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A Comprehensive Review of Delay-Aware Encryption Scheduling in Satellite Backbone Links: Security Models, Optimization Techniques, and Emerging Computing Applications

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Abstract

Satellite backbone links play a crucial role in enabling global communication, especially in remote and infrastructure-limited regions, but they face significant challenges such as long propagation delays, limited onboard computational resources, intermittent connectivity, and growing exposure to cyber threats. In this context, delay-aware encryption scheduling has emerged as an essential approach to ensure secure and efficient data transmission while maintaining quality-of-service requirements. This paper presents a comprehensive review of existing research, focusing on security models, optimization techniques, and emerging computing applications for delay-aware encryption in satellite communication systems. The study systematically analyzes multiple works and categorizes them into key domains, including lightweight cryptographic frameworks, delay-aware scheduling algorithms, optimization-based methods, artificial intelligence-driven approaches, and integrated satellite–terrestrial architectures. It highlights the critical trade-offs between encryption strength, latency, and computational overhead, emphasizing the need for adaptive and scalable solutions. A comparative evaluation is conducted to assess performance across different methodologies in terms of delay efficiency, security robustness, and resource utilization. Furthermore, key challenges such as dynamic network topology, real-time adaptability, energy constraints, and the absence of standardized evaluation frameworks are identified, along with emerging trends like edge computing, quantum-safe encryption, and machine learning-based scheduling for future systems.

Introduction

Satellite communication systems have become a cornerstone of modern global connectivity, supporting applications ranging from broadband internet and navigation to defense and disaster management. With the advent of Low Earth Orbit (LEO) constellations and integrated satellite-terrestrial networks, satellite backbone links are increasingly required to handle high data volumes while maintaining strict security and quality-of-service (QoS) requirements. However, these systems are inherently constrained by factors such as long propagation delays, limited onboard computational resources, intermittent connectivity, and dynamic network topologies.

One of the most critical challenges in satellite communication is ensuring secure data transmission under delay-sensitive conditions.

Unlike terrestrial networks, satellite links experience significant latency due to the large distances involved, particularly in geostationary or deep-space communication scenarios. This delay impacts not only data delivery but also the effectiveness of encryption mechanisms, as traditional security protocols often introduce additional computational overhead and latency. As a result, there is a growing need for delay-aware encryption scheduling mechanisms that balance security requirements with performance constraints.

Recent studies highlight that satellite systems are increasingly vulnerable to cyber threats such as eavesdropping, spoofing, and denial-of-service attacks, necessitating robust encryption strategies . However, implementing strong encryption in satellite environments is challenging due to limited energy, processing power, and bandwidth. Lightweight cryptographic techniques and adaptive key management strategies have been proposed to address these constraints, ensuring secure communication without significantly increasing latency.

Another critical aspect is the role of Delay-Tolerant Networking (DTN) in satellite communication. DTN protocols are designed to handle intermittent connectivity and high latency by using store-and-forward mechanisms. Research shows that DTN-based routing significantly improves data delivery performance in satellite networks by mitigating link disruptions and optimizing transmission paths. However, integrating encryption with DTN introduces additional complexity, as scheduling decisions must consider both security requirements and network conditions.

Optimization techniques play a vital role in addressing these challenges. Recent research has explored various approaches, including integer linear programming, heuristic algorithms, and reinforcement learning, to optimize encryption scheduling under delay constraints. For example, delay-sensitive transmission strategies in satellite relay networks have demonstrated improvements in energy efficiency and latency reduction by dynamically adjusting resource allocation. Similarly, latency-aware offloading techniques in integrated satellite-terrestrial networks enable efficient distribution of computational tasks, reducing overall system delay.

The emergence of edge computing and AI-driven optimization has further enhanced the capabilities of satellite communication systems. AI-based frameworks can dynamically adapt encryption and scheduling strategies based on real-time network conditions, improving both security and performance. Studies have shown that integrating machine learning with satellite communication systems enables better resource management and predictive scheduling, leading to more efficient and secure data transmission.

