UDC 621.37
DOI: 10.15587/1729-4061.2025.331607

DEVELOPMENT AND EVALUATION OF RADIO FREQUENCY MANAGEMENT APPROACHES FOR STRATOSPHERIC COMMUNICATION SYSTEMS

Askar Abdykadyrov
Doctor PhD*
Institute of Mechanics and Mechanical Engineering
named after Academician U. A. Dzholdasbekov
Kurmangazy str., 29, Almaty, Republic of Kazakhstan, 050010
Mukhit Abdullayev
PhD*
Ainur Kuttybayeva
Corresponding author
PhD*
E-mail: a.kuttybayeva@satbayev.university
Kalmukhamed Tazhen
Master's Student*
Nurlan Kystaubayev
Master's Student*
Muratbek Yermekbayev
PhD
Department of Telecommunications and Innovative Technologies
Gumarbek Daukeev Almaty University
of Power Engineering and Communications
Baitursynuly str., 126/1, Almaty, Republic of Kazakhstan, 050013
Tatyana Meshcheryakova
PhD*
Altynkul Turebekova
Master of Technical Sciences*
Nurlan Sarsenbayev
Head of Department
Department of Automation and Control**
*Department of Electronics, Telecommunications
and Space Technologies**
**Kazakh National Research Technical University named after K. I. Satpayev
Satbaev str., 22, Almaty, Republic of Kazakhstan, 050013

The object of the study is the methods of radio frequency resource management in stratospheric communication systems based on high altitude platform stations (HAPS). The problem addressed is the limited radio frequency spectrum, frequency overlap with fifth- and sixth-generation (5G/6G) networks, and the high probability of interference, which complicate efficient spectrum utilization and coordination. The obtained results indicate that within the frequency bands recommended by the International Telecommunication Union (ITU) – 21.4–22.0 GHz, 24.25–27.5 GHz, 47.2–47.5 GHz, and 47.9–48.2 GHz – the probability of interference reaches up to 70% in the 27.5–28.35 GHz band. By applying cognitive radio (CR) technology, interference levels decreased by 60%, and spectrum utilization efficiency increased by 35%. Dynamic spectrum access (DSA) improved spectrum efficiency by 30–45%, while spectrum sharing methods enhanced it by 40–60%. A brief explanation of the results shows that the proposed management approaches significantly increase the efficiency of radio frequency resource use and substantially reduce interference. For example, at a bandwidth of 100 MHz and a signal-to-noise ratio (SNR) of 10, the channel capacity reached approximately 332 Mbps. The distinctive features of the results lie in the comprehensive use of modern technologies that effectively address spectrum scarcity and interference issues, ensuring compatibility of HAPS with existing terrestrial and satellite communication systems. The proposed approaches are suitable for implementation in international and national spectrum coordination and licensing frameworks aimed at expanding broadband connectivity in underserved regions

Keywords: stratospheric communication, HAPS, spectrum, interference, 5G, 6G, frequency, integration, management, telecommunications

Received 03.04.2025
Received in revised form 08.05.2025
Accepted 28.05.2025
Published 25.06.2025

How to Cite: *Abdykadyrov, A., Abdullayev, M., Kuttybayeva, A., Tazhen, K., Kystaubayev, N., Yermekbayev, M., Mechsheryakova, T., Turebekova, A., Sarsenbayev, N. (2025). Development and evaluation of radio frequency management approaches for stratospheric communication systems. Eastern-European Journal of Enterprise Technologies, 3 (5 (135)), 17–29. https://doi.org/10.15587/1729-4061.2025.331607*

1. Introduction

The development of modern telecommunication systems forms the foundation of the information society [1]. Stable access to the Internet has become a key prerequisite for progress and inclusive development in vital sectors such as education, the economy, healthcare, and public safety. The digital divide hinders economic growth, limits access to essential services, and deepens global inequality.

One of the most promising technological solutions to this problem is the use of high altitude platform stations (HAPS) [2]. HAPS are unmanned aerial vehicles or aerostats that operate in the stratosphere at altitudes of 20–25 km to provide telecommunications services. These platforms are considered an intermediate solution between terrestrial and satellite systems [3]. A single HAPS device can cover a radius of 200–500 km and offers low signal latency, making it more efficient than traditional satellites. In addition, HAPS systems have great potential in emergency response, military operations, and the support of remote infrastructure.

One of the main barriers to large-scale implementation of this technology is the issue of radio frequency spectrum management [4, 5]. The radio spectrum is a limited and heavily regulated resource that cannot be simultaneously used by mobile communications, broadcasting, satellite, and military systems. To prevent frequency overlap, international coordination is essential [6].

The International Telecommunication Union (ITU) has proposed the following frequency bands for HAPS systems: 21.4–22.0 GHz, 24.25–27.5 GHz, 47.2–47.5 GHz, and 47.9–48.2 GHz. Although these frequencies offer high data throughput, they are susceptible to atmospheric attenuation and are currently used in 5G/6G networks, increasing the risk of mutual interference [7]. Moreover, many countries lack harmonized frequency compatibility between HAPS systems and terrestrial networks, which complicates licensing, international legal compliance, and coordination. The lack of unified national regulatory policies also slows down this process [8, 1].

By 2021, only 14 countries had designated specific frequency bands for HAPS systems. In the Republic of Kazakhstan, interest in this technology is growing, although the legal framework for HAPS has not yet been fully developed. According to the Ministry of Digital Development, Innovations and Aerospace Industry of the Republic of Kazakhstan, approximately 60% of the country's territory is still not fully covered by Internet services, particularly in rural and remote areas [8, 1].

HAPS systems could provide a solution to this issue. However, without efficient and equitable management of radio frequency resources, the full potential of these systems cannot be realized. Radio spectrum management involves not only technical, but also political, legal, and economic aspects [4, 5]. Therefore, research on the management of frequency spectrum for the sustainable development of stratospheric communication systems is of high importance.

Thus, developing radio frequency spectrum management for HAPS systems is a relevant and necessary scientific topic.

2. Literary review and problem statement

The paper [1] presents the results of research on the use of high altitude platform stations (HAPS) to support next-generation wireless networks, particularly in the context of 5G. It is shown that HAPS can provide wide-area coverage and low-latency access. However, unresolved issues remain related to spectrum overlap with terrestrial networks and insufficient coordination mechanisms.

According to [2], HAPS are considered promising for offloading urban traffic and acting as super macro base stations. But there were difficulties maintaining stable quality of service (QoS) due to atmospheric variability and limited onboard energy capacity.

The authors of [3] investigate interference modeling in dense wireless environments using stochastic methods. It was demonstrated that Poisson-based probabilistic approaches offer better accuracy for capturing dynamic interference behavior. Still, their integration into large-scale radio management remains underexplored.

Study [4] identifies regulatory fragmentation as a significant barrier to HAPS adoption. The reason for this may be policy discrepancies between aviation and telecommunications sectors, which complicate the implementation of unified spectrum management strategies.

The integration of HAPS with edge computing and Internet of Things (IoT) services is examined in [5]. It is shown that such architectures are feasible; however, the cost part in terms of energy consumption and QoS instability make reliable operation difficult.

Machine learning-based channel allocation techniques are presented in [6]. These methods improved spectral efficiency in simulations, but the lack of real-world testing and the complexity of training models under dynamic environments limit their current applicability.

Cognitive radio solutions for dynamic spectrum access are reviewed in [7]. While the potential to reduce interference and enhance spectrum utilization was demonstrated, unresolved issues remain related to latency in real-time decision-making and sensing inaccuracies.

Propagation constraints specific to millimeter-wave frequencies are evaluated in [8]. The authors model rain attenuation and fading effects, showing that signal degradation in humid or variable climates significantly limits coverage and throughput.

A multi-tier coordination framework for non-terrestrial networks is proposed in [9]. However, the fundamental impossibility of aligning cross-border policies without international cooperation was emphasized.

Paper [10] addresses the economic aspects of deploying HAPS in sparsely populated regions. It is shown that without public funding or cross-sector partnerships, commercial scalability remains limited.

Experimental results from low-altitude aerial systems are reported in [11] and [12], demonstrating basic communication capabilities. Nevertheless, these works fall short of replicating the operational environment of stratospheric HAPS platforms due to their limited altitude, endurance, and power constraints.

Dynamic spectrum access (DSA) strategies are quantified in [13]. Efficiency gains of up to 40% were recorded, but such systems depend heavily on real-time channel feedback and centralized coordination systems.

The problem of frequency coexistence between HAPS and satellites in shared spectrum bands is explored in [14]. It is shown that mutual interference is likely unless elevation-based isolation and strict power constraints are implemented.

A broader architectural view involving HAPS, terrestrial, and satellite networks is introduced in [15], emphasizing the difficulty of coordinating communication protocols across different altitudes and delay profiles.

Physical layer performance and antenna configurations are discussed in [16–18], with results supporting the use of adaptive modulation and optimized antenna placement. However, implementation of these solutions in energy-constrained environments remains a challenge.

