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A Novel 5G Fronthaul Architecture Based on Quantum Security Protection

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Abstract: In the digital age, 5G technology has significantly enhanced global communication capabilities, providing strong support for various industries. However, 5G falls short of achieving comprehensive intelligence within the Internet of Things (IoT), propelling the development of 6G technology. 6G is expected to further enhance network performance by integrating advanced technologies such as AI and quantum communication, while expanding application scenarios to include communication in extreme environments for comprehensive global connectivity. This paper proposes an innovative fronthaul architecture that applies Quantum Key Distribution (QKD) technology to the 5G fronthaul, leveraging its unconditionally secure key generation and distribution mechanism. In this design, costlier Alice devices are placed on the AAU side, while less expensive Bob devices are positioned on the DU side, optimizing deployment to reduce engineering costs and lower deployment barriers. The feasibility of this architecture is demonstrated by calculating the secure key rate. Comparative analysis with existing research is performed to clarify future research directions. These innovations not only enhance 5G network security but also offer new solutions for the security requirements of 6G networks, such as data security, network resilience, and algorithm transparency. Our research offers strategic value for future network security, laying the groundwork for reliable networks.

Keywords: 5G Fronthaul, 6G, Quantum Key Distribution, Network Security, Global Digital Transformation.

1. Introduction

Amid the wave of 21st-century digital transformation, the emergence of fifth-generation mobile communication technology (5G) represents an inevitable outcome of global digital transformation and advancements in ICT, marking a significant leap in global communications [1]. Since the 1980s, mobile communication technology has evolved from 1G to 4G, with each generation significantly improving connection speeds and network performance [2]. In the 21st century, the rapid development of emerging technologies such as the IoT, big data, and artificial intelligence (AI) has placed unprecedented demands on network bandwidth, latency, and connection density. With innovations in spectrum utilization, network architecture, and modulation coding, 5G leverages key technologies—such as massive multiple-input multiple-output (Massive MIMO), beamforming, TI-LFA technology, edge computing, and network slicing—to achieve extremely high data transmission rates (up to 20 Gbps), ultra-low latency (as low as 1 ms), and support for massive device connections

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(up to one million connections per square kilometer) [3]. This revolutionizes personal mobile communication experiences and provides a strong foundation for innovative applications in fields such as smart grids, telemedicine, autonomous driving, and high-precision machining. The significance of 5G lies in its technological advancements, which lay a solid foundation for the global digital economy and the construction of an intelligent society, heralding a new era of interconnected and intelligently linked systems [4].

Despite its exceptional performance across various fields, 5G technology continues to exhibit several limitations. For instance, 5G was initially designed to enable the Internet of Everything (IoE). However, due to limited capacity, 5G systems cannot fully support an intelligent and automated network for IoE services [5]. As data-centric and automated systems rapidly develop, their demands may soon exceed the capacity of 5G and existing mobile networks. Looking forward, the demand for smarter, more complex global networks poses new challenges for communication technology, making the exploration of next-generation mobile communication (6G) imminent. The vision for 6G is to advance from the IoE to the Internet of Intelligent Everything, creating a globally seamless, ultra-experiential, and highly efficient communication network. Compared to 5G, 6G will offer higher data transmission rates (theoretical peak of up to 1 Tbps) [6], lower latency (ideally sub-millisecond) [7], broader spectrum (extending into terahertz bands) [8], wider connectivity, more secure communication environments, and smarter network operations. 6G technology will not only deeply integrate cutting-edge technologies such as AI, quantum communication, and edge computing to offer users unprecedented communication experiences but will also address communication needs in extreme environments, such as deep-sea, high-altitude, and space network connectivity, achieving true global coverage and universal connectivity.

In the 6G era, networks will be deeply integrated into every aspect of societal operations, with security requirements reaching unprecedented levels. The primary security demands of 6G center on core issues such as data security, network resilience, device security, and algorithm transparency. Regarding data security, the 6G network architecture will be more complex, with new communication technologies, such as terahertz communication, potentially introducing physical layer security vulnerabilities that require updated standards for interference resistance and eavesdropping protection [9]. Network resilience focuses on the robustness and self-healing capabilities of network architecture, employing redundancy and dynamic adjustment mechanisms to protect against security threats such as distributed denial-of-service (DDoS) attacks and network intrusions [10]. Device security requires stringent certification for 6G terminals to prevent hardware vulnerabilities and software backdoors, ensuring safety at both the physical and logical levels [11]. For algorithm transparency, the deep integration of AI and big data in 6G networks makes algorithm security and data privacy protection essential, requiring vigilance against algorithmic bias and data misuse. This requires clear algorithmic logic and transparent decision-making processes to enhance user trust in network services [12]. The security requirements of 6G are indispensable to its technological framework and hold crucial strategic importance for building a secure, reliable, and trustworthy future network.

