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A Review of Quantum Communication with Photons: Principles, Protocols, and Progress

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Abstract- This paper presents a comprehensive review of quantum communication using photons, based primarily on the foundational work of Krenn, Malik, Scheidl, Ursin, and Zeilinger. The review covers core quantum mechanical principles such as qubits, superposition, entanglement, and the no-cloning theorem, and explains how these principles underpin secure quantum communication. Key protocols including Quantum Key Distribution (QKD) and quantum teleportation are discussed. The paper further explores long-distance ground-based and space-based experiments, and examines the emerging role of high-dimensional quantum states using Orbital Angular Momentum (OAM) of photons. The aim is to provide a structured understanding of the current state and future potential of quantum communication technologies.

Keywords – Quantum Communication, Photons, Qubits, Quantum Key Distribution (QKD), Quantum Teleportation, Entanglement, Orbital Angular Momentum (OAM), No-Cloning Theorem, BB84 Protocol, High- Dimensional Entanglement.

I. INTRODUCTION

Quantum physics, since its inception, has fundamentally transformed humanity's understanding of nature at the microscopic scale. Over the past few decades, the convergence of quantum mechanics and information science has given rise to the rapidly growing field of quantum information. This field offers powerful new paradigms for communication, computation, and data security — capabilities that far exceed what classical systems can provide [1].

This review paper examines the foundational principles of quantum communication with photons as presented by Krenn et al. [1] in their chapter titled "Quantum Communication with Photons" (published in Optics in Our Time, Springer, 2016). The content of this paper is drawn entirely from that source, and we acknowledge the original authors — Mario Krenn, Mehul Malik, Thomas Scheidl, Rupert Ursin, and Anton Zeilinger for their seminal contribution to the field.
Photons are among the most practical carriers of quantum information due to their minimal interaction with the environment, making them ideal for long-distance transmission. This paper reviews the core concepts of quantum bits, entanglement, quantum cryptography, teleportation, and the exciting frontier of high-dimensional quantum communication using the orbital angular momentum (OAM) of light.

II. QUANTUM BITS AND SUPERPOSITION

In classical computing and communication, information is represented as bits, each taking the value 0 or 1. A quantum bit, or qubit, extends this concept by exploiting the quantum mechanical principle of superposition — the ability of a quantum system to exist simultaneously in a combination of multiple states [1].

A photon is one of the most versatile physical realizations of a qubit. For instance, a photon's polarization — horizontal or vertical — can encode the values 0 and 1 respectively. More importantly, any arbitrary polarization state of a photon can be expressed as a superposition of horizontal and vertical components. Such polarization qubits can be generated, manipulated, and measured using relatively simple linear optical devices such as wave plates and beam splitters [1].

A fundamental distinction must be drawn between a coherent superposition and an incoherent mixture. In a coherent superposition, the quantum state carries definite phase relations. For example, a photon in an equal coherent superposition of horizontal and vertical polarization is diagonally polarized at +45°, and a polarizer at that angle will transmit it with 100% certainty. In contrast, an incoherent mixture gives only a 50% transmission probability [1].

Beyond polarization, photons also carry information in their spatial and temporal degrees of freedom. Using modes such as the Laguerre-Gaussian family, a photon can be prepared in a superposition of many orthogonal spatial modes, enabling what are called high-dimensional quantum states. The dimensionality of such states is limited only by the optical instruments used [1].

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A. The No-Cloning Theorem

The no-cloning theorem, proven by Wootters and Zurek in 1982 [2], states that it is fundamentally impossible to produce a perfect copy of an unknown quantum state without disturbing the original. This result follows directly from the linearity of quantum mechanics. It can be shown that any hypothetical cloning operation leads to contradictions when applied to superposition states [1].

The no-cloning theorem has profound implications for quantum communication. It ensures that any eavesdropper attempting to intercept and copy quantum signals will inevitably introduce detectable errors, thereby guaranteeing the security of quantum cryptographic protocols [1].

III. QUANTUM ENTANGLEMENT

One of the most remarkable phenomena in quantum mechanics is entanglement. When two or more particles are prepared in an entangled state, their individual quantum states cannot be described independently of one another. Instead, the complete information about the system is encoded entirely in the correlations between the particles [1].

A key feature of entanglement is that a measurement on one particle of an entangled pair instantaneously determines the state of the distant partner, regardless of the spatial separation between them. These instantaneous correlations, while surprising, do not allow information to be transmitted faster than light, as the measurement outcomes remain inherently random from the perspective of each observer independently [1].