Validation methods such as testbeds and scenario simulations are described in [19–21]. Yet, these do not fully replicate atmospheric conditions or long-range stratospheric behaviors, highlighting a lack of empirical depth in existing literature.

The reason many of these problems persist may be the technological immaturity of adaptive systems, high integration costs, and fragmented legal frameworks. These limitations make full-scale HAPS deployment impractical under current conditions.

A way to overcome these difficulties can be the integration of cognitive radio with probabilistic interference modeling, spectrum-aware energy algorithms, and compliance with ITU spectrum recommendations. This approach was outlined in [22–25], although much of the existing research remains theoretical.

All this suggests that it is advisable to conduct a comprehensive study on the development of intelligent radio frequency management strategies for HAPS. Such a study should integrate technical modeling, policy alignment, energy constraints, and validation across realistic environments to ensure sustainable deployment at scale.

3. The aim and objectives of the study

The aim of the study is to develop and evaluate effective radio frequency resource management strategies for high altitude platform station (HAPS) systems in order to ensure reliable integration into existing 5G/6G networks and enable broadband coverage in remote regions.

To achieve this aim, the following objectives are accomplished:

– to analyze international and national frequency allocation frameworks and identify technical limitations related to signal attenuation and propagation in different frequency bands;

– to simulate spectral efficiency using Shannon's capacity formula and evaluate interference reduction depending on distance;

– to model interference probability using Poisson distribution and assess energy consumption patterns based on transmission power;

– to study regulatory and coordination issues across different countries and frequency zones to identify deployment barriers;

– to evaluate advanced frequency management techniques such as dynamic spectrum access (DSA), cognitive radio (CR), and spectrum sharing in the context of ITU-R recommendations.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of the study is the methods of radio frequency resource management in stratospheric communication systems based on high altitude platform stations (HAPS).

The main hypothesis of the study is that the combined use of cognitive radio (CR), dynamic spectrum access (DSA), probabilistic interference modeling, and energy-aware transmission policies can significantly improve spectral efficiency, reduce interference levels, and support reliable integration of HAPS systems into existing 5G/6G communication infrastructures.

Assumptions made in the study include a fixed altitude of HAPS platforms at 20 km, homogeneous atmospheric conditions without rain attenuation or multipath effects, and a constant transmission time of 5 seconds for energy consumption analysis. The average interference arrival rate is modeled using a Poisson distribution with λ values ranging from 1 to 5. It is also assumed that spectrum access decisions are based on real-time channel state estimation.

Simplifications adopted in the study involve the exclusion of hardware implementation and field testing, relying solely on simulation-based methods. Antennas are considered ideal and omnidirectional, with no beamforming applied. Delay constraints and real-time scheduling mechanisms are not included. Additionally, the analysis is limited to frequency bands recommended by the International Telecommunication Union (ITU).

4. 2. Frequency allocation standards

As illustrated in Fig. 1, and in line with the recommendations of the International Telecommunication Union (ITU), the frequency bands 47–48.2 GHz and 48.2–50.2 GHz have been identified as promising candidates for HAPS-related applications (ITU-R F.2478-0, 2019) [14].

Fig. 1 illustrates the relative distribution of the 47–50.2 GHz frequency bands allocated for HAPS systems, based on ITU Radiocommunication Sector (ITU-R) F.2478-0 (2019) recommendations. The sub-band 48.2–50.2 GHz, with a total width of 2.0 GHz, constitutes approximately 62.5% of the total available spectrum, indicating its prominence for organizing communication channels in stratospheric networks.

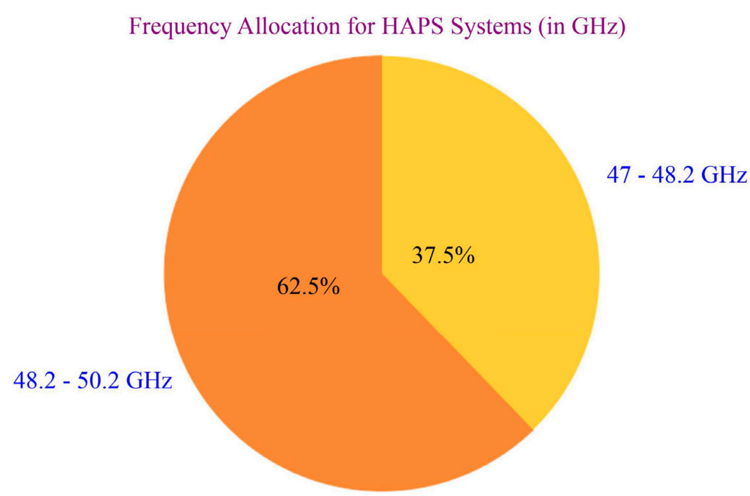

Fig. 1. Distribution of recommended frequency bands for high altitude platform stations according to ITU-R F.2478-0 (2019)

4. 3. Hardware and software environment

All simulations and analyses in this study were conducted using a personal computer equipped with an Intel Core i7-1165G7 processor, 16 GB RAM, and Windows 11 operating system. The modeling and visualization of results were carried out using the Python 3.11 programming language, specifically leveraging the following open-source libraries:

1. NumPy for numerical computation and array operations.
2. Matplotlib for data visualization and plotting graphs.

No real-time or hardware-based experimental platforms (such as physical HAPS drones or RF modules) were used at this stage. All data was simulated using mathematical models and verified numerically [15].

4. 4. Assumptions and simplifications

To simplify the modeling and isolate the behavior of key variables, the following assumptions were made. The HAPS altitude is fixed at 20 km. Atmospheric conditions are considered homogeneous and do not include multipath fading or rain scatter (ideal propagation assumed). The environment is assumed free of electromagnetic interference from other systems unless explicitly modeled. Transmission time (t) is fixed at 5 seconds for energy consumption analysis. The Poisson arrival rate (λ) varies from 1 to 5, representing low to moderate interference environments. All transmissions are assumed to be omnidirectional unless otherwise noted. No adaptive power control or beamforming is assumed in baseline scenarios.

4. 5. Initial data

The study uses the following parameters and datasets. Bandwidth (B) is set to 100 MHz (fixed). signal-to-noise ratio (SNR) varies from 5 dB to 20 dB. Transmission power (P) ranges from 1 W to 4 W. Distance (d) spans from 100 meters to 10,000 meters. Frequencies considered include 21.4–22.0 GHz, 27.5–28.35 GHz, and 47.2–47.5 GHz, based on ITU-R and FCC recommendations [14]. The propagation constant (λ) is defined for free-space loss models. The study relies on ITU recommendations: ITU-R F.2478-0 (2019) for spectrum allocation and ITU-R SF.1483 for interference thresholds [14].

4. 6. Research methods

4. 6. 1. Channel capacity modeling (Shannon theorem)

To estimate spectral efficiency and maximum data rates, it is possible to apply the Shannon-Hartley theorem

$$C = B \cdot \log_2\left(1 + SNR\right). \quad (1)$$

Here, C represents the channel capacity (in bits per second), B is the bandwidth (in Hz), and SNR denotes the signal-to-noise ratio. The formula was used to estimate the spectral efficiency of the communication channel under various SNR and bandwidth configurations.

This model allows to analyze the relationship between bandwidth, noise, and achievable throughput in HAPS systems [15].

4. 6. 2. Propagation loss modeling (Friis transmission equation)

To estimate interference due to distance and frequency, the Friis equation was used

$$I \approx \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{\left(4\pi d\right)^2}. \quad (2)$$

Here, P_t – the transmission power, G_t and G_r – the antenna gains of the transmitter and receiver, respectively, λ – the wavelength, and d – the distance.

4. 6. 3. Interference modeling (Poisson process)

Interference events were modeled using a Poisson distribution:

$$P\left(k, \lambda\right) = \frac{\lambda^k \cdot e^{-\lambda}}{k!}, \quad (3)$$

where $P(k,)$ denotes the probability of observing k interference events;

λ represents the mean arrival rate (expected number of events);

k denotes the interference event count (non-negative integer);

e denotes Euler's number (approximately 2.71828).

4. 6. 4. Energy consumption analysis

Energy usage of transmitters was calculated as:

$$E = P \cdot t, \quad (4)$$

where E – the energy consumed (in joules);

P – the transmission power (in watts);

t – the duration of transmission (in seconds).

This model was used to estimate energy usage under varying power conditions in simulated stratospheric communication scenarios. The simulation was implemented using Python (NumPy and Matplotlib), and considered values of power between 1 and 4 W at a fixed time interval of 5 seconds.

4. 6. 5. Advanced management techniques

The study also evaluated the impact of the following frequency management strategies:

– dynamic spectrum access (DSA) – modeled via adaptive spectrum slot allocation;

– cognitive radio (CR) – simulated as adaptive channel hopping based on spectrum sensing;

– spectrum sharing – assessed through effective utilization ratios across multiple users [15].

