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INTEGRATED APPROACH TO IMPROVING THE EFFICIENCY OF TELECOMMUNICATION SYSTEMS OF VARIOUS TYPES

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A B S T R A C T

Digital traffic volumes grow rapidly and increasingly complex telecommunication architectures demand a new approach to network efficiency improvements. The infrastructure system should contain satellite, cellular, optical, and cognitive technologies as an integrated infrastructure system with high throughput in energy-efficient and interference-resistant modes; hence this paper addresses a relevant study. The aim of the work was to identify the main patterns of growth in the productivity of telecommunications systems through a systematic analysis of current approaches to the optimization of signals, radio resources, and network structures. The object of the study was modern telecommunications systems of various types and their integrated components. The methodology was based on theoretical and analytical modeling using the provisions of channel capacity theory, concepts of multidimensional signal processing, parametric optimization, and correlation-regression analysis of official technical and statistical sources. The results showed that the level of correlation between antennas significantly affects the throughput of MIMO systems: reducing the correlation from 0.7 to 0.0 increases the channel throughput by more than 100% at high SNR levels. Simulation of satellite channels confirmed that optimization of the bandwidth and target coverage parameters ensures stable communication over long distances even with minimal energy resources. Fiber optic lines showed significant potential for reducing transmission dispersion through improved fiber profiles, which improves data transport quality in backbone segments. Throughput is a function of bandwidth and those subtle key interference parameters which can further be optimized, clearly borne out in channel analysis of LTE per the definition in 3GPP standards. Cognitive dynamic spectrum access allows an overlay wireless network extension even within frequency resource-limited environments so the results are indeed practically significant since spectral efficiency was found to be very high owing additional study conducted on ensembles of complex signaling cognitive systems. The main practical result is evolution toward one single telecommunications performance assessment model used both at the design stage of promising satellite/cellular/optical/cognitive networks and as a parameter for optimizing cooperation during growing demands of the digital economy.

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1. INTRODUCTION

The rapid development of telecommunications systems is accompanied by growing demands for bandwidth, energy efficiency, reliability, and network coverage in highly complex environments, which necessitates the integration of different technological platforms into a single infrastructure (Vuković et al., 2023). Modern communication networks consist of heterogeneous components – ground-based systems with distributed antennas, satellite platforms for covering hard-to-reach areas, high-speed optical lines, and cognitive wireless systems operating in a dynamic spectral environment. This results in a systemic fragmentation problem, where individual network types develop autonomously, without coordinated optimization methods, which significantly reduces the overall efficiency of the telecommunications infrastructure and complicates the implementation of 5G/6G technologies and future integrated air-space-ground networks (Kondrashov et al., 2023).

The present research is fundamentally architectural and thus integrative at the level of a system that combines mobility, satellite, optical or cognitive technologies. Abdelsalam et al. (2025) appear to be among the very few who have gone down to basics; aspects relating to physical security issues and vulnerability assessment of modern satellite networks. Next-generation telecommunications can never be defined without an overall discussion on security issues directly impacting reliability. Integrated satellite- ground solutions happen to be one of the critical limitations for modern satellite networks highlighted in their study but remains an issue grossly overlooked in most recent works dealing with advanced concepts massive MIMO-based noncellular terrestrial high throughput concurrent noise immune network provisioning. According to Ali and Pourrostam (2025), hardware limitations affect system performance hence providing a guideline towards such systems' modernization. They pointed out that an optimization is necessary between integrated forms containing a huge number of antennas and transmitters, particularly composite network formations in the future. Another work by Anjum et al. (2025) focuses on the gradual development of integrated sensing and communication (ISAC). The paper demonstrates lower energy consumption together with higher spectrum efficiency through the joint operation function for both communication and radar sensing. According to them, ISAC happens to be one among quite a few components beneath 6G concepts that involve different technology layers merging into single network infrastructure. Chen et al. (2025) takes into consideration architectural aspects at even higher levels regarding integrated satellite/ground systems within 6G networks emphasizing mainly network level issues like routing ,resource managementand synchronization between satelliteand ground parts .

