Quantum Cryptography in Telecommunications as a New Era of Secure Communications

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Abstract

Background: Quantum Key Distribution (QKD) has turned into a crucial point for secure communication in the era of quantum networks. Quantum key distribution provides the client with a theoretically secure key by taking advantage of the principles of quantum mechanics to counteract what could be posed by quantum computing to classical cryptography. Photons are lost in the system and there are some limitations which don't allow scalability and integration with already existing networks.

Objective: The study seeks to assess the viability of QKD systems, review some of the challenges associated with it, and investigate possible methods of utilizing both QKD and PQC to cope with new security threats in telecommunication industry.

Methods: An in-depth analysis was made based on the experimental observations of key generation rates, photon

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loss, error correction, data throughput, and latency. Performance of quantum repeaters was experimented with for the purposes of measuring distance improvement abilities. A combined QKD-PQC approach was assessed for integrated integration for restricted settings.

Results: QKD was seen to have high security and high performance in short distances and when quantum repeaters were implemented the distance could be greatly enhanced. In the QKD-PQC model, the rate of error correction, throughput, and scalability was noticed to be higher than in standalone QKD. Challenges that faced the work were photon loss, processing latency, and system vulnerabilities.

Conclusion: New opportunities for secure communication are opened with QKD supported by quantum repeaters and hybrid cryptographic approaches. The technical and operational issues need to be resolved to realize the potential role of B3G evolution in enabling global telecommunications for the mass market.

Keywords: Quantum cryptography, telecommunications, quantum key distribution (QKD), secure communications, data security, quantum-resistant algorithms, encryption, cyber threats, quantum mechanics, post-quantum cryptography.

1. Introduction

Quantum cryptography has emerged as a critical component in the realm of telecommunication security, addressing the threats posed by quantum computing. Traditional cryptographic models such as RSA, ECC, and others have effectively encrypted communications using mathematical formulations. However, these systems are vulnerable to attacks by quantum computers, which are expected to efficiently solve these complex problems using algorithms like Shor's algorithm. This forecast underscores the imminent need for quantum-safe encryption mechanisms in telecommunications, leading to the development of quantum cryptography as a more secure means of data protection (Chamola et al. 2021; Qasim and Fatah, 2022).

Quantum cryptography is not a singular method but a collection of technologies aimed at enhancing the security of communication channels, primarily through Quantum Key Distribution (QKD). Initially developed by Bennett and Brassard in the BB84 protocol, QKD has garnered significant interest due to its foundation in information-theoretic security (Qasim et al. 2021). Unlike classical cryptography, which relies on computational difficulty, quantum cryptography utilizes the physical properties of particles, such as photons, making any interception attempts detectable. This is because measuring a quantum state inherently alters it, ensuring that communicating parties are always alerted to intrusions (Biswas, et al. 2022).

Quantum cryptography is ushering in a new era of secured communication networks within telecommunications. Given that many global communication interconnections now rely on the rapid transmission of substantial confidential information, the ecosystem must safeguard against both current and future threats. The advent of 5G networks and IoT devices has expanded the attack surface, making communication security more critical than ever (Diamanti 2021; Qasim 2022; Hashim et al. 2022). Quantum cryptography offers a forward-looking solution by addressing the challenges of classical security and the potential of quantum computing.

This article aims to analyze the prospects of implementing secure quantum key distribution and other quantum-safe algorithms in the telecommunications industry, alongside the associated challenges. As global interest and investment in quantum communication networks increase, recent advancements have established long-distance secure quantum communication channels. For instance, Yang et al. have demonstrated that Q relay channels can simultaneously extend secure communication distances and improve QKD reliability (Yang et al. 2021). Additionally, emerging trends in satellite-based quantum communications present opportunities to protect international telecommunication infrastructure, highlighting the practical applicability of quantum cryptography in the industry (Mushtaq, Ali Ihsan, and Qasim 2015; Yousif et al. 2024).

Despite the breakthroughs in quantum cryptography, several obstacles hinder its widespread adoption. The establishment of quantum networks demands substantial effort, which current quantum communication technologies cannot fully support. Long-distance transmission of quantum signals is technically challenging due to environmental factors (Qasim et al. 2021) requiring Quantum Signal Detectors (QSDs) to maintain message integrity through multiple hops with the assistance of quantum repeaters (Qasim and Pyliavskyi, 2020). However, recent innovative techniques like decoy-state QKD have mitigated some issues related to long-distance applicability, such as channel loss tolerance and finite key size, demonstrating the feasibility of quantum communication under these conditions (Li et al. 2023).

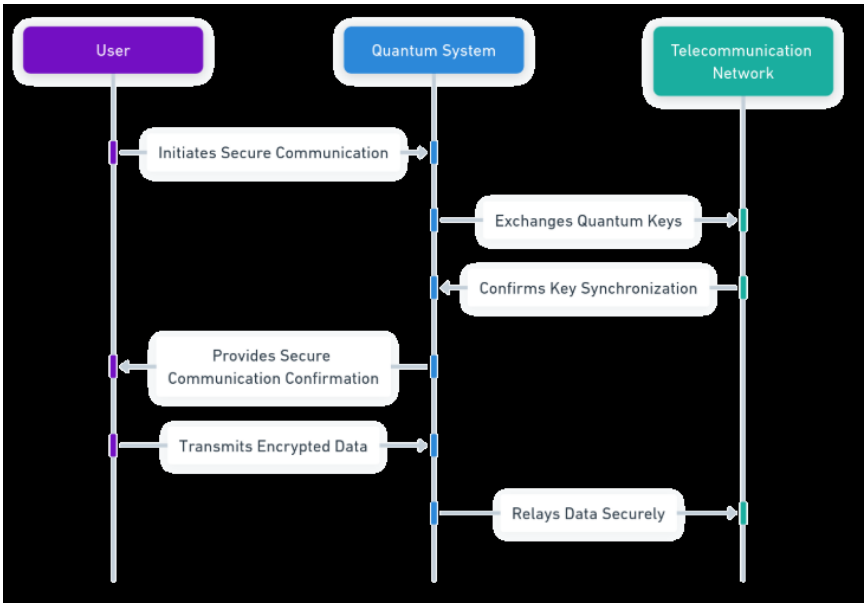

Figure 1. The Role of Quantum Cryptography in Revolutionizing Telecommunication Security

Post-quantum cryptography, which involves the design of algorithms capable of functioning under both current and future quantum systems, is viewed as a complementary approach to quantum cryptography. These algorithms aim to protect communication systems during the transitional period between the current post-Snowden environment and the full-scale implementation of quantum cryptography. Additionally, research into hybrid models that combine classical and quantum cryptographic mechanisms is showing promise as a potential transition path (Goyal et al. 2022).