5. Simulation results of radio frequency resource management for HAPS

5. 1. Radio frequency requirements of high altitude platform stations systems

High altitude platform stations (HAPS), located at high altitudes, are increasingly considered an alternative and promising solution for broadband communication. These systems provide communication services through stratospheric aerial platforms positioned at altitudes of 20 to 50 km, and play a particularly important role in rural and underdeveloped areas with limited infrastructure [1]. For the successful implementation of HAPS systems, clearly defined and harmonized frequency bands are essential.

A literature review [1] indicates that HAPS systems typically operate in the millimeter wave frequency bands, particularly in the ranges of 21.4–22 GHz, 27.5–28.35 GHz, and 47.2–47.5 GHz [12]. These frequencies have been recommended for HAPS use by international and national regulatory bodies such as ITU-R and the Federal Communications Commission (FCC) [2]. For example, in the 28 GHz band, HAPS can achieve a data rate of up to 1 Gbps, which is comparable to 4G and 5G networks [16]. Additionally, experimental trials in the 47 GHz band have demonstrated speeds of up to 2.1 Gbps, although the signal propagation range in this band is limited to just 2–3 km [17].

Recommendations from international organizations regarding HAPS frequency bands, data throughput capabilities, and signal propagation distances are summarized in Table 1 below.

According to Table 1, the recommended frequency bands for HAPS systems include 21.4–22 GHz, 27.5–28.35 GHz, and 47.2–47.5 GHz, which are approved by international organizations (ITU-R and FCC). In the 28 GHz band, HAPS systems can provide data throughput of up to 1 Gbps, while experimental tests in the 47 GHz band have achieved speeds up to 2.1 Gbps. However, the propagation range was limited to only 2–3 km.

Table 1

HAPS frequency ranges and data rates: international organizations' recommendations and signal propagation range

Frequency range (GHz)	Data rate	Application area	International organizations recommendations	Propagation range	Signal propagation
21.4–22	None	HAPS system recommended frequencies	ITU-R, FCC	None	No propagation data available
27.5–28.35	None	HAPS system recommended frequencies	ITU-R, FCC	None	No propagation data available
47.2 – 47.5	None	HAPS system recommended frequencies	ITU-R, FCC	None	No propagation data available
28 (HAPS)	1 Gbps	HAPS systems, 4G and 5G competition	ITU-R, FCC	Varied	Works at competitive level
47 (experimental)	2.1 Gbps	Experimental trials, propagation range of 2–3 km	None	2–3 km	Limited propagation range

The main advantage of millimeter-wave frequencies is the possibility of using wideband channels, which support high-speed data transmission. However, these frequencies have several limitations. Primarily, atmospheric absorption (particularly due to rain, fog, and cloudiness) significantly affects millimeter waves. For example, according to ITU-R Recommendation P.676-12, at a frequency of 22 GHz, signal attenuation due to water vapor can reach 0.4–0.6 dB/km, while at 47 GHz, it may range between 1.8–2.3 dB/km [16]. Additionally, rain attenuation in the 28 GHz band at an intensity of 10 mm/hour can reach up to 2 dB/km [17]. This poses challenges especially in tropical and high-rainfall regions.

These limitations affect the reliability of HAPS systems, as signal losses in radio frequencies can lead to connection interruptions or degraded service quality. Therefore, the frequency selection for HAPS systems should be based not only on technical aspects but also on climatic and geographic conditions. For instance, in dry climate regions (e. g., Central Asia or North Africa), the 47 GHz band may be relatively effective, while in tropical zones, lower frequencies (e. g., 21–22 GHz) are preferable.

The signal attenuation depending on the frequency in millimeter-wave bands can be observed in Fig. 2.

In Fig. 2, it is shown that signal attenuation increases with frequency. For instance, at 22 GHz, the signal attenuation is around 0.5 dB/km, whereas at 47 GHz, it reaches up to 2.1 dB/km, and at 28 GHz, it is approximately 2 dB/km.

Moreover, reliance on higher frequency bands requires increased accuracy in alignment, enhanced beamforming capabilities, and a denser physical network infrastructure. These factors contribute to the increased design complexity of HAPS systems [18].

5. 2. Interference analysis and frequency resource modeling in HAPS systems

From the graph presented in Fig. 3, the relationship between channel capacity (C) and the signal-to-noise ratio (SNR) for a 100 MHz bandwidth is illustrated. For instance, when SNR = 10, the channel capacity is approximately 332 Mbps. As the SNR value increases, the capacity rises logarithmically, reaching about 440 Mbps at SNR = 20. This demonstrates the potential of cognitive radio systems to utilize the frequency spectrum more efficiently.

From the graph shown in Fig. 4, it is evident that the level of interference decreases exponentially with increasing distance. For example, at a distance of 100 meters, the interference level is approximately 1.3×10^{-6}, whereas at 10,000 meters, it drops to around 1.3×10^{-12}. This demonstrates that increasing the communication distance is an effective way to reduce interference in the integration of HAPS and 4G/5G systems.

Currently, dynamic frequency allocation methods for HAPS-based communication systems are being actively researched. Modeling results have demonstrated that the average efficiency of frequency resource utilization in such systems ranges between 35% and 40% [19]. Moreover, study published in the IEEE journal [14] indicate that HAPS systems can improve urban communication quality by up to 60%.

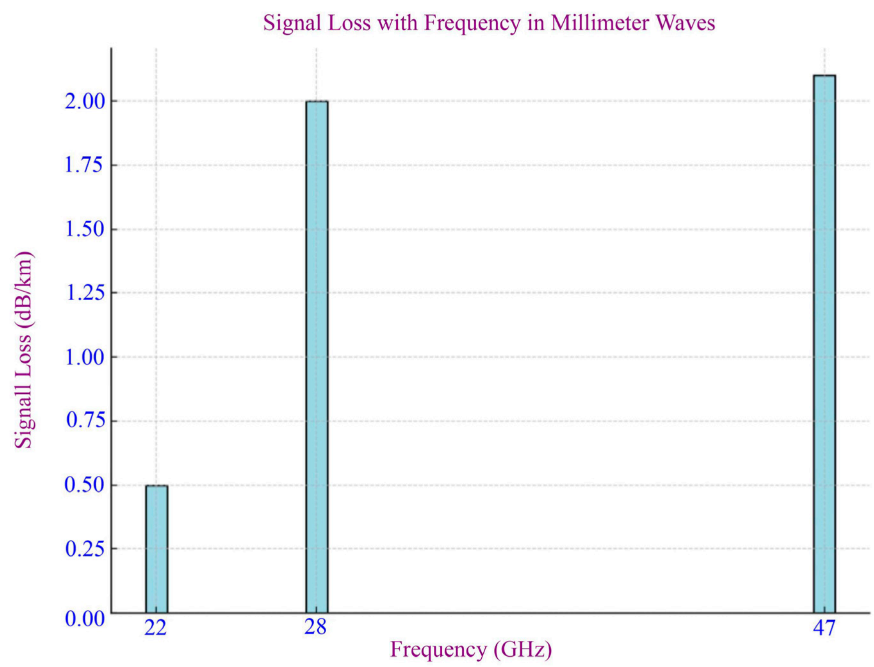

Fig. 2. Signal loss vs. frequency in millimeter waves

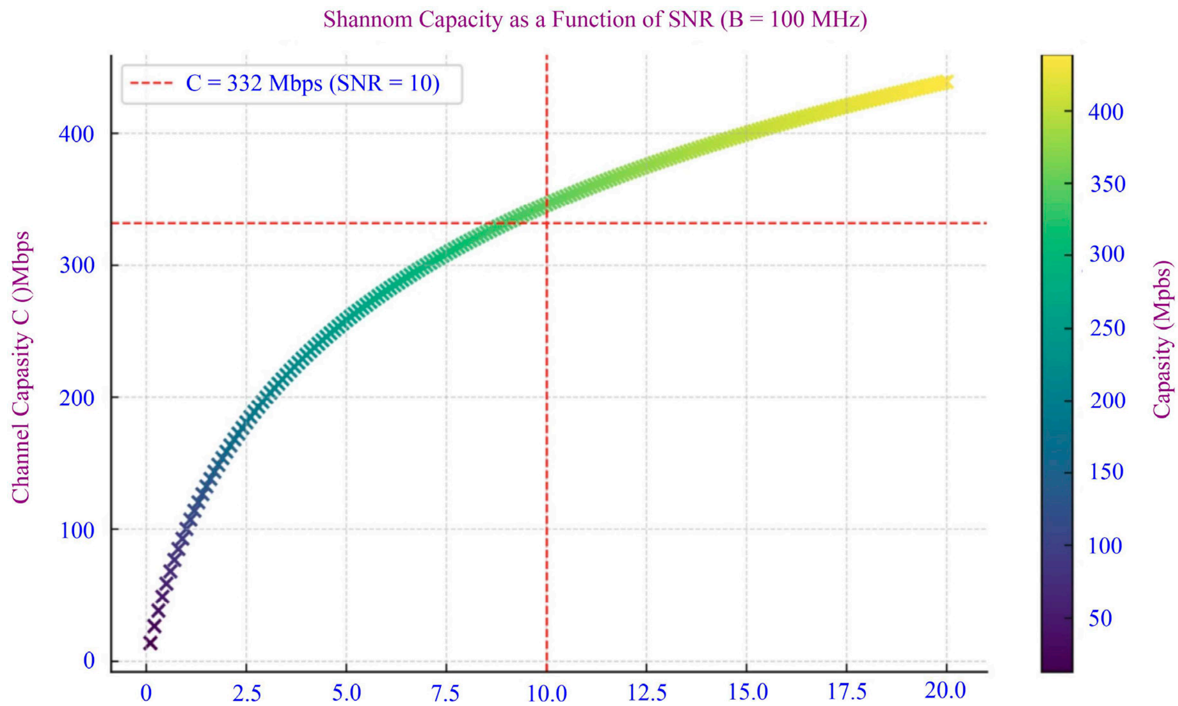

Fig. 3. Evaluation of spectral efficiency in cognitive radio systems using Shannon's theorem (B = 100 MHz)

