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Original Article

Dynamic Resource Allocation Methods in Hybrid Optical Satellite Networks for 5G/6G

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Abstract - *The relevance of the study is determined by the need to ensure stable Quality of Service (QoS) and efficient resource use in multi-domain telecommunication systems. Current approaches do not take into account traffic dynamics, load fluctuations, and inter-domain interaction in 5/6G architecture. The aim of the study is to develop a model for dynamic resource allocation in the Satellite Quantum Channels (SQC) → Fiber Optic Cores (FOC) → 5/6G hybrid architecture based on end-to-end cognitive orchestration, taking into account inter-segment dependencies, channel parameters, and QoS requirements. The study employed the following methods: model conceptualization, model detailing, evaluation of known methods, comparative analysis, advancing hypothesis, hypothesis justification, calculation for hybrid methods, and ranking of solutions. The results of the study demonstrated the appropriateness of implementing AI-Driven End-to-End Resource Orchestration in the SQC → FOC → 5/6G multi-segment architecture. The method demonstrated the best values: E2E latency – 0.890; throughput – 0.902; packet loss rate – 0.972; channel utilization – 0.976; blocking probability – 0.893; policy robustness – 0.813. The academic novelty is the first-proposed AI-Driven End-to-End Resource Orchestration model for cognitive resource allocation in the SQC → FOC → 5/6G hybrid network, which consistently optimizes channel parameters taking into account inter-segment dependencies, Quantum Bit Error Rate (QBER), Quantum Key Distribution (QKD) throughput, Open Broadcaster Software (OBS)/ Wavelength Division Multiplexing (WDM), beamforming, and network slicing. Further research may focus on the development of cognitive cross-domain-oriented dynamic resource orchestration systems capable of providing adaptive management of spectrum, power, and time slots in hybrid communication architectures with end-to-end integration of SQC, FOC, and 5/6G domains.*

Keywords - *Hybrid Network, Cognitive Orchestration, Quantum Communication, Resource Efficiency, End-To-End Optimization, Qos Guarantees, Dynamic Management.*

1. Introduction

Current exponential growth in traffic volumes, latency, and security requirements, especially in the context of critical applications (eHealth, automated management, quantum-secure transactions), necessitates the transformation of traditional telecommunication architectures. Hybrid optical satellite networks combining SQC, FOC, and next-generation mobile segments (5/6G) are considered a promising infrastructure to ensure end-to-end QoS and a high level of data protection through the use of QKD mechanisms, beamforming, and network slicing. The complexity of coordination between heterogeneous segments, the heterogeneity of channel parameters, and the variability of the load, however, require the creation of cognitive mechanisms for resource management. Therefore, the academic interest is focused on the study of hybrid approaches to dynamic resource allocation, which are able to provide adaptive inter-segment synchronization of bandwidth, power, and transmission time using Artificial Intelligence (AI). In this context, it is appropriate to develop and analyze end-to-end orchestration systems that take into account the full SQC → FOC → 5/6G stack and optimize network performance under high variability and multi-domain interaction.

1.1. Research Gap

This research on next-generation communication systems predominantly focuses on domain-specific optimization (e.g., optical transport, radio access, or SDN-based control) or limited cross-domain integration, without addressing full end-to-end coordination. Existing approaches fail to incorporate the interdependencies between heterogeneous segments, particularly in hybrid environments combining Quantum (SQC), Optical (FOC), and 5/6G networks. Moreover, critical parameters such as QBER, QKD throughput, cross-segment latency, and dynamic traffic variability remain insufficiently integrated into unified resource management models. As a result, there is a lack of comprehensive frameworks capable of ensuring coherent, adaptive, and globally optimized resource orchestration across all network layers.

1.2. Problem Statement

The core problem addressed in this study is the absence of an effective end-to-end cognitive resource orchestration mechanism for hybrid multi-segment communication architectures. Existing solutions do not provide synchronized control over bandwidth, latency, energy consumption, and security parameters across SQC, FOC, and 5/6G domains under dynamic network conditions.

This limitation leads to inefficiencies in resource utilization, degradation of QoS/QoE, and the inability to meet the stringent performance requirements of next-generation networks. Therefore, there is a need to develop an integrated orchestration model capable of adaptive, real-time optimization of network resources across heterogeneous communication segments.

The aim of the research is to develop and substantiate an effective model for dynamic network resource allocation in a hybrid optical satellite telecommunications architecture SQC → FOC → 5/6G based on end-to-end cognitive orchestration, which provides adaptive optimization of bandwidth, time slots, and transmission power taking into account inter-segment dependencies, quantum channel parameters (QBER, QKD throughput), transport delay, queue loading, and QoS requirements of the mobile domain.

The aim was achieved through the fulfillment of the following research objectives:

- Create a conceptual model of a hybrid telecommunications architecture with sequential integration of SQC, FOC, and 5/6G.
- Detail the functional-structural model of end-to-end data transmission through the SQC → FOC → 5/6G segments.
- Calculate technical and operational metrics of known segment-specific resource allocation methods.
- Conduct a comparative analysis of the effectiveness of segment-oriented methods based on multi-criteria QoS/QoE metrics.
- Advance a hypothesis about the need for end-to-end cognitive management in multi-segment networks.
- Justify the appropriateness of using hybrid methods of orchestrating SQC → FOC → 5/6G network resources.
- Calculate technical and operational metrics for five hybrid strategies of dynamic resource allocation.
- Perform a comparative ranking of hybrid methods to determine the most effective approach to resource management.

The conceptual framework was formed by reviewing current relevant publications. Ntontin et al. [1] justify the integration of SQC, FOC, and 5/6G as a basis for global secure communication, emphasizing the synergy of Low Earth Orbit (LEO) satellites, quantum networks, and AI-optimized channels in the post-2030 environment. Aldrin Joan Pandian, Mangal, Lakshmi, and Jasmine Selvakumari Jeya [2] focused on the management of such systems, who identified AI as a key component of managing Terahertz (THz) connections in 6G networks. In interaction with SQC and FOC, 6G is seen as an adaptive environment for scalable and secure data transmission.

Aldrin Joan Pandian et al. [2] identify AI as the key to managing THz connections in 6G, where the network, in combination with SQC and FOC, acts as an adaptive platform for secure data distribution.

In turn, Siddiky, Rahman, Uzzal, and Kabir [3] consider 6G as an environment for superconvergence of SQC, FOC, and THz networks with the transition to information-centric architectures with built-in security.

At the same time, Nande et al. [4] proposed Quantum Nonlinear Synchronization (QNS) for subnanosecond time coordination between SQC, FOC, and 5/6G, which is critical for the speed and reliability of next-generation networks.

Yang et al. [5] studied the environment for integrating SQC, FOC, and 5/6G, who considered the Space-Air-Ground Integrated Network (SAGIN) architecture as a dynamic access platform with secure and efficient resource allocation.

Suriya et al. [6] held the same position, who proved that achieving Ultra Reliable Low Latency Communications (URLLC) in 6G is possible only provided the integration of SQC, FOC, and 5/6G into a multi-layer architecture with heterogeneous node interaction.

Minoli & Occhiogrosso [7] further revealed advances in quantum technologies, who emphasized the role of “cat qubits” and quantum error correction in the creation of scalable networks capable of combining SQC, FOC, and 5/6G through a secure quantum internet infrastructure.

Narnavaram & Lo [8] explored other aspects of the development of quantum technologies, which justify the appropriateness of using Quantum Approximate Optimization Algorithm (QAOA), quantum sensors, and QKD to optimize efficiency, energy conservation, and security in 6G satellite networks with the integration of SQC, FOC, and 5/6G.

Urgelles et al. [9] explored the problems of assessing the quality of future quantum networks, emphasizing the need to review efficiency metrics and optimization approaches in 6G systems with the integration of quantum technologies.

Alshaer & Ismail [10] demonstrated optimism regarding the development of quantum technologies, who analyzed the potential of their integration into 6G to enhance security and throughput, focusing on the challenges of coordination with SQC, FOC, and 5/6G.