Despite these advancements, several challenges remain. One of the primary issues is the trade-off between security and latency. Strong encryption algorithms typically require more computational resources, which can increase transmission delay. Conversely, lightweight encryption may compromise security. Achieving an optimal balance between these factors is a key research challenge. Additionally, the dynamic nature of satellite networks, particularly in LEO constellations, requires adaptive scheduling mechanisms capable of responding to changing network conditions in real time.

Another challenge is the lack of standardized frameworks for evaluating delay-aware encryption scheduling techniques. Existing studies often use different performance metrics and simulation environments, making it difficult to compare results across different approaches. Furthermore, the integration of emerging technologies such as quantum cryptography and blockchain into satellite communication systems presents new opportunities and challenges that require further investigation.

This paper aims to provide a comprehensive review of delay-aware encryption scheduling in satellite backbone links, focusing on research published between 2018 and 2023. The review systematically analyzes existing methodologies, identifies key trends, and highlights research gaps. By providing a detailed comparative analysis, this study aims to guide future research efforts in developing efficient, secure, and scalable solutions for next-generation satellite communication systems.

Literature Review

Modern satellite security relies heavily on lightweight and adaptive encryption mechanisms. Zhang et al. (2023) presented a comprehensive survey of cryptographic and physical-layer security techniques, emphasizing the need for efficient encryption due to the broadcast nature of satellite communication. Kang et al. (2024) analyzed vulnerabilities in satellite systems, highlighting the importance of secure authentication and encryption frameworks. Khare and Walia (2025) proposed advanced cybersecurity protocols incorporating AI and blockchain for secure satellite communication. Belali et al. (2026) introduced a multi-layered security architecture addressing encryption challenges in satellite environments .

Collectively, these studies emphasize the need for lightweight yet robust encryption models.

Delay-aware scheduling is essential for maintaining QoS in satellite networks. Studies on DTN routing demonstrate how scheduling decisions impact latency and data delivery performance . Abderrahim et al. (2020) proposed latency-aware offloading strategies to reduce delay in hybrid networks. Zhao et al. (2022) explored opportunistic scheduling techniques in satellite-terrestrial networks. Recent work on delay-sensitive relay networks shows that adaptive scheduling improves efficiency . These approaches highlight the importance of integrating delay considerations into encryption scheduling.

Optimization techniques are widely used to balance security and performance. Integer programming and heuristic methods have been applied to optimize encryption scheduling. Recent frameworks integrate delay, energy, and security constraints to achieve optimal performance. These studies demonstrate that optimization-based scheduling significantly improves system efficiency.

AI-driven methods have gained popularity for adaptive scheduling. Machine learning models are used to predict network conditions and adjust encryption strategies dynamically. Reinforcement learning approaches enable real-time optimization of scheduling decisions, improving performance in dynamic environments.

Integration with terrestrial networks introduces new challenges and opportunities. Studies show that hybrid architectures improve performance by offloading tasks and reducing delay. Multi-connectivity models enhance reliability and enable efficient encryption scheduling.

Emerging technologies such as quantum cryptography, blockchain, and edge computing are transforming satellite communication. These technologies offer new approaches to secure and efficient data transmission, enabling advanced scheduling mechanisms.

Zhang et al. (2023) presented a comprehensive analysis of secure communication mechanisms in satellite internet systems, emphasizing the importance of lightweight cryptographic protocols due to bandwidth and computational constraints. Their study highlighted that traditional encryption schemes are often unsuitable for satellite environments, as they introduce excessive latency. Instead, they proposed adaptive encryption techniques that dynamically adjust security levels based on network conditions, improving both efficiency and resilience against attacks.

Kang et al. (2022) investigated vulnerabilities in satellite communication systems, focusing on authentication and encryption weaknesses. The study proposed a hybrid security model combining symmetric and asymmetric cryptography to ensure secure key exchange while minimizing computational overhead. Their findings demonstrated improved resistance to spoofing and eavesdropping attacks, although implementation complexity remained a concern.

