduces the BER value to very low levels. At the optimal distance (around 5 km)**,** BER reaches its lowest level (especially in the optimized method). Data transmission is most efficient at this distance. As the distance increases (after 3 km), BER increases again. While the optimized result (black curve) keeps the BER low, the non-optimized result (pink curve) performs much worse. Around 10 km, the BER with the non-optimized result approaches almost 1, meaning the error rate is very high.

The optimization method keeps the BER lower at all distances. BER initially decreases because the signal is transmitted more stably at first. After a point (about 2-3 km), the BER reaches its lowest level and rises again. When the optimum distance is exceeded, the signal weakens and the error rate increases. As a result, the optimized method performs much better, especially at longer distances.

Figure 5.6 shows that the optimized communication method is much more reliable, especially at long distances. As the distance increases, the error rate inevitably increases, in which case the optimization method successfully controls errors and increases data transmission performance.

A comparative analysis of optimized and non-optimized SINR values has been performed. SINR is a measurement expressing the signal strength ratio to noise and interference in wireless communication systems. The higher the SINR, the more reliable the communication and the lower the error rate. Figure 5.7 compares SINR transmission values to evaluate the performance of the algorithms developed in the study.

This comparison examines the level of SINR and the effect of the newly developed algorithm on communication performance.

Developed a method to optimize SINR and used the Packet Delivery Ratio (PDR) to verify the performance of this method. PDR is a metric that shows the proportion of error-free packets that are successfully delivered.

The calculation of the PDR is defined as follows:

$$PDR=\frac{number\ of\ error-free\ packet}{detection\ events\ in\ a\ specific\ time\ interval}$$

The test method includes:

- Measuring optimized SINR and non-optimized SINR values
- Examining the relationship between SINR and distance
- Examining the relationship between PDR and distance
- Examining the relationship between SINR and PDR

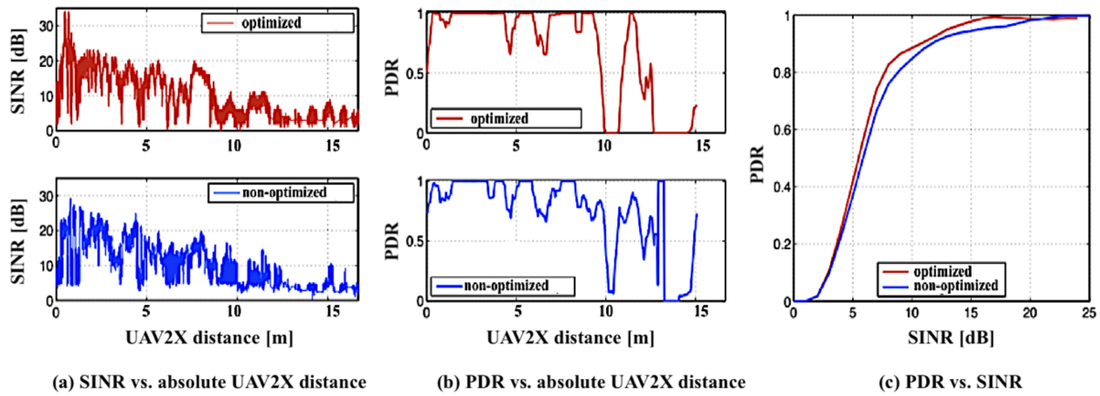


Figure 5.7. Impact of optimization on SINR and PDR

Figure 5.7(a) - SINR vs. UAV2X Distance

- The upper graph (red line) shows the SINR values of the optimized method.
- The lower graph (blue line) shows the SINR values of the non-optimized method.

Optimized SINR values are generally higher and more stable. Non-optimized SINR values have a lot of fluctuations and are generally lower.

An optimized method increases communication reliability by keeping the SINR more stable. A non-optimized method produces more unstable and lower SINR values.

Figure 5.7(b) - PDR vs. UAV2X Distance

- The upper graph (red line) shows the PDR values of the optimized method.
- The lower graph (blue line) shows the PDR values of the non-optimized method.

The optimized method generally offers a higher PDR rate, while the non-optimized method's PDR value is low.

The optimized method increases the rate of error-free packets. In the non-optimized method, the PDR remains low due to SINR fluctuations.

Figure 5.7(c) - PDR vs. SINR

The graph shows that PDR changes as SINR increases.

- The red curve (optimized method) and the blue curve (non-optimized method) show a similar trend, but the red curve reaches higher PDR values.

Especially when the SINR value drops below 5 dB, the difference between the two methods becomes very large.

The graph shows that the higher the SINR, the higher the PDR. The optimized method performs better in all cases.

The graph also indicates a direct relationship between SINR and PDR, and the optimized method provides higher PDR rates. Controlling SINR well ensures that packets are transmitted with less loss.

The optimized method increases the communication quality by keeping the SINR more stable and higher. When the SINR is high, the PDR is also high, meaning that more error-free packets are transmitted. In cases where the SINR is low (especially below 5 dB), the advantage provided by the optimization becomes much more obvious.

Simulation results show that the optimized method increases the reliability of the communication systems. This method increases reliability and performance by reducing packet losses in UAV communication. SINR optimization provides a more robust connection and less error transmission.

Some of the key observations noted in the simulations are listed below.

Energy Inefficiency;

- More relay nodes increase total energy consumption.
- UAV energy depends on transmission distance and power allocation.
- Relay nodes consume energy for both receiving and forwarding.

Error Propagation;

- BER increases with each additional relay node.
- The farther the UAV or relay nodes, the worse the link quality.

This approach is particularly effective for IoT networks, disaster recovery, and remote sensing, where UAVs enhance connectivity by overcoming obstacles and improving coverage.

A source (transmitter) and a destination (receiver) node are to be used for data transfer.

The data transmission path is calculated according to the following criteria:

- Overall path loss (Loss incurred by the data signal while travelling between nodes)
- Reference distance path loss (Signal loss calculated at the starting point)
- Connection efficiency is determined by neighbouring nodes (Which nodes can be suitable interconnection points)

Critical Parameters Used for Simulation

Some basic parameters are fixed for the sake of consistency of the results.

- Reference distance value = 1 (Basic distance determined for the starting point)
- Path loss exponent = 3 (Coefficient indicating how much the signal weakens as the distance increases)

Threshold values related to interference (noise) and signal quality are determined:

- γ_b (Minimum SINR) = 4 dB (Minimum SINR required for a connection to be valid)
- γ_d (Interference Threshold) = 2 dB (Threshold value determined so that the connection is not exposed to excessive interference)
- The threshold value of γ is varied to identify a successful end-to-end throughput link.

The aim is to test the SINR values to determine whether the connection is reliable during data transmission.

Optimized Link Selection and Comparison

The proposed algorithm determines the best connection paths between nodes. During this process, the optimized threshold value called γ_{opt} is determined using Algorithm 2 in Chapter 3.

The performance of the proposed method is compared with the classical search method.

- Classical search method: A traditional method that tests simple and direct connections.
- Proposed optimized method: An advanced method that optimizes SINR and interference conditions by selecting more efficient paths.

CHAPTER VI

Conclusion

The study emphasized that UAVs are crucial in transporting medical supplies in Healthcare 5.0. This process involves physically transporting medical equipment and instantly transmitting crucial information about the material. Data regarding the type, location, status, and delivery process of the transported medical equipment must be transmitted continuously. Furthermore, the information is ensured to be reliable and safeguarded against interception by unauthorized individuals.

Blockchain technology is integrated into this study to ensure data security, integrity, and transparency in UAV communication. Data must be safeguarded from unauthorized access and maintained as an immutable record when transporting medical equipment. The decentralized blockchain architecture fosters reliable communication among UAVs and concurrently augments delivery security by overseeing autonomous operations through smart contracts. Furthermore, the proposed system ensures real-time tracking and error detection, thus contributing to a more reliable and efficient framework for healthcare logistics.

This work integrates 5G technology into UAV communications, enabling faster and more reliable data transmission. UAVs in the healthcare industry have to transmit instant data while carrying medical supplies. The high data rate characteristic of 5G technology facilitates rapid transmission of information with minimal latency, typically within the millisecond range. UAVs transmit high-resolution images, sensor data and large amounts of telemetry information, especially for medical deliveries. The wide bandwidth provided by 5G enables these extensive data sets to be transmitted quickly and securely. 5G network technology enables UAVs to communicate with each other simultaneously and with low latency, optimize their routes by instantly analyzing signals from other UAVs, and share data directly without being dependent on cellular base stations. 5G's optimized network protocols enable UAVs to transmit maximum data with minimum energy consumption. 5G enables more efficient integration with blockchain systems by protecting data privacy through built-in security protocols and encryption methods.