A comprehensive synthesis of recent academic sources reveals the progressive development of both conceptual and technological foundations for integrating SQC, FOC, and 5/6G into unified multi-segment communication architectures. The reviewed studies collectively emphasize heterogeneous orchestration mechanisms, AI-driven routing and control, high-precision synchronization (including quantum timing), fault-tolerant quantum processing, and the transition toward Information-centric and THz-enabled communication paradigms.

Furthermore, the literature highlights critical enablers such as QKD-based security, dynamic spectrum management, and cross-layer optimization techniques across physical, transport, and access domains. However, despite these advances, existing research remains fragmented, primarily addressing isolated components or partial integrations without achieving full end-to-end coordination.

Given the inherent complexity of multi-segment environments, dynamic topology variability, and stringent QoS/URLLC requirements, there is a clear need for next-generation adaptive and intelligent resource management frameworks capable of ensuring coherent, scalable, and resilient network operation.

2. Research Method

2.1. Research Design

The research design is presented below (Figure 1).

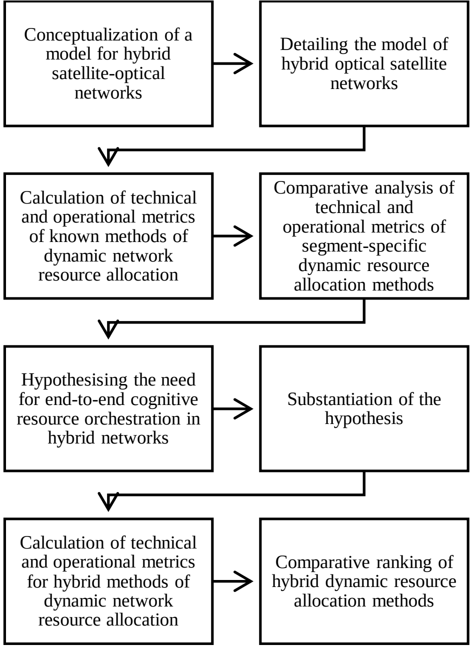

Fig. 1 Multi-iteration research design

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2.2. Methods

The study employed the following methods:

1. Conceptualization of the model of hybrid optical satellite networks. The method involves formalization of the architecture with integration of SQC, FOC, and 5/6G segments for end-to-end data transmission.
2. Detailing of the model of hybrid satellite-optical networks. The detailing of the model specifies the architecture of the multi-segment data transmission system SQC → FOC → 5/6G.
3. Calculation of technical and operational metrics of known methods of dynamic allocation of network resources. The method involves calculation of normalized technical and operational metrics of segment-specific approaches in SQC → FOC → 5/6G based on QoS, resource efficiency, scalability, and cryptographic stability, taking into account the load parameters and channel quality.
4. Comparative analysis of technical and operational metrics of segment-specific methods of dynamic resource allocation. The method involves a multi-criteria comparison of normalized performance metrics of segment approaches to resource allocation in the SQC → FOC → 5/6G system in terms of QoS, scalability, energy efficiency, and resilience.
5. Advancing a hypothesis regarding the need for end-to-end cognitive resource orchestration in hybrid networks. The method is based on a critical analysis of the limitations of isolated segment approaches to resource allocation in the SQC, FOC, and 5/6G domains.
6. Substantiation of the hypothesis. The method involves formalizing the requirements for end-to-end resource management and substantiating hybrid methods for bandwidth, time, and power orchestration, taking into account topology, QKD parameters, and intersegment dependencies.
7. Calculation of technical and operational metrics for hybrid methods for dynamic network resource allocation. The method involves quantitative evaluation of five hybrid traffic management strategies in SQC → FOC → 5/6G by normalized calculation of 21 technical and operational metrics according to a multi-criteria system.
8. Comparative ranking of hybrid methods of dynamic resource allocation. The method is based on a multi-criteria analysis of normalized metrics in SQC → FOC → 5/6G, which identifies the most effective approach to dynamic resource allocation.

2.3. Sample

The sample consists of dynamic resource allocation methods relevant to the SQC → FOC → 5/6G data transmission chain in hybrid optical satellite networks for 5/6G, which were considered in the context of this study and are described below – Table 1.

2.4. Instruments

Technical and operational metrics for assessing resource allocation were used as tools in this research, reflecting the performance, adaptability, stability, and efficiency of the studied hybrid optical satellite networks for 5/6G – Table 2.

Table 1. Dynamic resource allocation methods relevant to the SQC → FOC → 5/6G data transmission chain in hybrid optical satellite networks for 5/6G

Hybrid optical satellite network segment for 5/6G	Dynamic resource allocation methods	The essence of the method	Relevant research and detailed analysis
SQC	QKD-aware Bandwidth Allocation	Bandwidth allocation based on QKD performance	Alia et al. [11]; Nejabati, Wang, Kanellos & Simeonidou [12]
	Entanglement Routing Optimization	Adaptive route selection for entangled states between nodes	Nguyen, Hunt, Horton, Nguyen & Liu [13]; Abane, Cubeddu, Mai & Battou [14]
	Quantum Channel Quality-based Scheduling	Transmission scheduling based on QBER, attenuation, and photon loss	Kim, Kwak, Jung & Kim [15]; Williams, Panigrahy, McGregor & Towsley [16]
	LEO Dynamic Link Assignment	Channel allocation based on satellite movement and coverage changes	Chang, Wan, Lin, Xue & Sen [17]; Meng, Hu, Chen & Kang [18]; Turovsky et al. [19]
FOC	Elastic Optical Network (EON) Allocation	Dynamic allocation of spectral slots and wavelengths	Vasundhara & Mandloi, [20]; Hamidja, Koffi, Tiekoura, Adama & Babri [21]
	Traffic-aware Optical Burst Switching (OBS)	Adaptive aggregation of traffic into optical packets to reduce latency	Al Musalhi & Zebari [22]; Zhao et al. [23], Kremenetska et al. [24]
	Latency-Constrained Lightpath Selection	Optical route selection with consideration of end-to-end latency for critical data	Wang et al. [25]; Raffaelli, Amato, Monti & Tonini [26]; Kremenetska et al. [27]
	Cross-layer QoS Mapping	Bonding quantum/satellite QoS classes to optical channels	Mohammadani et al. [28]; Patil, Satre, Chavan & Kharade [29]
5/6G	QoS-Aware Dynamic Spectrum Allocation (DSA)	Adaptive frequency allocation in THz/mm bands for URLLC/eMBB	Louvros, Paraskevas & Chrysikos [30]; Han & Wang [31]
	AI-based Slice Resource Management	Resource allocation between 5G/6G network slices relying on AI-based solutions	Dubey, Singh & Mishra [32]; Nouruzi, Mokari, Azmi, Jorswieck & Erol-Kantarci [33]
	UE-Centric Beamforming Scheduling	End-device-level scheduling taking into account traffic and channel conditions	Park et al. [34]; Zhang et al. [37]
	Hybrid MAC Layer Prioritization	Change of MAC priorities depending on data received from SQC/FOC	Nauman et al. [36]; Valcarce, Kela, Mandelli & Viswanathan [37]

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Table 2. Technical and operational metrics for assessing resource allocation in hybrid optical satellite networks for 5/6G