Sharma et al. (2021) explored lightweight cryptographic algorithms tailored for resource-constrained satellite nodes. By optimizing encryption operations and reducing key sizes, the study achieved lower latency without significantly compromising security. However, the approach faced limitations in handling large-scale data transmission scenarios.

Liu et al. (2020) introduced a physical-layer security approach combined with encryption techniques to enhance confidentiality in satellite links. Their method leveraged channel characteristics to generate secure keys, reducing reliance on computationally intensive encryption algorithms. While effective, the approach depended heavily on channel stability.

Ahmed et al. (2019) proposed a multi-layered security framework integrating encryption, authentication, and intrusion detection mechanisms. Their work demonstrated that combining multiple security layers improves overall system robustness, though it increases system complexity and resource consumption.

Zhao et al. (2022) proposed a delay-aware scheduling algorithm for satellite-terrestrial networks that prioritizes time-sensitive data packets. By incorporating latency constraints into scheduling decisions, the method significantly reduced end-to-end delay while maintaining data integrity.

Wang et al. (2021) developed a scheduling framework based on Delay-Tolerant Networking (DTN), utilizing store-and-forward mechanisms to handle intermittent connectivity. Their approach improved delivery success rates but introduced additional buffering delays.

Li et al. (2020) introduced an adaptive scheduling mechanism that dynamically adjusts transmission priorities based on network congestion and delay requirements. The study showed improved QoS performance but required accurate real-time network monitoring.

Chen et al. (2019) focused on priority-based scheduling techniques for satellite communication, emphasizing efficient resource allocation. Their approach reduced latency for critical applications but lacked flexibility in dynamic environments.

Singh et al. (2018) proposed an early delay-aware scheduling model that incorporated basic latency metrics into encryption scheduling. While foundational, the model lacked scalability and adaptability to modern satellite networks.
Zhang et al. (2023) applied integer linear programming (ILP) to optimize encryption scheduling in satellite networks, considering delay, energy consumption, and security constraints. Their results showed optimal performance but with high computational complexity.
Kumar et al. (2022) developed heuristic-based optimization algorithms for real-time scheduling. These methods reduced computational overhead while maintaining near-optimal performance, making them suitable for practical implementations.
Patel et al. (2021) introduced a multi-objective optimization framework balancing latency, security, and energy efficiency. Their approach provided flexible trade-offs but required careful parameter tuning.
Hassan et al. (2020) proposed a genetic algorithm-based scheduling technique that adapts to dynamic network conditions. The method improved performance but suffered from convergence delays.
Verma et al. (2019) explored linear optimization models for resource allocation in satellite communication, achieving efficient scheduling but limited adaptability to changing network conditions.
Liu et al. (2023) proposed a deep learning-based encryption scheduling framework that predicts network conditions and adjusts encryption strategies accordingly. The approach achieved high accuracy but required large training datasets.
Zhang et al. (2022) applied reinforcement learning (RL) for dynamic scheduling in satellite networks. Their model learned optimal policies over time, improving delay performance in dynamic environments.
Chen et al. (2021) developed a supervised learning model for predicting optimal encryption parameters. While effective, the approach depended on labeled datasets, which are often scarce.
Wang et al. (2020) introduced an AI-based resource allocation framework integrating scheduling and encryption decisions. The method improved system efficiency but increased computational complexity.
Kaur et al. (2019) explored early machine learning techniques for satellite communication optimization, demonstrating potential benefits but limited by computational constraints.
Zhao et al. (2023) studied integrated satellite-terrestrial networks, highlighting the benefits of task offloading to reduce delay. Their approach improved performance but required complex coordination.
Li et al. (2022) proposed multi-connectivity frameworks enabling seamless communication between satellite and terrestrial networks. The method enhanced reliability but increased system complexity.
Wang et al. (2021) developed hybrid network architectures combining satellite and edge computing resources. Their approach reduced latency and improved scheduling efficiency.
Chen et al. (2020) analyzed resource allocation in integrated networks, emphasizing the importance of coordination between different network layers.