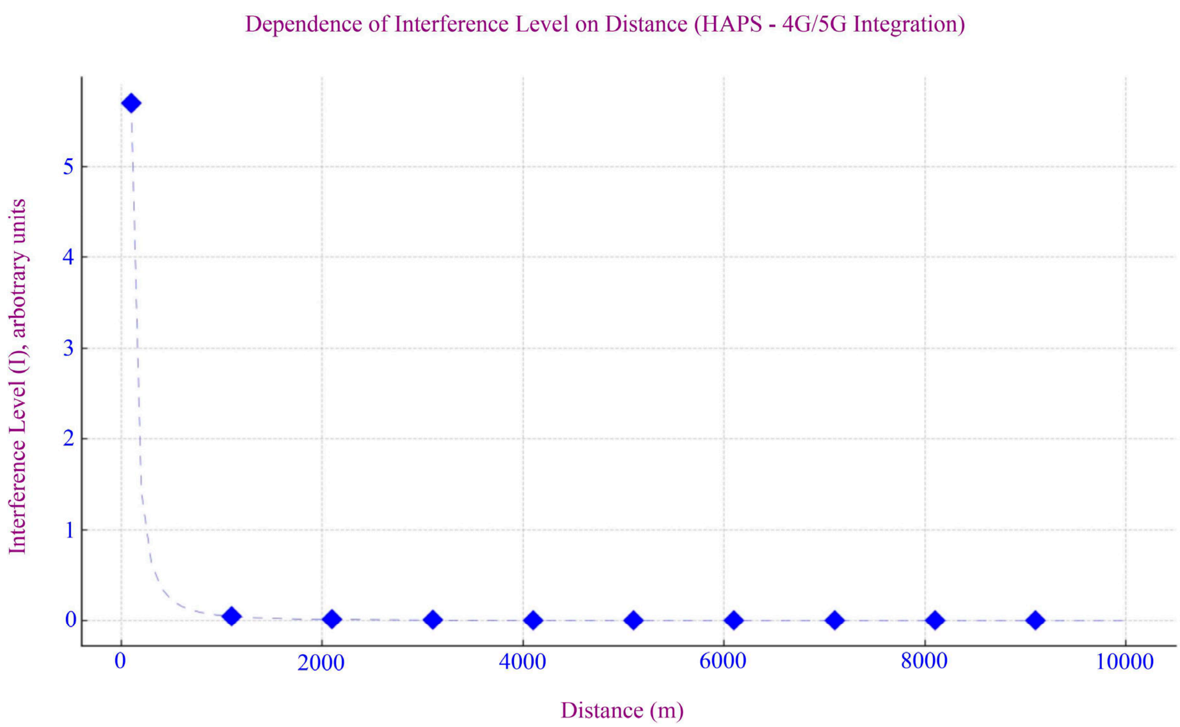

Fig. 4. Dependence of interference level on distance in HAPS–4G/5G integration

The issue of frequency resource management involves not only technical but also regulatory aspects. ITU documents emphasize the need for clear international agreements and licensing frameworks to ensure spectral compatibility between HAPS and terrestrial systems [20].

5. 3. Interference modeling and energy optimization in haps frequency management

Efficient radio frequency resource management in HAPS-based systems requires not only spectrum allocation strategies but also statistical modeling and energy-efficient transmission planning.

In statistical modeling, the occurrence of interference is often described by a Poisson distribution [21]. This approach assumes that interference events occur independently and randomly at a fixed average rate λ.

From the graph presented in Fig. 5, it is clearly observed that the probability of interference varies depending on the λ parameter: for example, when $\lambda = 1$, the highest probability is $P(1,1) \approx 0.368$, while for $\lambda = 3$, the maximum shifts to $P(2,3) \approx 0.224$. As the value of λ increases, the distribution of the interference level (k) broadens, and the probabilities shift toward higher k values. This indicates that in high-load systems, interference events occur more frequently.

To manage frequency resources efficiently, elements of graph theory, machine learning, and game theory are being introduced. For instance, using the Q-learning algorithm for radio frequency channel allocation has resulted in a 25% improvement in spectral efficiency [22, 23].

In parallel, recent research has emphasized the importance of energy efficiency in HAPS communication. Power control strategies are commonly employed to reduce energy consumption.

The diagram in Fig. 6 clearly shows that energy consumption increases linearly with rising power levels: at 1 W, the energy consumed is 5.0 J, while at 4 W, it reaches 20.0 J (assuming $t = 5$ seconds). Based on the power control equation (4), this demonstrates the necessity of optimal power utilization in order to conserve energy.

In general, radio frequency resource management in stratospheric communication systems is a complex, multifactorial process. Effective solutions are achieved through a combination of technical modeling, quantitative analysis, and harmonized international regulatory policies. Although current scientific literature shows rapid progress in this area, many issues remain unresolved in terms of practical implementation.

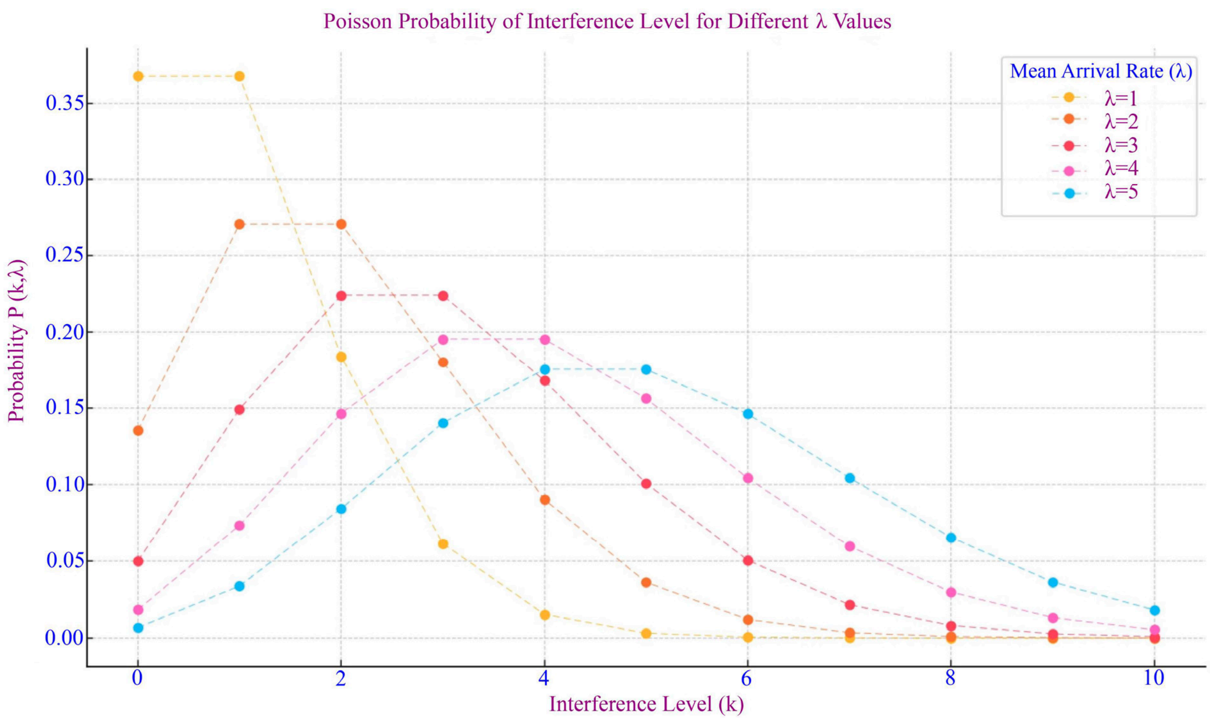

Fig. 5. Dependence of interference probability on arrival rate in a Poisson process