To optimize the communication processes of UAVs, three different communication paths were examined: UAV2UAV, UAV2Base Station, and UAV2X. UAV2X is a more comprehensive model that includes UAV2UAV and UAV2Base Station communications. Since UAVs, base stations, and onboard devices communicate with each other, all scenarios are assessed using a unified optimisation framework. UAV2X communication has dynamic variables such as different network conditions, moving nodes and varying signal levels. Given that parameters such as SINR, BER, and energy consumption are continually changing, the validity of the optimization process holds significant importance. Since the UAV2X model includes air and ground networks, it is chosen as the scenario closest to real-world applications, and the optimization strategies that are expected to give the best results for the whole system are applied to this scenario and included in the simulation.

In the initial phase, data transmission is simulated without optimization within the UAV communication process. At this phase, the weak points of the system are identified. There is a potential decrease in transmission quality if SINR is disregarded. Furthermore, in cases involving distance-based selection, SINR may be diminished, leading to an increase in BER.

Subsequently, a standard optimization algorithm was applied, considering SINR and distance. The approach prioritized selecting the shortest distance while ensuring strong signal quality. However, the algorithm was found to be incomplete as it does not dynamically track SINR changes.

Following the initiation of the transmission, it was realized that the system was inadequate without continuously monitoring the SINR of the nodes. Therefore, an advanced optimization process was integrated, and SINR was recalculated at each transmission step. The SINR and distance were re-evaluated at each hop. The UAV dynamically determined the route with the most substantial signal quality and the lowest error rate at each node. Through this methodology, a more comprehensive optimization approach was simulated, with constant power control, and the transmission power of the UAVs was kept constant at a certain level. Considering SINR priority, the node with the highest signal-to-interference noise ratio was identified at each hop. Using the shortest distance selection, the UAV transmitted data to the target with the least possible energy consumption.

Implementing advanced dynamic optimization techniques significantly enhances data reliability, with high accuracy and lower BER. Energy consumption is minimized, with no unnecessary hops. The transmission process has become more stable as the SINR is dynamically controlled at each hop.

The proposed model optimizes the path selection and considers the highest SINR values for the communication link to minimize the BER in transmission. The model's performance is verified by the BER value of 0.013. The communication link considers a fixed power for the transmission to minimize the vital energy consumption for such an operation. The calculated energy consumption for data transmission in the proposed model was approximately 0.03 nJ/bit, which is considered a significant achievement compared to other introduced models.

The proposed communication network's high performance clearly demonstrates its critical role in ensuring reliable and efficient data transmission in systems serving society.

REFERENCES

Abohashish, S. M., Rizk, R. Y., & Elsedimy, E. I. (2023). Trajectory optimization for UAV-assisted relay over 5G networks based on reinforcement learning framework. *EURASIP Journal on Wireless Communications and Networking*, *2023*(1), 55. https://doi.org/10.1186/s13638-023-02268-x

Aboumahmoud, I., Hossain, E., & Mezghani, A. (2024). Resource Management in RIS-Assisted Rate Splitting Multiple Access for Next Generation (xG) Wireless Communications: Models, State-of-the-Art, and Future Directions. *IEEE Communications Surveys & Tutorials*. https://doi.org/10.1109/COMST.2024.3471453

Adam, M. S., Abdullah, N. F., Abu-Samah, A., Amodu, O. A., & Nordin, R. (2025). Advanced Path Planning for UAV Swarms in Smart City Disaster Scenarios Using Hybrid Metaheuristic Algorithms. *Drones (2504-446X)*, *9*(1).

Adil, M., Song, H., Jan, M. A., Khan, M. K., He, X., Farouk, A., & Jin, Z. (2024). UAV-assisted IoT applications, QoS requirements and challenges with future research directions. *ACM Computing Surveys*, *56*(10), 1-35. https://doi.org/10.1145/3657287

Agiwal, M., Roy, A., & Saxena, N. (2016). Next generation 5G wireless networks: A comprehensive survey. *IEEE communications surveys & tutorials*, *18*(3), 1617-1655. https://doi.org/10.1109/COMST.2016.2532458

Ahmed, M., Soofi, A. A., Raza, S., Khan, F., Ahmad, S., Ullah, W., ... & Han, Z. (2025). Advancements in RIS-Assisted UAV for Empowering Multi-Access Edge Computing: A Survey. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2025.3527041

Ajakwe, S. O., & Kim, D. S. (2024). Facets of security and safety problems and paradigms for smart aerial mobility and intelligent logistics. *IET Intelligent Transport Systems*, *18*, 2827-2855. https://doi.org/10.1049/itr2.12579

Akhai, S. (2024). Innovating Healthcare Delivery. *Modelling of Virtual Worlds Using the Internet of Things*, 232.

Aljumah, A. (2024). UAV-Based Secure Data Communication: Multilevel Authentication Perspective. *Sensors*, *24*(3), 996. https://doi.org/10.3390/s24030996

Aloqaily, M., Bouachir, O., Boukerche, A., & Al Ridhawi, I. (2021). Design guidelines for blockchain-assisted 5G-UAV networks. *IEEE network*, *35*(1), 64-71. https://doi.org/10.1109/MNET.011.2000170

Alotaibi, A., Chatwin, C., & Birch, P. (2024). A Secure Communication Framework for Drone Swarms in Autonomous Surveillance Operations. *Journal of Computer and Communications*, *12*(11), 1-25. https://doi.org/10.4236/jcc.2024.1211001

Alqudsi, Y., & Makaraci, M. (2025). UAV swarms: research, challenges, and future directions. *Journal of Engineering and Applied Science*, *72*(1), 12. https://doi.org/10.1186/s44147-025-00582-3

Anagnostis, I., Kotzanikolaou, P., & Douligeris, C. (2025). Understanding and Securing the Risks of Unmanned Aerial Vehicle Services. *IEEE Access*. https://doi.org/10.1109/ACCESS.2025.3549861

Arpali, S. A., Eyyuboğlu, H. T., & Baykal, Y. (2008). Bit error rates for general beams. *Applied optics*, *47*(32), 5971-5975. https://doi.org/10.1364/AO.47.005971

Bahramisirat, F., Gregory, M. A., & Li, S. (2024). Multi-Access Edge Computing Resource Slice Allocation: A review. *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.3515077

Banafaa, M. K., Pepeoğlu, Ö., Shayea, I., Alhammadi, A., Shamsan, Z. A., Razaz, M. A., ... & Al-Sowayan, S. (2024). A comprehensive survey on 5G-and-beyond networks with UAVs: Applications, emerging technologies, regulatory aspects, research trends and challenges. *IEEE access*, *12*, 7786-7826. https://doi.org/10.1109/ACCESS.2023.3349208

Basulo-Ribeiro, J., & Teixeira, L. (2024). The Future of Healthcare with Industry 5.0: Preliminary Interview-Based Qualitative Analysis. *Future Internet*, *16*(3), 68. https://doi.org/10.3390/fi16030068

Bhandari, D., Kumar, D. A., & Sharath, P. C. (2024). Drones in Health. In *Drone Applications for Industry 5.0* (pp. 298-325). IGI Global. https://doi.org/10.4018/979-8-3693-2093-8.ch016

Bhandari, D., Kumar, D. A., & Sharath, P. C. (2024). Drones in Health. In *Drone Applications for Industry 5.0* (pp. 298-325). IGI Global. https://doi.org/10.4018/979-8-3693-2093-8.ch016

Bilgehan, B., & Sabuncu, Ö. (2023). An optimized device-to-device (D2D) blockchain network for the insurance industry. *International Journal of Communication Systems*, *36*(6), e5446. https://doi.org/10.1002/dac.5446

Bilgehan, B., & Sabuncu, Ö. (2023). Optimized blockchain network model for 6G cellular vehicle-to-everything communication. *Transactions on Emerging Telecommunications Technologies*, *34*(12), e4868. https://doi.org/10.1002/ett.4868

Biswas, A., & Wang, H. C. (2023). Autonomous vehicles enabled by the integration of IoT, edge intelligence, 5G, and blockchain. *Sensors*, *23*(4), 1963. https://doi.org/10.3390/s23041963

Bóveda, S. A., Gónzález, A. F., Terrón, L. V., Artolazábal, J. A. R., & Negro, J. A. R. (2024). Key Technologies for UAVs in Search and Rescue (SAR) and Surveillance Operations. In *Applying Drones to Current Societal and Industrial Challenges* (pp. 97-129). Springer, Cham. https://doi.org/10.1007/978-3-031-55571-8_4

Brata, M., & Zakia, I. (2024). Path Loss Estimation at Sub-6 GHz and Millimeter Wave Frequencies Using Fine-Tuning. *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.3465653

Campbell, H. A., Bosiocic, V., Hvala, A., Brady, M., Campbell, M. A., Skelton, K., & Luiz, O. J. (2024). Emerging Research Topics in Drone Healthcare Delivery. *Drones*, *8*(6), 258. https://doi.org/10.3390/drones8060258

Chakraborty, A., Chai, E., Sundaresan, K., Khojastepour, A., & Rangarajan, S. (2018, December). SkyRAN: a self-organizing LTE RAN in the sky. In *Proceedings of the 14th international conference on emerging networking EXperiments and technologies* (pp. 280-292). https://doi.org/10.1145/3281411.3281437

Chang, J. Y., Chen, S. S., & Chen, K. H. (2025). Enhanced Multi-UAV-Assisted Data Transmission Control Strategy in Wireless Sensor Networks. *IEEE Sensors Journal*. https://doi.org/10.1109/JSEN.2025.3541124

Chapnevis, A., & Bulut, E. (2025). Time-efficient approximate trajectory planning for AoI-centered multi-UAV IoT networks. *Internet of Things*, *29*, 101461.