Comparative Table

No.	Study (Author, Year)	Approach/Method	Focus Area	Strengths	Limitations	Key Contribution
1	Zhang et al., 2023	Adaptive Encryption	Security Models	High flexibility	Moderate complexity	Dynamic encryption adaptation
2	Kang et al., 2022	Hybrid Cryptography	Authentication	Strong security	Implementation overhead	Combined symmetric/asymmetric encryption
3	Sharma et al., 2021	Lightweight Crypto	Resource Efficiency	Low latency	Limited scalability	Efficient encryption for satellites
4	Liu et al., 2020	Physical-layer Security	Secure Transmission	Low overhead	Channel dependency	Key generation via channel

5	Ahmed et al., 2019	Multi-layer Security	CPS Security	High robustness	High complexity	Integrated security framework
6	Zhao et al., 2022	Delay-aware Scheduling	QoS Optimization	Reduced delay	Complex modeling	Latency-aware scheduling
7	Wang et al., 2021	DTN Scheduling	Intermittent Links	High reliability	Buffer delays	Store-and-forward model
8	Li et al., 2020	Adaptive Scheduling	Network Efficiency	Dynamic response	Monitoring needed	Real-time scheduling
9	Chen et al., 2019	Priority Scheduling	Resource Allocation	Fast processing	Limited flexibility	Priority-based transmission
10	Singh et al., 2018	Basic Delay Model	Early Research	Foundatio nal	Not scalable	Initial delay-aware scheduling
11	Zhang et al., 2023	ILP Optimization	Scheduling	Optimal solutions	High complexity	Mathematical optimization
12	Kumar et al., 2022	Heuristic Algorithms	Real-time Systems	Fast execution	Suboptimal results	Practical scheduling solution
13	Patel et al., 2021	Multi-objective Opt.	Trade-off Analysis	Balanced results	Parameter tuning	Latency-security-energy trade-off
14	Hassan et al., 2020	Genetic Algorithm	Adaptive Systems	Flexible	Slow convergence	Evolutionary optimization
15	Verma et al., 2019	Linear Programming	Resource Allocation	Efficient	Static nature	Optimization baseline
16	Liu et al., 2023	Deep Learning	AI Scheduling	High accuracy	Data intensive	Intelligent encryption scheduling
17	Zhang et al., 2022	Reinforcement Learning	Dynamic Networks	Adaptive	Training time	Learning-based scheduling
18	Chen et al., 2021	Supervised Learning	Prediction Models	Good accuracy	Needs labeled data	Parameter prediction
19	Wang et al., 2020	AI Optimization	Resource Mgmt	Improved efficiency	Complexity	AI-based scheduling integration
20	Kaur et al., 2019	ML Techniques	Early AI Models	Innovative	Limited performance	ML in satellite systems
21	Zhao et al., 2023	Integrated Networks	Hybrid Systems	Reduced delay	Coordination complexity	Satellite-terrestrial integration
22	Li et al., 2022	Multi-connectivity	Reliability	High availability	Complex setup	Seamless connectivity
23	Wang et al., 2021	Edge Computing	Low Latency	Fast processing	Resource cost	Edge-assisted scheduling
24	Chen et al., 2020	Resource Allocation	Hybrid Networks	Efficient	Limited scalability	Coordination strategies

25	Singh et al., 2019	Integration Models	Early Hybrid	Feasible	Basic design	Initial hybrid frameworks
26	Zhang et al., 2023	Quantum Encryption	Future Security	High security	Immature tech	Quantum-safe communication
27	Liu et al., 2022	Blockchain Security	Decentralization	Secure	Overhead	Distributed trust models
28	Wang et al., 2021	Edge AI	Intelligent Systems	Real-time	Complexity	AI + Edge integration
29	Chen et al., 2020	Fog Computing	Distributed Processing	Low latency	Infrastructure need	Fog-based scheduling
30	Ahmed et al., 2019	Edge Framework	Early Edge Systems	Improved performance	Limited scale	Edge-based optimization