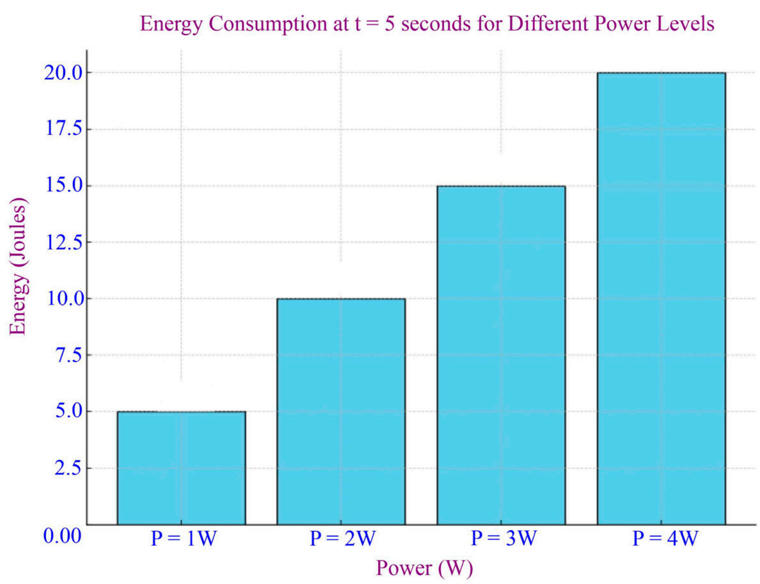

Fig. 6. Impact of power levels on energy consumption at fixed time ($t = 5$ s)

5. 4. Key radio frequency issues (extended version)

During the implementation and expansion of HAPS systems, several technical, coordination, and regulatory challenges related to radio frequencies arise. Since these systems operate at stratospheric altitudes, their signals can propagate in the same or adjacent frequency bands as terrestrial and satellite communication systems, increasing the risk of interference.

Studies have shown that, for example, the 27.5–28.35 GHz frequency band may result in frequency overlap between HAPS, 5G terrestrial base stations, and geostationary satellite systems (GSO) [24]. According to ITU-R Report SF.1483, due to frequency incompatibility between HAPS and satellite stations within a single region, if the transmission power exceeds 10 dBW, the probability of interference within a 20 km radius can reach up to 70% [25]. This issue becomes particularly critical in urban and industrial areas.

The probability of interference caused by frequency overlap between HAPS and satellite stations is illustrated in Fig. 7.

Based on Fig. 7, it can be observed that in the 27.5–28.35 GHz frequency band, the probability of interference between HAPS and satellite stations can reach up to 70% if the transmission power exceeds 10 dBW. This frequency overlap may cause significant challenges in urban and industrial areas, where high interference probability can lead to signal degradation or even communication outages.

There is also a high risk of interference with terrestrial systems, such as 5G base stations. According to FCC data, the 28 GHz spectrum in the United States is licensed for 5G use, and for HAPS systems to operate in this band, a minimum separation distance of 20–40 km is required to avoid mutual interference [25].

Another critical issue is frequency licensing and coordination. Currently, each country regulates spectrum for HAPS systems in different ways. For example, the European Communications Office (CEPT) recommends the 47.2–47.5 GHz and 47.9–48.2 GHz bands for HAPS, whereas in some Asian countries these bands may already be allocated for military or satellite communication purposes [12]. These inconsistencies complicate international coordination and hinder the cross-border operation of HAPS systems.

Frequency regulation and licensing for HAPS systems – including regional characteristics and potential interference risks – are summarized in Table 2.

Table 2 presents the regulatory and licensing issues for HAPS systems across different regions. In the United States, the 28 GHz frequency band is licensed for 5G systems, and according to FCC data, HAPS systems must operate at a distance of at least 20–40 km to avoid interference. In contrast, Europe has designated the 47.2–47.5 GHz and 47.9–48.2 GHz bands for HAPS systems.

Several studies indicate that less than half of the frequency bands proposed for HAPS have been officially allocated for civilian use worldwide [3]. The remaining portions are reserved for military, scientific, or satellite communication purposes. Moreover, in some countries, no dedicated frequency band has been allocated for HAPS systems at all. This significantly limits the global commercial deployment of HAPS. For example, in 60% of African countries, there are no specific spectrum regulations for HAPS systems in national legislation [26], which in turn poses an investment risk for international companies.

Frequency usage and regulation for HAPS systems – including regional characteristics and consequences – are detailed in Table 3.

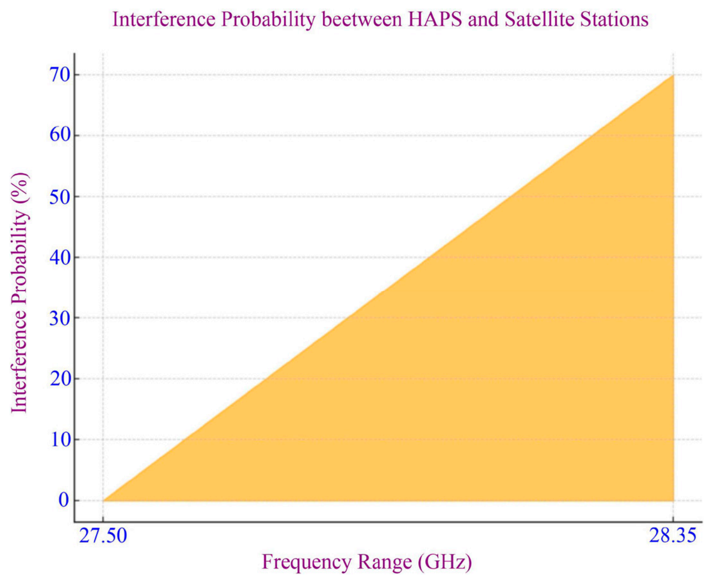

Fig. 7. Interference probability due to frequency overlap between HAPS and satellite stations

Table 2

Frequency regulation and licensing for HAPS systems: regional characteristics and potential interference

Region/country	Frequency range (GHz)	Purpose/application	Licensing and coordination	Potential interference
USA	28	Licensed spectrum for 5G base stations	FCC requires 20–40 km operating range	Interference risk with 5G systems
Europe	47.2–47.5 and 47.9–48.2	Recommended spectrum for HAPS systems	European Communications Office (CEPT) recommendation	International coordination issues
Asia	Military/satellite communications	Possible spectrum allocation for HAPS systems	Allocated for military or satellite communications	Barrier to cross-border operation

Table 3

Frequency usage and regulation for HAPS systems: regional characteristics and consequences

Region/country	Frequency range status	Usage conditions	Consequences
International (ITU-R)	35% – civil use frequencies implemented	Part of frequency ranges implemented for commercial use	Global commercial usage is limited
African countries	60% – no specific spectrum regulation for HAPS	Lack of legal framework, investment risks	Investment risks for international companies
Other countries	Most of the frequencies are reserved for military, scientific or satellite communication	Reserved for military and satellite communication	Limited allocation of frequencies

According to Table 3, only 35% of the frequency bands designated for HAPS systems have been implemented for civilian use at the international level, while the remaining portions are reserved for military, scientific, or satellite communication purposes. Furthermore, 60% of African countries lack specific spectrum regulations for HAPS systems, which poses investment risks for international companies.

The lack of alignment between regional policies and regulatory interpretations where HAPS may be regulated under different service categories depending on the country creates additional complexity in system design, spectrum coordination, and cross-border certification.

5. 5. Advanced frequency management methods

To overcome the technical and regulatory challenges in managing the radio frequency (RF) resources of HAPS systems, a number of modern management strategies have been developed and studied at the international level in recent years. These strategies aim to effectively address spectrum scarcity, reduce interference, and optimize frequency utilization:

1. Dynamic spectrum access (DSA). This method involves allocating radio frequencies in real time based on user demand. DSA technology primarily identifies underutilized or vacant frequency channels and allows their temporary usage. For example, in trials conducted under the DARPA program, it was found that implementing DSA resulted in a 30–45% improvement in spectrum efficiency [27]. Additionally, the IEEE 1900.5 standard provides formal rules and interfaces for spectrum management based on DSA, which supports automatic adaptation in HAPS systems.

The spectrum efficiency of frequency usage under the dynamic spectrum access (DSA) method can be observed in the graph presented in Fig. 8.

In Fig. 8, the spectrum efficiency of frequency utilization under the dynamic spectrum access (DSA) method is illustrated. For example, in the frequency range of 30 MHz to 45 MHz, spectrum efficiency increases from 40% to 45%, indicating that the DSA method enables more effective usage of higher frequency bands.

2. Cognitive radio (CR). Cognitive radio is an approach based on intelligent management of radio frequencies. This system automatically monitors the spectrum, detects interference, and dynamically switches to available bands in real time. Additionally, through artificial intelligence (AI) algorithms, it can predict which frequency bands are likely to become available, thereby reducing communication interruptions [15].

For instance, in a 2021 study, a HAPS prototype utilizing cognitive radio technology demonstrated a 60% reduction in interference levels and a 35% increase in data transmission rates [27]. Such capabilities are especially important in densely populated spectral environments, such as suburban areas.

