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Research and performance analysis for the DWDM-QKD 5G fronthaul architecture

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Abstract. 5G is another age of broadband portable correspondence innovation including high speed, low latency, and large connectivity, and quantum cryptography is a technology of the combination of quantum mechanics and cryptography. In order to combine 5G fronthual with the QKD (quantum key distribution), we conduct research on this paper. First, this paper proposes DWDM-QKD (dense wavelength division multiplexing-quantum key distribution) 5G fronthaul architecture. It contains AAU (active antenna unit) sites, multiplexer, de-multiplexer, and DU (distributed unit) sites. Second, the spontaneous Raman scattering noise interference model is analyzed theoretically, and the secure key rate calculation theory is used. Finally, the simulation evaluates the performance of QKD in the proposed architecture, the reduction of classical power can lead to an increase in the secure key rate.

Keywords: 5G fronthaul, QKD, wavelength division multiplexing, spontaneous raman scattering noise, secure key rate.

1. Introduction

With the formal freezing of 3GPP 5G NSA (non-standalone) and SA (standalone) networking standards, Chinese operators have simultaneously started to plan and design 5G pilot and pre-commercial schemes, and the pace of 5G commercialization has gradually accelerated [1].

To meet the needs of users for more diversified network use and a better experience, mobile fronthaul networks have become the focus of research in the current industry. The fronthaul carries the CPRI/eCPRI (Common Public Radio Interface/Enhanced Common Public Radio Interface) signals between AAU and DU. Short-distance and cost-sensitive characteristics characterize 5G fronthaul [2]. Flexible 5G fronthaul has become an important factor in balancing the latency, throughput, and reliability needs of advanced 5G applications. 5G is an open network that hackers can easily control or attack. At present, there were 11,638 security incidents in May 2022 alone [3]. Network security is of great significance to the construction of 5G. QKD (Quantum Key Distribution) satisfies "absolute security," that is, random keys, different key lengths, and one key at a time, which can provide a security guarantee and anti-eavesdropping function for 5G fronthaul [4].

QKD is based on the probabilistic properties of quantum states, and its security is guaranteed by the three fundamental physical laws of quantum mechanics rather than by computational complexity [5-6]. effectively ensure the key’s security and have the ability to prevent eavesdropping. QKD uses a

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single photon as the carrier of information. The four polarization states of light are divided into two groups of conjugate bases, and two polarization states in each group are orthogonal to each other. Alice selects the random basis group to determine the polarization of the photon and transmits the photon and polarization state to Bob. Bob randomly selects the basis group to determine the polarization state of the photon based on the polarization state determined by Alice. The two then compare the photons and retain the same bits as the key.

Integrating QKD with classical telecom fibers is an important issue at the moment. The quantum signal is much weaker than the classical signal. When sharing the same fiber with conventional data, noise impairments would significantly reduce the performance of QKD due to the significant power gap between the two types of signals. CWDM (Coarse Wavelength Division Multiplexing)—QKD has been considered a feasible interference reduction scheme since 1997. However, the transmission loss limits the transmission distance of the QKD system and the transmission loss in the O-band is significantly higher than that in the C-band.[7] DWDM (Dense Wavelength Division Multiplexing) QKD is more compatible with commercial optical network facilities but more challenging due to noise problems, such as FWM (Four-Wave Mixing) and SpRS (spontaneous Raman scattering) noise.

Jia-Ning et al. proposed an improved scheme called JOCA (Joint Optimized Channel Allocation) [7]. JOCA is suitable for DWDM-QKD systems that have multiple quantum and classical channels. JIA-NING's experimental results show that JOCA provides a reduction of virtually the entire FWM noise and 23% of the Raman noise. According to Kawahara et al., quantum channel transmission wavelengths can be multiplexed with classical channels of clock signals and/or post-processing signals. QKD systems can be multiplexed with classical channels when used with typical APD detectors, but are not applicable to low-noise detectors, such as SSPDs [8]. All of the above studies have been conducted in depth in the study of simultaneous transmission of classical and quantum signals, but the study of using QKD to ensure the security of 5G fronthaul networks has not been conducted yet.

This paper focuses on the DWDM-QKD 5G fronthaul architecture and analyzes the spontaneous Raman noise and secure key rate. This paper shows that in the C-band, bringing the classical signal close to the quantum signal reduces the noise within the specific bands.

