Communication via Quantum Particles

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Abstract- *Quantum communication is developed on a batch of disruptive concepts and technologies. Quantum communication based on the laws of quantum physics i.e. nearly related to quantum information processing and quantum teleportation. Its most interesting application is protecting information channels with the assistance of quantum cryptography. Innovation will continue to run the global economy into the upcoming decade. This paper explains principles of quantum communication, superposition, entanglement & some applications scenarios like quantum teleportation and Quantum Key Distribution (QKD) technology. This paper also explained basic postulates of quantum mechanics.*

Key words: **quantum mechanics, polarization, superposition, quantum entanglement, cryptography, QKD.**

1. INTRODUCTION

today electronics is beginning to face physically fundamental limitations (well described by the Moore law) which are posing some concerns about the long-term applicability for the next generations infrastructures. It is a common belief that, in the upcoming days, electronic technologies will be more and more complemented by Quantum Optics.

Quantum Optics has been a well-established field of research in physics since the end of the seventies. While in Telecommunications optics has been used mainly for wavelengths transmission with lasers over optical fibers, Quantum Optics is a clever technique to transport and control optical signals with a greater number of degrees of freedom [3]. In should be mentioned that Quantum Optics has also influenced observation techniques with multiple telescopes, and it has introduced the anti-bunching properties that are nowadays used to make sure that the system of concern is quantum, or to make sure that one even features a single photon.

As the need of increased bandwidth for the present day, data rate increases and together the security and computational requirement, the classical approaches cease to give a reliable solution in the field of communication and computing. This dilemma along with the growth of quantum physics led to the birth of Quantum Communication.

Quantum communication is a area of applied quantum physics nearly related to quantum data processing and teleportation. Its most amazing application is securing information channels against eavesdropping by means of quantum cryptography. The most well-known and developed application of quantum cryptography is quantum key distribution (QKD) [9,11].

2. POSTULATES OF QUANTUM MECHANICS

In quantum mechanics, there are five basic postulates connecting with quantum communication, which are the result of experimental observations. They divided their place with axioms in the Euclidean Geometry. We then have a look at the postulates below one by one [15].

2.1 First Postulate (state space)

It explains any isolated physical system will correspond to a vector space, which usually called a Hilbert space. The system state will be shown by a unit vector in this space [15].

A very simple example of a closed physical system is two-dimensional Hilbert space. The two-dimensional vector $v = [a, b]^T = a\mathbb{O} + b\mathbb{I}$, where $\mathbb{O} = [1,0]^T$ and $\mathbb{I} = [01]^T$stand for the orthonormal basis vectors of the Hilbert space V and a, b ∈ C, represents the state of the system [1]. The quantum state vector's coordinates are called probability amplitudes as in describing the situation of particles in Schrodinger wave function they play the role of amplitudes.

2.2 Second Postulate (Hermitian operators)

In quantum mechanics, the mechanical quantity F, which can be observed in any experiment, could be described by a linear Hermitian operator [15]. Hermitian operators play an integral role in quantum mechanics due to their properties, such as their eigenvalues are always real. This is important because their eigenvalues correspond to physical properties of a system, which cannot be imaginary or complex.

2.3 Third Postulate (evolution)

It expresses that the evolution of any closed system over time can be characterized by unitary transformation, which depend only on the starting and ending time of the evolution [1].

2.4 Fourth postulate (composite system)

Considering a physical system composed by two individual system X and Y. The state space of composite system H can be determined through the tensor product of X and Y, that is H = X⊗Y. Then if we define x ∈ X, y ∈ Y, then we can get the joint state of the composite system to be h = x⊗y [1].

2.5 Fifth Postulate (measurement)

Any quantum measurement can be described by means of a set of measurement operators i.e. {Mm}, where m stands for the possible results of the measurement [1]. It satisfies the completeness equation:

$$\sum_m M_m^{\dagger} M_m = 1$$

These operators are applied on the state space of system measured. If the state of quantum system before the measurement is v, then the probability of obtaining the result m after measurement is given by

$$P(M|v) = v^{\dagger} M_m^{\dagger} M_m v$$

The state of the system after the measurement is:

$$v' = \frac{M_m v}{v^{\dagger} M_m^{\dagger} M_m v}$$

Finally, the completeness equation states that the sum of probabilities is equal to one:

$$\sum_m P(M|v) = \sum_m v^{\dagger} M_m^{\dagger} M_m v \equiv 1$$

Thus, these are postulates that rule the quantum world of communication. To do the research and manipulations one might require knowledge of mathematics. Even if you are not too much into mathematics it is not hard to understand the concepts and principles which are explained in the paper. Let us consider one by one.

3. CONCEPT AND PRINCIPLES OF QUANTUM COMMUNICATION

The most fundamental physical concepts and principles of quantum communication are

3.1 Superposition

Superposition is a fundamental phenomenon of quantum mechanics where two or more quantum states can be added together "superposed," and the outcome will be another valid quantum state. The feature of a quantum system means it exists in several quantum states at the same time. Superposition principle permits the description of a physical system as a superposition of alternatives [4].