2. Literature Review

Currently, 6G technology is in the early stages of theoretical research and technological exploration. Countries and regions including China, the United States, the European Union, and Japan have initiated research and development programs for 6G technology. Current 6G research focuses primarily on key technology areas, including terahertz (THz) communication, holographic communication, intelligent reflecting surfaces (IRS), space-ground integrated networks, and network slicing [13][14]. Terahertz communication utilizes high-frequency spectrum resources to enable ultra-high-speed data transmission [15]. Holographic communication combines visual and auditory sensory information to deliver an immersive communication experience [16]. IRS technology

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enhances wireless signal coverage and transmission efficiency by intelligently controlling electromagnetic wave reflection and refraction. Space-ground integrated networks aim to create a unified network architecture for seamless global coverage [17]. Network slicing employs Software-Defined Networking (SDN) to provide customized network services for diverse application scenarios [18]. However, the advancement of 6G technology brings new security challenges, as previously mentioned. To address these challenges, quantum encryption communication emerges as especially important for its theoretically unbreakable security features [19]. Quantum encryption communication, through Quantum Key Distribution (QKD) technology, theoretically ensures absolute confidentiality of communication data during transmission. As a result, research and application of quantum encryption communication have become essential for ensuring 6G network security.

This paper's innovation lies in integrating QKD technology with existing 5G technology, proposing a novel quantum-secure 5G fronthaul network architecture. This architecture supports the effective parallel transmission of quantum and data signals by positioning Alice devices on the AAU side and Bob devices on the DU side, eliminating the need for large-scale infrastructure replacement. The feasibility of this architecture is validated by calculating the secure key rate, ensuring data confidentiality and integrity during transmission and effectively addressing escalating information security challenges.

The research findings suggest that this architecture not only enhances 5G network security but also offers new solutions and insights for 6G network security requirements. In the 6G era, as networks become more deeply integrated into every aspect of social operations, security demands will reach unprecedented heights. The quantum-secure 5G fronthaul network architecture proposed here, leveraging quantum encryption communication technology, can theoretically provide unconditional communication security, a critical component for developing a secure, reliable, and trustworthy future network.

3. Quantum Key Distribution

The BB84 protocol, a foundational method in the field of quantum key distribution (QKD), was proposed by Charles Bennett and Gilles Brassard in 1984. Its purpose is to securely distribute cryptographic keys between two parties, even in the presence of potential eavesdroppers. The core principle relies on quantum mechanics, specifically the no-cloning theorem and the measurement-induced disturbance, to secure the key. The protocol employs quantum bits (qubits) as information carriers, achieving secure key distribution through the random selection and measurement of quantum states.

Photon properties, including polarization, phase, and frequency, can be encoded as qubits. The original BB84 protocol uses individual photons as information carriers and categorizes the four polarization states of light into two sets of conjugate bases, each containing two orthogonal polarization states: the Horizontal-Vertical Basis and the Diagonal Basis.

The BB84 protocol key distribution process includes the following steps:

- Information Agreement: The transmitter (Alice) and the receiver (Bob) agree on an encoding method, including the selection of orthogonal conjugate bases and the correspondence between quantum states and binary data.
- Information Sending: Alice prepares single photons as carriers of quantum information. She generates a random sequence and selects one of the two bases for each bit. According to the random sequence, she modulates the photons' physical properties to encode the data into corresponding quantum states. For example, using a polarizing beam splitter, Alice can choose between

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horizontal and vertical bases, and by adding a quarter-wave plate, she can select between 45° and 135° bases.