Quantum entanglement has been experimentally verified in numerous experiments over several decades, with results consistently confirming the predictions of quantum mechanics and ruling out local hidden variable theories [1]. Both polarization and orbital angular momentum can serve as the degree of freedom for entanglement, enabling a rich variety of quantum communication protocols.

Mutually Unbiased Bases

Mutually unbiased bases (MUBs) are sets of measurement bases with the property that a quantum state precisely defined in one basis is entirely undetermined in any other. For polarization qubits, three MUBs exist: horizontal/vertical (H/V), diagonal/anti-diagonal (D/A), and left/right-circular (L/R) polarization. This property is the fundamental ingredient enabling security in quantum key distribution [1].

In higher-dimensional systems, the number of MUBs increases with dimension in a non-trivial way. For prime- power dimensions d, the number of MUBs is d+1. Interestingly, the number of MUBs for certain non-prime- power dimensions (such as d=6) remains an open mathematical question, with deep implications for quantum communication security [1].

IV. QUANTUM COMMUNICATION SCHEMES

Quantum Key Distribution (QKD)

Quantum Key Distribution is a method that allows two parties — conventionally called Alice and Bob — to establish a shared secret key whose security is guaranteed by the laws of physics rather than computational hardness [1]. This is a fundamental advantage over classical cryptography, where the security of public-key systems such as RSA depends on the assumed difficulty of factoring large numbers — a difficulty that quantum computers using Shor's algorithm [3] can overcome.
The first and most widely studied QKD protocol is BB84, proposed by Bennett and Brassard in 1984 [4]. In this protocol, Alice sends single photons to Bob, each encoded randomly in one of four polarization states drawn from two complementary bases (H/V or D/A). Bob measures each photon randomly in one of these two bases. After transmission, they publicly announce their choice of bases (not results), discard measurements where their bases differed, and retain only the matching ones to form the sifted key [1].

The security of QKD is rooted in the no-cloning theorem and superposition. Any eavesdropper (Eve) attempting to intercept the quantum channel must perform measurements, which will disturb the quantum states and introduce detectable errors into the sifted key. If the measured error rate exceeds a threshold, the key is discarded; otherwise, classical post-processing steps (error correction and privacy amplification) are applied to yield a final secure key [1].

An alternative entanglement-based QKD protocol was proposed by Ekert in 1991 [5]. In this scheme, Alice and Bob share an entangled photon pair and perform measurements in randomly chosen bases. The intrinsic randomness of the entangled state ensures that neither party (nor any potential eavesdropper) can predict the key bits, and verification of entanglement certifies the security of the protocol even if the photon source is untrusted [1].

Quantum Teleportation

Quantum teleportation is a protocol by which the quantum state of a particle is transferred to a distant particle, without physically transmitting the particle itself and without the quantum state ever existing at any intermediate location [1]. It is important to note that teleportation does not violate the no-cloning theorem — the original state is destroyed as part of the protocol — nor does it allow faster-than-light communication, since a classical channel is required to complete the transfer.
The protocol requires three qubits: the qubit to be teleported (qubit 1, in Alice's possession) and a pre-shared entangled pair

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(qubits 2 and 3, held by Alice and Bob respectively). Alice performs a joint Bell-state measurement (BSM) on qubits 1 and 2, which yields one of four random outcomes. She then communicates this outcome to Bob via a classical channel. Using this classical information, Bob applies the appropriate correction operation to qubit 3, which then collapses into the original state of qubit 1 [1].

Quantum teleportation is a critical component of quantum repeaters — devices required to extend quantum communication over large distances by performing entanglement swapping between adjacent links in a network [1].

V. LONG-DISTANCE QUANTUM COMMUNICATION

Ground-Based Experiments

A central experimental challenge in quantum communication is maintaining quantum coherence and entanglement over large distances. Several landmark free- space experiments have been conducted to test and validate this. A notable milestone was achieved by Ursin et al. in 2007 [6], who distributed entangled photon pairs between the Canary Islands of La Palma and Tenerife over a 144 km free-space link. This demonstrated that photon entanglement can survive real-world atmospheric propagation over distances relevant to satellite-to-ground links [1].