2. Architecture design

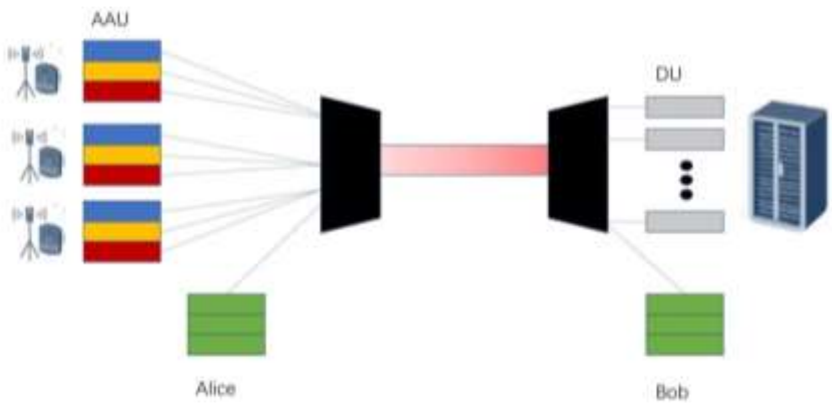

Figure 1. DWDM-QKD 5G fronthaul (AAU: active antenna unit; DU: distributed unit.).

We have designed a DWDM-QKD 5G fronthaul architecture with DWDM technology. The architecture contains AAU sites, multiplexers, demultiplexers, and DU sites. As shown in Fig. 1, Alice is assigned to the AAU site, and Bob is assigned to the DU site. The classical uplink signals are sent from the AAU at different optical wavelengths and arrive at the DU after multiplexers combine and demultiplex their assignments. Classical downlink signals are sent from the DU and arrive at the AAU site after multiplexer and demultiplexer assignments to each AAU according to different wavelengths.

The quantum signal is unidirectional, from the AAU site to the DU site. The quantum signal and the classical signal are placed in the C-band, which ranges from 1530 nm to 1565 nm, and optical fiber exhibits the lowest loss in the C-band.

Since we designed the architecture in which the keys generated between Alice and Bob are to be supplied to multiple pairs of AAUs and DUs at the same time, the architecture we designed is suitable for scenarios with weak encryption requirements.

Based on QKD, we design the architecture with an anti-eavesdropping function, which will have a 25% error rate in the case of eavesdropping. A DWDM-based network can deliver various types of data flow over a single fiber at different wavelengths. This enables the co-transmission of classical and quantum signals.

3. Noise analysis

In wavelength multiplexing systems, spontaneous Raman scattering caused by the classical channel potentially diminishes the QKD system's performance because of the quantum channel's lower signal power.

The spontaneous Raman scattering noise arises from the Raman effect: as the classical signal enters the optical fiber for transmission, it interacts with the fiber to produce a nonlinear If the intensity of the classical signal is less than a specified threshold, the Raman scattering noise is generated without disrupting the thermal equilibrium between the molecules of the fiber medium. If the intensity of the classical signal is less than the specified threshold and does not disrupt the thermal equilibrium between the molecules of the fiber medium, the Raman scattering noise is generated with a spectral bandwidth of about 200 nm, which is spontaneous Raman scattering and belongs to the intra-band noise. The spontaneous radiation of photons can occur in any direction, and there is no phase relationship. The spontaneous Raman scattering noise radiating forward along the fiber transmission direction is called forward spontaneous Raman scattering noise (P_f), and the backward spontaneous Raman scattering noise along the fiber transmission direction is called backward spontaneous Raman scattering noise (P_b).

$$P_f = \frac{P_{in} * p * \Delta x * (e^{-a_c L} - e^{-a_q L})}{a_q - a_c} \tag{1}$$

$$P_b = \frac{P_{in} * p * \Delta x * \left[1 - e^{-(a_c + a_q) * L}\right]}{a_q + a_c} \tag{2}$$

In the formula, P_{in} denotes the transmitting power of the classical signal; p is the spontaneous Raman scattering coefficient; it is related to the received bandwidth Δx of the quantum signals and the wavelength of the classical and quantum signals; a_q and a_c denote the fiber loss coefficients of quantum and classical signals, respectively; L is the fiber length [9].

4. Estimation of secure key rate for QKD systems - GLLP formula

Gottesman, Lo, Lutkenhanus, and Preskill collaborated to propose a method to calculate the key generation rate of a non-ideal quantum key distribution system. The calculation formula is named the GLLP formula. The derivation process of this paper is complicated; here we only give the conclusions used in this paper.