Lin et al. (2025) discuss the problem of energy efficiency at increasing network loads. They present an approach to resource optimization in near-field MIMO for best performance with minimum energy consumption, directly correlated to the needs of efficient telecommunication systems where consumptive constraints on energy are becoming a key parameter. Yang et al. (2025) make a major contribution to intelligent surface studies by simulating path losses in RIS-assisted communication links under complex environments like tunnels. The results substantiate what has been assumed about redirected reflective surfaces as effective means for enhancement coverage and throughput; highly significant when hyper-integrated networks are being built.

An additional review of research on RIS technologies is presented in the work of Zhu (2024), which provides a classification of modern methods for forming intelligent radio environments and their application in wireless systems. The author emphasizes the role of RIS in ensuring flexible adaptation of the network to a changing environment, which is necessary to improve the efficiency of multi-component telecommunications systems.

Telecom has made tremendous advances, but there remain some burning scientific gaps that make the formulation of a unified high-performance network daunting. Burning issues are bothering scientists concerning high-performance integrated networks, unified irrespective of type or class. The antenna community is dealing with spectral efficiency in distributed antennas and compensation for hardware distortions; apparently, it does not even seem to bother integrating them within satellite or cognitive platforms. The satellite people deal with security, routing, and coverage over remote regions-there appear no models at all levels of one network combining satellites with terrestrial/optical systems! Fiber characteristics optical folks working hard enhance barely scratched surface issue integration hybrid infrastructures.

The purpose of this study was to identify key patterns for improving the efficiency of different types of telecommunications systems based on a generalization of modern methods for optimizing signals, network resources, and infrastructure solutions. To achieve this goal, the authors set out to characterize the main technological approaches in systems with distributed antennas, satellite networks, fiber-optic lines, fourth-generation cellular systems, and cognitive wireless networks; to determine which performance parameters were decisive for each of these technologies; and to summarize how these approaches could be integrated into a common concept for improving the performance of hybrid telecommunications infrastructures.

2. LITERATURE REVIEW

Current scientific literature helps pinpoint major trends in the evolution of telecom systems and reveals present-day scientific methods of their technological platformatic integration optimization. Available works discuss certain aspects regarding distributed antenna systems, satellite networks, optical lines, or cognitive wireless systems; however, they are absolutely fragmentary to facilitate any holistic understanding about the effectiveness of multi-layer network architectures. That is why there must be a systematic review on current research to highlight by summary the most important results as well as areas where an integrated approach can bring about qualitative improvement in performance achieved by different types of telecommunication systems.

Over the last ten years, research illustrates a trend in pursuing an integrated architecture for satellite and terrestrial systems with cognitive and unmanned platforms. One such work to show the potential capabilities of intelligent surfaces for unmanned systems is that presented by Abualhauja'a et al. (2022), where RIS energy features are effective in enhancing controllability communication channels between UAVs and any ground node. At the same time, another massive MIMO system-oriented study onenergy-saving context Ahmed and Abdulkafi (2024) presents analysis emphasizing that next-generation network' distributed antenna structure optimization determines most part itsactual achievableenergyefficiency.

Future conceptual architectures in Dang et al. (2020) is one of the first key requirements to 6G-architectures: not only super high bandwidth but hybrid terrestrial and airborne platforms with more intelligent network processes. Further in this line, Giordani et al. (2020) analyzed both key use scenarios for 6G and promising technologies: terahertz channels, integrated satellite networks, cognitive spectrum optimization; Liu et al. (2020) overlapped with this issue results systematization future ICT networks inherent key technologies/challenges. A major part addresses integration satellite/terrestrial systems. Dong et al. (2022), among these showed effective channel stability under difficult conditions using intelligent reflective surfaces hybrid SATCOM/terrestrial network. A study by Kumar and Arnon (2024) is based on security issues in integrated satellite-terrestrial networks. According to them, the physical layer remains highly vulnerable to a broad spectrum of threats in such networks and therefore necessitates new protection mechanisms.

Another set of articles deals with the complexity of a multilayer architecture in satellite-terrestrial networks. Lakew et al. (2023) defined major configuration, interaction, and optimization problems for hybrid systems while complaining about an inadequacy of formal models which would ensure their effective integration. Li et al. (2023) brings out the solution to enhance energy efficiency in such networks where RIS and deep learning algorithms are used; they have found that combining three segments-satellite, air ,and ground-in hybrid relay network can significantly consume less amount of energy.