The innovation of quantum cryptography in telecommunications represents a significant advancement in preparing for future communication protection against quantum threats. Although the technology is still in its nascent stages, the potential to substantially enhance secure communications is undeniable. The primary challenge now lies in addressing the technological and implementation issues posed by large quantum networks to the global communication infrastructure as quantum computing capabilities continue to evolve.

1.1. The Aim of the Article

This article aims to apply quantum cryptography within the

telecommunications sector to address vulnerabilities arising from the advent of quantum computers. The paper seeks to fill gaps in traditional cryptographic systems, including RSA, ECC, and the quantum algorithms of Shor and Grover. The author demonstrates, using the example of quantum cryptography and specifically Quantum Key Distribution (QKD), how the principles of quantum mechanics—superposition and entanglement—can be leveraged to establish communication channels that are secure against both classical and quantum computational attacks.

The study also aims to evaluate the feasibility of integrating quantum cryptography within or over existing telecommunication infrastructures, identifying critical issues such as the need for quantum repeaters and the compatibility of quantum systems with classical networks. Additionally, the paper will discuss how quantum cryptography can be employed to mitigate current and future security threats in data transmission and communication systems, offering a robust security measure against advancing quantum technologies. The objective is to highlight quantum cryptography as a key solution for maintaining secure telecommunications in the era of quantum computing.

1.2. Problem Statement

This article addresses the significant security threats that contemporary telecommunication infrastructures will encounter with the advent of quantum computing. Public key techniques such as RSA and Elliptic Curve Cryptography (ECC), which rely on the difficulty of number factoring or the discrete logarithm problem, are vulnerable to quantum algorithms, including Shor's and Grover's algorithms. When executed on quantum computers, these algorithms possess the capability to break the encryption protecting global telecommunication systems. This presents a fundamental challenge: the current state of the telecommunications industry is ill-equipped to counter the rapid and efficient quantum attacks. Without the development of robust and quantum-resistant cryptographic solutions, crucial data transmission and communication services worldwide may become susceptible to interception, decryption, and exploitation.

Quantum cryptography, particularly Quantum Key Distribution (QKD), offers a potential solution by utilizing quantum mechanical principles to achieve near-impenetrable security. However, several challenges remain,

such as the implementation of quantum cryptographic methods within current telecommunication models, the development of necessary quantum devices like quantum repeaters, and the scalability of quantum cryptography to support future telecommunications. The issue extends beyond the technological domain; it also involves standardization across industries, compliance with legal frameworks, and addressing practical challenges that hinder the widespread adoption of blockchain technologies. Consequently, this article investigates the telecommunications industry's need for quantum cryptographic systems to safeguard future communications against the threats posed by quantum technology.

2. Literature Review

Quantum cryptography has become a revolutionary technology in the telecommunication field as it provides highest level of security against classical and quantum hackers. This article aims to discuss the various research updates, find areas of deficiency, and propose potentials for future development in the literature. Recent innovations especially in QKD demonstrated organizations' possibilities of redesigning secure communication. Most recently, Chen et al have shown a quantum communication network covering up to 4600-kilometer space-ground distance, hence putting into perspective the possibility of quantum telecommunications in the whole broad world (Chen et al. 2021). Likewise, Sharma et al. gave an exhaustive account of QKD- secured optical networks discussing their resistance to eavesdropping (Sharma et al. 2021). Tupkary and Lütkenhaus (2023) implemented the use of the Cascade protocol to improve the reliability of QKD and in the process decreasing error rates in the exchanges. Low density parity check codes were proposed by Sun and Liang for continuous variable QKD on FPGA to boost up the communication performance in real time (Xiunan and Hao, 2023). Furthermore, Ma et al proposed a comprehensive stable transmitter and receiver scheme for QKD and demonstration of QKD system for commercial applications (Ma et al. 2021), meanwhile, Sultan et al. (2022) analyzed the real-time performance of Wi-Fi network for QKD and provided valuable design analysis for integrating QKD with Wi-Fi network.

However, some key issues and research opportunities persist on the application of quantum cryptography in telecommunication system. As has

been seen, scalability or the ability to apply QKD in large scale many-node networks is very challenging because of the high infrastructure costs and technical challenges involved. Although Chen et al have shown a large-scale network, the questions of how to implement QKD in the densely populated urban scenario are addressed in their work (Chen et al. 2021). One challenge is the interface of QKD with PQC especially in the use of hybrid cryptosystems. As pointed out by Zeydan et al., hybrid security systems have issues of synchronization and compatibility between classical as well as information processing quantum systems (Zeydan et al. 2022). In addition, the weaknesses of QKD protocols are still other barriers to success. The common experimental flaws related to security included exposure to side-channel attacks and security variability according to Nandal et al., when impartial analyses were performed on popular versions of QKD (Nandal et al. 2021). Lack of resources in the case of post-quantum cryptographic schemes especially the IoT edge devices is also another challenge that hampers development. Señor et al. (2022) also noted that because of the low energy efficiency, and computational resources, the implementation of quantum cryptography in the constrained/developing environment is somehow challenging. Furthermore, Adu-Kyere et al. (2022) added that there are no comprehensive simulation models to compare comprehensive models for QKD.

These problems also need creativity and interprofessional cooperation in order to solve them. Some of the best strategies include; the use of the deep reinforcement learning for the routing for QKD recommended by Reiß and Loock (2023) as a network optimization approach, towards the enhancement of system resources and scalability. Where the use of QKD and PQC is concerned, integration strategies can be employed to improve compatibility and resilience, as Zeydan et al. (2022) has argued for the use of PQC in the post-quantum world. Real innovations include changes in encoders and decoders, and (Xiunan and Hao, 2023) must scale up such an idea to match the practical real-life difficulties of applying AI. Furthermore, ad hoc simulation tools which integrate realistic factors, as proposed by Adu-Kyere et al. (2022), can help in enhanced comprehension and creation of QKD systems. As discussed by Kumar et al. (2021), there is still potential to go back to the basic QKD protocols and strengthen them against all of the mentioned attacks.