Metrics	Brief description	Mathematical formula
Quality of service metrics (QoS / QoE)		
End-to-End Latency	Total delay between sender and receiver across all segments (ms/s)	$L_{total} = \sum_{i=1}^{3} \left(\frac{L_i \times \rho_i}{R_i} \right)$, where $i \in \{1,2,3\}$ – corresponds to segments: 1 = SQC, 2 = FOC, 3 = 5/6G; L_i – average queue length in the i th segment (e.g., in packets); ρ_i – load factor (incoming traffic to bandwidth ratio) in the i segment; R_i – i segment bandwidth (in packets/s or bits/s)
Jitter	Inter-packet delay variation is critical for real-time applications.	$J_{total} = \sqrt{\frac{1}{N} \times \sum_{i=1}^{N} \left(L_i - \overline{L} \right)^2}$, where L_i – delay of the i th packet; $\overline{L}$ – average delay value for all packets; N – total number of measured packets
Throughput	The amount of data successfully transmitted over a channel per unit of time (bit/s, Gb/s)	$T_{total} = \frac{D_{success}}{\sum_{i=1}^{3} t_i}$, where $D_{success}$ – total volume of successfully transmitted data (in bits or packets); t_i – time of data passing through the i th segment (SQC, FOC, 5/6G), s
Packet Loss Rate	Fraction of lost or dropped packets (%) because of buffering or channel errors	$PLR_{total} = 1 - \prod_{i=1}^{3} \left(1 - PLR_i \right)$, where PLR_i – the fraction of lost packets in the i th segment (SQC, FOC, 5/6G) determined by using the formula: $PLR_i = \frac{\left(N_{lost} \right)_i}{\left(N_{sent} \right)_i}$, N_{lost} – number of lost packets; N_{sent} – total number of sent packets
Bit Error Rate / QBER	For SQC - probability of errors in the quantum channel	$BER\left(QBER\right)_{total} = 1 - \prod_{i=1}^{3} \left(1 - BER\left(QBER\right)_i \right)$, where $BER\left(QBER\right)_i$ – probability of bit error (quantum bit error) in the i th segment (SQC, FOC, 5/6G), which is determined by using the formula: $BER\left(QBER\right)_i = \frac{\left(N_{error}^{detected} \right)_i}{\left(N_{total}^{detected} \right)_i}$, where $N_{error}^{detected}$ – number of bits (quantum bits) transmitted with errors (detected during parity checking); $N_{total}^{detected}$ – total number of detected

		(measured) bits (quantum bits).
Service Availability	Probability of service availability at the selected time (% of time)	$A_{total} = \prod_{i=1}^{3} A_i$, where A_i – availability of a separate segment i (SQC, FOC, 5/6G), i.e., the probability that the segment is operating correctly at any given time: $A_i = \frac{MTBF_i}{MTBF_i + MTTR_i}$ where $MTBF_i$ – mean time between failures, s; $MTTR_i$ – mean recovery time after failure, s
Resource efficiency metrics		
Channel Utilization	Available bandwidth utilization (%)	$U_{total} = \frac{\sum_{i=1}^{3} D_i}{\sum_{i=1}^{3} (C_i \times T)}$, where D_i – the volume of data actually transmitted in the i th segment (SQC, FOC, 5/6G) (for example, in packets) C_i – the maximum channel capacity of the i th segment (SQC, FOC, 5/6G) (for example, in packets); T – the duration of observation (data transmission time), s
Spectral Efficiency	Number of bits transmitted per 1 Hz (bits/Hz)	$\eta_{total} = \frac{\sum_{i=1}^{3} D_i}{\sum_{i=1}^{3} B_i \times T}$, where D_i – the volume of successfully transmitted data in the i th segment (SQC, FOC, 5/6G) (e.g., in packets); B_i – the bandwidth of the i th segment (SQC, FOC, 5/6G) (e.g., in packets); T – the duration of the observation (data transmission time), s
Resource Allocation Fairness	How fairly are resources distributed between threads/segments?	$F = \frac{\left(\sum_{i=1}^{3} x_i \right)^2}{3 \times \sum_{i=1}^{3} x_i^2}$, where x_i – the amount of resource allocated to the i th segment (SQC, FOC, 5/6G).
Blocking Probability	Probability of resource allocation failure (under overload)	$P_{block}^{total} = 1 - \prod_{i=1}^{3} \left(1 - \left(P_{block} \right)_i \right)$, where $\left(P_{block} \right)_i$ – probability of blocking a resource in the i th segment (SQC, FOC, 5/6G, determined by using the formula:

		$$(P_{block})_i = \frac{\frac{(A_i)^{c_i}}{c_i!}}{\sum_{k=0}^{c_i}\frac{(A_i)^k}{k!}},$$ where c_i – number of available serving channels (resources) in the i th segment (SQC, FOC, 5/6G); A_i – load in Erlangs (demand intensity × average service time), which is determined by using the formula: $A_i = \lambda_i \times h_i$, where λ_i – intensity of requests in the i th segment (SQC, FOC, 5/6G); h_i – average request service time, s
Adaptability and scalability metrics		
Adaptation Time	Algorithm response time to changing conditions (ms/s)	$$T_{adapt} = \max\left(T_{detect}^{(i)} + T_{decide}^{(i)} + T_{apply}^{(i)}\right),$$ where $T_{detect}^{(i)}$ – time to detect changes in requests in the i th segment (SQC, FOC, 5/6G); $T_{decide}^{(i)}$ – time required to calculate a new resource allocation in the i th segment (SQC, FOC, 5/6G); $T_{apply}^{(i)}$ – time to apply decisions in the i th segment (SQC, FOC, 5/6G); the $\max$ operator considers the slowest segment as the limiting one for end-to-end adaptation
Policy Robustness	Stability of decisions made to changes in traffic or channel quality	$$R_{policy} = 1 - \frac{1}{3} \times \sum_{i=1}^{3} \frac{\left\|\pi_i' - \pi_i\right\|}{\pi_i},$$ where π_i' – optimal policy for the i th segment (SQC, FOC, 5/6G) before changes; π_i – new policy after changes in the conditions for the i th segment (SQC, FOC, 5/6G).
Scalability	Ability to work effectively with an increasing number of nodes/traffic	$$S = \frac{P(N)}{C(N)},$$ where $P(N)$ – system performance with the number of nodes N; $C(N)$ – system outlay with the same number of nodes N
Cross-Segment Coordination Efficiency	How effectively are dependencies between segments taken into account when making decisions?	$$E_{coord} = 1 - \frac{1}{3} \times \sum_{i=1}^{3} \frac{\left\|\Delta r_i - \Delta r_{i-1}\right\|}{\Delta r_i},$$ where Δr_i – changing the allocated resource in the i th segment (SQC, FOC, 5/6G) in response to a change in traffic or conditions; Δr_{i-1} – changing the resource in the previous segment

Energy efficiency and reliability metrics		
Energy Consumption per Bit	Energy consumption per 1 bit (J/bit or mJ/MB)	$E_{bit} = \frac{\sum_{i=1}^{3} E_i}{D_{total}}$, where E_i – total power consumption in the i th segment (SQC, FOC, 5/6G); D_{total} – total number of successfully transmitted bits in the chain SQC → FOC → 5/6G
Idle Resource Ratio	Share of unused resources with available traffic (% idle)	$R_{idle} = \frac{1}{3} \times \sum_{i=1}^{3} \left(1 - \frac{R_i^{used}}{R_i^{total}} \right)$, where R_i^{used} – actually used resource volume in the i th segment (SQC, FOC, 5/6G); R_i^{total} – generally available resource volume in the i th segment (SQC, FOC, 5/6G)
Fault Tolerance	Resilience to segment/channel loss (ability to redirect traffic)	$F = \prod_{i=1}^{3} \left[1 - P_{fail}^{(i)} \times \left(1 - P_{reroute}^{(i)} \right) \right]$, where $P_{fail}^{(i)}$ – probability of failure of the i th segment (SQC, FOC, 5/6G); $P_{reroute}^{(i)}$ – probability of successful traffic redirection in case of failure of the i th segment (SQC, FOC, 5/6G)
Stability	No fluctuations in resource allocation under stable conditions	$S = 1 - \frac{1}{3 \times T} \times \sum_{i=1}^{3} \sum_{t=1}^{T} \left\| \frac{r_i(t) - r_i(t-1)}{r_i(t-1)} \right\|$, where T – number of observation time intervals; $r_i(t)$ – the amount of resource allocated to the i th segment (SQC, FOC, 5/6G) at the moment of time t
Security metrics (for SQC / QKD integrations)		
QKD Throughput	Number of keys generated by the system per unit of time (bit/s)	$T_{QKD} = \min \left(\frac{K_{gen}^{SQC}}{t}, \frac{K_{trans}^{FOC}}{t}, \frac{K_{sync}^{5/6G}}{t} \right)$, where K_{gen}^{SQC} – key generation speed in the SQC segment; K_{trans}^{FOC} – key transport/retransmission speed via FOC; $K_{sync}^{5/6G}$ – synchronization capability of the 5/6G mobile interface for delivering keys to end devices; t – selected time interval, s
Key Utilization Efficiency	Share of keys used for encryption (vs. generated)	$\eta_{key} = \frac{K_{used}}{K_{gen}}$, where K_{used} – the number of quantum keys actually used to encrypt traffic (in FOC or 5/6G segments); K_{gen} – the total number of keys generated in the SQC segment for the same time