3.2 Polarization

Polarization is the orientation of oscillations in the plane perpendicular to the transverse wave's direction of travel. Even though in the quantum context, light is treated as a group of particles called photons, they preserve the property of polarization and follows the postulates.

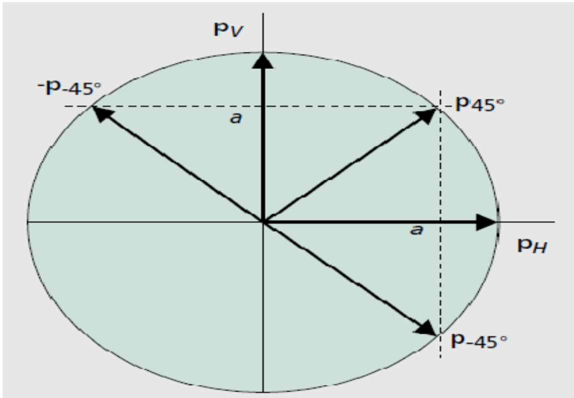

Fig. 1: Horizontal and vertical polarization of light.

The above figures explain the horizontal as well as vertical polarization of light and the vector representation of polarization.

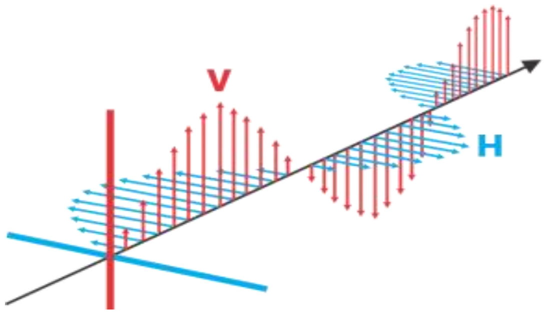

Fig. 2: Vector representation of different photon polarizations [8]

In Fig. 2 p_v and p_h represents the horizontal and vertical polarization and p_θ represents the angular polarization [1].

In classical approach, if we want to transmit a logic 1 bit, we may send either horizontal or vertical polarized light and nothing for logic 0 bit or further option is to encode vertical polarized light as logic 1 and horizontal as logic 0 and transmit it. In both the cases it is easy to determine the information sent from the received bit [1]. Now instead if 45-degree polarized light is transmitting no one can say whether it is logic 1 or logic 0 as it is equal distance from both the axes. Thus, a quantum measurement device decodes half it as logic 1 and remaining as logic 0. This identification is completely random and is the beauty of quantum mechanics. It highlights the indefinity of quantum mechanics. How does it make sense? A genuine query. How to know which bit was sent and when? In order to answer these questions, let us take the example of coin tossing experiment [1].

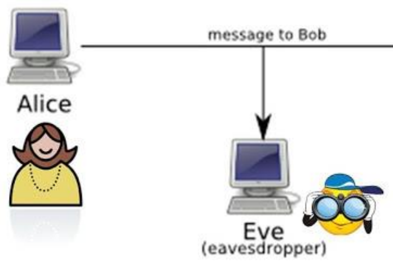

Fig. 3: Alice transmits message to bob and eavesdropper.

Above picture shows that there are three persons Alice, Bob and Eve(eavesdropper). If Alice wants to transmit information say '1' and '0' to Bob which they agree on a code that 'tail' represents '0' and 'head' represents '1'. Their communication was not at all a problem until when Eve came in between. Eve take the coin sent by Alice and flips its state randomly which left Bob in confusion. Now Alice and Bob learned quantum mechanics and decided to utilize its properties. Thus, now rather than just sending the coin, Alice rotated the coin and sent it to Bob. Eve again took the coin and flipped its state and transferred it to Bob without his knowledge. But now Bob knows, it's not the head or tail that represents the information but the direction of rotation and he simply decodes clock wise as logic 1 and anti-clock wise as logic 0. Thus by adding no redundant bit, faithful communication was created between Alice and Bob even in the presence of Eve. This analogy can now be extended to real framework by replacing the coin by photon and the rotation by polarization. Even though certain properties are different, if the polarization is preserved, successful communication can be achieved [1,8].

3.3 Entanglement

Entanglement is another beautiful physical phenomena observed in quantum world. Entanglement is that the essence of quantum physics. Quantum entanglement occurs when a group of particles interact in a way that each quantum state cannot be described independently of the states of the others. Entanglement describes correlations between physical systems that cannot be modelled by classical means [4]. This surely provides a way to improve security and probability of future communication.

Imagine that there are two coins which can be entangled to explain the scenario. One person tosses a coin so much times and records the times for the coin to show the results i.e. "heads" and "tails", which is about half times each respectively. One thing to clear up is that each result is unpredictable before the measurement. Then this person tosses a second coin that would generate similar but different results. After that, if we take a look at the records of the experiment, it will show a correlation. When one-coin shows "heads", another definitely show "tails". Since we have described the states of the two coins to be entangled. Before the toss and measurement, the outcome is unknown, but will be correlated. As soon as one coin is tossed, the probability of outcomes generated by tossing another coin is decided. Although people cannot predict each result individually, the final outcomes are correlated and there will be no uncertainty of second coin if we already toss a coin. Let us now relate the analogy to quantum communication world. Now consider the photons, if they`re entangled, they will be separated of infinite distance, but their measurement will still perform exact correlation of the result [15].