The starting point of the GLLP formula is that for a source with multiple photons, only a single photon pulse from it can generate a secure key. The lower bound S for the amount of secure key using the BB84 protocol is as follows:

$$S \geq q * \left(Q_1 * [1 - H(e_1)] - Q_\mu * f * H\left(E_\mu\right)\right) \tag{3}$$

Where $H(x) = -x * log_2(x) - (1 - x) * log_2(1 - x)$ is is the Shannon entropy function in binary form. f is the error correction efficiency of classical error correction codes, and q denotes the basis

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vector comparison efficiency. In the BB84 system with balanced basis vectors, the selection probability of both basis vectors is the same, and q =1/2. In unbalanced basis vectors, the value of q can be made close to 1 by increasing the selection probability of a certain basis vector. Q_μ and E_μ denote the total count rate and the BER (bit error ratio) in the signal state, respectively, and Q_1 and e_1 denote the single-photon count rate and the single-photon phase BER in the signal state, respectively. Q_μ and E_μ can be measured directly in the experiment. Q_μ and E_μ can be measured directly in experiments, and Q_1 and e_1 cannot be measured directly in experiments but can be estimated by the decoy-state method [10].

5. Simulation analysis.

Based on the above-proposed architecture, noise analysis, and secure key rate analysis, we simulate and analyze the noise power and secure key rate in this section. First, we analyze the Raman scattering noise spectrum, and second, we analyze the noise on the quantum channel, mainly consisting of the forward Raman scattering noise, the backward Raman scattering noise, and the total noise of both. Finally, we have analyzed the impact of each type of noise on the security key rate.

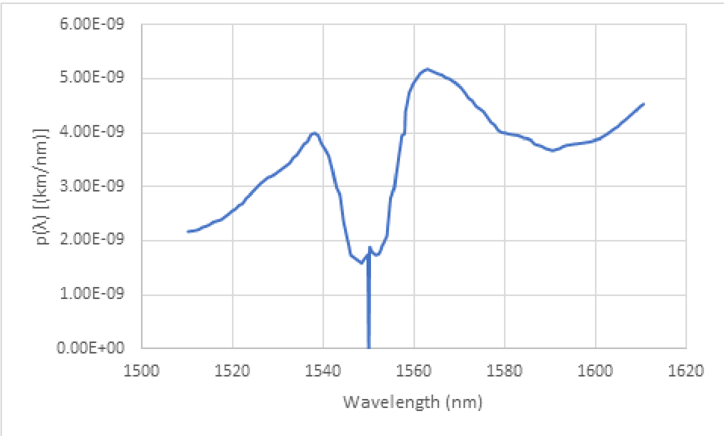

Figure 2. Measured Raman cross section of a pump laser wavelength centered at 1550 nm in a fiber [11].

As shown in Fig. 2, we simulated the $p(\lambda_c, \lambda_q)$ which denotes the normalized Raman cross section. In our paper, this parameter is deduced from the measurement results of $p(1550nm, \lambda_\delta)$ in Fig. 1. The distance between λ_δ and 1550 nm is equal to the distance between λ_c and λ_q. λ_c and λ_q are the wavelengths of the classical signal and the quantum signal, respectively.

The noise on both sides of 1550 nm is roughly symmetrical, but the long wavelength noise is greater than the short wavelength noise. The closer to the classical signal wavelength, the smaller the noise. The noise is minimized when both wavelengths are the same.

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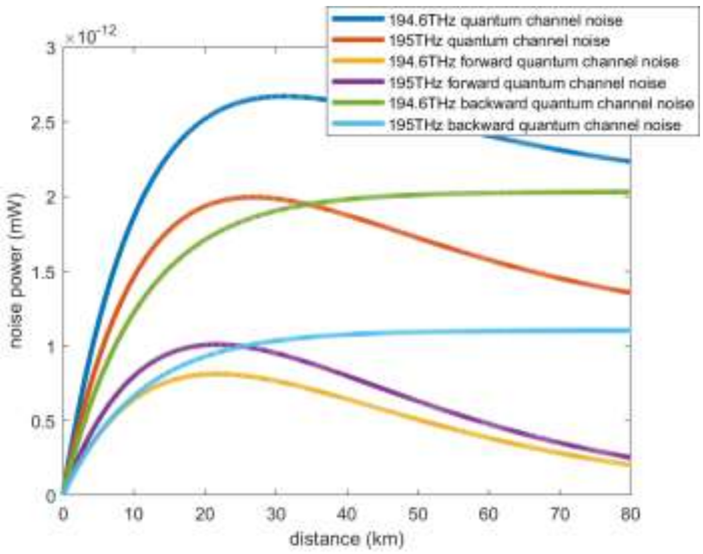

Figure 3. The relationship between noise power and distance.