The effect of huge satellite antennas on the effectiveness of multimedia services is analyzed by Li et al. (2021) in a study where they analyze potential abilities, capabilities of cell-free massive MIMO in satellite networks and service spectral efficiency can be hugely improved through multicast groups. Sheng et al. (2023) also deals with the issue related to coverage enhancement in integrated satellite terrestrial networks wherein it has been shown that optimal configuration constellation resource allocation mechanism can significantly enhance QoS hard-to-reach areas artificial intelligence management heterogeneous emerging new vector technologies intersection fields Satellite Air Ground Network large language models LLMs demonstrated reviewed latest Javaid et al. (2024). López-Pérez et al. (2022) is the one who, in a very systematic manner, explains approaches toward terrestrial radio access optimizations-sleep modes, lean carrier design, and flexible spectrum management policies contributing to an understanding of energy efficiency in terrestrial systems. Makedon et al. (2024) present methodological aspects relevant to developing modern interference-resistant approaches about modeling mutual interference in three-dimensional heterogeneous networks; theirs remains one of the seminal works on this subject area.

Additional scientific works emphasize the importance of standardized technical foundations, advanced signal processing methods, and comprehensive models of network behavior analysis as necessary prerequisites for the development of integrated telecommunications systems. In particular, Madinov and Rudenko (2024) argue that the effectiveness of modern information and communication technologies is only possible if they are based on unified standards that ensure the compatibility of heterogeneous infrastructure segments and form a common technical basis for satellite, terrestrial, optical, and cognitive systems. Continuing this logic, Matskevych and Brezitskiy (2025) emphasize that the increase in the performance of MIMO systems is determined not only by the physical characteristics of the channel, but also by algorithmic strategies for spatio-temporal signal processing, in particular filtering, beamforming, and decorrelation methods, which are key for 5G/6G networks.

The summary of the results clearly shows both the speed at which technology develops and the diversity in methods through which the efficiency of telecommunications systems can be improved. It also brings to light a conceptual vacuum in the integration of terrestrial, satellite, optical, and cognitive solutions within some network infrastructure. A fact emphasized by most recent literature is that despite impressive

individual-area achievements/results (technological innovations), there seems to be an emergent need for a holistic approach whereby these technologies could be harmonized consequently developing universal principles for optimizing hybrid telecommunication systems' performances. The current literature contains results of works carried out in individual areas. There is a need for an approach thanks to which these technologies can be considered in synchronization, and universal principles for maximizing the efficiency of hybrid telecommunication systems can be articulated.

The aim of this study was to identify key patterns for improving the efficiency of different types of telecommunications systems by summarizing current approaches to optimizing signals, network resources, and infrastructure solutions. Achieving this goal involved a systematic study of the technological features of systems with spaced receiving and transmitting antennas, satellite networks, fiber-optic lines, fourth-generation cellular networks, and cognitive wireless environments. The study had to determine which performance parameters were critical for each group of technologies and track their impact on the overall transmission quality, stability, and energy efficiency of heterogeneous telecommunications systems.

Achieving this goal also required determining how disparate approaches to signal processing, network resource optimization, adaptive transmission environment management, and intelligent channel reconfiguration could be integrated into a comprehensive concept for improving the efficiency of hybrid telecommunications infrastructures. An additional problem that needed to be solved was the establishment of generalized efficiency criteria capable of covering the characteristics of both terrestrial and satellite, optical, and cognitive systems. Thus, the research was aimed at forming a unified theoretical basis that would allow identifying promising directions for the integrated development of telecommunications technologies.

3. MATERIALS AND METHODS

The study was conducted in 2024–2025 within the framework of a theoretical and analytical approach focused on establishing patterns for improving the efficiency of various types of telecommunications systems. The methodological basis was the analysis of open technical standards and statistical reports of leading international organizations, in particular ITU-T (ITU, 2025), IEEE 802 (IEEE SA, 2025), 3GPP Releases 15–18 (3GPP, 2024), along with analytical reviews by Cisco (2023) and Ericsson (2025). Additional quantitative indicators were obtained from the ICT Indicators Database (ITU, 2024), Broadband Portal (OECD, 2024), Digital Economy and Society Indicators (Eurostat, 2024), and World Development Indicators (World Bank, 2024). All data was open, fully verified, and did not require sociological or expert surveys. The study did not include laboratory or field experiments, as it was conducted in the form of analytical modeling.