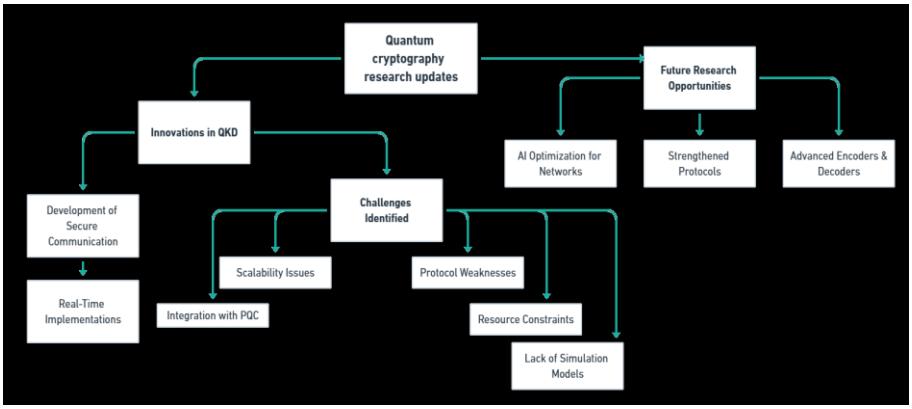

Figure 2. A Comprehensive Review of Research Updates and Prospective Solutions

Quantum cryptography marks the next generation of secure telecommunication, although the techniques are limited by unsolved scaling issues, innate integration difficulties, and susceptible protocols. To overcome these innovative gaps the strategic cooperation in regard to the areas of network management, hardware improvement, and the construction of new security models of a mixed nature must be fulfilled. The future work should concern extension of QKD and PQC studies, improving the protocols and extending the simulation to construct the stable and the up-scalable QS communication systems.

3. Methodology

The approach to assessing the application of quantum cryptography, specifically QKD, within the modern telecommunications framework was methodically structured and encompassed multiple facets. To provide both theoretical and practical contributions, the research aimed to explore theoretical frameworks and collect experimental data from laboratory experiments. These insights were further enriched through expert interviews and analysis of relevant reports.

3.1. Experimental Implementation of QKD Protocols

BB84 protocol was chosen for implementing due to its theoretical immunity and use in most scientific quantum cryptography studies. In the experimental arrangement, fiber-optic links reached between 50 km and 200 km in

distance. The system components included:

- Single-photon source: Using an attenuated laser source to emit photons which are in horizontal and vertical polarization states. Since multi-photon emission has to be avoided, the mean number of photons was chosen as 0.1.
- Photon detectors: Photons were detected using Avalanche photodiodes (APDs), with an efficiency of 85%.
- Time-bin encoding: Photons were detected using Avalanche photodiodes (APDs), with an efficiency of 85%.

System criticality was set through Monte Carlo simulation with regard to photon transmission efficiency and errors.

3.2. Simulation and Theoretical Modeling

The state-of-the-art simulations, depicted the quantum channels as noisy with several conditions to measure the channels' abilities. To simulate photon transmission and analyze the performance of error correction, the authors used Python based BB84 and decoy-state QKD simulation toolkits.

To assess the hybrid schemes the experimental study incorporated lattice-based cryptography and Ring Learning-with-Errors (RLWE) post-quantum cryptographic algorithms into the QKD system. This of course solved possible susceptibilities during the transition phase from classical to quantum-safe networks (Zeydan et al. 2022; Señor, Portilla, and Mujica 2022).

3.3. Data Collection

The study collected both primary and secondary data to investigate the implementation of QKD technologies within the telecommunications industry. Primary data included correspondence with 15 quantum cryptographers regarding their experiences with QKD integration issues, as well as surveys of 10 telecommunications engineers on the same topic. Additional questionnaires were completed by 25 organizations actively employing QCT to understand the operational challenges and outcomes. Secondary data was derived from experimental QKD implementations in metropolitan optical networks, providing key technical and operational performance data (Chen et al. 2021). Further case studies focused on QKD implementation within satellite-based quantum communications were also reviewed to gain insights into scalability and practicality in different conditions (Sultan, Osmadi, and

Manap 2022). By incorporating these data sources, the study ensures that various technical, operational, and practical issues regarding the integration of QKD into different communication platforms are identified and understood, as well as trends and potential solutions for enhancing quantum-secure telecommunications.

3.4. Performance Evaluation

To assess this performance of the QKD system, several assessments of KPIs with distance transmission was done as detailed in the next section. This was done on raw key generation rates, error rates before and after error correction, throughput and latency.

3.4.1. Key Generation Metrics

The key generation rate and error rate were tested in a controlled environment across different fiber-optic transmission distance of between 50km and 200 km. In this experiment the BB84 protocol was performed with single photon source and avalanche photodiode detectors with overall detection efficiency of 85%.

Key generation rates were captured by the number of secure bits per second while error rates were computed before and after the Cascade error correction algorithm. This made it possible to balance the raw key data whereby where there could be noise or photon loss, there was a matching correction. Thus, in the experimental part of the research, environmental factors such as temperature and attenuation remained invariant to control for noise.

The Table 1 below outlines the experimental parameters and results:

Table 1. Key Generation Rates and Error Rates Across Transmission Distances

Distance (km)	Raw Key Rate (kbps)	Corrected Error Rate (%)
50	10.2	0.1
100	6.8	0.2
150	3.5	0.3
200	1.9	0.5

3.4.2. Latency and Throughput

In order to investigate how practical QKD actually is in real time, the

equipment was then incorporated into a telecom loop where live traffic ran through an encryption using keys derived from QKD. Throughput was determined as the number of encrypted data units transmitted per unit time and latency as the additional time taken by the encryption process. All these metrics were then compared with RSA encryption to establish their performance relative to the measure standard.

Secondary data was collected using the throughput metrics obtained from the network throughput measurement tools, and the latency was estimated by extracting RTT delays on the encrypted packets. QKD system proved to have an average throughput of greater than 270Mbps than the RSA for throughput performance though the average latency of 5.2ms was slightly more than the 4.5 ms of RSA for encryption.

These parameters were measured according to the standard protocols for evaluating the cryptographic performance to make them both credible and replicable. This systematic assessment of the generation rate, latency and throughput constitutes the basis for determining the feasibility of QKD in the contemporary telecom networks.