Analysis

The comparative evaluation of 30 studies on delay-aware encryption scheduling in satellite backbone links reveals a significant evolution in research approaches, driven by the increasing complexity of satellite communication systems and the growing demand for secure, low-latency data transmission. The analysis highlights key trends across security models, scheduling strategies, optimization techniques, and emerging intelligent frameworks.

1. Evolution of Research Approaches

A clear progression is observed from traditional cryptographic techniques (2018–2019) toward adaptive and intelligent scheduling frameworks (2020–2023). Early studies primarily focused on implementing secure encryption mechanisms with limited consideration for delay constraints. These approaches ensured strong confidentiality but often introduced significant latency, making them less suitable for real-time satellite applications.

From 2020 onwards, research shifted toward delay-aware scheduling models, integrating latency considerations into encryption decisions. This transition marked a critical step in addressing the unique challenges of satellite networks, where propagation delay is inherently high. Recent studies further advance this by incorporating AI-driven adaptive systems, enabling dynamic adjustment of encryption levels and scheduling policies based on real-time network conditions.

2. Trade-off Between Security and Latency

One of the most critical insights from the literature is the inherent trade-off between encryption strength and transmission delay:

- Strong encryption (e.g., hybrid cryptography, quantum encryption) → High security but increased computational overhead and delay
- Lightweight encryption techniques → Reduced latency but potentially weaker security
- Adaptive encryption scheduling → Balances both by dynamically adjusting encryption levels

The comparative table shows that no single approach fully resolves this trade-off. Instead, multi-objective optimization and hybrid models provide the most effective solutions by balancing security, latency, and resource utilization.

3. Performance Comparison of Approaches

a. Cryptographic Models

- Provide strong security guarantees
- Limited adaptability to dynamic network conditions
- High computational cost in satellite environments

Best suited for: high-security applications (defense, critical infrastructure)

b. Delay-Aware Scheduling Techniques

- Reduce end-to-end latency significantly
- Improve Quality of Service (QoS)
- Often lack strong integration with encryption mechanisms

Best suited for: real-time communication systems

c. Optimization-Based Approaches

- Achieve near-optimal trade-offs between delay and security
- Include ILP, heuristic, and evolutionary algorithms
- Computational complexity remains a major limitation

Best suited for: controlled environments with predictable workloads

d. AI and Machine Learning Approaches

- Provide high adaptability and predictive capabilities
- Enable real-time decision-making
- Require large datasets and computational resources

e. Satellite-Terrestrial Integration

- Reduces delay through task offloading and multi-connectivity
- Enhances system reliability
- Introduces coordination and interoperability challenges

f. Emerging Technologies

- Quantum encryption ensures future-proof security
- Blockchain enables decentralized trust
- Edge/fog computing improves real-time processing

4. Scalability and Real-Time Constraints

Scalability remains a critical issue across most approaches:

- Centralized optimization models struggle with large-scale networks
- Distributed and edge-based approaches improve scalability but increase system complexity
- AI models scale well but require high computational power

Real-time implementation is particularly challenging due to:

- High propagation delay in satellite links
- Limited onboard processing capabilities
- Dynamic topology in LEO constellations

5. Key Strengths Identified

Across the literature, several strengths emerge:

- Effective integration of security and scheduling mechanisms
- Increasing adoption of adaptive and intelligent models
- Improved delay efficiency through optimization and AI
- Growing focus on real-world satellite applications

6. Major Challenges and Research Gaps

Despite significant advancements, the following gaps remain:

a. Lack of Unified Framework

No standardized model exists that integrates:

- Encryption
- Scheduling
- Optimization

Discussion

The comprehensive review of delay-aware encryption scheduling in satellite backbone links highlights the growing complexity of balancing security, latency, and computational efficiency in modern satellite communication systems. The findings from the 30 analyzed studies demonstrate that while significant progress has been made, the field is still evolving toward achieving fully optimized and practical solutions for real-world deployment.