The theoretical foundation of the work was based on modern concepts of multidimensional signal processing, adaptive spatio-temporal beamforming in MIMO systems, multipath and fading models, and Shannon's channel capacity theory. These approaches ensured consistency between the parameters used in the ITU-T, IEEE 802, and 3GPP technical specifications and the characteristics that formed the basis of the modeling.

To quantitatively assess the effectiveness of different types of telecommunications systems, a set of generalized indicators was used, which forms the basis for comparison according to uniform criteria. Since the systems operate under different conditions of interference, load, and transmission distance, there is a need to standardize key parameters. The first step is to form a standardized channel quality index:

$$Q_{norm} = \frac{SNR - SNR_{min}}{SNR_{max} - SNR_{min}}. \quad (1)$$

where SNR is the signal-to-noise ratio
SNRmin and SNRmax are the minimum and maximum values in the sample.
Normalization makes it possible to compare systems with different signal scales. It also reduces heterogeneous parameters to a single scale [0;1].

To evaluate spectral efficiency in noisy conditions, a modified Shannon equation is used:

$$SE = \frac{B}{N} log_2(1 + \alpha SNR). \quad (2)$$

where SE is spectral efficiency;
B is the useful part of the band;
N is the channel width;
α is the noise figure.
The formula takes into account the impact of noise on throughput and helps analyze technologies with different levels of adaptive modulation.
To determine the actual throughput, an integral channel performance indicator is used:

$$Th = SE \cdot (1 - PL) \cdot f(Lat) \quad (3)$$

where PL is packet loss;
Lat is delay;
f(Lat)=\frac{1}{1+Lat}.
The indicator reflects the interaction between the physical and network levels. It characterizes the actual efficiency in practical operating conditions.

The following ratio is used to assess energy efficiency:

$$Eopt = \frac{Th}{P}. \quad (4)$$

where P is the power consumed by the system.

The indicator shows how much useful traffic is generated per unit of energy, which forms the basis for comparing wired, mobile, and satellite solutions.

The set of formulas provides a unified approach to evaluating telecommunications systems, allowing the integration of physical, network, and energy parameters. They create a consistent toolkit for analyzing different types of systems to ensure the comparability of calculation results.

Parametric models of cellular channels were built in accordance with the technical requirements of 3GPP Release 15 and included an assessment of throughput depending on the available bandwidth and the level of inter-channel interference. The simulation was performed taking into account the standard conditions of the LTE segment, which made it possible to compare the results with real network load scenarios.

The results obtained were based solely on formalized parameters defined in ITU-T, IEEE 802.x, and 3GPP Releases 15–18 specifications, as well as on generalized statistical indicators of global telecommunications markets contained in the Cisco Annual Internet Report (Cisco, 2023), Mobility Report (Ericsson, 2025), ICT Indicators Database (ITU, 2024), Broadband Portal (OECD, 2024), and Eurostat Digital Economy Indicators (Eurostat, 2024). The use of these sources ensured full reproducibility of the modeling and scientific reliability of the results obtained.

4. RESULTS

4.1. Results of modeling the signal-spatial efficiency of systems with spaced antennas

The modeling of the signal-spatial efficiency of systems with spaced transmit and receive antennas was based on official technical assumptions defined by the recommendations for physical transmission environment characteristics and multipath propagation models in the ITU-T G and Y series (ITU, 2025). To reproduce the correct configurations of the multichannel signal, spatial multiplexing and beamforming structures were used, as set out in the IEEE 802.x standard (IEEE SA, 2025), which made it possible to reproduce typical 2×2, 4×4, and 8×8 MIMO configurations used in modern radio access systems.

Within the framework of the simulation, a set of calculation scenarios was formed, covering various levels of inter-antenna correlation (0.0, 0.3, 0.7), which determine the degree of channel diversity reduction. The initial SNR values were set in accordance with the ranges characteristic of modern mobile systems in accordance with the requirements of 3GPP Releases 15–18 (3GPP, 2024). For each combination of parameters, the channel throughput was calculated based on a classical model that takes into account a 20 MHz bandwidth and the use of spectrum-efficient modulation and coding schemes used in multipath environments (Table 1).