Eavesdropping Detection Rate	Probability of detecting an attack in the SQC segment	$P_{detect} = 1 - \prod_{i=1}^{3}\left(1 - P_{err}^{(i)} \times \delta^{(i)}\right)$, where $P_{err}^{(i)}$ – probability of detected error in the i th segment (SQC, FOC, 5/6G); $\delta^{(i)} \in \{0,1\}$ – monitoring sensitivity to interception in the i th segment (SQC, FOC, 5/6G): 1 – active detection, 0 – passive or absent
Normalization of calculation parameters		
Minimax normalization	A method of linear scaling of parameter values to the range [0;1]. Minimax normalization enables unifying the dimensions and scales of different technical and operational metrics (for example, latency in milliseconds and throughput in Gbps) for their comparison and multi-criteria analysis of the effectiveness of dynamic resource allocation methods in a hybrid network.	$x_{norm} = 1 - \frac{x - x_{\min}}{x_{\max} - x_{\min}}$, where x_{norm} – normalized value of the calculated parameter in the range [0;1], x, $x_{\min}$, $x_{\max}$ – corresponding calculated values of the parameter: current value, minimum value, and maximum value in the range

Source: created by the authors

3. Results and Discussion

The model of hybrid optical satellite networks for 5/6G will be conceptualized in accordance with the chosen research methodology, which involves the use of telecommunication systems in a sequential data transmission chain SQC → FOC → 5/6G – Figure 2.

This concept (Figure 2) illustrates end-to-end data transmission over a hybrid network: quantum signals are transmitted from a satellite to a ground station, where the data is routed over a fiber-optic network, and then delivered to end users via a high-speed mobile interface.

The created concept (Figure 2) is detailed below, taking into account the integration of the minimum necessary number of elements for implementing hybrid data transmission - Figure 3.

The chart (Figure 3) demonstrates the architecture of a multi-segment telecommunication system combining SQC, FOC, and 5/6G networks. In the SQC segment, a quantum channel based on the BB84 protocol is implemented, where the satellite QKD module generates single-photon states that are received by the ground station via a quantum optical link.

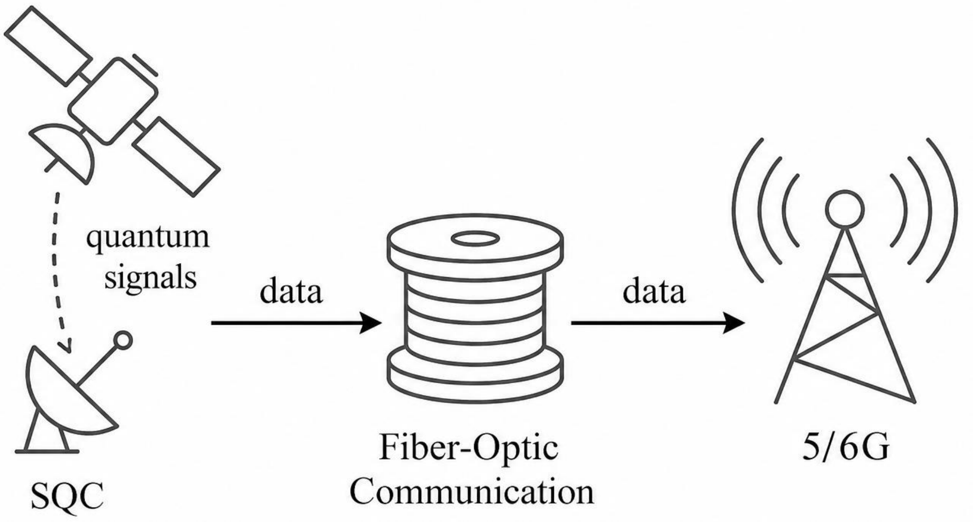

Fig. 2 Conceptualization of the SQC → FOC → 5/6G data transmission chain model

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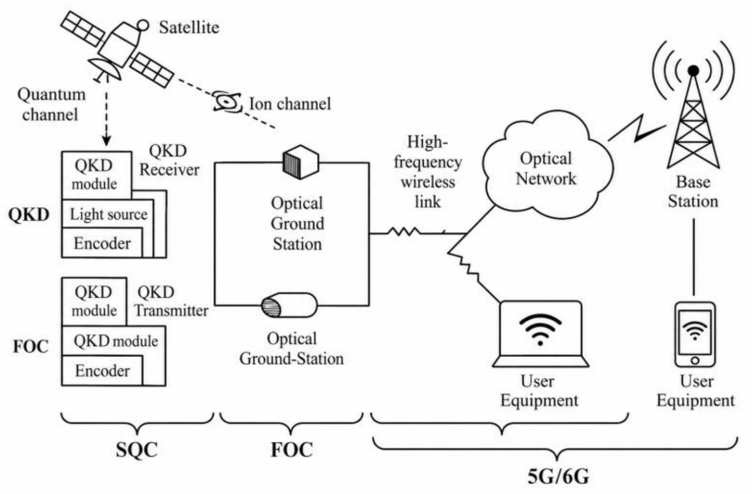

Fig. 3 Detailed concept of the data transmission chain model SQC → FOC → 5/6G

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Table 3. Calculation of technical and operational metrics of known methods of dynamic network resource allocation

Dynamic resource allocation methods	End-to-End Latency	Jitter	Throughput	Packet Loss Rate	Bit Error Rate / QBER	Service Availability	Channel Utilization	Spectral Efficiency	Resource Allocation Fairness	Blocking Probability	Adaptation Time	Policy Robustness	Scalability	Cross-Segment Coordination Efficiency	Energy Consumption per Bit	Idle Resource Ratio	Fault Tolerance	Stability	QKD Throughput	Key Utilization Efficiency	Eavesdropping Detection Rate
QKD-aware Bandwidth Allocation	0.965	0.760	0.847	1.000	0.980	0.553	0.843	0.677	0.685	0.762	0.722	0.918	0.814	0.718	0.767	0.750	0.924	0.669	0.747	0.572	0.317
Entanglement Routing Optimization	0.798	0.830	0.589	1.000	0.482	0.707	0.672	0.930	0.920	0.723	0.757	0.567	0.403	0.648	0.723	0.885	0.880	0.642	0.655	0.543	0.487
Quantum Channel Quality-based Scheduling	0.444	0.993	0.624	0.634	0.512	0.817	0.458	0.668	0.566	0.758	0.623	0.523	0.696	0.764	0.710	0.745	0.605	0.646	0.599	0.646	0.578
LEO Dynamic Link Assignment	0.441	0.727	0.640	0.455	0.769	0.564	0.708	0.809	0.719	0.871	0.515	0.760	0.597	0.569	0.613	0.653	0.708	0.525	0.835	0.770	0.470
Elastic Optical Network (EON) Allocation	0.923	0.984	0.877	0.673	0.539	0.858	0.640	0.883	0.731	0.846	0.753	0.806	0.702	0.968	0.719	0.760	0.982	0.498	0.509	0.845	0.524
Traffic-aware Optical Burst Switching (OBS)	0.992	0.638	0.588	0.988	0.922	0.980	0.836	0.571	0.987	0.660	0.820	0.842	0.677	0.792	0.838	0.756	0.535	0.745	0.899	0.596	0.678
Latency-Constrained Lightpath Selection	0.635	0.977	0.801	0.761	0.585	0.781	0.599	0.705	0.605	0.801	0.786	0.669	0.759	0.536	0.476	0.766	0.725	0.795	1.000	0.842	0.563
Cross-layer QoS Mapping	0.868	0.503	0.631	0.690	0.957	0.588	0.576	0.685	0.600	0.869	0.538	0.528	0.634	0.625	0.989	0.842	0.713	0.516	0.827	0.550	0.468