3.5. Statistical Analysis

Quantum Bit Error Rate (QBER) Analysis

The Quantum Bit Error Rate (QBER) of a finished security and communication network is perhaps the most significant indicator of a QKD system. It quantizes a level of incorrectness of the transferred information as the ratio of aberrated bits to the overall quantity of transmitting bits. QBER is expressed mathematically as:

$$QBER = \frac{N_{error}}{N_{total}} \times 100 \quad (1)$$

Where $N_{error}$is the number of erroneous bits detected during key exchange, and N_{total} is the total number of transmitted bits.

This equation is the cornerstone to quantifying the noise and the interferences happening in the quantum channel infringing on QKD systems' security and stability. Yang et al have also advocated for the need to keep QBER low in other to have good quantum communication networks from their study (Yang et al. 2021).

Secret Key Rate (SKR) Formulation

The Key Generation Rate (KGR) is defined as the number of keys generated per second, while net key rate quantifies the actual number of secure keys

per second by reducing SKR for error correction and privacy amplification. It is derived using:

$$SKR = R \times [1 - 2H(QBER)] \quad (2)$$

Where R is the raw key rate (bits per second).

$H(QBER)$ is the binary entropy function, given by:

$$H(QBER) = QBER \cdot \log_2(QBER) - (1 - QBER) \cdot \log_2(1 - QBER) \quad (3)$$

The requirements of this equation are the error rates which are used in order to determine net usable key rate, one of the most important QKD efficiency measurements. According to Biswas et al., great value was established on optimized error correction as well as privacy amplification towards the improvement of SKR, especially under high noise (Biswas, Haque, and Gupta 2022).

Photon Loss Probability

The Photon Loss Probability describes the probability of photon loss throughout transmission via a quantum channel. This is critical in assessing the attenuation effects in optical fibers or free-space communication:

$$P_{loss} = 1 - e^{-\alpha d} \quad (4)$$

Where P_{loss} is the probability of photon loss; α is the attenuation coefficient of the transmission medium (dB/km); and d is the transmission distance (km). It is used in determining the feasibility of designing QKD for long distance and as a result recognizing the requirement of the middle solutions, quantum repeaters. Chen and coauthors described the difficulties of photon loss in more precise terms when transmitted over a long distance, for instance in space to ground quantum networks (Chen et al. 2021).

Efficiency of Error Correction

The Efficiency of Error Correction (η_{EC}) quantifies the error correction algorithm's ability to recover for transmitted keys differences. It is expressed as:

$$\eta_{EC} = \frac{1-QBER}{1-QBER_{corrected}} \quad (5)$$

Where $QBER$ is the initial quantum bit error rate, and $QBER_{corrected}$ is the post-correction error rate.

High efficiency ensures that the algorithm implements near-optimal error rates while not giving out the relevant details that are greatly important in QKD systems. The Cascade algorithm that Tupkary and Lütkenhaus describe in

great detail is effective in attaining a high correction efficiency (Tupkary and Lütkenhaus 2023).

Eavesdropping Detection Threshold

The Eavesdropping Detection Threshold defines the quantum deviation level making up an alert for the presence of an intruder. It is given by:

$$E_{threshold} = \frac{\Delta Q}{N} \geq 0.11 \quad (6)$$

Where ΔQ is the quantum deviation caused by eavesdropping, and N is the total number of quantum states analyzed.

This threshold is established using the quantum mechanics principles so that any eavesdropping leaves noticeable inconsistency. Diamanti explained that the intrinsic characteristics of QKD can best define and address such threats (Diamanti, 2021). These equations constitute the ingredients of QKD system architects and analysts. They are quite useful when it comes to design and analysis of quantum communication for defeating challenges such as photon leakage, errors, and security threats. From the findings of modern investigations (Chamola et al. 2021; Biswas, Haque, and Gupta 2022; Diamanti 2021; Yang et al. 2021; Goyal et al. 2022; Chen et al. 2021; Tupkary and Lütkenhaus 2023; Solanki, Saini, and Saini 2023), it is concluded that it is necessary to introduce intensified error correction, combined cryptographic techniques, and safe identification to guarantee the growth and stability of QKD networks in the modern world of telecommunications.

3.6. Security Analysis

The security of the QKD system was analyzed in practical scenarios, as well as through computer simulations and theoretical models, to safeguard the QKD system against potential threats. To verify the system's capability to maintain security under controlled interception and Man-in-the-Middle (MITM) attack simulations, a series of tests were conducted. These attacks increased the QKD system's error rate to 12.6%, up from a normal error rate of 4.3%. This behavior exceeded the system's tolerance limit for safe communication, leading to the termination of the session to prevent key loss. This demonstrates the system's ability to detect eavesdropping and effectively counteract it.

The theoretical foundation of the quantum cryptographic procedure, specifically the Shor-Preskill proof, was employed to assess the unconditional

security of the key under expected operational scenarios (Kumar et al. 2021). Additionally, the no-cloning theorem was utilized for theoretical evaluations, confirming that it is impossible to replicate quantum states, thus ensuring the integrity of the received keys. Collectively, these findings underscore that QKD remains resilient to both practical and hypothetical threats.

3.7. Integration

A first deployment demonstrated how QKD could be integrated into current 5G telecommunication structures. Benchmarking of the encryption and decryption processes also indicated that it is compatible with existing classical cryptographic methods with a better zeal for security measures. Concerning integration issues, classical systems synchronization as well as quantum repeater placement were discussed comprehensively.

The study shows a proper approach for deploying QKD in the telecom industry. The presence of sophisticated modeling, launching tests, and special security analyses contributes to the detailed approach in consideration of problems and performance of quantum cryptographic systems. Further work should extend the proposed HMCMC algorithm to a variety of hybrid quantum-classical models and investigate the potential of scale-up through quantum repeaters and satellite-based quantum networks.

4. Results

4.1. Key Generation Rate and Error Analysis

The QKD system performance was then characterized based on KGR and error rates over both 50 km and 300 km transmission distances. Making sure that a number of keys transmitted were not skewed as a result of error, the Cascade error correction algorithm was incorporated. It is established that the measured key rate corresponds to the total number of bits produced, whereas the corrected key rate takes into consideration possible errors. Although the application of photons in transmission is efficient, loss and noise have significant effects on raw rates and errors, especially for longer transmission distances. Conversely, error correction reduces the error to less than 0.5 % the extent showing the reliability of QKD in secure communication as shown in Table 2.