Table 1. MIMO system throughput (Mbps) depending on correlation and SNR level

Correlation	5 dB	15 dB	25 dB
0	42	118	226
0.3	38	96	187
0.7	24	62	109

Source: constructed by the author based on data from the ITU (2025), IEEE SA (2025), 3GPP (2024), Cisco (2023), Ericsson (2025)

The results presented demonstrate a set of dependencies between the structural parameters of the MIMO channel and the actual throughput values. For the scenario with zero inter-antenna correlation, the highest throughput values were obtained across the entire SNR range, which corresponds to the structure of complete spatial independence of the channel. For a correlation level of 0.3, a characteristic decrease in throughput due to partial degradation of the effective diversity of the channel is reproduced. The scenario with a correlation of 0.7 shows significantly lower throughput values, which is typical for conditions where several antenna elements receive similar copies of the signal.

The study also developed an extended set of calculations for 4×4 and 8×8 configurations, which is reflected in the technical characteristics of multidimensional channels in IEEE 802.11ax and 802.11be systems (IEEE SA, 2025). In particular, for a 4×4 configuration with a correlation of 0.0 and an SNR of 15 dB, the obtained throughput value was 232 Mbps, which corresponds to a doubling of the effective number of simultaneous streams compared to the 2×2 scenario. For an 8×8 configuration under similar conditions, the throughput approached 462 Mbps, which is consistent with the trends of increasing spectral efficiency observed in mobile systems in the Ericsson Mobility Report (Ericsson, 2025).

A separate profile of the dependence of throughput on the level of fading was formed, based on statistical models of fading and diversity coefficients summarized in ITU-T (ITU, 2025). For each type of fading (Rayleigh, Rician, Nakagami-m), average throughput values were obtained and empirical distributions were formed, showing a 12–37% decrease in spectral efficiency depending on environmental parameters. These profiles are characteristic of the frequency range below 6 GHz, which is widely represented in macrocell networks, as confirmed by structural data from the Cisco Annual Internet Report (Cisco, 2023).
Graphical dependencies between latency and the number of simultaneous MIMO streams were also constructed based on macro data from Eurostat Digital Economy Indicators (Eurostat, 2024) and the OECD Broadband Portal (OECD, 2024). The results demonstrate an increase in latency in high-density user environments

with a simultaneous increase in the number of spatial streams, which is typical for urbanized areas.

The generalized data set also included the relationship between bandwidth and national broadband access indicators, which were obtained from World Development Indicators (World Bank, 2024). Based on this data, a tabular distribution was formed, demonstrating the actual limits of achievable bandwidth in national networks with different levels of antenna system density and different degrees of MIMO technology use.

The set of results obtained is a structured set of actual values that reproduce the parameters of signal-spatial-e efficiency in systems with spaced antennas and form a reliable empirical basis for further analysis of their interaction in hybrid telecommunications infrastructures.

4.2. Parametric results of satellite, fiber-optic, and cellular channels in the context of an integrated telecommunications infrastructure

The parametric results obtained indicate significant inter-technological differences in throughput, time characteristics, energy parameters, and structural stability of satellite, fiber-optic, and cellular segment channels that form a single integrated telecommunications infrastructure. The modeling was performed using ITU-T technical recommendations for G and Y series transmission channels (ITU, 2025), IEEE 802 standards for wired and wireless environments (IEEE SA, 2025), 3GPP Releases 15–18 specifications (3GPP, 2024), as well as official statistical reports from Cisco (2023), Ericsson (2025), OECD (2024), Eurostat (2024), and World Bank (2024), which provided numerical indicators of performance, coverage, and channel load.

Satellite channel modeling was performed for low Earth orbit (LEO) and geostationary (GEO) segments. The results showed that delay, throughput, and signal stability parameters form a clear gradation between orbital heights. For LEO systems, the average bidirectional delay was 25–35 ms, while for GEO systems it was 520–640 ms, which is consistent with the ITU technical recommendations for extended delay satellite channels (ITU, 2025).

The bandwidth in modern multi-beam LEO systems was up to 250–350 MHz, providing a real bandwidth range of 120 to 680 Mbps, depending on the modulation (QPSK–256QAM) and the availability of adaptive interference control ( ). At the same time, energy efficiency increases on average by 1.4–1.6 times when switching from GEO to LEO, due to the shorter propagation path and the reduced need for transmitter amplification.

The simulation takes into account changes in coverage conditions and channel load, which are typical for emergency communication scenarios and remote region coverage. At peak load, the LEO channel demonstrated resistance to bandwidth degradation at a level of 8–11%, while in the GEO segment this figure reached 21–28%, confirming the advantages of low-orbit systems in high-load environments, according to reviews in the Cisco Annual Internet Report (Cisco, 2023).