QoS-Aware Dynamic Spectrum Allocation (DSA)	0.878	0.748	0.838	0.748	0.829	0.602	0.545	0.802	0.579	0.597	0.632	0.703	0.647	0.494	0.603	0.366	0.794	0.460	0.534	0.708	0.589
AI-based Slice Resource Management	0.931	0.506	0.740	0.694	0.525	0.778	0.674	0.816	0.824	1.000	0.900	0.645	0.664	0.865	0.798	0.796	0.457	0.696	0.589	0.742	0.685
UE-Centric Beamforming Scheduling	0.837	0.748	0.818	0.630	0.558	0.638	0.697	0.757	1.000	0.694	0.557	0.648	0.630	0.772	0.469	0.709	0.723	0.735	0.610	0.664	0.486
Hybrid MAC Layer Prioritization	0.626	0.619	0.762	0.527	0.817	0.924	0.390	0.764	0.802	0.604	0.640	0.680	0.655	0.654	0.449	0.873	0.862	0.578	0.480	0.778	0.614

Source: created by the authors

After decoding the keys, the QKD receiver transmits the session keys to the optical node, where a classical QKD transceiver is activated to encapsulate the key information as part of the Optical Burst Switching (OBS) or Wavelength-Division Multiplexing (WDM). At the last stage, traffic distribution is carried out over a heterogeneous access environment (NR/THz), with data reaching the end user via a mobile node with support for network segmentation (network slicing), beamforming, and end-to-end encryption using dynamically updated quantum keys.

According to the initially defined resource allocation methods in the studied segments of the hybrid telecommunication network (Table 1), their technical and operational metrics (Table 2) will be calculated, and the possibility of applying the considered methods for the entire created concept will be established — Table 3.

A comparative analysis of the set of calculated indicators of QoS, resource efficiency, scalability, adaptability, reliability, and cryptographic stability, among segment-specific methods of dynamic resource allocation (Table 3), found that the Elastic Optical Network (EON) Allocation method demonstrated the highest results. This approach, with its flexible management of spectral slots and dynamic allocation of wavelengths in the fiber-optic environment, provides increased throughput, high spectral efficiency, and low blocking probability, which makes it effective in the FOC segment.

All considered methods have a narrow domain focus and do not take into account inter-segment dependencies, which makes end-to-end traffic optimization impossible. Their fragmentation causes asynchronous control, loss of QoS guarantees, and limited adaptation to load changes in the SQC → FOC → 5/6G architecture. According to the advanced hypothesis, the analysis indicates the necessity of developing and applying adaptive methods for dynamic network resource allocation. It is currently appropriate to apply hybrid methods for end-to-end resource orchestration focused on the full stack of segments – Table 4.

Table 4. Hybrid methods for dynamic allocation of network resources in the SQC → FOC → 5/6G chain

Hybrid methods for dynamic network resource allocation	Brief description of the method
AI-Driven End-to-End Resource Orchestration	Implements a centralized approach to managing bandwidth, time slots, and transmission power at the level of the entire transmission, taking into account the specifications of quantum channels (QBER, QKD rate), optical dispersion, and radio interfaces of THz/mm wave bands
Cross-Domain Reinforcement Learning Agents	Provides an adaptive resource allocation policy based on deep reinforcement learning (DRL), which formalizes the state space of all segments (delays, queues, loading, noise level) and makes real-time decisions for balancing QoS/QoE

SDN-Orchestrated Multi-Segment Allocation	Based on a software-defined (SDN) network architecture, where the SDN controller coordinates the logic of resource allocation between all segments through policy abstraction (Policy Abstraction Layer) and routing tables management for SQC/FOC/5G
Latency-Aware Joint Scheduling	Enables simultaneous traffic planning based on end-to-end delay estimation in all segments (e.g., using heuristics or ILP models), ensuring compliance with the URLLC criteria
Queue-Aware Flow Control Protocols	Implements predictive queue management using traffic predictors and dynamic window control, which prevents packet accumulation at transmission bottlenecks, particularly in multi-hop routing involving inter-satellite links

Source: created by the authors

Accordingly, hybrid approaches (Table 4) provide interdependent, end-to-end, QoS-oriented dynamic resource allocation taking into account all the properties of SQC, FOC, and 5/6G, which is critically important for scalable and secure next-generation communication platforms.

According to the developed methodology, the identified hybrid methods of dynamic network resource allocation in the SQC → FOC → 5/6G chain were calculated – Table 5 (Appendix 1).

To enhance the interpretability of the multi-criteria results, a comparative visualization of normalized metrics (range [0;1]) for segment-specific and hybrid methods was performed.

Figure 4 aggregates 9 key indicators (latency, throughput, utilization, blocking probability, robustness, adaptation, energy, QKD throughput, detection rate) across 6 methods, enabling direct identification of performance differentials and cross-domain efficiency patterns.

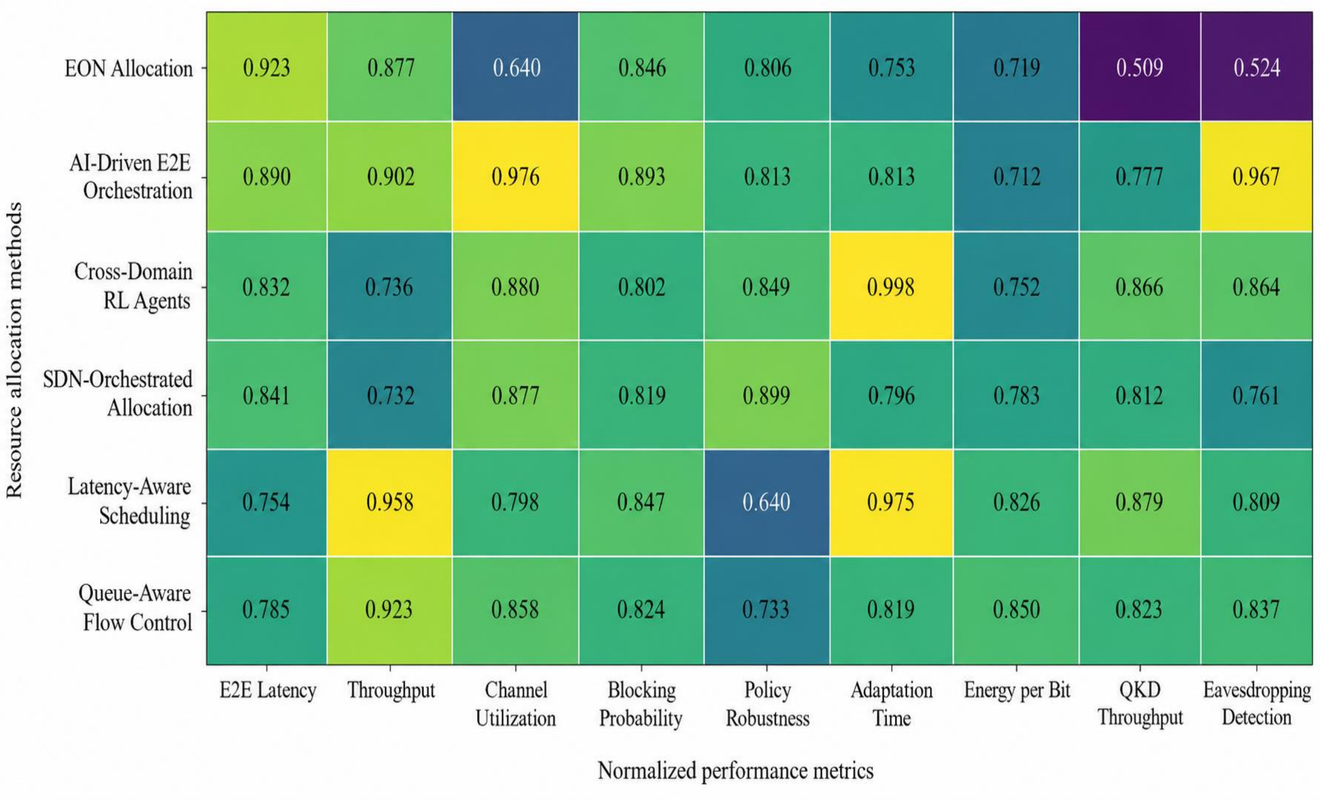

Fig. 4 Comparative performance of segment-specific and hybrid resource allocation methods across key normalized metrics

Source: created by the authors

The AI-driven orchestration method demonstrated dominant performance across most metrics: throughput = 0.902, channel utilization = 0.976, blocking probability = 0.893, robustness = 0.813, with competitive latency = 0.890 (Figure 4). Compared to EON (throughput = 0.877; utilization = 0.640), the gain reached +2.9% and +52.5%, respectively, confirming cross-segment optimization efficiency. Hybrid methods showed balanced profiles, but only the AI-driven approach ensured simultaneous maximization of ≥5 metrics (>0.80), indicating superior global coordination.