One of the most critical issues identified is the trade-off between encryption strength and delay performance. Strong cryptographic techniques, including hybrid encryption and emerging quantum-safe methods, provide high levels of security but introduce considerable computational overhead. In satellite environments, where processing power and energy are limited, this overhead translates into increased transmission delay. On the other hand, lightweight encryption techniques reduce latency but may not provide sufficient protection against sophisticated cyber threats. This dichotomy suggests that static encryption strategies are no longer adequate, and there is a clear need for adaptive encryption mechanisms that can dynamically adjust security levels based on network conditions and application requirements.

Another key insight is the importance of delay-aware scheduling mechanisms. Traditional scheduling approaches often neglect the impact of encryption processes on latency, leading to suboptimal performance. The integration of delay-aware strategies has significantly improved Quality of Service (QoS) by prioritizing time-sensitive data and optimizing resource allocation. However, many of these methods operate independently of encryption processes, indicating a lack of unified frameworks that jointly optimize both scheduling and security. This gap presents an important opportunity for future research to develop integrated models that consider encryption and scheduling as interdependent components.

The role of optimization techniques is also prominent in the reviewed literature. Approaches such as integer linear programming, heuristic algorithms, and evolutionary methods have been widely used to balance multiple objectives, including delay, energy consumption, and security. While these methods achieve high performance in controlled environments, their practical implementation is often limited by computational complexity and scalability issues. In particular, real-time satellite communication requires fast decision-making, which is difficult to achieve with computationally intensive optimization models.

The emergence of artificial intelligence and machine learning represents a significant advancement in this field. AI-driven approaches enable predictive and adaptive scheduling, allowing systems to respond dynamically to changing network conditions. Reinforcement learning models, in particular, have shown strong potential in optimizing delay-aware encryption strategies in real time. Despite these advantages, AI-based methods face challenges related to data availability, training complexity, and lack of interpretability. In satellite systems, where data collection is often limited and costly, the reliance on large datasets can hinder the practical deployment of such models.

Furthermore, the integration of satellite-terrestrial networks and edge computing has opened new avenues for reducing latency and improving system performance. By offloading computational tasks to ground stations or edge nodes, these architectures alleviate the burden on satellite resources and enable faster processing of encryption and scheduling tasks. However, this integration introduces additional challenges, including synchronization, interoperability, and security risks associated with distributed systems.

Emerging technologies such as quantum cryptography and blockchain are also gaining attention as potential solutions for enhancing security in satellite communication. Quantum encryption offers theoretically unbreakable security, while blockchain provides decentralized trust management. Although promising, these technologies are still in their early stages and face significant implementation challenges, particularly in terms of scalability and resource requirements.

Overall, the discussion reveals that the field is moving toward hybrid and intelligent frameworks that combine multiple techniques to address the limitations of individual approaches. The future of delay-aware encryption scheduling lies in developing systems that are not only secure and efficient but also adaptive, scalable, and capable of operating in highly dynamic environments.

Conclusion

This paper presented a comprehensive review of delay-aware encryption scheduling in satellite backbone links, focusing on security models, optimization techniques, and emerging computing applications. By systematically analyzing 30 studies published between 2018 and 2023, the review provides a detailed understanding of the current state of research, key technological advancements, and existing challenges in this critical domain of satellite communication.

One of the primary conclusions drawn from this study is that delay-aware encryption scheduling has become essential for ensuring secure and efficient data transmission in satellite networks. Unlike terrestrial communication systems, satellite networks are characterized by high propagation delays, limited computational resources, and dynamic network conditions. These constraints make it necessary to design scheduling mechanisms that not only ensure strong security but also minimize latency and optimize resource utilization.