Chaudhari, B. S. (2025). Enabling Tactile Internet via 6G: Application Characteristics, Requirements, and Design Considerations Top of Form. *Future Internet*, *17*(3), 122. https://doi.org/10.3390/fi17030122

Chen, S., Wei, K., Pei, T., & Long, S. (2025). AoI-Guaranteed UAV Crowdsensing: A UGV-assisted deep reinforcement learning approach. *Ad Hoc Networks*, 103805. https://doi.org/10.1016/j.adhoc.2025.103805

Chen, W., Zhu, J., Liu, J., & Guo, H. (2024). A fast coordination approach for large-scale drone swarm. *Journal of Network and Computer Applications*, *221*, 103769. https://doi.org/10.1016/j.jnca.2023.103769

Chiti, F., Morosi, S., & Bartoli, C. (2024). An Integrated Software-Defined Networking–Network Function Virtualization Architecture for 5G RAN–Multi-Access Edge Computing Slice Management in the Internet of Industrial Things. *Computers*, *13*(9), 226. https://doi.org/10.3390/computers13090226

Clerigues, D., Wubben, J., Calafate, C. T., Cano, J. C., & Manzoni, P. (2024). Enabling resilient UAV swarms through multi-hop wireless communications. *EURASIP Journal on Wireless Communications and Networking*, *2024*(1), 39. https://doi.org/10.1186/s13638-024-02373-5

Coiera, E. (2006). Communication systems in healthcare. *Clinical Biochemist Reviews*, *27*(2), 89.

Crane, R. K. (2003). *Propagation handbook for wireless communication system design*. CRC press.

Dağaşan, A., & Karaşan, E. (2025). Resilient Multi-Hop Autonomous UAV Networks With Extended Lifetime for Multi-Target Surveillance. *IEEE Transactions on Network and Service Management*. https://doi.org/10.1109/TNSM.2025.3528495

Demir, K., Tumen, V., Kosunalp, S., & Iliev, T. (2024). A deep reinforcement learning algorithm for trajectory planning of swarm UAV fulfilling wildfire reconnaissance. *Electronics*, *13*(13), 2568. https://doi.org/10.3390/electronics13132568

Deng, H., Xia, D., Cai, H., Yan, Q., Xu, P., & Dai, B. (2024). An Efficient Coding Scheme for the AWGN Relay Network With Receiver–Transmitter Feedback. *IEEE Systems Journal*. https://doi.org/10.1109/JSYST.2024.3437232

Dhandapani, G., Lavadiya, S., Aldosary, S., & El-Shafai, W. (2024). Fractal-shaped super UWB (96THz) of quadpot MIMO antenna for 6G communication. *Optical and Quantum Electronics*, *56*(10), 1613. https://doi.org/10.1007/s11082-024-07416-1

Dhar Dwivedi, A., Singh, R., Kaushik, K., Rao Mukkamala, R., & Alnumay, W. S. (2024). Blockchain and artificial intelligence for 5G-enabled Internet of Things: Challenges, opportunities, and solutions. *Transactions on Emerging Telecommunications Technologies*, *35*(4), e4329. https://doi.org/10.1002/ett.4329

Erpek, T., O'Shea, T. J., Sagduyu, Y. E., Shi, Y., & Clancy, T. C. (2020). Deep learning for wireless communications. *Development and Analysis of Deep Learning Architectures*, 223-266. https://doi.org/10.1007/978-3-030-31764-5_9

Eskandari, M., & Savkin, A. V. (2024). Integrating UAVs and RISs in Future Wireless Networks: A Review and Tutorial on IoTs and Vehicular Communications. *Future Internet*, *16*(12), 433. https://doi.org/10.3390/fi16120433

Fadel, H. A., & Jamel, T. M. (2024, April). Evaluating the Performance of 5G Modulation and Beyond: A Review Study. In *2024 21st International Multi-Conference on Systems, Signals & Devices (SSD)* (pp. 727-734). IEEE. https://doi.org/10.1109/SSD61670.2024.10548506

Fang, M. E. I., Yuqing, L. I. U., Shuo, G. A. O., Jiahui, L. I., Hui, K. A. N. G., Sujin, H. O. U., & Geng, S. U. N. (2025). Secure and energy-efficient UAV-assisted maritime communication under multiple eavesdroppers with imperfect CSI and collusion. *Chinese Journal of Aeronautics*, 103477. https://doi.org/10.1016/j.cja.2025.103477

Fang, Z., & Savkin, A. V. (2024). Strategies for optimized uav surveillance in various tasks and scenarios: A review. *Drones*, *8*(5), 193. https://doi.org/10.3390/drones8050193

Fotohi, R., Abdan, M., & Ghasemi, S. (2022). A self-adaptive intrusion detection system for securing UAV-to-UAV communications based on the human immune system in UAV networks. *Journal of Grid Computing*, *20*(3), 22. https://doi.org/10.1007/s10723-022-09614-1

García-Gil, S., Murillo, J. M., & Galán-Jiménez, J. (2024). Enabling ultra reliable low latency communications in rural areas using uav swarms. *Ad Hoc Networks*, *163*, 103603. https://doi.org/10.1016/j.adhoc.2024.103603

Garg, T., Gupta, S., Obaidat, M. S., & Raj, M. (2024). Drones as a service (DaaS) for 5G networks and blockchain-assisted IoT-based smart city infrastructure. *Cluster Computing*, *27*(7), 8725-8788. https://doi.org/10.1007/s10586-024-04354-1

Ghaffar, M. A., Peng, L., Aslam, M. U., Adeel, M., & Dassari, S. (2024). Vehicle-UAV Integrated Routing Optimization Problem for Emergency Delivery of Medical Supplies. *Electronics*, *13*(18), 3650. https://doi.org/10.3390/electronics13183650

Ghamari, M., Rangel, P., Mehrubeoglu, M., Tewolde, G. S., & Sherratt, R. S. (2022). Unmanned aerial vehicle communications for civil applications: A review. *IEEE Access*, *10*, 102492-102531. https://doi.org/10.1109/ACCESS.2022.3208571

Ghribi, E., Khoei, T. T., Gorji, H. T., Ranganathan, P., & Kaabouch, N. (2020, July). A secure blockchain-based communication approach for UAV networks. In *2020 IEEE international conference on electro information technology (EIT)* (pp. 411-415). IEEE. https://doi.org/10.1109/EIT48999.2020.9208314

Godugu, K. K., & Vappangi, S. (2025). UAV-Assisted Communication: Unmanned Aerial Vehicles in Vehicle-to-Everything Communication Networks. In *5G and Beyond Wireless Communications* (pp. 89-103). CRC Press.

Goldsmith, A. (2005). *Wireless communications*. Cambridge university press.

Gómez-Déniz, E., & Gómez-Déniz, L. (2013). A generalisation of the Rayleigh distribution with applications in wireless fading channels. *Wireless Communications and Mobile Computing*, *13*(1), 85-94. https://doi.org/10.1002/wcm.1097

Guo, H., Wang, Y., Liu, J., & Liu, C. (2023). Multi-UAV cooperative task offloading and resource allocation in 5G advanced and beyond. *IEEE Transactions on Wireless Communications*, *23*(1), 347-359. https://doi.org/10.1109/TWC.2023.3277801

Gupta, N., Agarwal, S., Mishra, D., & Kumbhani, B. (2023). Trajectory and resource allocation for UAV replacement to provide uninterrupted service. *IEEE Transactions on Communications*, *71*(12), 7288-7302. https://doi.org/10.1109/TCOMM.2023.3307559

Gupta, R., Kumari, A., & Tanwar, S. (2021). Fusion of blockchain and artificial intelligence for secure drone networking underlying 5G communications. *Transactions on Emerging Telecommunications Technologies*, *32*(1), e4176. https://doi.org/10.1002/ett.4176

Gupta, R., Nair, A., Tanwar, S., & Kumar, N. (2021). Blockchain-assisted secure UAV communication in 6G environment: Architecture, opportunities, and challenges. *IET communications*, *15*(10), 1352-1367. https://doi.org/10.1049/cmu2.12113

Gupta, R., Tanwar, S., & Kumar, N. (2021). Blockchain and 5G integrated softwarized UAV network management: Architecture, solutions, and challenges. *Physical communication*, *47*, 101355. https://doi.org/10.1016/j.phycom.2021.101355

Hafeez, S. (2024). *Blockchain-based secure Unmanned Aerial Vehicles (UAV) in network design and optimization* (Doctoral dissertation, University of Glasgow).