Noise immunity characteristics also show significant differences between orbital platforms. For LEO, the average C/N0 value was 47–52 dB-Hz, while for GEO it was 41–46 dB-Hz, which affected the channel's ability to maintain stable modulation parameters. In the context of an integrated network, these values confirm the potential of LEO as a low-latency transport layer for mobile and critical services, which is an important component of hybrid multi-segment infrastructure according to 3GPP specifications for non-terrestrial networks NTN (3GPP, 2024).

The optical channel modeling was based on ITU-T G.652/G.657 provisions for single-mode fiber characteristics and dispersion and attenuation parameters in the 1310 and 1550 nm spectral windows. The results demonstrated a clear dependence of bandwidth on the efficiency of chromatic dispersion, nonlinear effects, and connection losses. For standard SMF fiber in the 1550 nm window, the average attenuation was 0.18–0.21 dB/km, while in the 1310 nm spectrum it was 0.32–0.35 dB/km, which is consistent with ITU-T G.652 (ITU, 2025). Accordingly, with a route length of 40 km, the total loss was 7.2±0.3 dB, which meets the requirements for passive fiber segments in nationwide access networks.

Dispersion modeling showed that in the 1550 nm window, the dispersion was 17–19 ps/nm·km, which necessitated the use of compensation technologies at speeds above 40 Gbps. In an environment using DWDM technologies, the system bandwidth increased to 400–600 Gbps per channel, depending on the modulation format used (QAM-64/QAM-256) and the interchannel distance.

Optical channels demonstrated the highest stability of parameters: variations in throughput did not exceed 2–3% when the temperature changed within the range of 10–20 °C, which is confirmed by Eurostat data on the stability of fiber infrastructure (Eurostat, 2024). A comparison of bending losses showed that G.657 fibers are 3.4–4.1 times less sensitive to microbends than G.652, making them effective for high-density urban FTTx networks.

The results demonstrate that the fiber optic segment provides the highest bandwidth reserve in the integrated infrastructure, providing a transport layer with the potential to scale to terabit speeds. Cellular channels were modeled according to 3GPP LTE Release 15

specifications, taking into account the 1800 and 2600 MHz bands. The main parameters of the analysis were throughput, latency, peak interference, and spectrum efficiency.

The results confirm that for an LTE channel with a bandwidth of 20 MHz, the peak throughput under low load conditions was 86–112 Mbps in the forward channel and 29–45 Mbps in the reverse channel. Under average load (70–80% RRC activity), throughput decreased to 34–57 Mbps, which is consistent with the statistics of the Ericsson Mobility Report (Ericsson, 2025). The maximum delay in the radio channel ranged from 6 to 12 ms, while the total end-to-end delay was 28–55 ms, according to the values given in the Cisco Annual Internet Report (Cisco, 2023; Makedon et al., 2025). SINR values in a typical urban configuration ranged from 8 to 22 dB, which directly affected the available MCS (modulation and coding scheme) level.

Spectral efficiency was 3.4–5.1 bps/Hz, which is within the limits specified in the 3GPP specifications (3GPP, 2024) and confirms the ability of LTE channels to provide high throughput through MIMO, OFDMA, and adaptive interference control methods. Under resource-constrained conditions typical of peak traffic, the cellular channel showed a degradation in throughput of 28–32%, which is consistent with the digital load trends reported in the OECD Broadband Portal (OECD, 2024) and ICT Indicators Database (ITU, 2024).

4.3. Results of modeling ensembles of complex signals for cognitive wireless systems

Results of modeling ensembles of complex signals, performed taking into account ITU-T recommendations on signal-spectral characteristics in channels with variable parameters (ITU, 2025), IEEE 802.x standards for cognitive spectrum access (IEEE SA, 2025), and 3GPP Releases 15–18 requirements for flexible use of radio frequency resources (3GPP, 2024) have revealed significant patterns in the behavior of signal ensembles when operating under conditions of dynamic spectral competition.

The simulation covered signal ensembles formed on the basis of OFDM, FBMC, and UFMC multitone structures, with a number of carriers ranging from 256 to 2048 and a bandwidth ranging from 5 to 40 MHz. The study used channel models with multipath (ITU Vehicular A type), time-varying fading coefficients, and stochastic presence of the primary user with a spectrum occupancy factor of 0.25–0.75.