The entanglement is very important in the quantum world, and can be applied to many applications of communication like quantum teleportation, quantum cryptography, quantum key distribution etc.

4. QUANTUM COMMUNICATION APPLICATION

4.1 Quantum Teleportation

Quantum teleportation is a technology that works on the transformation between scattered quantum entanglements and few physical information to transmit quantum states to impulsive distances. It is a very important communication methodology for transferring quantum states, and it id the premise of scalable quantum networks and distributed quantum computing. In quantum teleportation, the two communicating parties in two distant places initial share a pair of entangled particles. Then one among them distinguishes the particles of the quantum state to be transmitted (generally not associated with entangled particles) from the entangled particles in its own hand, and informs the opposite party of the results of the discrimination. The opposite party can perform the corresponding unitary operation depend on the obtained information. Entangled state pre-distribution, independent quantum source interference and pre-feedback are the three major components of quantum teleportation [15].

4.2 Quantum Cryptography

Cryptography is the process of encrypting data, or converting simple text into confuse text so that only someone who has the right "key" can read it. Quantum cryptography, by extension, directly uses the principles of quantum mechanics for encryption of data and transmit it in a way that cannot be hacked, that's why security of quantum cryptography is guaranteed by the principles of quantum mechanics [16].

The most well-known and popular application of quantum cryptography is quantum key distribution (QKD). The principle of operation of a QKD system is quite straightforward: Imagine you have two people, Alice and Bob, who want to send a secret message to each other that no one else can interrupt. With QKD, Alice transmits Bob a series of polarized photons over a fiber optic cable. This cable doesn't need to be secured because the photons have a scrambled quantum state.

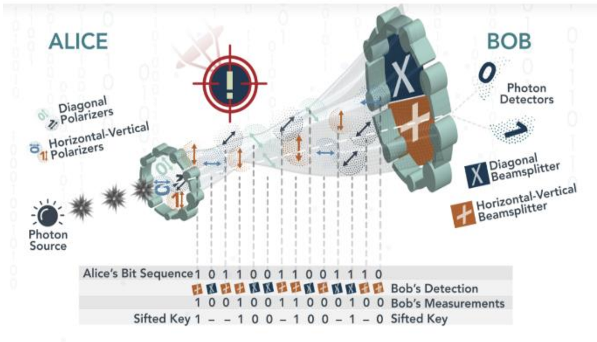

Fig. 4: encryption & decryption of photon.

If an eavesdropper, attempt by Eve, tries to watch on the conversation, she has got to read each photon to read the key. Then she must pass that photon towards Bob. By reading the photon, Eve will almost surely disturb the transmitted quantum states. Thus, by carefully estimating the error rate of the transmitted quantum states, Alice and Bob know with great confidence the quantum channel error rate. This alerts Alice and Bob that someone is watching and the key has been compromised, so they throw out the key. Alice has send a replacement key to Bob that`s not compromised, then Bob can use that key to read the secret [10,16].

Typical set-up:

In a typical QKD set-up, the photons are generated by photon source, encrypt into binary values and then send to the receiver either via any medium. The receiver then decodes the state of photons and determine them using single photon sensitive detectors. There are several methods for encrypting and decrypting the photons [6]:

- via polarization: the binary information (i.e., representing "0" and "1") defined by the polarization of the single photons, e.g. binary "0" correlates with the horizontally and 45 degree left polarized photon while binary "1" with vertically and 45 degree right polarized photon.

- via the phase, which requires the use of a interferometer system: the phase difference $\Delta\varphi = \varphi$Alice - φBob of the two interferometers is then used for encrypting the binary values, e.g., a phase difference $\Delta\varphi=\pi$ correlates with the binary "1" and the phase difference $\Delta\varphi=0$ correlates with the binary "0".

- via entangled photons, which requires one transmitter of entangled photon pairs and two receivers (Alice and Bob) each outfit with a polarizer. Alice and Bob set the two angles at their specific polarization rotator discretely. If the angles of Alice and Bob are similar, then both photons behave precisely the same at the beam splitter, i.e., they're either transmitted (binary "1") or reflected (binary "0").

5. CONCLUSION

Quantum mechanics is beginning to play an important role in the field of communication. I have reviewed the main postulates of quantum mechanics, Superposition, polarization, quantum entanglement and various important application like teleportation, cryptography and quantum key distribution. In the upcoming years, quantum communication is move to take over and replace its classical counter parts in the field of communication. Quantum field opens a door in many sectors of expertise like algorithm development, memory manufacturing, networking, space communication and many more. So, it is an ideal teaching tool and is attracting smart young physicists who are studying to construct the bridge between quantum physics and communication technologies.

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