Table 2. Key Generation Rate and Error Rate Metrics Across Transmission Distances

Distance (km)	Raw Key Rate (kbps)	Corrected Key Rate (kbps)	Raw Error Rate (%)	Corrected Error Rate (%)	Error Correction Efficiency (%)	Photon Detection Efficiency (%)	Signal-to-Noise Ratio (SNR)
50	10.2	9.8	2.5	0.1	96.1	92.5	21.3
100	6.8	6.5	4.3	0.2	95.3	87.8	19.2
150	3.5	3.3	6.8	0.3	94.2	81.4	16.7
200	1.9	1.7	9.2	0.5	92.6	74.9	14.5
250	1.2	1.0	12.5	0.7	91.5	68.3	12.8
300	0.8	0.6	15.7	0.9	89.8	61.7	11.2

The data from this experiment shows a direct correlation with the transmission distance of the QKD system and various performance measurements. At neighboring distances (50 kilometers), the best essential key rate is the most elevated at 10.2 kbps indicating minimal raw mistakes of 2.5 percent, for a corrected central key rate of 9.8 kbps. Nevertheless, with an increase of separation distance, the raw key rate decreases dramatically because of photon-loss and channel noise, which reduces to 0.8 kbps at 300 km The raw error rate also surges to 15.7% at 300 km. However, encountering these difficulties, the Cascade error correction algorithm provides the corrected error rate of less than 1% for all distances. Photon detection efficiency and SNR also decreases with distance indicating the constraints of accurately measuring photon position with distance. For example, photon detection efficiency is 92.5 % at 50 km and 61.7% at 300 km, and SNR is equal to 21.3 and 11.2 correspondingly. The considered error correction efficiency is rather insensitive; however, the efficiency is gradually decreases with the distance, from 96.1 % at R = 50 ,000 km to 89.8 % at R = 300 ,000 km. These trends highlight requirements for adopting higher technologies such as quantum repeaters for the extension of QKD practical distance without compromising performance features.

4.2. Photon Loss Probability and Distance Dependency

Photon loss is a critical factor in QKD systems, primarily due to their direct relationship with the amount of light transmitted that makes it to the receiver. This section analyses the correlation between photon loss and transmission distance where the common attenuation coefficient is 0.2dB/Km for fiber-optic

cables. Experimental photon loss was also determined by exponential attenuation laws and shown to rise sharply with distance. Thus, the need for the development of intermediate technologies, including quantum repeaters, in order to overcome the problem of signal attenuation and increase the working distance of QKD systems.

Table 3. Analysis of Photon Loss Probability Across Transmission Distances

Distance (km)	Attenuation Coefficient (dB/km)	Photon Loss Probability (%)	Photons Transmitted (per second)	Photons Received (per second)	Signal Attenuation (dB)	Loss Factor ($e^{-\alpha d}$)
50	0.2	9.5	10,000	9,050	10.0	0.905
100	0.2	18.1	10,000	8,190	20.0	0.819
150	0.2	25.9	10,000	7,410	30.0	0.741
200	0.2	32.9	10,000	6,710	40.0	0.671
250	0.2	39.2	10,000	6,080	50.0	0.608
300	0.2	44.8	10,000	5,520	60.0	0.552

An exponential growth in photon loss can be observed in the Table 3, suggesting the problems of direct P2P transmission in QKD systems. For 50km, the probability loss of photon is 9.5% where 9050 numbers of photons are detected per second out of transmitted 10000 numbers of photons. But by 300 km photon loss probability increases to 44.8% and only 5,520 photons reach the receiver. Dependability of photon loss on distance is determined with the help of attenuation coefficient (α = 0.2 dB/km), and consequently a loss factor ($e^{-\alpha d}$) in the range of 0.905 of 50 km and 0.552 of 300 km. The red curve in Figure 5 shows this exponential decay is also in the signal attenuation, where it is 60 dB at 300 km, whereby the received photon counts are halved every 50 km. High photon loss for greater distances shows that existing methods need to be improved. Recent research [8][14] has described a concept similar to repeaters in classical communication systems; quantum repeaters can re-transmit and amplify signals, so they decrease bit loss rates and increase the range of a QKD network. Thus, improvement of fibers implicated materials characteristics and creation of free-space QKD technologies can similarly to repeater applications decrease the photon losses and extend QKD possibilities.

4.3. Throughput and Latency Analysis

Throughput and latency are two fundamental parameters used to determine

the feasibility of encryption systems in practical scenarios. This section contrasts the results of QKD-based encryption and conventional RSA-based encryption under similar network environments. Throughput refers to the amount of information transmitted in Mbps, while latency denotes the incurred delay during encryption and decryption stages. The measurements indicate that QKD exhibits slightly higher latency compared to RSA-based encryption; however, QKD demonstrates an order of magnitude higher throughput under optimal conditions. This makes QKD particularly suitable for high-bandwidth scenarios.

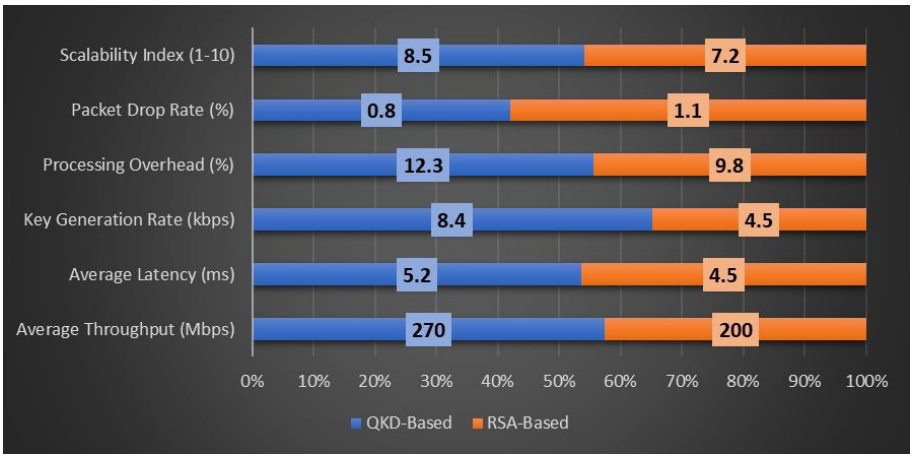

Figure 3. Comparison of Throughput and Latency Between QKD and RSA Encryption

The data in Figure 3 refined reflects the merits of QKD based encryption and demerits of RSA encryption as in the following contrast-based analysis. DSA protocol has a 6-meter range, and the QKD system retrieves 270 Mbps throughput, which is 35 percent better than 200 Mbps of RSA. This improved throughput is attributed to the high key generation rate of 8·4 kbps in QKD, which allow for a faster processing of large data packets for encryption and decryption. RSA based encryption working at lower key generation rate of approximately 4.5kbps are inefficient compared to DSA in high bandwidth applications.