The race for long-distance quantum teleportation produced a remarkable parallel between Austrian and Chinese research groups. In 2012, the Chinese group successfully teleported quantum states across a 97 km free- space channel over Qinghai Lake [7]. Just eight days later, the Austrian group reported quantum teleportation over 143 km between La Palma and Tenerife [8]. These results collectively demonstrated the feasibility of ground-to- satellite quantum communication [1].

Space-Based Quantum Communication

Ground-based experiments are ultimately limited by the curvature of the Earth, which prevents line-of-sight links beyond a few hundred kilometers. The logical extension is to deploy quantum communication infrastructure in space. Several international programs in Europe, China, the USA, Singapore, and Canada have been actively pursuing satellite-based quantum communication [1].

The primary technological challenges include minimizing photon loss due to atmospheric absorption, beam diffraction, pointing errors, and turbulence — all of which contribute typical link losses of 30 to 40 dB in satellite-to-ground scenarios. These challenges require bright entangled photon sources, high-efficiency single- photon detectors, and precise time synchronization between the satellite and ground stations [1].

Quantum repeaters represent the long-term technological solution for fiber-based global networks. First proposed in 1998 [9], quantum repeaters combine entanglement swapping and quantum memories to extend communication range beyond the limits imposed by photon loss in optical fibers, which currently restrict direct quantum communication to a few hundred kilometers [1].

VI. HIGH-DIMENSIONAL QUANTUM COMMUNICATION

Orbital Angular Momentum of Photons

While polarization is limited to a two-dimensional (qubit) Hilbert space, the orbital angular momentum (OAM) of photons offers a discrete, theoretically unbounded state space. Photons carrying OAM are described by Laguerre-Gaussian modes, characterized by an integer quantum number ℓ that can range from negative infinity to positive infinity. This allows a single photon to carry far more than one bit of information [1]. The ability to encode information in high-dimensional OAM states brings two major advantages: increased information density (more bits per photon) and enhanced robustness against noise and eavesdropping. Recent classical optical experiments have demonstrated data transmission rates exceeding 100 Tbit/s using OAM multiplexing alongside other degrees of freedom [1]. In the quantum domain, OAM-based QKD protocols have been developed and experimentally demonstrated, including a seven-dimensional BB84 analog achieving 2.05 bits per sifted photon [10].

High-Dimensional Entanglement

Photon pairs can be entangled in their OAM, creating high-dimensional entangled states that share significantly more information non-locally than standard qubit entanglement. Experiments have confirmed two-photon entanglement in 100 or more dimensions of spatial mode structure. In such states, the outcome of measuring one photon's OAM immediately determines the outcome for the distant partner, yet neither photon had a definite value before measurement [1].

Multi-photon, multi-dimensional entanglement has also been demonstrated. A three-photon state asymmetrically entangled in their OAM — with two photons in a three-dimensional space and one in a two- dimensional space — was produced and verified. Such states enable layered quantum communication protocols, where multiple parties can share nested layers of secure information [1].

Transmission of Twisted Photons

A practical challenge for OAM-based quantum communication is preserving the spatial mode structure of photons during

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transmission. Conventional optical fibers cause different OAM modes to mix, destroying the encoded information. While specially designed fibers have shown promising results for short-range classical OAM transmission, they have not yet been demonstrated in the quantum regime [1].

Free-space transmission is the most viable approach, particularly for Earth-to-satellite links where it is the only option. Recent experiments across a 3 km intra-city link in Vienna demonstrated that high-dimensional OAM entanglement can survive free-space propagation through atmospheric turbulence, with adaptive optics techniques offering a path toward further improvement [1].

VII. CONCLUSION

Quantum communication with photons represents one of the most promising frontiers of modern technology. By exploiting quantum mechanical principles — superposition, entanglement, and the no-cloning theorem — it is possible to establish communication channels whose security is guaranteed by the laws of nature rather than computational assumptions.

This review, based on the foundational work of Krenn, Malik, Scheidl, Ursin, and Zeilinger [1], has surveyed the core theoretical concepts, key protocols (QKD and teleportation), experimental milestones in long-distance communication, and the emerging paradigm of high- dimensional quantum communication using OAM. Together, these developments suggest that a global quantum communication network, connecting ground stations and satellites across continents, is not merely a theoretical vision but an achievable technological goal.

Significant challenges remain, including the development of efficient quantum memories, practical quantum repeaters, and robust sources of high-dimensional entangled photon pairs compatible with the space environment. However, the trajectory of experimental achievements — from laboratory demonstrations to inter- island links and satellite proposals — points clearly toward a quantum communication revolution in the years ahead.

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