Hafeez, S., Khan, A. R., Al-Quraan, M. M., Mohjazi, L., Zoha, A., Imran, M. A., & Sun, Y. (2023). Blockchain-assisted UAV communication systems: A comprehensive survey. *IEEE Open Journal of Vehicular Technology*, *4*, 558-580. https://doi.org/10.1109/OJVT.2023.3295208

Hajlaoui, E., Zaier, A., Khlifi, A., Ghodhbane, J., Hamed, M. B., & Sbita, L. (2020, September). 4G and 5G technologies: A Comparative Study. In *2020 5th International Conference on Advanced Technologies for Signal and Image Processing (ATSIP)* (pp. 1-6). IEEE. https://doi.org/10.1109/ATSIP49331.2020.9231605

Han, S. I. (2022). Survey on UAV deployment and trajectory in wireless communication networks: Applications and challenges. *Information*, *13*(8), 389. https://doi.org/10.3390/info13080389

Haq, A. U., Sefati, S. S., Nawaz, S. J., Mihovska, A., & Beliatis, M. J. (2025). Need of UAVs and Physical Layer Security in Next-Generation Non-Terrestrial Wireless Networks: Potential Challenges and Open Issues. *IEEE Open Journal of Vehicular Technology*. https://doi.org/10.1109/OJVT.2025.3525781

Harbi, Y., Medani, K., Gherbi, C., Senouci, O., Aliouat, Z., & Harous, S. (2023). A systematic literature review of blockchain technology for Internet of Drones security. *Arabian Journal for Science and Engineering*, *48*(2), 1053-1074. https://doi.org/10.1007/s13369-022-07380-6

Hoang, T. M., Nguyen, B. C., Thanh, H. L. T., Tran, X. N., & Hiep, P. T. (2024). Finite block length noma mu pairing uav-enable system: performance analysis and optimization. *IEEE Transactions on Mobile Computing*. https://doi.org/10.1109/TMC.2024.3368159

Hosseini, N., Jamal, H., Haque, J., Magesacher, T., & Matolak, D. W. (2019, March). UAV command and control, navigation and surveillance: A review of potential 5G and satellite systems. In *2019 IEEE Aerospace Conference* (pp. 1-10). IEEE. https://doi.org/10.1109/AERO.2019.8741719

Hussain, R. (2021). Shared Aperture Slot-Based Sub-6 GHz and mm-Wave IoT Antenna for 5G Applications. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2021.3050383

Imam-Fulani, Y. O., Faruk, N., Sowande, O. A., Abdulkarim, A., Alozie, E., Usman, A. D., ... & Taura, L. S. (2023). 5G frequency standardization, technologies, channel models, and network deployment: Advances, challenges, and future directions. *Sustainability*, *15*(6), 5173. https://doi.org/10.3390/su15065173

Islam, S., Atallah, Z. A., Budati, A. K., Hasan, M. K., Kolandaisamy, R., & Nurhizam, S. (2024). Mobile Networks Toward 5G/6G: Network Architecture, Opportunities and Challenges in Smart City. *IEEE Open Journal of the Communications Society*. https://doi.org/10.1109/OJCOMS.2024.3419791

Ivascu, L. N., & Jahankhani, H. (2024). An Investigation into Counter Drones Digital Forensics Aided by Remote Identification. In *Space Governance: Challenges, Threats and Countermeasures* (pp. 195-227). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-62228-1_7

Jagatheesaperumal, S. K., Rahouti, M., Chehri, A., Xiong, K., & Bieniek, J. (2025). Blockchain-based security architecture for unmanned aerial vehicles in b5g/6g services and beyond:

A comprehensive approach. *IEEE Open Journal of the Communications Society*. https://doi.org/10.1109/OJCOMS.2025.3528220

Jain, N., Gambhir, A., & Pandey, M. (2024). Unmanned Aerial Networks—UAVs and AI. In *Recent Trends in Artificial Intelligence Towards a Smart World: Applications in Industries and Sectors* (pp. 321-351). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-6790-8_12

Jajala, K. K., & Buduri, R. (2024). Efficient and secure routing with UAV: GuidedPheromone update based on improved Ant colony optimization and fuzzy logic for congestion control in vehicular ad-hoc network. *International Journal of Information Technology*, *16*(7), 4089-4110. https://doi.org/10.1007/s41870-024-01978-9

Jiang, W., Zhou, Q., He, J., Habibi, M. A., Melnyk, S., El-Absi, M., ... & Leung, V. C. (2024). Terahertz communications and sensing for 6G and beyond: A comprehensive review. *IEEE Communications Surveys & Tutorials*. https://doi.org/10.1109/COMST.2024.3385908

Kang, M., & Alouini, M. S. (2006). Capacity of MIMO Rician channels. *IEEE Transactions on Wireless Communications*, *5*(1), 112-122. https://doi.org/10.1109/TWC.2006.1576535

Khan, M. A., Javaid, S., Mohsan, S. A. H., Tanveer, M., & Ullah, I. (2024). Future-proofing security for UAVs with post-quantum cryptography: A review. *IEEE Open Journal of the Communications Society*. https://doi.org/10.1109/OJCOMS.2024.3486649

Khan, S., Malik, B. T., & Koziel, S. (2025). Highly compact dual-band frequency selective surface for path-loss and coverage improvement in millimeter-wave advanced wireless applications. *Scientific Reports*, *15*(1), 7029. https://doi.org/10.1038/s41598-025-91884-2

Khan, W. U., Mahmood, A., Bozorgchenani, A., Jamshed, M. A., Ranjha, A., Lagunas, E., ... & Popovski, P. (2024). Opportunities for intelligent reflecting surfaces in 6G empowered V2X communications. *IEEE Internet of Things Magazine*. https://doi.org/10.1109/IOTM.001.2300096

Kihero, A. B., Tusha, A., & Arslan, H. (2021). Wireless channel and interference. *Design and Analysis of Wireless Communication Signals: A Laboratory-Based Approach*.

Kolasa, K. (2023). *The digital transformation of the healthcare system: healthcare 5.0*. Taylor & Francis. https://doi.org/10.4324/b23291

Kou, L., Ding, S., Wu, T., Dong, W., & Yin, Y. (2022). An intrusion detection model for drone communication network in sdn environment. *Drones*, *6*(11), 342. https://doi.org/10.3390/drones6110342

Krouk, E., & Semenov, S. (Eds.). (2011). *Modulation and coding techniques in wireless communications*. John Wiley & Sons.

Kumar, A., Yadav, A. S., Gill, S. S., Pervaiz, H., Ni, Q., & Buyya, R. (2022). A secure drone-to-drone communication and software defined drone network-enabled traffic monitoring system. *Simulation Modelling Practice and Theory*, *120*, 102621. https://doi.org/10.1016/j.simpat.2022.102621

Kumar, N., & Chaudhary, A. (2024). Surveying cybersecurity vulnerabilities and countermeasures for enhancing UAV security. *Computer Networks*, *252*, 110695. https://doi.org/10.1016/j.comnet.2024.110695

Kumar, P. (2023). TRANSMISSION MEDIA: A COMPREHENSIVE ANALYSIS OF WIRED AND WIRELESS COMMUNICATION CHANNELS FOR MODERN DATA COMMUNICATION SYSTEMS. *Modern Data Networks*, 93.

Laghari, A. A., Jumani, A. K., Laghari, R. A., Li, H., Karim, S., & Khan, A. A. (2024). Unmanned aerial vehicles advances in object detection and communication security review. *Cognitive Robotics*. https://doi.org/10.1016/j.cogr.2024.07.002

Lathi, B. P. (1968). *Communication systems* (pp. 214-217). New York: Wiley.