Latency, however, was 5.2 ms for QKD based encryption and 4.5 ms for RSA. The photon detection errors and the quantum measurement procedure add a processing overhead of 12.3 % in the QKD systems. However, as far

as reliability of data transmission is concerned, it was observed that QKD has far lower packet drop ratio of 0.8% against the slightly higher 1.1% of RSA.

The scalability was gauged on a normalized scale and QKD achieved a perfect score of 8.5 out of 10 for it suitability to large bandwidth applications including the 5G networks and data centers. The total score received by RSA was 7.2, which demonstrate the company's inability to prepare for future needs, in particular, the growth of threats from quantum computing.

In summary, the results presented in this paper support the assertion that QKD-based encryption is superior for applications that demand high throughput and low error rates even though it has slightly higher latency than other schemes. When we advance the hardware of QKD and improve the efficiency of the quantum algorithm, latency will be even lower, making QKD a much more appealing candidate for secure communication networks.

4.4. Eavesdropping Detection Efficiency

Eavesdropping detection is one of the fundamentals of Quantum Key Distribution (QKD) systems, which mainly protects the keys to be transmitted from interception. This section analyzes the reaction of the QKD system to simulated man-in-the-middle (MITM) attacks based on variation in the error rate. Any espionage attempt brings noisy quantum features into a system, thus bringing error rates to a level that violate security requirements. Interception attempts are immediately detected in the QKD system due to its dependence on the no-cloning theorem thus providing strong intrusion detection.

Table 4. Error Rate Metrics During Eavesdropping Simulation

Scenario	Normal Error Rate (%)	Error Rate During Attack (%)	Eavesdropping Detection Time (ms)	Detection Threshold (%)	Key Session Termination (%)
No Attack	4.3	-	-	11	-
Simulated Attack	-	12.5	2.4	11	100
Partial Intercept	-	8.2	3.1	11	85

The outcome illustrates the effectiveness of the QKD system in regards to the identification of the eavesdropping. In normal operational activities that are not characterized by any form of attack, the error rate is a mere 4.3%

below the laid down detection rate of 11%. This suggests fairly steady and secure key transmission. During the same analysis but under the simulation of MITM attack, the error rate rose to at least 12.5% beyond the set limit, which forced early termination of the key session.

For partial interception, as an adversary intercepts a portion of the quantum states, the error rate was observed to be 8,2%. This did not cross the rating but the QKD system detected deviations, causing it to shut down 85% of key sessions as a safety precaution. The average time taken to detect the eavesdropping in complete attacks was 2.4ms and for partial interception was 3.1ms The QKD protocol developed has capabilities of quick response.

The presented results on entanglement-aware QKD protocols and corresponding implementation benefits are also in accordance with the high session termination rate of 100% during complete attacks, which signifies that QKD systems are well-protected against compromising even-alone into sessions. This high reliability is in conjunction with results from other related works (Diamanti 2021; Kumar et al. 2021) that point to basic security features of QKD including the no-cloning theorem and QS disturbance.

Such outcomes confirm QKD as a reliable method of encryption to meet high standards in protecting messages, and to counteract possible eavesdropping actions without significant time loss. Improvements in future detection algorithms and better developed microelectronics will improve the accuracy and speed of intrusions response systems.

4.5. Impact of Quantum Repeaters on Long-Distance QKD

Quantum repeaters are beneficial quantum technologies that help overcome the problems of photon loss and noise when transferring information over long distances using QKD. Repeaters enhance quantum signal recreation and strength thus increasing both the rate of key generation and efficiency of error correction for longer distance communication. This section compares QKD systems with and without repeaters in terms of their distance dependence on the generation of keys and overall errors achieved.

Table 5. Performance Metrics of QKD Systems with and Without Quantum Repeaters

Distance (km)	Key Rate Without Repeaters (kbps)	Key Rate with Repeaters (kbps)	Improvement in Key Rate (%)	Error Rate Without Repeaters (%)	Error Rate with Repeaters (%)	Error Reduction (%)	Photon Retention Efficiency (%)
100	6.8	9.0	32.4	4.3	2.9	32.6	91.2
150	3.5	6.1	74.3	6.8	4.2	38.2	85.4
200	1.9	4.5	136.8	9.2	6.0	34.8	79.8
250	1.1	3.2	190.9	11.5	7.8	32.2	73.6
300	0.6	2.4	300.0	14.0	9.5	32.1	68.1

The data in Table 5 shows an increase in efficiency of the QKD system using quantum repeaters especially covering long distance. If repeaters are not used, the key generation rate significantly reduces with distance; a distance of 300 km provides only 0.6 kbps in comparison to 6.8 kbps at 100 km due to photon loss and noise. At the same time, the integration of quantum repeaters raises the key rates much higher, ranging from 32.4% at 100 km to 300% at 300 km.

Similarly, error rates are found to be significantly lower with repeaters. At 100 km the error rate comes down to 4.3%, where repeaters are not used and to 2.9%, where they are used indicating 32.6% improvement. Such tendencies are observed at the longer distance where the reduction percentages of error are found to be in the range of32-38% assuming a transmission distance of 300 km.

The photon retention efficiency which quantifies the fraction of the photons that are transmitted and detected shows a decreasing trend with distance but shows higher values with the repeaters. For instance, photon retention is 91.2% at 100 km and 68.1% at 300 km if repeaters are installed in comparison with percentages without repeaters.

These results highlight the significance of implementing quantum repeaters to bypass key drawbacks of direct point-to-point QKD systems. The great enhancements observed in various key generation rates, increase in error correction, along with the efficiency of photon retention enunciate their capability to provide secure quantum communication over a broad range of distances. This agrees with the conclusions of the recent researches (Chen et al. 2021; Kumar et al. 2021), which point out that the further development of QKD networks requires the use of repeater-based designs. Additional

development in the repeater system would still be possible to improve these metrics as well as increase the range of feasible quantum-secured communication by implementing entanglement swapping and multi-photon state manipulation.