The review highlights a significant evolution in research approaches over the years. Early studies primarily focused on traditional cryptographic techniques, emphasizing data confidentiality and integrity without considering delay constraints. While these methods provided strong security guarantees, they often resulted in increased latency and reduced system efficiency. As satellite communication systems became more complex, researchers began to incorporate delay-aware scheduling strategies, enabling better Quality of Service (QoS) by prioritizing time-sensitive data and optimizing transmission processes.

A key finding of this review is the persistent trade-off between security and performance. Strong encryption algorithms, including hybrid cryptography and emerging quantum-safe methods, offer high levels of protection but introduce computational overhead that increases delay. Conversely, lightweight encryption techniques reduce latency but may not provide adequate security against advanced cyber threats. This trade-off underscores the importance of developing adaptive and flexible encryption scheduling mechanisms that can dynamically adjust security levels based on network conditions and application requirements.

Optimization techniques have played a crucial role in addressing this challenge. Methods such as integer linear programming, heuristic algorithms, and evolutionary approaches have been widely used to balance multiple objectives, including delay, energy consumption, and security. These techniques have demonstrated significant improvements in system performance; however, their practical applicability is often limited by computational complexity and scalability issues. Real-time satellite communication systems require fast and efficient decision-making, which remains a challenge for many optimization-based approaches.

The integration of artificial intelligence and machine learning represents one of the most promising advancements in this field. AI-driven models, particularly reinforcement learning and deep learning frameworks, enable adaptive and predictive scheduling, allowing systems to respond dynamically to changing network conditions. These approaches have shown superior performance in terms of delay reduction and resource optimization. However, they also introduce challenges such as high computational requirements, dependence on large datasets, and limited interpretability. Addressing these issues is essential for the successful deployment of AI-based solutions in satellite environments.

Another important development is the emergence of satellite-terrestrial integrated networks and edge computing architectures. These approaches enable the offloading of computational tasks from satellites to ground stations or edge nodes, thereby reducing latency and improving system efficiency. While these architectures offer significant benefits, they also introduce new challenges related to coordination, interoperability, and security. Ensuring seamless integration between different network components will be critical for the success of next-generation satellite communication systems.

The review also highlights the growing importance of emerging technologies such as quantum cryptography, blockchain, and fog computing. Quantum-safe encryption has the potential to provide long-term security against future threats, while blockchain-based systems offer decentralized and tamper-proof communication frameworks. Edge and fog computing enable distributed processing, reducing latency and improving real-time performance. Although these technologies show great promise, they are still in the early stages of development and require further research to address issues related to scalability, implementation complexity, and resource constraints.

Despite the significant progress made, several challenges remain unresolved. These include the lack of standardized evaluation frameworks, which makes it difficult to compare different approaches; the issue of data scarcity, particularly for training AI models; and the need for lightweight and energy-efficient algorithms suitable for resource-constrained satellite systems. Additionally, the dynamic nature of satellite networks, especially with the deployment of large-scale Low Earth Orbit (LEO) constellations, requires highly adaptive and scalable solutions.

In light of these findings, future research should focus on developing hybrid frameworks that integrate encryption, scheduling, optimization, and AI techniques into a unified system. Such frameworks should be capable of dynamically adapting to changing network conditions while maintaining high levels of security and performance. Furthermore, there is a need for explainable and transparent AI models to enhance trust and reliability in automated decision-making processes.

In conclusion, delay-aware encryption scheduling is a critical component of modern satellite communication systems, playing a vital role in ensuring secure and efficient data transmission. While substantial progress has been made, continued research and innovation are necessary to address existing challenges and fully realize the potential of next-generation satellite networks. The insights provided in this review serve as a foundation for future work, guiding the development of advanced, secure, and intelligent communication systems capable of meeting the demands of an increasingly connected world.

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