Lessi, C. C., Gavrielides, A., Solina, V., Qiu, R., Nicoletti, L., & Li, D. (2024). 5G and beyond 5G technologies enabling industry 5.0: network applications for robotics. *Procedia Computer Science*, *232*, 675-687. https://doi.org/10.1016/j.procs.2024.01.067

Li, Y., Wu, R., Gan, L., & He, P. (2024). Development of an effective relay communication technique for multi-UAV wireless network. *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.3400728

Li, Z., Chen, Q., Li, J., Huang, J., Mo, W., Wong, D. S., & Jiang, H. (2024). A secure and efficient UAV network defense strategy: Convergence of blockchain and deep learning. *Computer Standards & Interfaces*, *90*, 103844. https://doi.org/10.1016/j.csi.2024.103844

Liang, J., Huang, X., Xu, Q., Liu, Y., Zhang, J., & Huang, J. (2023). A Novel UAV-Assisted Multi-Mobility Channel Model for Urban Transportation Emergency Communications. *Electronics*, *12*(14), 3015. https://doi.org/10.3390/electronics12143015

Maguluri, D. S., Velagala, L. P., & Hossain, G. (2024, April). Securing Healthcare 5.0: Exploring BYOD Cyber Risks, Misuse Cases, and Best Practices. In *2024 12th International Symposium on Digital Forensics and Security (ISDFS)* (pp. 1-6). IEEE. https://doi.org/10.1109/ISDFS60797.2024.10527340

MahmoudZadeh, S., Yazdani, A., Kalantari, Y., Ciftler, B., Aidarus, F., & Al Kadri, M. O. (2024). Holistic review of UAV-centric situational awareness: Applications, limitations, and algorithmic challenges. *Robotics*, *13*(8), 117. https://doi.org/10.3390/robotics13080117

Malini, M. C., & Chandrakala, N. (2022). Emerging 5G Wireless Technologies: Overview, Evolution, and Applications. *Evolutionary Computing and Mobile Sustainable Networks: Proceedings of ICECMSN 2021*, 335-349. https://doi.org/10.1007/978-981-16-9605-3_23

Malviya, R., Sundram, S., Dhanaraj, R. K., & Kadry, S. (Eds.). (2024). *Digital Transformation in Healthcare 5.0: Volume 2: Metaverse, Nanorobots and Machine Learning*. Walter de Gruyter GmbH & Co KG.

Manikandan, A., Babu, R. T. S., Ganesh, S. J., & Sanjay, T. (2025). Generative adversarial networks based adaptive modulation and coding for next-generation 5G communication systems. *Discover Applied Sciences*, *7*(2), 91. https://doi.org/10.1007/s42452-025-06509-0

Mao, Y., Yang, X., Wang, L., Wang, D., Alfarraj, O., Yu, K., ... & Yu, F. R. (2024). A high-capacity MAC protocol for UAV-enhanced RIS-assisted V2X architecture in 3D IoT traffic. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2024.3387997

Medard, M. (2000). The effect upon channel capacity in wireless communications of perfect and imperfect knowledge of the channel. *IEEE Transactions on Information theory*, *46*(3), 933-946. https://doi.org/10.1109/18.841172

Meng, K., Wu, Q., Xu, J., Chen, W., Feng, Z., Schober, R., & Swindlehurst, A. L. (2023). UAV-enabled integrated sensing and communication: Opportunities and challenges. *IEEE Wireless Communications*. https://doi.org/10.1109/MWC.131.2200442

Minh, B. V., Le, A. T., Le, C. B., Nguyen, S. Q., Phan, V. D., Nguyen, T. N., & Voznak, M. (2023). Performance prediction in UAV-terrestrial networks with hardware noise. *IEEE Access*, *11*, 117562-117575. https://doi.org/10.1109/ACCESS.2023.3325478

Mishra, D., & Natalizio, E. (2020). A survey on cellular-connected UAVs: Design challenges, enabling 5G/B5G innovations, and experimental advancements. *Computer Networks*, *182*, 107451. https://doi.org/10.1016/j.comnet.2020.107451

Mohsan, S. A. H., Othman, N. Q. H., Li, Y., Alsharif, M. H., & Khan, M. A. (2023). Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intelligent Service Robotics*, *16*(1), 109-137. https://doi.org/10.1007/s11370-022-00452-4

Mohsan, S. A. H., Othman, N. Q. H., Li, Y., Alsharif, M. H., & Khan, M. A. (2023). Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intelligent Service Robotics*, *16*(1), 109-137. https://doi.org/10.1007/s11370-022-00452-4

Molisch, A. F. (2012). *Wireless communications* (Vol. 34). John Wiley & Sons.

Mozaffari, M., Saad, W., Bennis, M., Nam, Y. H., & Debbah, M. (2019). A tutorial on UAVs for wireless networks: Applications, challenges, and open problems. *IEEE communications surveys & tutorials*, *21*(3), 2334-2360. https://doi.org/10.1109/COMST.2019.2902862

Nalini, M. (2024). AI-Powered Drones for Healthcare Applications. *Artificial Intelligence for Autonomous Vehicles*, 131-149. https://doi.org/10.1002/9781119847656.ch6

Narandžić, M., Hong, A., Kotterman, W., Thomä, R. S., Reichardt, L., Fügen, T., & Zwick, T. (2011). Channel Modeling. *OFDM: Concepts for Future Communication Systems*, 15-31. https://doi.org/10.1007/978-3-642-17496-4_2

Nawaz, H., Ali, H. M., & Laghari, A. A. (2021). UAV communication networks issues: A review. *Archives of Computational Methods in Engineering*, *28*(3), 1349-1369. https://doi.org/10.1007/s11831-020-09418-0

Nguyen, H. X., Trestian, R., To, D., & Tatipamula, M. (2021). Digital twin for 5G and beyond. *IEEE Communications Magazine*, *59*(2), 10-15. https://doi.org/10.1109/MCOM.001.2000343

Ning, N., Zhou, S., Bao, W., & Li, X. (2024). A Study on the Maximum Reliability of Multi-UAV Cooperation Relay Systems. *Sensors*, *24*(9), 2886. https://doi.org/10.3390/s24092886

Ning, Z., Li, T., Wu, Y., Wang, X., Wu, Q., Yu, F. R., & Guo, S. (2025). 6G Communication New Paradigm: The Integration of Unmanned Aerial Vehicles and Intelligent Reflecting Surfaces. *IEEE Communications Surveys & Tutorials*. https://doi.org/10.1109/COMST.2025.3526251

Oestges, C., Clerckx, B., Raynaud, L., & Vanhoenacker-Janvier, D. (2002). Deterministic channel modeling and performance simulation of microcellular wide-band communication systems. *IEEE Transactions on Vehicular Technology*, *51*(6), 1422-1430. https://doi.org/10.1109/TVT.2002.804846

Ogunbunmi, S., Chen, Y., Blasch, E., & Chen, G. (2024). A survey on reputation systems for uav networks. *Drones*, *8*(6), 253. https://doi.org/10.3390/drones8060253

Okyere, J. K. F. (2024, June). An Overview of Techniques for Enhancing Energy Efficiency in 5G Networks. In *2024 International Conference on Circuit, Systems and Communication (ICCSC)* (pp. 1-6). IEEE. https://doi.org/10.1109/ICCSC62074.2024.10617181

Özbek, E., Ekici, S., & Karakoc, T. H. (2023). An Evaluation on Landing Gear Configurations of Fixed-Wing, Rotary-Wing, and Hybrid UAVs. In *Unmanned Aerial Vehicle Design and Technology* (pp. 153-165). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-45321-2_9

Pandey, G. K., Gurjar, D. S., Yadav, S., Jiang, Y., & Yuen, C. (2024). UAV-assisted communications with RF energy harvesting: A comprehensive survey. *IEEE Communications Surveys & Tutorials*. https://doi.org/10.1109/COMST.2024.3425597

Pattepu, S., Datta, A., Appasani, B., Khan, M. S., Mukherjee, A., & Novak, M. (2024). Next-Gen Smart Healthcare Using UAV Assisted Cooperative Communication: A Deep Learning Approach. *IEEE Transactions on Consumer Electronics*. https://doi.org/10.1109/TCE.2024.3502913

Poikonen, J. (2009). Efficient channel modeling methods for mobile communication systems.