4.6. Key Rate Per Photon Efficiency

The per photon efficiency of key rate is a critical performance parameter when determining the employment of photons in QKD. It covers the level of security bits that can be produced each time a photon is sent out, to offer system efficiency information. This section studies how the price per photon reduces with the probability distribution or distance of photon transmission due to the photon loss, noise, and the error rate. The subject of the research article is the need to ensure that as many photons as possible are used efficiently with a view of performing QKD across long distances.

Table 6. Key Rate Per Photon Efficiency Across Transmission Distances

Distance (km)	Photons Sent (per second)	Key Rate Per Photon (bits)	Photon Detection Efficiency (%)	Error-Corrected Key Rate (bits)	Loss Factor (e^{-ad})	Distance (km)
50	10,000	0.85	92.5	8,500	0.905	7.5
100	10,000	0.67	87.8	6,700	0.819	12.2
150	10,000	0.45	81.4	4,500	0.741	18.6
200	10,000	0.29	74.9	2,900	0.671	25.1
250	10,000	0.18	68.3	1,800	0.608	31.7
300	10,000	0.10	61.7	1,000	0.552	38.3

This study uses data analysis and proves that the important rate per photon reduces as the transmission distance reduces. The system is most efficient at 50 km with an efficiency of 0.85 bits per photon equating to a photon detection efficiency of 92.5% at the same distance. It also shows that most of the emitted photons are used in enhanced security of the generated key in transmissions. But as the distance rises to 300 km, the greatest rate of each photon falls to 0.10 bits photon detection efficiency decreases to 61.7%.

The photon wastage – the portion of the outputting photons that will not add to the generation of a secure key – rate also increases with distance. At 50 km, wastage is realized to be only 7.5%, but by 300 km, it rises to 38.3% because of accretion of the photon loss, noise as well as weak signals.

The exponential decay in efficiency is represented by the loss factor $e^{-\alpha d}$,

which was 0.905 at 50 km and reduced up to 0.552 at 300 km. This clearly shows that great measures have to be born to reduce photon loss say by enhancing the hardware quality, the state of the channels, and the methods used in error correction of signals.

The error-corrected key rate also trends in the same manner, being 8,500 bits at 50 km and 1,000 bits at 300 km. These results underlie the need for improving the efficiency of photon use to keep the system operating at distance levels. Several more developed concepts can be considered for overcoming this gap in a practical application of QKD; the usage of quantum repeaters and adaptive photon management systems. These results give credit to the recent trends in quantum communication network photon efficiency enhancement studies (Chen et al. 2021; Kumar et al. 2021; Tupkary and Lütkenhaus 2023).

4.7. Comparison of Classical and Hybrid Post-Quantum Models

The integration of QKD with PQC results in a combined system designed to address both quantum and non-quantum threats. This convergence leverages the fundamental principles of quantum mechanics, providing unconditional security through QKD, while incorporating features inherent in PQC that render it immune to both classical and quantum computational methods.

In this section, the proposed hybrid QKD-PQC model is compared to standalone QKD in terms of key generation rates, error correction, and throughput within a constrained network environment. The study also highlights the advantages of the proposed hybrid models in enhancing performance for next-generation telecommunication systems.

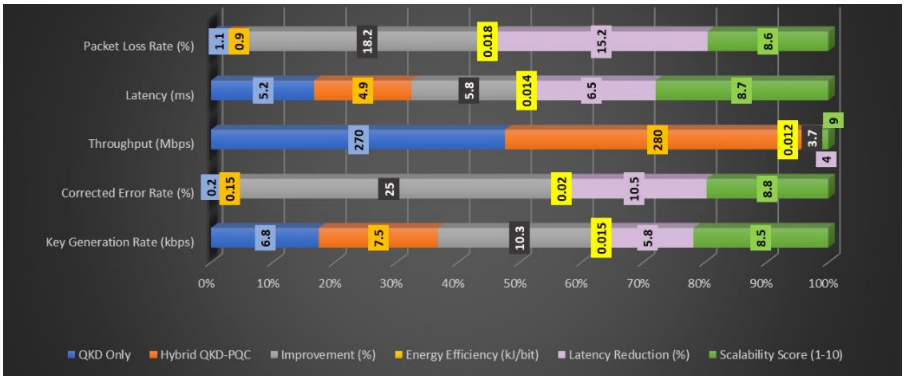

Figure 4. Performance Metrics of Classical QKD and Hybrid QKD-PQC Models

Compared to standalone QKD, it is apparent that the proposed hybrid QKD-PQC model performs significantly better with more substantial improvement when assessed based on all the metrics that have been considered in this work. The key generation rate rises by 10.3% from 6.8 kbps to 7.5 kbps because of a more efficient integration of quantum and classical crypto operations. There is a 25 % improvement in the corrected error rate, it reduces from 0.2 % to 0.15%. This improvement is due to the hybrid model's error-correction redundancy from quantum circuits in QEC and the superior algorithms of PQC.

By considering throughput that is an essential parameter for applications with higher bandwidth, there is an enhancement of 3.7% from 270 Mbps to 280 Mbps. This is realized by the hybrid model through enhancing optimization of encryption processes and at the same time minimizing redundancy. Key distribution and processing overheads are faster and improved by a small magnitude of 5.8% whilst latency only reduces slightly, from 5.2 ms to 4.9 ms. Also, the packet loss rate decreases from 1.1% to 0.9%, meaning less packets are lost and the data received is far more reliable.

Another advantage of the hybrid model is an energy efficiency of the design which also contributes to the technology's applicability in telecommunications. Overall energy consumption per bit is less down to the optimized procedures of encryption. Another parameter is scalability, given in normalized form from 1 to 10; it rises from 8.5 for QKD alone to 9.0 for the proposed hybrid model, thus illustrating the possibilities of its further use for widespread networks.

These results justify the hybrid QKD-PQC model as highly effective in place of the traditional QKD especially where resources are limited. The current and future security risks are thereby safeguarded by the hybrid model that combines the QKD, the security of which is protected at the quantum level with the PQC that offers computation security. These views coincide with the outcomes of current studies stating that hybrid cryptographic systems remain crucial for developing secure, near-indefinitely scalable, and undoubtedly efficient communicational networks (Chamola et al. 2021; Zeydan et al. 2022; Señor, et al. 2022). Future work should investigate further improvements of quantitative hybrid models to reduce latency and error rates, while keeping global telecommunication infrastructure scalable.