The results of multi-criteria comparative analysis of the calculated data (Table 5) show that AI-Driven End-to-End Resource Orchestration is the most effective method of dynamic resource allocation in the hybrid optical satellite network SQC → FOC → 5/6G.

This approach minimizes end-to-end latency (E2E latency), reduces interpacket delay variations (jitter), increases channel utilization, and also provides stable support for target QoS parameters under high network dynamics – Figure 5.

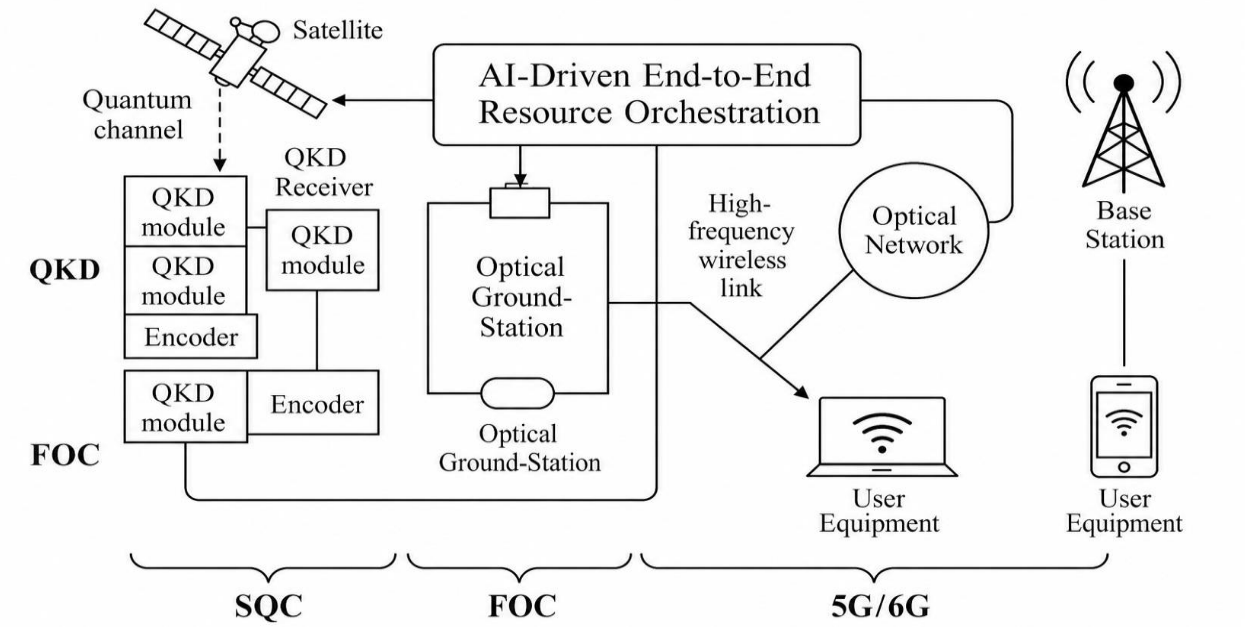

Fig. 5 Optimized concept of SQC → FOC → 5/6G data chain model with integrated AI-Driven End-to-End Resource Orchestration

Source: created by the authors

The high efficiency of this method (Figure 5) is determined by the use of a centralized cognitive orchestration system that performs global optimization of the transmission resource graph, synchronizing the distribution of frequency spectrum, time slots, and transmission power between all segments. Furthermore, the integrated AI core takes into account buffer states, topological variability, and channel capacity in each domain, which ensures an effective response to short-term traffic fluctuations, reduces the blocking probability, improves the level of policy adaptation to external conditions (policy robustness), and guarantees stable performance (stability) with variable request intensity. Therefore, AI-Driven End-to-End Resource Orchestration is the most appropriate mechanism for end-to-end management of heterogeneous next-generation quantum optical mobile networks.

The relevance of the obtained results is verified by discussing the publications in the defined research vector. Moazzen et al. [39] propose AI orchestration in optical and inter-domain segments of 6G to support QoS/KVI. Instead, the proposed model covers the full path SQC → FOC → 5/6G, taking into account quantum channels and inter-segment coherence. Li, Fan, and Wu [40] consider the B5G/6G architecture with an emphasis on spectral and antenna technologies. Instead, this study focuses on cognitive resource orchestration in a hybrid SQC → FOC → 5/6G environment, taking into account inter-segment and quantum parameters. Hassan & Keti [41] explore the potential of SDN and AI/ML for 5G/6G networks at a conceptual level. In contrast, this study implements a cognitive model of end-to-end resource orchestration in SQC → FOC → 5/6G, taking into account cross-domain parameters and QoS/QKD requirements. Sun et al. [42] emphasize the importance of Explainable AI for transparent resource management in 6G. In turn, this study focuses on the cognitive efficiency of AI orchestration in SQC → FOC → 5/6G without relying on XAI interpretations. Othman et al. [43] focus on the potential of UAV, THz, and IRS as drivers of 6G architecture. At the same time, this study emphasizes cognitive resource orchestration in SQC → FOC → 5/6G to provide end-to-end QoS in a heterogeneous environment.

Tyagi, Tiwari, Gupta, and Mishra [44] summarize the technical and security aspects of 6G in the context of smart infrastructure. In contrast, this study proposes end-to-end AI orchestration in SQC → FOC → 5/6G for dynamic QoS control in multi-segment variability. Liu et al. [45] consider ISEA as the integration of sensor and computing in 6G. In turn, this study focuses on end-to-end SQC → FOC → 5/6G resource orchestration to stabilize QoS in multi-segment high-load environments.

Kulkarni, Goudar, Vinayak B., & HT [46] summarize the challenges of 6G communications, including ultra-massive MIMO and THz communications. In contrast, this study demonstrates the effectiveness of a practical implementation of AI orchestration in a hybrid SQC → FOC → 5/6G architecture. Gote et al. [47] emphasize the potential of ML/DL in 6G for spectrum management and security. In turn, this study demonstrates an applied implementation of end-to-end AI resource management in SQC → FOC → 5/6G with proven technical and operational benefits. Syed, Hussain, and Bashir [48] analyze the strategic impact of AI/ML on 5G/6G architecture. In contrast, this study demonstrates a practical implementation of AI orchestration in SQC → FOC → 5/6G with proven achievement of QoS metrics.

The improved performance compared to state-of-the-art approaches is attributed to the integrated consideration of three factors that are typically addressed in isolation. First, joint optimization of frequency, time, and power is performed at a global level, eliminating conflicts between local allocation policies and reducing cumulative inter-segment delays. Second, Quantum-Specific Parameters (QBER, QKD throughput) are incorporated into the classical QoS control loop, enabling adaptation not only to traffic dynamics but also to channel conditions, thereby improving transmission stability.

Third, the AI-driven cognitive orchestration enables real-time reconfiguration of resource allocation policies based on queue states, topology variations, and load fluctuations, which reduces blocking probability and increases resource utilization. Collectively, these mechanisms produce cross-segment synergy that is not achievable in segment-specific or partially integrated approaches, thereby explaining the observed improvements in latency, throughput, and energy efficiency.