Qazzaz, M. M., Zaidi, S. A., McLernon, D. C., Hayajneh, A. M., Salama, A., & Aldalahmeh, S. A. (2024). Non-terrestrial uav clients for beyond 5g networks: A comprehensive survey. *Ad Hoc Networks*, *157*, 103440. https://doi.org/10.1016/j.adhoc.2024.103440

Rachakonda, L. P., Siddula, M., & Sathya, V. (2024). A comprehensive study on IoT privacy and security challenges with focus on spectrum sharing in Next-Generation networks (5G/6G/beyond). *High-Confidence Computing*, 100220. https://doi.org/10.1016/j.hcc.2024.100220

Reiser, M. (1982). Performance evaluation of data communication systems. *Proceedings of the IEEE*, *70*(2), 171-196. https://doi.org/10.1109/PROC.1982.12261

Rzig, I., Jafaar, W., Jebalia, M., & Tabbane, S. (2024, May). Dependency-aware task offloading in cooperative UAV-HAPS-assisted vehicular networks. In *2024 International Wireless Communications and Mobile Computing (IWCMC)* (pp. 1541-1546). IEEE. https://doi.org/10.1109/IWCMC61514.2024.10592360

Sabuncu, Ö., & Bilgehan, B. (2023). Statistical RMS delay spread representation in 5G mm-Wave analysis using real-time measurements. *Wireless Networks*, *29*(6), 2539-2549. https://doi.org/10.1007/s11276-023-03332-6

Sabuncu, Ö., & Bilgehan, B. (2024). Revolutionizing healthcare 5.0: Blockchain-driven optimization of drone-to-everything communication using 5G network for enhanced medical services. *Technology in Society*, *77*, 102552. https://doi.org/10.1016/j.techsoc.2024.102552

Sadıkoğlu, F., Bilgehan, B., & Sabuncu, Ö. (2022, November). An Effective Probabilistic Model for Clutter Signal Representation. In *World Conference Intelligent System for Industrial Automation* (pp. 165-172). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-53488-1_20

Salameh, A. I., & El Tarhuni, M. (2022). From 5G to 6G—challenges, technologies, and applications. *Future Internet*, *14*(4), 117. https://doi.org/10.3390/fi14040117

Saunders, S. R., & Aragón-Zavala, A. A. (2024). *Antennas and propagation for wireless communication systems*. John Wiley & Sons.

Shah, I. A. (2024). Privacy and security challenges in unmanned aerial vehicles (UAVs). *Cybersecurity in the Transportation Industry*, 93-115. https://doi.org/10.1002/9781394204472.ch5

Shaikh, P. W., & Mouftah, H. T. (2025). Edge Computing-Aided Dynamic Wireless Charging and Trip Planning of UAVs. *Journal of Sensor and Actuator Networks*, *14*(1), 8. https://doi.org/10.3390/jsan14010008

Shakhatreh, H., Sawalmeh, A., Hayajneh, K. F., Abdel-Razeq, S., & Al-Fuqaha, A. (2024). A systematic review of interference mitigation techniques in current and future UAV-assisted wireless networks. *IEEE open journal of the communications society*. https://doi.org/10.1109/OJCOMS.2024.3392623

Shamsabadi, A. A., Yadav, A., Gadallah, Y., & Yanikomeroglu, H. (2025). Exploring the 6G Potentials: Immersive, Hyperreliable, and Low-Latency Communication. *IEEE Vehicular Technology Magazine*. https://doi.org/10.1109/MVT.2025.3531346

Shannon, C. E. (1984). Communication in the presence of noise. *Proceedings of the IEEE*, *72*(9), 1192-1201. https://doi.org/10.1109/PROC.1984.12998

Sharma, J., & Mehra, P. S. (2023). Secure communication in IOT-based UAV networks: A systematic survey. *Internet of Things*, *23*, 100883. https://doi.org/10.1016/j.iot.2023.100883

Sharvari, N. P., Das, D., Bapat, J., & Das, D. (2023). Connectivity and collision constrained opportunistic routing for emergency communication using UAV. *Computer Networks*, *220*, 109468. https://doi.org/10.1016/j.comnet.2022.109468

Siddiky, M. N. A., Rahman, M. E., Uzzal, M. S., & Kabir, H. M. D. (2025). A Comprehensive Exploration of 6G Wireless Communication Technologies. *Computers*. https://doi.org/10.3390/computers14010015

Singh, B., & Kaunert, C. (2024). Unmanned aerial vehicle. *Cognitive Machine Intelligence: Applications, Challenges, and Related Technologies*, 108. https://doi.org/10.1201/9781003500865

Smith, D. R. (2012). *Digital transmission systems*. Springer science & business media. https://doi.org/10.1007/978-1-4419-8933-8

Smyrnaios, M., & Schön, S. (2013). Multipath Propagation, Characterization and Modeling. *Geodetic Sciences: Observations, Modeling and Applications*, 99. https://doi.org/10.5772/54567

Sobouti, M. J., Mohajerzadeh, A., Adarbah, H. Y., Rahimi, Z., & Ahmadi, H. (2024). Utilizing UAVs in wireless networks: advantages, challenges, objectives, and solution methods. *Vehicles*, *6*(4), 1769-1800. https://doi.org/10.3390/vehicles6040086

Son, S., Kwon, D., Lee, S., Jeon, Y., Das, A. K., & Park, Y. (2023). Design of secure and lightweight authentication scheme for UAV-enabled intelligent transportation systems using blockchain and PUF. *IEEE Access*, *11*, 60240-60253. https://doi.org/10.1109/ACCESS.2023.3286016

Souri, A., Hussien, A., Hoseyninezhad, M., & Norouzi, M. (2022). A systematic review of IoT communication strategies for an efficient smart environment. *Transactions on Emerging Telecommunications Technologies*, *33*(3), e3736. https://doi.org/10.1002/ett.3736

Sufyan, A., Khan, K. B., Khashan, O. A., Mir, T., & Mir, U. (2023). From 5G to beyond 5G: A comprehensive survey of wireless network evolution, challenges, and promising technologies. *Electronics*, *12*(10), 2200. **https://doi.org/10.3390/electronics12102200**

Suleiman, T. A., & Adinoyi, A. (2023). Telemedicine and smart healthcare—the role of artificial intelligence, 5G, cloud services, and other enabling technologies. *International Journal of Communications, Network and System Sciences*, *16*(3), 31-51. https://doi.org/10.4236/ijcns.2023.163003

Sun, J., Yuan, G., Song, L., & Zhang, H. (2024). Unmanned Aerial Vehicles (UAVs) in Landslide Investigation and Monitoring: A Review. *Drones*, *8*(1), 30. https://doi.org/10.3390/drones8010030

Sundaresan, K., Chai, E., Chakraborty, A., & Rangarajan, S. (2018). SkyLiTE: End-to-end design of low-altitude UAV networks for providing LTE connectivity. *arXiv preprint arXiv:1802.06042* *https://doi.org/10.48550/arXiv.1802.06042*

Sziroczak, D., Rohacs, D., & Rohacs, J. (2022). Review of using small UAV based meteorological measurements for road weather management. https://doi.org/10.1016/j.paerosci.2022.100859

Tarafder, P., Chun, C., Ullah, A., Kim, Y., & Choi, W. (2025). Channel Estimation in 5G-and-Beyond Wireless Communication: A Comprehensive Survey. *Electronics*, *14*(4), 750. https://doi.org/10.3390/electronics14040750

Taştan, M. C., & Ilhan, H. (2025). Performance evaluation of magic square based spatial modulation in UAV communication. *Journal of the Franklin Institute*, *362*(1), 107337. https://doi.org/10.1016/j.jfranklin.2024.107337

Thakur, N., Chouskey, P., Bansal, N., & Chopra, M. (2024). Systematic Review of Recent Trends of Industry 5.0 with Assistive Technologies in Higher Education and Smart Healthcare. *Applied Assistive Technologies and Informatics for Students with Disabilities*, 277-299. https://doi.org/10.1007/978-981-97-0914-4_16

Thantharate, P., Thantharate, A., & Kulkarni, A. (2024). GREENSKY: A fair energy-aware optimization model for UAVs in next-generation wireless networks. *Green Energy and Intelligent Transportation*, *3*(1), 100130. https://doi.org/10.1016/j.geits.2023.100130

Tsoulos, G. (Ed.). (2018). *MIMO system technology for wireless communications*. CRC press.