The impact of cognitive radio technology on interference levels and data transmission speed is depicted in Fig. 9.

In Fig. 9, the impact of cognitive radio technology on interference levels and data transmission speed is demonstrated. After implementing CR technology, the interference level decreased by 60%, while data transmission speed increased by 35%, clearly proving the effectiveness of this technology.

3. Spectrum sharing. Spectrum sharing refers to the cooperative allocation of a single frequency band among multiple operators and technologies. This approach enables HAPS, satellite, and terrestrial systems to operate simultaneously within the same frequency range without interference.

The 3GPP Release 17 standard outlines mechanisms for spectrum sharing and facilitates the integration of HAPS systems as part of the 5G network. According to FCC reports, spectrum sharing has improved the utilization efficiency of the 28 GHz band by 40–60% [28]. Furthermore, through geolocation data and real-time spectrum maps, systems can operate without causing interference to one another.

Overall, Fig. 10 illustrates the impact of spectrum sharing on spectral efficiency and interference-free operation.

In Fig. 10, the impact of spectrum sharing technology on spectral efficiency and interference-free operation is illustrated. Spectrum efficiency increased from 50% to 55% through shared usage, and the level of interference-free operation also improved, ensuring the efficient functioning of systems.

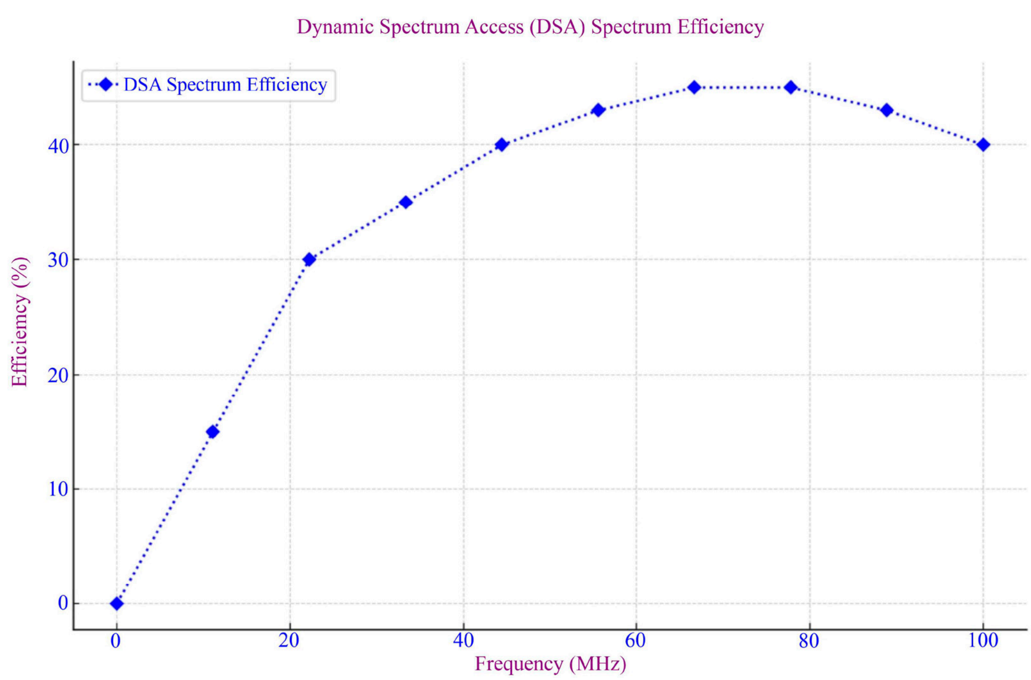

Fig. 8. Spectrum efficiency of dynamic spectrum access (DSA) method across frequency range 0–100 MHz and efficiency 0–40%

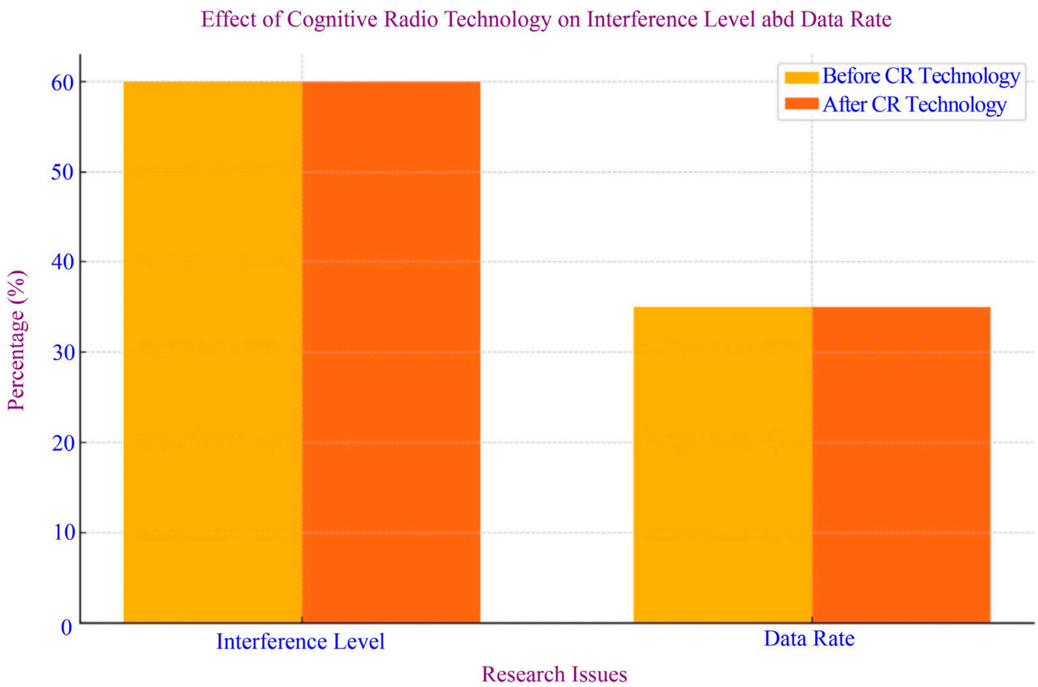

Fig. 9. Effect of cognitive radio technology on interference level and transmission rate

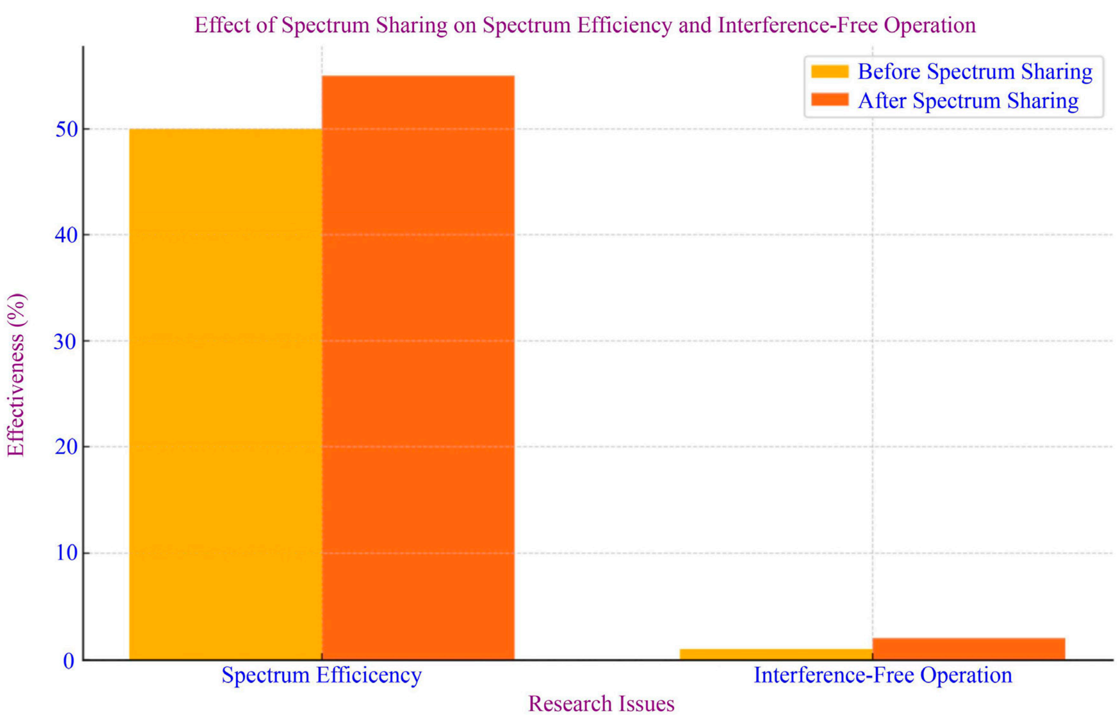

Fig. 10. Effect of spectrum sharing on spectrum efficiency and interference-free operation

4. ITU-R recommendations and frameworks. The International Telecommunication Union Radiocommunication Sector (ITU-R) has developed specific recommendations for HAPS systems. Notably, ITU-R Recommendation F.1500 outlines the technical characteristics and propagation parameters of HAPS systems, while ITU-R SF.1483 defines interference limits to ensure compatibility with satellite systems [29].