As shown in Fig. 3, we simulated the relationship between noise power and distance. For a classical power of $1{*}10^{-3}$ mW, the quantum channel's sum noise power increases and then decreases with distance. The sum noise power of the 194.6 THz channel starts to decrease at 31.5 km, and the sum noise power of the 195 THz channel starts to decrease at 26.5 km. The backward noise power of the quantum channel increases with distance, but the growth trend slows down at 40 km. The forward noise power increases and then decreases with distance. It has a large difference between forward and backward noise power at 194.6 THz in the quantum channel. Also, at the 195THz quantum channel, it has equal forward and backward noise power at 25.3 km, and the backward noise power is greater than the forward noise power.

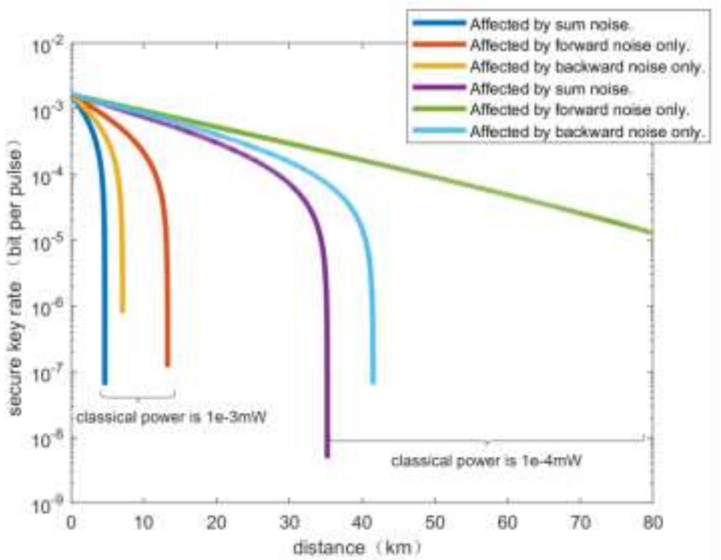

Figure 4. The relationship between secure key rate and distance.

As shown in Fig. 4, we simulated the relationship between secure key rate and distance. The secure key rate decreases slowly and then plummets as the distance increases. With the classical power of

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$1*10^{-3}$ mW, the secure key rate starts to plummet after 3.4 km. It decreases from $3.2*10^{-4}$ (bits/pulses) to $6.3*10^{-8}$ (bits/pulses) (4.6 km). With a classical power of $1*10^{-4}$ mW, the secure key rate starts to plummet after 31.6km. It decreases from $4.6*10^{-5}$ (bit/pulse) to $4.8*10^{-5}$ (bits/pulses) (35.2 km). It is clear from the images that the backward noise has a greater effect on the secure key rate. In the case of classical power of $1*10^{-3}$ mW, the channel can transmit up to 13.2km if it is affected by forward noise only, and up to 7km if it is affected by backward noise only. In the case of classical power of $1*10^{-3}$ mW, the channel can transmit up to 80 km or more if it is affected only by forward noise, and up to 41 km if it is affected only by backward noise.

According to the above simulation, The Raman cross section of the classical signal at different wavelengths can be regarded as a translation of the curve in Fig. 1. Therefore, in the c-band, if the quantum signal is sufficiently close to the classical signal, the Raman noise will be minimized. The reduction of classical power can lead to an increase in the secure key rate. Therefore, when designing a quantum-safe 5G fronthaul architecture, a channel with low noise should be selected, and the power of the classical signal should be reduced as much as possible while ensuring the performance of the classical system.

6. Conclusion

In the previous four sections, we built the architecture, analyzed the noise, calculated the secure key rate, and analyzed the simulation.

1) Build the architecture: combine DWDM with quantum key distribution using the BB84 protocol. The DWDM-QKD 5G fronthaul architecture is appropriate for short-distance fronthaul with low cryptographic requirements.

2) Analyze the noise: the quantum channel in WDM is affected by spontaneous Raman scattering of the classical channel. We analyze the forward and backward noise.

3) Calculate the secure key rate: The lower bound of the number of secure keys using the BB84 protocol is calculated by the GLLP formula.

4) Analytical simulation: The Raman cross section of a pump laser wavelength centered at 1550 nm in fiber, the relationship between distance and noise power, and the relationship between distance and secure key rate are simulated separately.

Based on the above, we can find that the quantum channel is mainly affected by the spontaneous Raman scattering of the classical channel, and the reduction of classical power can lead to an increase in the secure key rate. A channel with low noise should be selected, and the power of the classical signal should be reduced as much as possible while ensuring the performance of the classical system.

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