- Information Measurement: When the photons reach Bob, he randomly selects a measurement basis—either the horizontal-vertical basis or the diagonal basis. Photon measurements can be completed using a polarizing beam splitter and a quarter-wave plate. Due to possible attenuation along the transmission path, not all photons sent by Alice are detected. Bob records the positions of the detected photons (valid photons) and assumes that the others are lost in the quantum channel. Basis matching between Alice and Bob is performed only for the valid photons.
- Basis Reconciliation: Alice and Bob exchange information about their chosen bases over a classical (public) channel, without revealing the actual measurement results. If both parties used the same basis, they deem the basis reconciliation successful and retain the polarization information corresponding to the photons sent and measured.
- Key Generation: Using the retained polarization states and the predefined correspondence between polarization states and binary bits '0' and '1,' Alice and Bob generate a shared secret key sequence.

4. Quantum-secure 5G Fronthaul Network

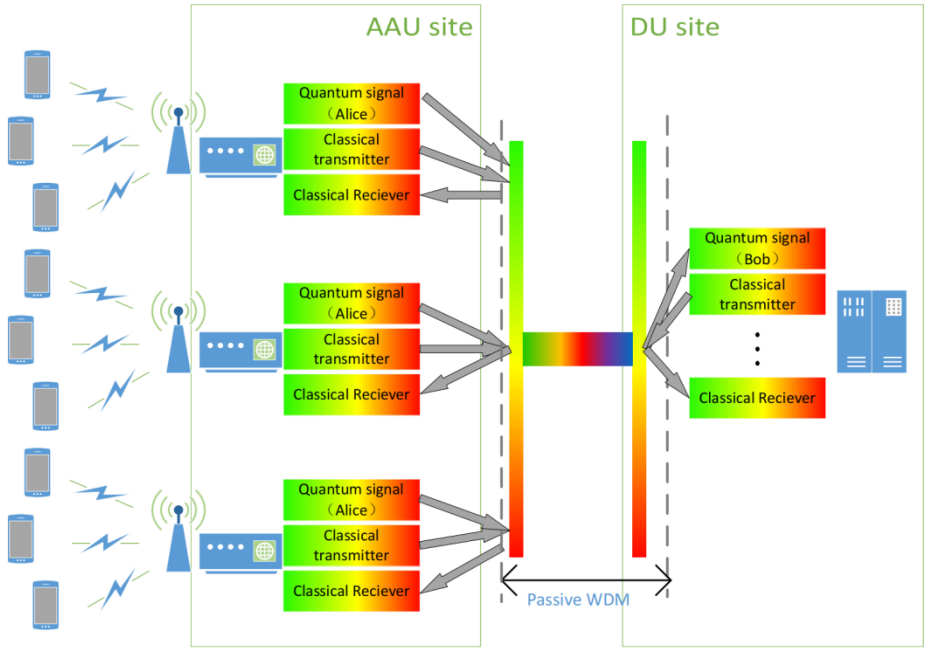

Figure 1: 5G fronthaul architecture based on quantum security protection

The BB84 protocol forms the foundation of QKD, with many subsequent protocols building upon and extending its principles. In practice, the BB84 protocol can be implemented via optical fiber or free-space communication, with continuous technological advancements enhancing its efficiency and security.

In 5G networks, particularly in the fronthaul section, secure data transmission is crucial, as this section typically involves sensitive communication between base stations and the core network. Implementing QKD technology in the 5G fronthaul offers an unconditionally secure mechanism for key generation and distribution. In this setup, Alice (the transmitter) is positioned on the AAU side, and Bob (the receiver) on the DU side. In the 5G fronthaul architecture, AAUs significantly outnumber DUs, and Alice incurs a higher cost than Bob. This arrangement effectively reduces engineering costs and lowers deployment barriers.

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There are three primary modes of signal transmission. The first mode is bidirectional data signaling, where information is transmitted in both directions—from transmitter to receiver and vice versa. This mode is common in modern communication systems, especially in applications requiring two-way interaction, such as phone calls and instant messaging. In the 5G fronthaul, signals can be transmitted from the AAU to the DU and vice versa, exemplifying a typical bidirectional data signal. The second mode is unidirectional quantum signaling, where, during the key distribution process, Alice transmits quantum bits to Bob, who can only receive without transmitting.

Next, consider the issue of mismatched key and data generation rates: if keys are generated continuously while communication data fluctuates significantly over time, time-sharing encryption can be applied. For instance, during high-traffic periods, such as daytime, keys are generated continuously to ensure real-time availability, and any surplus keys are stored. During low-traffic periods, such as nighttime, new keys are not generated; instead, stored keys are used directly. Additionally, not all data requires encryption—quantum keys can be generated only for critical information transmission. These approaches help conserve keys and reduce costs while maintaining secure information transmission.