Most existing studies concentrate on isolated architectural components (e.g., SDN control planes, XAI frameworks, ISEA paradigms) or partial integration strategies, thereby neglecting inter-segment dependencies and the need for coordinated multi-domain optimization. In contrast, the proposed approach introduces a unified AI-driven end-to-end resource orchestration model that simultaneously manages frequency allocation, temporal scheduling, and transmission power across SQC, FOC, and 5/6G domains.

Unlike earlier studies, the model explicitly integrates Quantum-Specific Parameters (QBER, QKD throughput) with classical QoS metrics, enabling synchronized decision-making under dynamic traffic conditions. This holistic orchestration ensures improved system-level performance, as evidenced by higher normalized throughput (0.902), reduced latency (0.890), and enhanced channel utilization (0.976), while maintaining robustness (0.813) and cross-segment coordination efficiency (0.697). Consequently, the novelty is the formalization and empirical validation of a cognitively adaptive, multi-segment orchestration framework that outperforms segment-specific and partially integrated solutions in terms of stability, energy efficiency, and scalability.

3.1. Limitation

The model does not take into account atmospheric attenuation in SQC/FOC and does not integrate edge/fog infrastructure to minimize latency in a multi-segment environment.

3.2. Recommendations

The results can be used to build cognitive resource management systems in multi-segment networks with integration of SQC, FOC, and 5/6G. The proposed approach is effective for dynamic inter-domain orchestration of spectrum, power, and time with support for QoS and secure channelization.

4. Conclusion

The summarized research findings confirm the appropriateness of implementing end-to-end cognitive resource orchestration in the hybrid optical satellite architecture SQC → FOC → 5/6G. The multi-criteria analysis found that AI-Driven End-to-End Resource Orchestration provides optimal performance indicators: E2E latency — 0.890, throughput — 0.902, packet loss rate — 0.972, channel utilization — 0.976, blocking probability — 0.893, and policy robustness — 0.813.

Compared to segment-oriented approaches, this method achieves higher cross-domain coordination (cross-segment coordination efficiency — 0.697), adaptability (adaptation time — 0.813), and energy efficiency (energy consumption per bit — 0.712). It also demonstrates high security indicators: QKD throughput — 0.777, key utilization efficiency — 0.737, and eavesdropping detection rate — 0.967. This makes it suitable for implementation in scalable new-generation secure systems.

The academic novelty of the research is the first-proposed model of end-to-end cognitive resource allocation in the hybrid SQC → FOC → 5/6G network. The developed AI-Driven End-to-End Orchestration system provides integrated management of channel parameters, taking into account inter-segment dependencies and variable network dynamics. The practical significance of the research is the creation of an intelligent resource management architecture for Quantum-Optical 5/6g Networks. The proposed model ensures latency minimization, blocking reduction, and stable QoS in highly dynamic mission-critical applications.

Declaration of Competing Interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author Contribution

The contribution to the paper is as follows: Vasyl Voloshyn: study conception and design; Oleg Boyko: data collection; Mykola Madinov, Nataliia Khabiuk: analysis and interpretation of results; Nataliia Halahan: draft preparation. All authors approved the final version of the manuscript.

References

[1] Konstantinos Ntontin et al., "A Vision, Survey, and Roadmap toward Space Communications in the 6G and Beyond Era," *Proceedings of the IEEE*, vol. 113, no. 9, pp. 987-1023, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[2] W. Aldrin Joan Pandian et al., *The Role of Artificial Intelligence in 6G Networks, Architecture, Protocol, Transmission, and Applications*, RFID, Microwave Circuit, and Wireless Power Transfer Enabling 5/6G Communication, IGI Global, pp. 1-40, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[3] Md Nurul Absar Siddiky et al., "A Comprehensive Exploration of 6G Wireless Communication Technologies," *Computers*, vol. 14, no. 1, pp. 1-57, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[4] Swaraj Shekhar Nande et al., "Integrating Quantum Synchronization in Future Generation Networks," *Scientific Reports*, vol. 15, pp. 1-22, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[5] Kai Yang et al., "Communications in Space-Air-Ground Integrated Networks: An Overview," *Space: Science & Technology*, vol. 5, pp. 1-20, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[6] M. Suriya et al., "Terrestrial-Satellite Communication Techniques and Challenges for 6G," *2024 International Conference on IoT Based Control Networks and Intelligent Systems (ICICNIS)*, Bengaluru, India, pp. 112-117, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Daniel Minoli, and Benedict Occhiogrosso, *Quantum Communication and Quantum Internet Applications*, Auerbach Publications, pp. 1-394, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[8] Kiran Mai Narnavaram, and Dr. Dan Chia-Tien Lo, "Revolutionizing Quantum-Accelerated Optimization for Quantum Enhanced 6G LEO Satellite Networks (Q-LEO)," 2025. [Google Scholar]

[9] Helen Urgelles et al., *In-Network Quantum Computing for Future 6G Networks*, Advanced Quantum Technologies, vol. 8, no. 2, pp. 1-12, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[10] N. Alshaer, and T. Ismail, *AI-Integrated Quantum Networks for 6G*, Intelligent Photonics Systems, 1st ed., CRC Press, pp. 1-18, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[11] Obada Alia et al., "Dynamic DV-QKD Networking in Trusted-Node-Free Software-Defined Optical Networks," *Journal of Lightwave Technology*, vol. 40, no. 17, pp. 5816-5824, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Reza Nejabati et al., "Optical Network Architecture Supporting Dynamic and End-to-End Quantum Secure Networking," *2021 European Conference on Optical Communication (ECOC)*, Bordeaux, France, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[13] Dung H. P. Nguyen et al., "Maximizing Entanglement Routing Rate in Quantum Networks: Approximation Algorithms," *IEEE Transactions on Network Science and Engineering*, vol. 12, no. 3, pp. 1939-1952, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[14] Amar Abane et al., "Entanglement Routing in Quantum Networks: A Comprehensive Survey," *IEEE Transactions on Quantum Engineering*, vol. 6, pp. 1-39, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[15] Joongheon Kim et al., "Quantum Scheduling for Millimetre-Wave Observation Satellite Constellation," *2021 IEEE VTS 17th Asia Pacific Wireless Communications Symposium (APWCS)*, Osaka, Japan, 2021. [CrossRef] [Publisher Link]

[16] Albert Williams et al., "Scalable Scheduling Policies for Quantum Satellite Networks," *2024 IEEE International Conference on Quantum Computing and Engineering (QCE)*, Montreal, Canada, pp. 1760-1769, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[17] Alena Chang et al., "Entanglement Distribution in LEO Satellite-Based Dynamic Quantum Networks," *GLOBECOM 2024 - 2024 IEEE Global Communications Conference*, Cape Town, South Africa, pp. 4485-4490, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[18] Meng Meng et al., "Dynamic Beam Pattern Based on Cooperation Multi-Agent VDN-D3QN for LEO Satellite Communication System," *IEEE Transactions on Green Communications and Networking*, vol. 9, no. 2, pp. 725-738, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[19] Oleksandr Turovsky et al., "Development of a Model for Calculating the Dilution of Precision Coefficients of the Global Navigation System at a Given Point in Space," *Computer Science, Automation, Measurements In Agriculture And Environmental Protection*, vol. 15, no. 1, pp. 79-87, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[20] Vasundhara, and Abhilash Mandloi, “Deep Learning for Core Allocation and Fragmentation Minimization in an Elastic Optical Network with Space Division Multiplexing,” *Journal of Optics*, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[21] Kamagaté Beman Hamidja et al., “Resource Optimization in Elastic Optical Networks Using Threshold-Based Routing and Fragmentation-Aware Spectrum Allocation,” *Open Journal of Applied Sciences*, vol. 15, no. 1, pp. 168-186, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[22] M. Madinov, “Optical Communication Line,” *Computer-Integrated Technologies: Education, Science, Production*, vol. 55, pp. 286-292, 2024. [Google Scholar]