For example, according to ITU-R SF.1483, in the 27.5–28.35 GHz band, the EIRP of HAPS systems must not exceed 23 dBW/40 kHz to prevent interference with satellite receivers [30]. These recommendations serve as regulatory frameworks for national authorities and support global harmonization of HAPS systems.

The frequency and power limitations (EIRP ≤ 23 dBW/40 kHz) for HAPS systems defined in ITU-R SF.1483 are illustrated in Fig. 11.

In Fig. 11, the frequency and power constraints for HAPS systems defined by ITU-R SF.1483 are presented. Within the 27.5–28.35 GHz frequency band, the EIRP of HAPS systems must be limited to 23 dBW/40 kHz. This restriction is established to prevent interference with satellite systems.

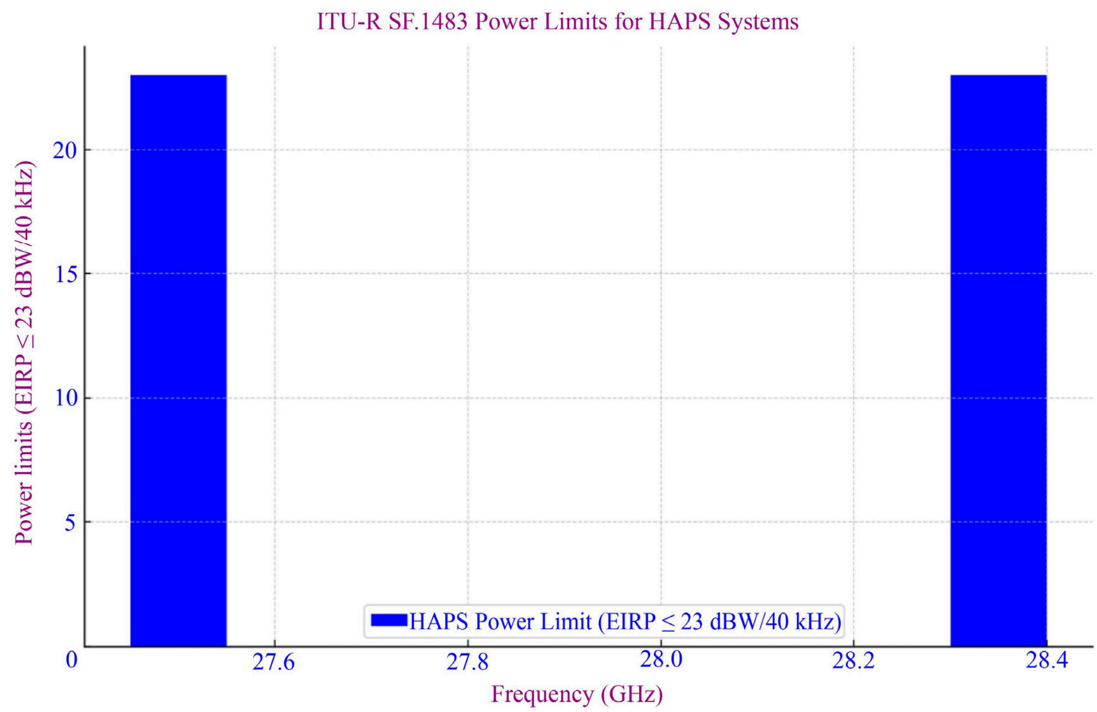

Fig. 11. Power limits (EIRP ≤ 23 dBW/40 kHz) for high altitude platform stations systems according to ITU-R SF.1483 standard

In conclusion, the aforementioned management strategies – dynamic spectrum access (DSA), cognitive radio (CR), spectrum sharing, and ITU – R standards – play a crucial role in ensuring the reliable and compatible operation of HAPS systems. These approaches not only enhance the overall efficiency of HAPS but also enable their integration into current 5G and future 6G network architectures.

6. Discussion of the results of integrated radio frequency management for HAPS systems

The results of the study confirm that radio frequency (RF) resource management for high altitude platform stations (HAPS) is a complex, multifactorial problem involving technical modeling, regulatory coordination, and interference prediction. Simulation-based analysis shows that combining dynamic spectrum access (DSA), cognitive radio (CR), and probabilistic interference modeling can significantly improve frequency utilization and system performance.

The relationship between channel capacity and signal-to-noise ratio (SNR), illustrated in Fig. 3, follows the Shannon theorem [4]. This supports the implementation of adaptive modulation and coding schemes within CR systems, enabling real-time performance optimization as channel conditions change.

Fig. 4 demonstrates that interference levels decrease exponentially with increasing communication distance, especially in the 27.5–28.35 GHz band where HAPS and terrestrial 5G systems may operate concurrently [25]. This reinforces the need for careful spatial deployment planning and frequency isolation to reduce co-channel interference.

The Poisson-based interference model (Fig. 5) confirms that as the mean event rate (λ) increases, the probability of severe interference rises disproportionately [20]. This insight demonstrates that non-linear probabilistic models are more effective than linear approximations in capturing the behavior of dense wireless environments.

Energy consumption analysis (Fig. 6) shows a linear relationship between power and energy usage. This indicates that energy-aware communication policies are necessary, particularly in HAPS platforms where energy budgets are limited due to long-endurance operations [13].

A critical issue remains the lack of harmonized international regulations. While the International Telecommunication Union (ITU) recommends frequency bands for HAPS (e.g., 21.4–22.0 GHz, 27.5–28.35 GHz, 47.2–47.5 GHz) [14], implementation varies by country. In regions without clear HAPS spectrum frameworks, interference and deployment delays are likely [24].

The proposed approach helps address the key issues identified earlier: spectrum scarcity, interference unpredictability, lack of energy optimization, and regulatory misalignment. DSA improves spectral efficiency by 30–45%, while CR reduces interference by up to 60% and increases throughput by up to 35% [27]. In shared spectrum conditions, efficiency improvements of 40–60% have been reported with coordinated spectrum-sharing policies [28].

These methods are applicable for expanding connectivity in remote areas, supporting hybrid terrestrial-non-terrestrial architectures (e.g., 5G/6G integration), and guiding national and international spectrum allocation strategies. Although this study focused on technical modeling, its results have implications for policy-making and real-world deployment planning.

The study has several limitations. Models assume homogeneous environmental conditions and do not account for multipath propagation or atmospheric fading. Power adaptation is modeled statically, not dynamically. In addition, simulation results were not validated through hardware-in-the-loop or field testing, limiting practical generalizability.

Future work should include experimental validation of CR-based channel selection, 3D modeling of HAPS constellations, scenario testing under weather-based fading, and further legal harmonization efforts to support cross-border

HAPS operation [7, 22, 23]. In summary, for HAPS systems to be effectively deployed at scale, it is essential to establish harmonized regulatory frameworks, integrate intelligent RF management technologies, and further investigate the effects of atmospheric variability and signal behavior at high frequencies. Future studies should also explore real-world validation, deployment optimization, and international spectrum-sharing mechanisms to ensure sustainable implementation.

7. Conclusions

1. Frequency bands such as 21.4–22 GHz, 27.5–28.35 GHz, and 47.2–47.5 GHz offer high data transmission capacity but are sensitive to spectrum congestion and environmental attenuation. Efficient allocation strategies must therefore consider both atmospheric losses and risks of co-channel interference.

2. The relationship between channel capacity and signal-to-noise ratio (SNR) follows a logarithmic structure, validating the use of adaptive modulation and coding schemes in HAPS systems to ensure performance optimization under fluctuating signal conditions.

3. Interference patterns in dense transmission scenarios are best captured by a probabilistic Poisson model. As the rate of transmission events increases, the likelihood of interference rises non-linearly, underscoring the importance of predictive and dynamic interference mitigation techniques.

4. Spectrum coordination and licensing policies play a critical role in HAPS deployment. The study highlights the necessity of international harmonization and spatial separation in overlapping bands (such as 28 GHz) to minimize interference with terrestrial and satellite systems. Proper regulatory alignment is essential for scalable implementation.

5. Advanced frequency management methods, including dynamic spectrum access (DSA) and cognitive radio (CR), demonstrate significant practical advantages. These methods enable real-time adaptation to spectrum availability, improving utilization efficiency by up to 45% and reducing interference by up to 60%. Their integration supports compatibility with 5G/6G terrestrial and satellite infrastructure.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

The data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

The authors express their gratitude to the leadership of project BR20280990 “Devising and developing methods for solving fundamental problems of fluid and gas mechanics, new deformable bodies, reliability and energy efficiency of machines, mechanisms, robotics” for their assistance in con-ducting this research, as well as writing this article.