Umer, A., Müürsepp, I., Alam, M. M., & Wymeersch, H. (2025). Reconfigurable Intelligent Surfaces in 6G Radio Localization: A Survey of Recent Developments, Opportunities, and Challenges. *IEEE Communications Surveys & Tutorials*. https://doi.org/10.1109/COMST.2025.3536517

Venkatasivarambabu, P., & Agrawal, R. (2024). Enhancing UAV navigation with dynamic programming and hybrid probabilistic route mapping: an improved dynamic window approach. *International Journal of Information Technology*, *16*(2), 1023-1032. https://doi.org/10.1007/s41870-023-01671-3

Virk, S. S., & Chennupati, S. K. (2024). Performance Evaluation of mmWave Communication for Real-Time UAV-Base Station Links. *International Journal of Sensors, Wireless Communications and Control*. https://doi.org/10.2174/0122103279324756240928113451

WAN, F., YASEEN, M. B., RIAZ, M. B., SHAFIQ, A., THAKUR, A., & RAHMAN, M. O. (2024). Advancements and challenges in uav-based communication networks: a comprehensive scholarly analysis. *Results in Engineering*, 103271. https://doi.org/10.1016/j.rineng.2024.103271

Wang, C. X., You, X., Gao, X., Zhu, X., Li, Z., Zhang, C., ... & Hanzo, L. (2023). On the road to 6G: Visions, requirements, key technologies, and testbeds. *IEEE Communications Surveys & Tutorials*, *25*(2), 905-974. https://doi.org/10.1109/COMST.2023.3249835

Wang, D., Cao, Y., Lam, K. Y., Hu, Y., & Kaiwartya, O. (2024). Authentication and key agreement based on three factors and PUF for UAVs-assisted post-disaster emergency communication. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2024.3371101

Wang, J., Jiao, Z., Chen, J., Hou, X., Yang, T., & Lan, D. (2023). Blockchain-aided secure access control for UAV computing networks. *IEEE Transactions on Network Science and Engineering*. https://doi.org/10.1109/TNSE.2023.3324639

Wang, P., Xiang, X., Wang, R., Dong, P., & Li, Q. (2024). A Design of NLOS Communication Scheme Based on SC-FDE with Cyclic Suffix for UAV Payload Communication. *Drones*, *8*(11), 648. https://doi.org/10.3390/drones8110648

Wang, T., Wen, C. K., Wang, H., Gao, F., Jiang, T., & Jin, S. (2017). Deep learning for wireless physical layer: Opportunities and challenges. *China Communications*, *14*(11), 92-111. https://doi.org/10.1109/CC.2017.8233654

Witvliet, B. A. (2015). Near vertical incidence skywave: interaction of antenna and propagation mechanism.

Wu, C., Tang, Y. M., Kuo, W. T., Yip, H. T., & Chau, K. Y. (2024). Healthcare 5.0: a secure and distributed network for system informatics in medical surgery. *International Journal of Medical Informatics*, *186*, 105415. https://doi.org/10.1016/j.ijmedinf.2024.105415

Wu, Q., Guan, X., & Hua, M. (2023). Fundamentals of IRS. In *Intelligent Reflecting Surface For B5G/6G Wireless Networks: Information and Power Transmission* (pp. 1-13). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-44172-1

Wu, Y., Dai, H. N., Wang, H., & Choo, K. K. R. (2021). Blockchain-based privacy preservation for 5G-enabled drone communications. *IEEE Network*, *35*(1), 50-56. https://doi.org/10.1109/MNET.011.2000166

Xia, H., Bertoni, H. L., Maciel, L. R., Lindsay-Stewart, A., & Rowe, R. (1993). Radio propagation characteristics for line-of-sight microcellular and personal communications. *IEEE Transactions on antennas and propagation*, *41*(10), 1439-1447. https://doi.org/10.1109/8.247785

Xiong, R., Xiao, Q., Wang, Z., Xu, Z., & Shan, F. (2024). Leveraging lightweight blockchain for secure collaborative computing in UAV Ad-Hoc Networks. *Computer Networks*, *251*, 110612. https://doi.org/10.1016/j.comnet.2024.110612

Yin, J., Tang, Z., Lou, J., Guo, J., Cai, H., Wu, X., ... & Jia, W. (2024). QoS-Aware Energy-Efficient Multi-UAV Offloading Ratio and Trajectory Control Algorithm in Mobile Edge Computing. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2024.3452111

Zeng, Y., Lyu, J., & Zhang, R. (2018). Cellular-connected UAV: Potential, challenges, and promising technologies. *IEEE Wireless Communications*, *26*(1), 120-127. https://doi.org/10.1109/MWC.2018.1800023

Zeng, Y., Zhang, R., & Lim, T. J. (2016). Wireless communications with unmanned aerial vehicles: Opportunities and challenges. *IEEE Communications magazine*, *54*(5), 36-42. https://doi.org/10.1109/MCOM.2016.7470933

Zeqiri, R., Idrizi, F., & Halimi, H. (2019, October). Comparison of Algorithms and Technologies 2G, 3G, 4G and 5G. In *2019 3rd International symposium on Multidisciplinary studies and Innovative Technologies (ISMSIT)* (pp. 1-4). IEEE. https://doi.org/10.1109/ISMSIT.2019.8932896

Zhan, C., Yan, H., Fan, R., Hu, H., Xu, S., & Yang, J. (2025). Online Energy and Interference Management for Dynamic Target Tracking With Cellular-Connected UAV. *IEEE Transactions on Mobile Computing. https://doi.org/10.1109/TMC.2025.3532276*

Zhang, X., Li, J., Zhou, J., Zhang, S., Wang, J., Yuan, Y., ... & Li, J. (2025). Vehicle-to-Everything Communication in Intelligent Connected Vehicles: A Survey and Taxonomy. *Automotive Innovation*, 1-33. https://doi.org/10.1007/s42154-024-00310-2

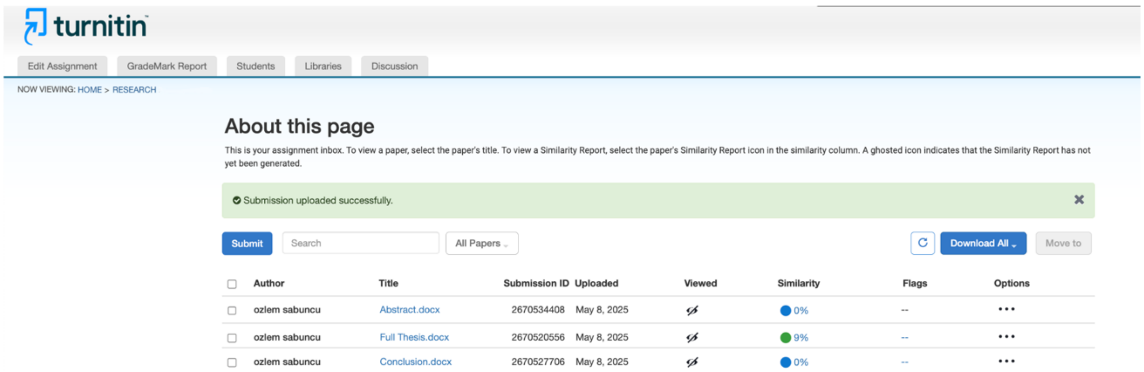
Zhang, Z., Huang, Y., Huang, W., Pan, W., Liao, Y., & Zhou, S. (2024). An auto-upgradable end-to-end pre-authenticated secure communication protocol for UAV-aided perception intelligent system. *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2024.3413010

Zhao, Z. H., Sun, H., Zhang, N. X., Xing, T. H., Cui, G. H., Lai, J. X., ... & He, H. J. (2024). Application of unmanned aerial vehicle tilt photography technology in geological hazard investigation in China. *Natural Hazards*, *120*(13), 11547-11578. https://doi.org/10.1007/s11069-024-06611-3

Zolanvari, M., Jain, R., & Salman, T. (2019). Potential data link candidates for civilian unmanned aircraft systems: A survey. *IEEE Communications Surveys & Tutorials*, *22*(1), 292-319. https://doi.org/10.1109/COMST.2019.2960366

APPENDICES

Similarity Report



Prof. Dr. Bülent Bilgehan

Curriculum Vitae

1. **Name Surname : Özlem Sabuncu**
2. **Date of Birth : 30.09.1997**
3. **Title : Lecturer**
4. **State of Education : PhD**
5. **Current Institution : Near East University**

Degree	Department	University	Date
Bachelor's Degree	Biomedical Engineering	Near East University	2015-2019
Master's Degree	Electrical and Electronic Engineering	Near East University	2019-2021
PhD	Electrical and Electronic Engineering	Near East University	2021-2025

6. **Master / PhD Thesis**

6.1.Title of Master Thesis and Supervisor

Artificial Intelligence Model to Assist and Evaluate the Kidney Stone on Computed Tomography Image **-**Prof. Dr. Bülent Bilgehan

6.2.Title of PhD Thesis / Medical Specialization Thesis and Supervisor

Enhanced Unmanned Aerial Vehicle Communication Optimization in Healthcare 5.0 via Blockchain and 5G -Prof. Dr. Bülent Bilgehan

7. **Publications**

7.1. Articles published in internationally referred journals (SCI, SSCI, AHCI, ESCI)

1. Bilgehan, B., Kayed, L., & Sabuncu, Ö. (2022). General probability distribution model for wireless body sensors in the medical monitoring system. *Biomedical Signal Processing and Control*, *77*, 103777. https://doi.org/10.1016/j.bspc.2022.103777