This architecture enhances the security of 5G fronthaul communications by applying QKD technology. Unauthorized eavesdroppers cannot decrypt the communication content, thus preserving data confidentiality and integrity. For cost efficiency, we position the more expensive Alice devices on the AAU side, where they are most needed, while placing the less costly Bob devices on the DU side. This design achieves high security and cost reduction by minimizing the use of expensive equipment. Moreover, this architecture is compatible with existing 5G networks, enabling easy integration into current systems with minimal infrastructure modifications. Its compatibility across various 5G network environments broadens its application potential. In summary, this 5G fronthaul architecture integrates QKD technology with optimized device placement to achieve enhanced security, cost-effectiveness, and wide applicability, making it an ideal solution for secure 5G communications.

5. Secure Key Rate Analysis

Integrating QKD into the 5G fronthaul architecture ensures the confidentiality and integrity of data during transmission. In practical applications, calculating the secure key rate is essential. The secure key rate measures the speed and security of key generation in QKD systems, directly affecting whether quantum communication systems can provide sufficiently fast and secure key services in real-world environments. Analyzing the secure key rate is crucial as it evaluates QKD systems' performance against potential threats, such as eavesdropping attacks, noise interference, and device imperfections.

In 2004, Gottesman, Lo, Lutkenhaus, and Preskill proposed a method for calculating the key generation rate in non-ideal QKD systems (systems with imperfect devices and channels). This calculation method is known as the GLLP formula. The derivation in their paper is complex; here, we only present the relevant conclusions for this article.

The GLLP formula assumes that only single-photon pulses from multi-photon sources can generate secure keys. Based on this, the lower bound (S) of the secure key rate using the BB84 protocol is expressed as:

$$S \geq Q_{\mu}\{-H_2(e_{\mu}) + \Omega[1 - CH_2(e_1)]\} \tag{1}$$

In this equation, Q_{μ} and E_{μ} represent the gain of the signal state and the quantum bit error rate (QBER), respectively. Here, gain refers to the ratio of signals detected by Bob after basis choice to the total signals sent by Alice. $\Omega=Q_1/Q_{\mu}$ indicates the percentage of detected single-photon signals

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out of the total signals sent by Alice, while e_1 represents the QBER caused by single-photon signals. $H_2(x) = -x\log_2(x) - (1-x)\log_2(1-x)$ is the binary Shannon entropy function.

Next, we will provide a detailed explanation of the decoy-state QKD protocol.

A weak coherent light source with phase randomization is used, where the number of photons in its light pulses follows a Poisson distribution. The density matrix of the quantum state generated by Alice is as follows:

$$\rho_\mu = \int_0^{2\pi} \frac{d\theta}{2\pi} |\sqrt{\mu}e^{j\varphi} >< \sqrt{\mu}e^{j\varphi}| = \sum_{n=0}^{\infty} e^{-\mu} \frac{\mu^n}{n!} |n >< n| \quad (2)$$

Here, $|0 >< 0|$ is the vacuum state, and $|n >< n|$ represents the density matrix of the n-photon state.

The attenuation of the optical fiber quantum channel is exponential. Let αdB represent the attenuation coefficient of the quantum channel between Alice and Bob, and let lkm denote the length. Then the attenuation between them is:

$$t_{AB} = 10^{-\alpha l/10} \quad (3)$$

Assuming the detection efficiency is η_D, the probability of a photon sent by Alice being detected by Bob is:

$$\eta = t_{AB}\eta_D \quad (4)$$

Infrared single-photon detectors are generally threshold detectors that can distinguish between the vacuum state and non-vacuum states but cannot differentiate the number of photons. Therefore, when Alice sends an n-photon state, the probability of Bob obtaining a detection result is:

$$\eta = 1 - (1-\eta)^n \quad (5)$$

Let Y_n be the conditional probability that Bob can produce a detection result when Alice emits an n-photon state. Y_n represents the background counting rate, which is the count when Alice emits the vacuum state. This count mainly arises from the detector's dark counts and other background noise. The n-photon state detected by Bob has two main sources: the signal state and background noise. Assuming that the background noise is independent of the signal state, we have:

$$Y_n = Y_0 + \eta_n - Y_0\eta_n \approx Y_0 + \eta_n = Y_0 + 1 - (1-\eta)^n \quad (6)$$