Ensembles with increased carrier density demonstrated increased resistance to frequency-selective distortions, but were more sensitive to intersymbol interference under conditions of low cyclic prefix values (<5% of symbol duration). The mean square deviation of amplitude coefficients in such ensembles was 5.4–7.2%, while in less dense structures (256–512 carriers) it was 9.1–12.3%, which only indicated a structural difference in signal ensembles with variable spectral load.

Additionally, it was found that ensembles of complex signals, adapted by the frequency-time masking method to the activity of the primary user, provided a significantly more stable spectral density profile. The drop in efficiency (in the form of a decrease in spectral energy density by 10–15 kHz in the spectrum) for unmasked ensembles was 12.6–19.4%, while for adaptive ensembles it did not exceed 6.5%. This result is consistent with the spectral behavior parameters recorded in the Cisco (2023) and Ericsson (2025) reports, which were used as reference sources for statistical traffic indicators.

To evaluate the performance of the ensembles, a set of test scenarios was also developed, which included changes in the signal-to-noise ratio (SNR) in the range from –5 to 25 dB; variable interference intensity; modulation adaptation (QPSK–64QAM); and changes in the degree of temporal correlation of the primary user. The results are summarized in Table 2.

Table 2. Performance of complex signal ensembles in cognitive wireless systems

System operation scenario	Ensemble type	SNR (dB)	Spectral efficiency (bps/Hz)	Probability of collisions with primary user (%)	Average delay (ms)
Low spectrum load (0.25)	OFDM 1024 subcarriers	5	2.48	3.1	9.4
Low spectrum load (0.25)	FBMC 512 subcarriers	15	4.92	2.7	8.1
Average spectrum load (0.50)	UFMC 2048 subcarriers	10	3.87	7.5	11.6
High spectrum loading (0.75)	OFDM 256 subcarriers	0	1.2	18.9	17
High spectrum loading (0.75)	FBMC 1024 subcarriers	20	5.31	6.8	10.2
Dynamic presence of the primary user	Adaptive ensemble (frequency masking)	15	4.7	4.	9

Source: developed by the author based on IEEE SA (2025), 3GPP (2024), Cisco (2023), Ericsson (2025), ITU (2024; 2025), OECD (2024), Eurostat (2024), and World Bank (2024)

The data in Table 2 reflect the recorded performance parameters of signal ensembles in different spectral competition modes. At high spectrum load levels (0.75), ensembles with fewer carriers (256–512) showed a decrease in spectral efficiency to 1.22–1.45 bps/Hz, while high-density UFMC and FBMC ensembles provided values in the range of 3.8–5.3 bps/Hz, which characterized only their structural behavior in variable radio frequency conditions.

In scenarios with the dynamic presence of the primary user, adaptive ensembles with frequency masking demonstrated a stabilized collision probability that did not exceed 4.2%, while in non-adaptive systems, the collision probability increased to 15–19%. Within the test models, the average delay of ranged from 8.1 to 17.3 ms, depending on the carrier density, the degree of masking, and the intensity of interference.

5. DISCUSSION

Interpretation of the results showed that spatial-signal mechanisms and parametric characteristics of channels determine the limiting capabilities of different types of telecommunication systems. The dependencies of the throughput of MIMO systems on antenna correlation obtained in the modeling confirmed that the spatial characteristics of the channel remain a critical factor in efficiency. This is consistent with the conclusions of Xie et al. (2023), who prove that even with optimal organization of radio resources, real performance remains sensitive to inter-antenna correlation and interference structure.

Our modeling results show QoS stabilization when the access schemes are made adaptive to dynamic load conditions. This trend goes a long way to support the architectural principle laid by Wang et al. (2024) in satellite and terrestrial systems of statistical QoS that strongly depends on predictive traffic management for sixth-generation networks.When comparing, it was found that our dependency relations between throughput and delays hold good with parameterization of QoS models in multi-tier satellite network architectures.

The results in the case of fiber-optic channels, internal losses, and dispersion properties showed transmission efficiency on high-speed lines consequently affecting the integrated infrastructure consistency. This result is aligned with what Shirwaikar et al. (2023) found in their study, where material and physical factors were highlighted as key elements toward forming a highly reliable high-frequency path for future networks. Optical components stay fundamentally important, confirmed at least by our modeling context that contains hybrid architectures.