2. Gürman, M., Bilgehan, B., Sabuncu, Ö., & Mirzaei, O. (2023). A powerful probabilistic model for noise analysis in medical images. *International Journal of Imaging Systems and Technology*, *33*(3), 999-1013. https://doi.org/10.1002/ima.2283

3. Bilgehan, B., & Sabuncu, Ö. (2023). An optimized device-to-device (D2D) blockchain network for the insurance industry. *International Journal of Communication Systems*, e5446. https://doi.org/10.1002/dac.5446

4. Sabuncu, Ö., & Bilgehan, B. (2023). Statistical RMS delay spread representation in 5G mm-Wave analysis using real-time measurements. *Wireless Networks*, 1-11. https://doi.org/10.1007/s11276-023-03332-6

5. Sabuncu, Ö., Bilgehan, B., Kneebone, E., & Mirzaei, O. (2023). Effective deep learning classification for kidney stone using axial computed tomography (CT) images. *Biomedical Engineering/Biomedizinische Technik*, (0). https://doi.org/10.1515/bmt-2022-0142

6. Bilgehan, B., & Sabuncu, Ö. (2023). Component-Related Phase Noise Evaluation Method for the LC Oscillators. *Circuits, Systems, and Signal Processing*, 1-20. https://doi.org/10.1007/s00034-023-02472-6

7. Bilgehan, B., & Sabuncu, Ö. (2023). Optimized blockchain network model for 6G cellular vehicle-to-everything communication. *Transactions on Emerging Telecommunications Technologies*, *34*(12), e4868. https://doi.org/10.1002/ett.4868

8. Sabuncu, Ö., & Bilgehan, B. (2024). Revolutionizing Healthcare 5.0: Blockchain-Driven Optimization of Drone-to-Everything Communication Using 5G Network for Enhanced Medical Services. *Technology in Society*, 102552. https://doi.org/10.1016/j.techsoc.2024.102552

9. Sabuncu, Ö., & Bilgehan, B. (2025). Novel Statistical Modelling and Optimization Techniques of Fading Channel Coefficients for 5G Network Performance. *Journal of Network and Systems Management*, *33*(2), 42. https://doi.org/10.1007/s10922-025-09905-4

10. Sabuncu, Ö., & Bilgehan, B. (2025). Human-Centric IoT-Driven Digital Twins in Predictive Maintenance for Optimizing Industry 5.0. *Journal of Metaverse*, *5*(1), 64-72. https://doi.org/10.57019/jmv.1596909

7.2. Articles published in other internationally refereed journals

1. Bilgehan, B., & Sabuncu, Ö. (2024). Applying P-NOMA in UAV-Assisted IoT Networks for Enhanced Wireless Communication. *NEU Journal for Artificial Intelligence and Internet of Things, 4(2),*

7.3. Assertions presented in international scientific congresses and published in the proceedings

1. Sabuncu, Ö., & Bilgehan, B. (2021, December). Performance Evaluation for Various Deep Learning (DL) Methods Applied to Kidney Stone Diseases. In *2021 International Conference on Forthcoming Networks and Sustainability in AIoT Era (FoNeS-AIoT)* (pp. 1-3). IEEE. https://doi.org/10.1109/FoNeS-AIoT54873.2021.00010

2. Bilgehan, B., & Sabuncu, Ö. (2022, August). Synchronization and Analysis of Chaotic Circuit with Application to Communication in the internet of things (IoT) Services. In *2022 International Conference on Artificial Intelligence in Everything (AIE)* (pp. 674-678). IEEE. https://doi.org/10.1109/AIE57029.2022.00132

3. Sadıkoğlu, F., Sabuncu, Ö., & Bilgehan, B. (2023, March). A Comparative Analysis of the Different CNN Models Using Fuzzy PROMETHEE for Classification of Kidney Stone. In *15th International Conference on Applications of Fuzzy Systems, Soft Computing and Artificial Intelligence Tools–ICAFS-2022* (pp. 77-84). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-25252-5_15

4. Sadıkoğlu, F., Bilgehan, B., & Sabuncu, Ö. (2023, September). Fixed Power Optimized Path Selection Using Fuzzy Pairing for C-V2X Communication. In *International Conference on Theory and Applications of Fuzzy Systems and Soft Computing* (pp. 20-27). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-76283-3_6

5. Sadıkoğlu, F., Bilgehan, B., & Sabuncu, Ö. (2024, November). An Effective Probabilistic Model for Clutter Signal Representation. In *World Conference Intelligent System for Industrial Automation* (pp. 165-172). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-53488-1_20

6. Sadıkoğlu, F., Bilgehan, B., & Sabuncu, Ö. (2024, April). Optimized Solution for Multipath Faded Mm-Wave Signal in IoT Network. In *International Conference on Smart Environment and Green Technologies* (pp. 153-160). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-81564-5_19

7. Sadıkoğlu, F., Sabuncu, Ö., & Bilgehan, B. (2024, April). Revolutionizing Connectivity: Exploring Blockchain Integration in Advanced Communication Networks. In *International Conference on Smart Environment and Green Technologies* (pp. 227-233). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-81564-5_28

7.4. International books published, or chapters for a book

1. Sabuncu, Ö., & Bilgehan, B. (2025) Transforming UAV Framework with Blockchain, IoT, and Workflow Sorting: Integrating Technologies for Medical Delivery. *AI Horizons: From Learning to Understanding— Navigating Challenges Across Industries*. https://doi.org/10.1007/978-3-031-86749-1

2. Bilgehan, B., & Sabuncu, Ö. (2025) UAV-Assisted Dynamic IoT Network Deployment in Disaster Zones. *AI Horizons: From Learning to Understanding— Navigating Challenges Across Industries*. https://doi.org/10.1007/978-3-031-86749-1

3. Bilgehan, B., & Sabuncu, Ö. (2025) Predictive Modelling of Outdoor Wireless Propagation for Future 5G Networks in Cyprus. *AI Horizons: From Learning to Understanding— Navigating Challenges Across Industries*. https://doi.org/10.1007/978-3-031-86749-1

7.5. Articles published in national refereed journals

7.6. Assertions presented in national scientific congresses and published in the proceedings.

7.7. Other publications

8. Projects

9. Administrative Services

1. Vice Head of the Department of Electrical and Electronics Engineering
2. Board Member of the Science, Technology, and Engineering Applications and Research Center

10. Professional Affiliations

11. Fellowships and Awards

1. ISSN International Best Researcher Award, Titles are Awarded by, ISSN AWARDS with, World Research Council & Times of Research
2. One of the top three papers that received the Best Paper Award at the IEEE International Conference on AI in Everything (AIE), 2022.
3. Near East University 2022 Young Researcher Award

4. World Top Scientists Awards under the category of "Best Researcher Award"
5. Near East University 2023 Young Researcher Award
6. Oral Presentation Award at the International Conference on Smart Environment and Green Technology (ICSEGT 2024).
7. Near East University 2024 Young Researcher Award

12. Please fill out the chart below for undergraduate and graduate courses you have given in the last 2 years.

Academic Year	Semester	Course	Weekly Course Hours		Number of Students
			Theoretical	Practical	
2023 - 2024	Fall	Bilgisayar Uygulamaları	2	1	20
	Fall	Elektrik Malzemeleri	2	1	20
	Fall	Elektriksel Ölçme Tekniği	2	1	20
	Fall	Mantık Devreleri	2	1	10
	Fall	Mühendislik Tasarımı I.	2	1	10
	Spring	Elektronik I.	2	2	20
	Spring	Mühendislik Tasarımı II.	2	2	20
	Spring	Bilgisayar Uygulamaları	2	1	20
	Spring	Haberleşme Sistemleri	3	1	30
	Spring	Elektriksel Ölçme Tekniği	2	1	20
2024 - 2025	Fall	Bilgisayar Uygulamaları	2	1	20
	Fall	Mantık Devreleri	2	2	20
	Fall	Elektrik Malzemeleri	2	2	20
	Fall	Sinyaller ve Sistemler	3	1	30
	Fall	Mühendislik Tasarımı I.	2	1	20
	Spring	Haberleşme Sistemleri	3	1	30

	Spring	Elektriksel Ölçme Tekniği	2	1	30
	Spring	Bilgisayar Uygulamaları	2	1	20
	Spring	Mühendislik Tasarımı II.	3	1	10
	Spring	Elektromanyetik Dalga Yayılımlı Antenler	3	1	20

13. Organizations/Companies Previously Affiliated With

No	Institution Name	Date	Title
1	Near East University	09.2019 - 09.2021	Research Assistant
2	Near East University	09.2021 - Present	Lecturer