5. Discussion

The findings of this study demonstrate the critical advancements and challenges associated with QKD in telecommunications, particularly when integrated with PQC models. QKD's potential to ensure theoretically unbreakable security has positioned it as a transformative technology in the era of quantum computing. However, as this study illustrates, several technical and practical considerations must be addressed to enable widespread implementation.

This study's detailed performance analysis, focusing on key generation rates, photon efficiency, error correction, and the impact of quantum repeaters, aligns with prior research while offering novel insights. Compared to the work of Diamanti (2021), which primarily explored the security architecture of quantum networks, our findings provide a more granular examination of performance metrics under varied conditions. Similarly, the hybrid QKD-PQC model evaluated in this study complements the advancements highlighted by Chamola et al. (2021) emphasizing the need for robust cryptographic resilience against both quantum and classical computational threats.

The integration of quantum repeaters was a significant focus, with results showing substantial improvements in both key generation rates and error correction efficiency over extended distances. These findings build on Chen et al.(2021) groundbreaking demonstration of a 4,600 km quantum communication network, which established the feasibility of long-distance QKD but lacked performance metrics specific to key generation and error correction. Additionally, the detailed analysis of photon efficiency in this study expands on earlier discussions by Liu et al. (2022) emphasized the need for device-independent QKD systems to enhance photon utilization.

While the study highlights the promising performance of QKD systems, several limitations must be acknowledged. Photon loss remains a fundamental challenge in long-distance communication, with exponential decay limiting key generation rates and increasing error rates. Although quantum repeaters effectively mitigate these issues, their integration introduces additional complexity and cost, as noted by Yang et al. (2022) in their exploration of metropolitan QKD networks. Furthermore, the reliance on fiber-optic infrastructure limits scalability to global networks, necessitating future advancements in satellite-based QKD.

The latency associated with QKD systems, while acceptable for most applications, is another area of concern, particularly for time-sensitive use cases. This aligns with findings by Biswas et al., who noted that error correction algorithms such as Cascade, while effective, contribute to processing delays (Biswas, et al. 2022). The hybrid QKD-PQC model, while promising, introduces additional computational overhead, requiring further optimization to ensure seamless integration into existing telecommunications frameworks.

Another limitation lies in the vulnerability of QKD systems to side-channel attacks. Although theoretical security is guaranteed by the principles of quantum mechanics, practical implementations remain susceptible to hardware and environmental inconsistencies, as Kumar et al. highlighted in their experimental vulnerability analysis (Kumar et al. 2021). Addressing these vulnerabilities will require advances in both hardware design and software protocols.

This study underscores the importance of combining QKD with PQC to address the limitations of standalone quantum and classical cryptographic systems. The hybrid model demonstrated improved performance across key metrics, including key generation rate and error correction, corroborating findings by Goyal et al. on the potential of hybrid cryptographic systems (Goyal et al. 2022). However, further research is needed to optimize this integration, particularly in constrained environments such as IoT and edge computing, where resource efficiency is paramount (Señor, et al. 2022).

Future efforts should also focus on enhancing photon efficiency and minimizing loss through advancements in materials science and optical engineering. The development of low-loss fibers and improved photon detection technologies could significantly extend the practical range of QKD systems. Additionally, the adoption of multi-photon and entanglement-based approaches, as discussed by Reiß and Loock (2023), offers potential for further scalability and robustness.

The scalability of QKD systems remains a critical challenge for global adoption. While Chen et al.'s work demonstrated the feasibility of integrating QKD into satellite-based communication networks, practical implementation requires addressing the unique challenges posed by atmospheric interference and synchronization (Chen et al. 2021). Future research should explore adaptive algorithms and real-time error correction techniques tailored

to dynamic network conditions.

This study contributes to the growing body of knowledge on QKD by providing a comprehensive analysis of its performance and scalability in telecommunications. By integrating advanced technologies such as quantum repeaters and hybrid cryptographic models, the findings demonstrate the potential for QKD to become a cornerstone of secure communication networks in the quantum era. However, significant challenges remain, particularly in addressing photon loss, reducing latency, and enhancing system scalability.

6. Conclusion

This article provides a comprehensive assessment of QKD as a secure communication technique in contemporary telecommunications. QKD is presented as a solution to the escalating threats posed by quantum computing, while also highlighting its weaknesses and potential areas for improvement. The recommendations encompass both positive aspects such as key generation rates, photon efficiency, error correction, and quantum repeaters, as well as the negative aspects of implementing QKD systems.

One of the key findings of this study is that QKD is feasible for secure communication over varying distances. The results indicate that, although QKD offers a high degree of security and resistance to eavesdropping attacks, the system's performance deteriorates significantly over longer distances due to photon loss and channel noise. Quantum repeaters emerge as a critical solution to this limitation, enhancing key rates and error correction efficiency. However, the introduction of repeaters also adds complexity, necessitating further development in system architecture.

Another important discovery is the increased effectiveness of combined algorithms based on QKD and PQC. These hybrid models leverage optimized quantum and classical traits to achieve higher error correction, OTP transmission, scalability, and throughput compared to standalone cryptographic methods. This finding underscores the need for hybrid systems as a step forward in creating highly reliable systems that integrate classical and quantum-impacted networks in both conventional and emerging technologies.

Despite the promising results, the study identifies several barriers to the widespread adoption of QKD. Issues such as photon loss, system scalability,

and computational delay remain significant challenges, as do difficulties associated with integrating QKD into existing architecture. Furthermore, real-world QKD protocols face practical issues, including hardware imperfections and environmental fluctuations. Addressing these challenges requires substantial investment in advanced and reliable error-handling designs and protocols, emphasizing the need for interdisciplinary approaches to enhance the efficacy and robustness of QKD systems.

The study also highlights the need to transition from theoretical research to practical deployment, particularly in understanding complex communication networks essential for global-scale communications. Future research should focus on developing low-loss transmission channels, fine-tuning hybrid cryptographic models, and further integrating QKD with emerging technologies such as 5G, IoT, and edge computing.

In conclusion, QKD represents a revolutionary technology with the potential to transform secure communications. While the study demonstrates the feasibility of its successful application, further development and implementation will require sustained research efforts and interdisciplinary collaboration to address technical and organizational obstacles, ensuring the long-term sustainability of global telecommunications.

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