Here, we neglect the product terms as they are generally of a lower order and, when multiplied, become higher-order small quantities. We define the probability of Alice emitting an n-photon state, multiplied by the conditional probability of Bob obtaining a detection result at that time, as the measurement gain of the n-photon state (Q_n).

$$Q_n = Y_n P_\mu(n) = Y_n \frac{\mu^n}{n!} e^{-\mu} \quad (7)$$

When Alice emits an n-photon state, errors in Bob's measurements arise from background noise and incorrect measurement results of the signal light:

$$e_n = \frac{e_0 Y_0 + e_{Det}\eta_n}{Y_n} \quad (8)$$

where e_{Det} represents the probability of incorrect detection results caused by the signal light, for example, in the classical BB84 protocol, when the signal light reaches the wrong detector. This parameter is typically determined by the interference performance and stability of the optical system. The general formula for the gain is:

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$$Q_\mu = \sum_{n=0}^{\infty} Y_n P_\mu(n) = \sum_{n=0}^{\infty} Y_n \frac{\mu^n}{n!} e^{-\mu} = Y_0 + 1 - e^{-\eta\mu} \tag{9}$$

Therefore, the overall error rate is:

$$E_\mu Q_\mu = \sum_{n=0}^{\infty} e_n Y_n P_\mu(n) = \sum_{n=0}^{\infty} e_n Y_n \frac{\mu^n}{n!} e^{-\mu} = e_0 Y_0 + e_{Det}(1 - e^{-\eta\mu}) \tag{10}$$

Since background light is generally considered completely random, the probabilities of obtaining correct and incorrect detection results are both 1/2, that is, $e_0=1/2$.

This approach enables an accurate estimation of the lower limit of the secure key amount, providing feasibility support for implementing this framework.

6. Comparison Analysis and Result Discussion

Current research on applying quantum security technology to 5G fronthaul mostly integrates QKD technology with wavelength division multiplexing techniques, allowing quantum signals and classical signals to be transmitted in the same optical fiber. This research focuses on quantum signal interference caused by multi-wave mixing noise and calculates the secure key rate using interference models such as spontaneous Raman scattering noise. The performance of QKD is then simulated and evaluated, exploring methods to improve the secure key rate.

In contrast, this research focuses on the specific device layout within a novel architecture, without evaluating noise. It proposes an innovative 5G fronthaul architecture that places the more expensive Alice device on the AAU side and the less expensive Bob device on the DU side.

The advantage of this research, compared to most existing studies, lies in its greater emphasis on balancing security and cost-efficiency. By optimizing device placement, it achieves cost reduction without sacrificing security, which is crucial for practical deployment and operation. The proposed architecture is highly compatible with existing 5G networks and can be easily integrated into current systems without requiring large-scale infrastructure changes. This aspect, which is less addressed in existing research, represents a unique advantage of this paper. Furthermore, the paper not only focuses on the security of 5G networks but also anticipates the security needs of 6G networks. This forward-thinking approach offers strategic value for the development of future network technologies.

7. Conclusions

This paper presents a pioneering integration of QKD technology into the 5G fronthaul network, resulting in a novel architecture that significantly enhances data security. Our innovation focuses on the strategic placement of QKD devices within the existing 5G infrastructure, enabling a seamless upgrade without requiring extensive capital investment. The secure key rate analysis, based on the GLLP formula, confirms the feasibility of our approach and offers a sustainable solution to the escalating security demands of modern networks. In addition, a comparison analysis with existing research have been conducted, analyzing our advantages and shortcomings, and clarifying the direction for future research.

The practical application of this research provides substantial value to network operators by bolstering the security of their services, which, in turn, enhances customer trust and market competitiveness. The proposed architecture's compatibility with current 5G networks ensures a smooth transition, minimizing both deployment costs and operational complexities. Furthermore, by offering resilience against evolving cyber threats, this solution provides a robust foundation for operators as they prepare for the shift to 6G. In essence, our research paves the way for a new era of secure and efficient communication networks, equipping operators with the tools necessary to address the challenges of the digital economy.

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