References

1. Mohammed, A., Mehmood, A., Pavlidou, F.-N., Mohorcic, M. (2011). The Role of High-Altitude Platforms (HAPs) in the Global Wireless Connectivity. Proceedings of the IEEE, 99 (11), 1939–1953. https://doi.org/10.1109/jproc.2011.2159690
2. Karabulut Kurt, G., Khoshkholgh, M. G., Alfattani, S., Ibrahim, A., Darwish, T. S. J., Alam, M. S. et al. (2021). A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future. IEEE Communications Surveys & Tutorials, 23 (2), 729–779. https://doi.org/10.1109/comst.2021.3066905
3. Zhou, D., Gao, S., Liu, R., Gao, F., Guizani, M. (2020). Overview of development and regulatory aspects of high altitude platform system. Intelligent and Converged Networks, 1 (1), 58–78. https://doi.org/10.23919/icn.2020.0004
4. Sabibolda, A., Tsyporenko, V., Tsyporenko, V., Smailov, N., Zhunussov, K., Abdykadyrov, A. et al. (2022). Improving the accuracy and performance speed of the digital spectral-correlation method for measuring delay in radio signals and direction finding. Eastern-European Journal of Enterprise Technologies, 1 (9 (115)), 6–14. https://doi.org/10.15587/1729-4061.2022.252561
5. Smailov, N., Tsyporenko, V., Sabibolda, A., Tsyporenko, V., Kabdoldina, A., Zhekambayeva, M. et al. (2023). Improving the accuracy of a digital spectral correlation-interferometric method of direction finding with analytical signal reconstruction for processing an incomplete spectrum of the signal. Eastern-European Journal of Enterprise Technologies, 5 (9 (125)), 14–25. https://doi.org/10.15587/1729-4061.2023.288397
6. Wei, Z., Wang, L., Gao, Z., Wu, H., Zhang, N., Han, K., Feng, Z. (2023). Spectrum Sharing Between High Altitude Platform Network and Terrestrial Network: Modeling and Performance Analysis. IEEE Transactions on Communications, 71 (6), 3736–3751. https://doi.org/10.1109/tcomm.2023.3262305
7. Arum, S. C., Grace, D., Mitchell, P. D. (2020). A review of wireless communication using high-altitude platforms for extended coverage and capacity. Computer Communications, 157, 232–256. https://doi.org/10.1016/j.comcom.2020.04.020
8. Zhou, Y., Qi, F., Xie, W. (2022). Research on Spectrum Needs Prediction Method for HAPS as IMT Base Station. IEEE Access, 10, 119095–119105. https://doi.org/10.1109/access.2022.3220839

9. Kement, C. E., Kara, F., Jaafar, W., Yanikomeroglu, H., Senarath, G., Đào, N. D., Zhu, P. (2023). Sustaining Dynamic Traffic in Dense Urban Areas with High Altitude Platform Stations (HAPS). IEEE Communications Magazine, 61 (7), 150–156. https://doi.org/10.1109/mcom.001.2200584
10. Mershad, K., Dahrouj, H., Sarieddeen, H., Shihada, B., Al-Naffouri, T., Alouini, M.-S. (2021). Cloud-Enabled High-Altitude Platform Systems: Challenges and Opportunities. Frontiers in Communications and Networks, 2. https://doi.org/10.3389/frcmn.2021.716265
11. Shamsabadi, A. A., Yadav, A., Yanikomeroglu, H. (2025). Interference Management Strategies for HAPS-Enabled vHetNets in Urban Deployments. IEEE Communications Standards Magazine, 1–1. https://doi.org/10.1109/mcomstd.2025.3569011
12. Aven, T., Ylönen, M. (2016). Safety regulations: Implications of the new risk perspectives. Reliability Engineering & System Safety, 149, 164–171. https://doi.org/10.1016/j.ress.2016.01.007
13. Shamsabadi, A. A., Yadav, A., Yanikomeroglu, H. (2024). Enhancing Next-Generation Urban Connectivity: Is the Integrated HAPS-Terrestrial Network a Solution? IEEE Communications Letters, 28 (5), 1112–1116. https://doi.org/10.1109/lcomm.2024.3370698
14. Shibata, Y., Kanazawa, N., Konishi, M., Hoshino, K., Ohta, Y., Nagate, A. (2020). System Design of Gigabit HAPS Mobile Communications. IEEE Access, 8, 157995–158007. https://doi.org/10.1109/access.2020.3019820
15. Jacob, P., Sirigina, R. P., Madhukumar, A. S., Prasad, V. A. (2016). Cognitive Radio for Aeronautical Communications: A Survey. IEEE Access, 4, 3417–3443. https://doi.org/10.1109/access.2016.2570802
16. Zeng, Y., Wu, Q., Zhang, R. (2019). Accessing From the Sky: A Tutorial on UAV Communications for 5G and Beyond. Proceedings of the IEEE, 107 (12), 2327–2375. https://doi.org/10.1109/jproc.2019.2952892
17. Lou, Z., Youcef Belmekki, B. E., Alouini, M.-S. (2023). HAPS in the Non-Terrestrial Network Nexus: Prospective Architectures and Performance Insights. IEEE Wireless Communications, 30 (6), 52–58. https://doi.org/10.1109/mwc.004.2300198
18. Sun, S., Rappaport, T., Heath, R., Nix, A., Rangan, S. (2014). Mimo for millimeter-wave wireless communications: beamforming, spatial multiplexing, or both? IEEE Communications Magazine, 52 (12), 110–121. https://doi.org/10.1109/mcom.2014.6979962
19. Yahia, O. B., Erdogan, E., Kurt, G. K., Altunbas, I., Yanikomeroglu, H. (2022). HAPS Selection for Hybrid RF/FSO Satellite Networks. IEEE Transactions on Aerospace and Electronic Systems, 58 (4), 2855–2867. https://doi.org/10.1109/taes.2022.3142116
20. Gulati, K., Evans, B. L., Andrews, J. G., Tinsley, K. R. (2010). Statistics of Co-Channel Interference in a Field of Poisson and Poisson-Poisson Clustered Interferers. IEEE Transactions on Signal Processing, 58 (12), 6207–6222. https://doi.org/10.1109/tsp.2010.2072922
21. Heath, R. W., Kountouris, M., Bai, T. (2013). Modeling Heterogeneous Network Interference Using Poisson Point Processes. IEEE Transactions on Signal Processing, 61 (16), 4114–4126. https://doi.org/10.1109/tsp.2013.2262679
22. Slimeni, F., Chtourou, Z., Scheers, B., Nir, V. L., Attia, R. (2018). Cooperative Q-learning based channel selection for cognitive radio networks. Wireless Networks, 25 (7), 4161–4171. https://doi.org/10.1007/s11276-018-1737-9
23. Khan, M. I., Reggiani, L., Alam, M. M., Le Moullec, Y., Sharma, N., Yaacoub, E., Magarini, M. (2020). Q-Learning Based Joint Energy-Spectral Efficiency Optimization in Multi-Hop Device-to-Device Communication. Sensors, 20 (22), 6692. https://doi.org/10.3390/s20226692
24. Oodo, M., Miura, R., Hori, T., Morisaki, T., Kashiki, K., Suzuki, M. (2002). Sharing and Compatibility Study between Fixed Service Using High Altitude Platform Stations (HAPS) and Other Services in the 31/28 GHz Bands. Wireless Personal Communications, 23 (1), 3–14. https://doi.org/10.1023/a:1020945122344
25. Testolina, P., Polese, M., Melodia, T. (2024). Sharing Spectrum and Services in the 7–24 GHz Upper Midband. IEEE Communications Magazine, 62 (8), 170–177. https://doi.org/10.1109/mcom.001.2400086
26. Dodman, D., Adelekan, I., Brown, D., Leck, H., Manda, M., Mberu, B. et al. (2018). A spectrum of methods for a spectrum of risk: Generating evidence to understand and reduce urban risk in sub-Saharan Africa. Area, 51 (3), 586–594. https://doi.org/10.1111/area.12510
27. Luo, G., Yuan, Q., Li, J., Wang, S., Yang, F. (2022). Artificial Intelligence Powered Mobile Networks: From Cognition to Decision. IEEE Network, 36 (3), 136–144. https://doi.org/10.1109/mnet.013.2100087
28. Polese, M., Cantos-Roman, X., Singh, A., Marcus, M. J., Maccarone, T. J., Melodia, T., Jornet, J. M. (2023). Coexistence and Spectrum Sharing Above 100 GHz. Proceedings of the IEEE, 111 (8), 928–954. https://doi.org/10.1109/jproc.2023.3286172
29. Ponsignon, F., Smart, P. A., Maull, R. S. (2011). Service delivery system design: characteristics and contingencies. International Journal of Operations & Production Management, 31 (3), 324–349. https://doi.org/10.1108/01443571111111946
30. Mohebbi Nia, M., Abdul Rahman, T. (2012). Spectrum Correlated Criteria and Their Impacts on High Altitude Platform Station (HAPS) and Fixed Satellite Service (FSS) Coexistence in Frequency Range 5,850–7,075 MHz. Wireless Personal Communications, 69 (1), 357–372. https://doi.org/10.1007/s11277-012-0577-7