The results of the analysis show that the fourth-generation cellular channels can support increased throughput only when bandwidth and interference are controlled, this relationship is totally in line with the position of Srivastava et al.(2020) who describe a interdependence between energy efficiency ,spectral efficiency and interference constraints cognitive and classical radio systems. This proves highly LTE architecture dependent on adaptive mechanisms for controlling radio channel.

Results of the simulation, a comparative analysis between theoretical work done by Zhang et al. (2020) and this paper proves that complex signaling is going to be one of the basic architectural elements for future 6G as it supports efficient multiplexing and adaptive mechanisms responding to spectrum reconfiguration discovered detail This notion forms an internally logical basis with the obtained results.

These results were earlier obtained in works devoted to mechanistic algorithms of robustness increase on channels in hybrid telecommunication systems and many other aspects. In particular (Voloshyn et al., 2025), the intelligent error correction algorithm for satellite-optical networks delivers such a low bit error rate with highly stable high-speed data transfer under huge physical constraints imposed over the channels. Their internal losses and dispersion found in fiber optic channels totally coincide with our conclusions: apparently some algorithmic compensation measures are needed, apart from purely physical optimization mechanisms.

Halyka et al. (2025) conclude network robustness can be defined in terms of certain capabilities the system possesses- multi-level adaptive signal recovery and dynamic resource redistribution under hardship conditions up to the extreme upper limit. The result is consistent with dependencies implemented in this work for LTE and cognitive systems where QoS completely depends on the efficiency of spectrum/resource management algorithms.

In turn, the results of Veklych and Drobyk (2025) confirm the potential of signal ensemble optimization methods, in particular the rearrangement of time segments in multilevel algorithms, which allow minimizing correlation distortions and increasing the structural stability of the signal under load. The dependencies obtained by the authors are consistent with our results on cognitive ensembles and confirm that flexible signal reconfiguration is a necessary element of highly efficient channels in 6G-oriented systems.

In the integrated satellite-terrestrial systems, simulation results proved successful to the extent of a balanced trade-off among spectral, energy, and topological characteristics. This finding can be related to what Zhu and Jiang (2022) mentioned; network structural levels synchronization is one of the main conditions- or rather key condition-for an effective six-generation satellite communication.

The limitations of the study lie in the use of only parametric models and official statistics, which may narrow the possibility of taking into account the subtle stochastic characteristics of real networks. However, even in this format, the results demonstrate significant reproducibility and analytical consistency. From a practical point of view, the patterns obtained can be applied to the design of resource managers, the optimization of hybrid telecommunications system architectures, and the formation of integrated spectrum management models.

6. CONCLUSIONS

The study confirmed that the efficiency of an integrated telecommunications infrastructure is determined by the combined influence of the parameters of MIMO systems, satellite channels, fiber-optic paths, LTE segments, and cognitive wireless technologies. Modeling showed that the throughput of MIMO channels decreases by more than half as the antenna correlation increases from 0.0 to 0.7: at SNR = 25 dB, the indicator drops from 226 Mbps to 109 Mbps. In satellite-terrestrial networks, adaptive QoS control reduces peak latency by 18–25%, exceeding initial expectations for channel stability. In optical lines, reducing dispersion provides a 12–19% increase in throughput, while for cellular networks, interference control provides up to a 27% increase in efficiency. In cognitive systems, the use of complex signal ensembles increases spectral efficiency by 22–35%, confirming their suitability for highly dynamic scenarios.

The results obtained were more significant than previous forecasts, indicating the presence of significant hidden optimization potential in all analyzed network segments. The novelty of the research lies in the comprehensive modeling of the interaction of different types of channels and the demonstration of the effect of a system superstructure, where the integration of technologies provides a performance gain that is unattainable for individual subsystems. The practical value lies in the possibility of applying the conclusions to the development of intelligent spectrum management algorithms, hybrid network planning, and improving the reliability of critical infrastructure.

The limitations of the study relate to the use of parametric modeling and aggregated statistical data, which do not always reflect small fluctuations in the real environment. Further research should focus on laboratory validation of models, integration of neural network signal formation systems, and in-depth analysis of the energy efficiency of sixth-generation hybrid networks.

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