[23] Nasser Al Musalhi, and Gheyath Mustafa Zebari, “Dynamic Bandwidth Allocation Energy Efficient Operation for WDM/TDM PON Architectures: A Survey,” *East Journal of Computer Science*, vol. 1, no. 1, pp. 71-78, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[24] Yisong Zhao et al., “Optical Switching Data Center Networks: Understanding Techniques and Challenges,” *Computer Networks and Communications*, vol. 1, no. 2, pp. 276-291, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[25] A. YA. Kremenetska et al., “Multilevel Model of Terrestrial and Nonterrestrial Telecommunications Using Optical Wireless Technologies,” *Connectivity*, no. 3, 2021. [Google Scholar]

[26] Yunwu Wang et al., “Availability-Aware and Delay-Sensitive RAN Slicing Mapping Based on Deep Reinforcement Learning in Elastic Optical Networks,” *IEEE Transactions on Network and Service Management*, vol. 21, no. 6, pp. 6026-6040, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[27] Carla Raffaelli et al., “Reliable Slicing in Optical Metro Networks with Reconfigurable Backup Resources,” *2022 13th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, Porto, Portugal, pp. 863-866, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[28] Yana Kremenetska et al., “High-Altitude Configuration of Non-Terrestrial Telecommunication Network Using Optical Wireless Technologies,” *International Journal of Communication Networks and Information Security (IJCNIS)*, vol. 13, no. 3, pp. 394-400, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[29] H. Mohammadani Khalid et al., “Highest Cost First-Based QoS Mapping Scheme for Fiber Wireless Architecture,” *Photonics*, vol. 7, no. 4, pp. 1-20, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Shankar M. Patil et al., “AI-Based Prediction of Transmission Quality in Cognitive Optical Networks,” *Journal of Optical Communications*, vol. 47, no. 2, pp. 375-388, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[31] Spiros (Spyridon) Louvros, Michael Paraskevas, and Theofilos Chrysikos, “QoS-Aware Resource Management in 5G and 6G Cloud-Based Architectures with Priorities,” *Information*, vol. 14, no. 3, pp. 1-18, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[32] Wudan Han, and Xianbin Wang, “Diverse and Differentiated QoS Provisioning for 6G Communications via Demand-Aware Prioritization and DEI-Based Resource Allocation,” *IEEE Transactions on Wireless Communications*, vol. 23, no. 12, pp. 18346-18362, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[33] Monika Dubey, Ashutosh Kumar Singh, and Richa Mishra, “AI Based Resource Management for 5G Network Slicing: History, Use Cases, and Research Directions,” *Concurrency and Computation: Practice and Experience*, vol. 37, no. 2, pp. 1-23, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[34] Ali Nouruzi et al., “AI-Based E2E Resilient and Proactive Resource Management in Slice-Enabled 6G Networks,” *IEEE Transactions on Network Science and Engineering*, vol. 12, no. 2, pp. 1311-1328, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[35] Kwonyeol Park et al., “Anomaly Detection-Based UE-Centric Inter-Cell Interference Suppression,” *IEEE Open Journal of the Communications Society*, vol. 6, pp. 1512-1527, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[36] Han Zhang et al., “On-Device Intelligence for 5G RAN: Knowledge Transfer and Federated Learning Enabled UE-Centric Traffic Steering,” *IEEE Transactions on Cognitive Communications and Networking*, vol. 10, no. 2, pp. 689-705, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[37] Ali Nauman et al., “Injecting Cognitive Intelligence into Beyond-5G Networks: A MAC Layer Perspective,” *Computers and Electrical Engineering*, vol. 108, pp. 1-25, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[38] Alvaro Valcarce et al., “The Role of AI in 6G MAC,” *2024 Joint European Conference on Networks and Communications & 6G Summit (EUCNC/6g Summit)*, Antwerp, Belgium, pp. 723-728, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[39] Shadi Moazzen et al., “Towards E2E Optimum Service Delivery in AI-Native Future Networks,” *TechRxiv*, pp. 1-8, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[40] Pengfei Li, Jiaxin Fan, and Jianhong Wu, “Exploring the Key Technologies and Applications of 6G Wireless Communication Network,” *IScience*, vol. 28, no. 5, pp. 1-20, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[41] Omer Mohammed Salih Hassan, and Faris Keti, “A Review on the Challenges and Opportunities of Software Defined Networks toward 5G and 6G,” *European Journal of Applied Science, Engineering and Technology*, vol. 3, no. 2, pp. 55-66, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[42] Haochen Sun et al., “Advancing 6G: Survey for Explainable AI on Communications and Network Slicing,” *IEEE Open Journal of the Communications Society*, vol. 6, pp. 1372-1412, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[43] Wagdy M. Othman et al., "Key Enabling Technologies for 6G: The Role of UAVs, Terahertz Communication, and Intelligent Reconfigurable Surfaces in Shaping the Future of Wireless Networks," *Journal of Sensor and Actuator Networks*, vol. 14, no. 2, pp. 1-73, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[44] Amit Kumar Tyagi et al., *6G-Enabled Technologies for Next Generation: Fundamentals, Applications, Analysis and Challenges*, John Wiley & Sons, pp. 1-464, 2025. [Google Scholar] [Publisher Link]

[45] Zhiyan Liu et al., "Integrated Sensing and Edge AI: Realizing Intelligent Perception in 6G," *IEEE Communications Surveys & Tutorials*, vol. 28, pp. 2725-2770, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[46] Anjanabhargavi Kulkarni et al., "Bridging the Gap to 6G: Leveraging the Synergy of Standardization and Adaptability," *EAI Endorsed Transactions on Scalable Information Systems*, vol. 12, no. 1, pp. 1-18, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[47] Pradnyawant M. Gote et al., "From 5G to 6G: The Role of AI, Machine Learning, and Deep Learning in Wireless Systems," *2025 4th International Conference on Sentiment Analysis and Deep Learning (ICSADL)*, Bhimdatta, Nepal, pp. 447-452, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[48] Qazi Saima Syed, Irfan Bashir, and Shakir Hussain, *Artificial Intelligence and Machine Learning as Pioneers in Advancing 5G/6G Network Capabilities*, 5G/6G Advancements in Communication Technologies for Agile Management, IGI Global, pp. 1-18, 2025. [CrossRef] [Google Scholar] [Publisher Link]

Appendix 1

Table 5. Calculation of technical and operational metrics of hybrid methods of dynamic network resource allocation

	End-to-End Latency	**Jitter**	**Throughput**	**Packet Loss Rate**	**Bit Error Rate / QBER**	**Service Availability**	**Channel Utilization**	**Spectral Efficiency**	**Resource Allocation Fairness**	**Blocking Probability**	**Adaptation Time**	**Policy Robustness**	**Scalability**	**Cross-Segment Coordination Efficiency**	**Energy Consumption per Bit**	**Idle Resource Ratio**	**Fault Tolerance**	**Stability**	**QKD Throughput**	**Key Utilization Efficiency**	**Eavesdropping Detection Rate**
AI-Driven End-to-End Resource Orchestration	0.890	0.839	0.902	0.972	0.831	0.831	0.976	0.911	0.812	0.893	0.813	0.813	0.869	0.697	0.712	0.805	0.769	0.875	0.777	0.737	0.967
Cross-Domain Reinforcement Learning Agents	0.832	0.855	0.736	0.806	0.859	0.758	0.880	0.802	0.827	0.802	0.998	0.849	0.765	0.916	0.752	0.867	0.693	0.744	0.866	0.909	0.864
SDN-Orchestrated Multi-Segment Allocation	0.841	0.826	0.732	0.792	0.813	0.935	0.877	0.709	0.876	0.819	0.796	0.899	0.932	0.925	0.783	0.825	0.877	0.928	0.812	0.835	0.761
Latency-Aware Joint Scheduling	0.754	0.915	0.958	0.844	0.930	0.879	0.798	0.879	0.973	0.847	0.975	0.640	0.916	0.857	0.826	0.857	0.691	0.832	0.879	0.968	0.809
Queue-Aware Flow Control Protocols	0.785	0.810	0.923	0.876	0.808	0.891	0.858	0.927	0.794	0.824	0.819	0.733	0.874	0.871	0.850	0.831	0.737	0.816	0.823	0.786	0.837

Source: created by the authors