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Entanglement and Superposition in Quantum Computing and Communication

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ABSTRACT
Quantum computing and communication is the future of mass communication. Although we still don't know how much time it will take to become reality. It has all ingredient like security, immune to eavesdropping, high speed, and much more needed for a secure communication which we will never achieve with classical communication. Quantum mechanical phenomenon such as entanglement and superposition are key for Quantum computing and communication. With advancement in technology, scientists and physicist are able to understand these phenomenon better and better, which ultimately leads to advancement in Quantum computing and communication. This paper focus on the quantum mechanical phenomenon like entanglement and superposition and briefly discussed itsapplication in Quantum computing and communication. Different methods of preparation of qubits are also explained in this paper. Some example of quantum communication such as teleportation, Quantum Key Cryptography, Dense codingare explained theoreticallyin simple words. Finally, reviewed some paper on implementation and current updates of quantum computing and communication in real world.
Key words: Entanglement, Superposition, Quantum Communication, Teleportation, Quantum Key Cryptography, Dense coding

I. INTRODUCTION

Classical approach of communication is not efficient in providing security and high speed. As the technology get advance this type of communication will face more and more problems in coming future. Currently banks, business sector, IT industries, military, and government etc. are using classical approach of communication for transfer of money, important data, and highly secure files through internet. Before quantum computer, scientists believed this way of communication to besecured. Because it is impossible for a conventional computer to factor numbers that are longer than 2048 bits, which is the basis of the most commonly used form of RSA encryption [1].Moreover, conventional computers are supposed to take more than hundred years to find the prime factor of such big number. So, it pose no risk in communication until and unless quantum computer comes in play in field of computing and communication. Shor's algorithm which is a quantum algorithm discovered by the Peter Shor in 1994, can be used by quantum computer tofactors large numbers and crack trapdoor based codes within reasonable time period. A powerful quantum computer can factorise any big number with ease and in reasonable time, enough time for eavesdropper to hack and obtain secure data. This result shock the security industry all over the world.

If we look into the development of quantum computing and communication, Richard Feynman was the first who put his opinion that conventional way of computing is not enough to represent and solve complex equation within reasonable time. He gave the idea that quantum mechanical phenomenon could be used to computeand simulate such complex equation by representing the data at quantum level. The University of Geneva in Switzerland was the first to verify the quantum secret sharing scheme based on the GHZ triplet state with empirical evidence in 2006 [2]. From birth to till year 2021, different companies like IBM, Google, IonQ and Rigetti are working hard to build a universal quantum computer which can overcome all the limitations of conventional computer. This paper is organized as follows: section 2 discussed about qubits, section 3 focus on different methods for preparation of qubits. Some important quantum gates are explained in section 4. Section 5, briefly discuss the quantum mechanical phenomenon. In section 6 we have explained application of quantum communication like teleportation, QKD and dense coding and lastly section 7 is about conclusion and summary of this paper.

II. QUBIT

A qubit is a quantum bit, the counterpart in quantum computing to the binary digit or bit of classical computing [3]. In quantum computing, a qubit or quantum bit is the basic unit of quantum information. To define the quantum unit of information the name qubit was coined by Schumacher [1995]. The general pure state of a qubit system has the following form, [4]

$$|\psi\rangle = \cos\frac{\theta}{2}|0\rangle + e^{i\phi}\sin\frac{\theta}{2}|1\rangle.$$

In conventional computer, semiconductor devices such as transistors and capacitorsare used to represent binary bit to store information. For example, a fully charged capacitor can represents 1 and a discharged capacitor can represents 0. The limitation of the binary digit is, it can either stay in the state 0 or 1 at a time. This limitation has been overcome by the quantum bit. An atom or ion in a controlled quantum state can behave as a qubit. Quantum world has some peculiar features like superposition which enables the qubit to represents all quantum states between 0 and 1 including 0 and 1 simultaneously.

The Bloch sphere is used to visualize the states of a single qubit. The different axes can be seen on the Bloch-sphere represents the three mutually unbiased bases that exist for a two-dimensional Hilbert-space. In quantum physics, a state $|\psi\rangle$is used to describe the physical state of the system, and in mathematical terms it is defined as a vector in a Hilbert space. Hilbert space represents in physical terms are different degrees of freedom of the system. Such degrees of freedom can be the spatial coordinates (transverse spatial), temporal properties (longitudinal spatial), polarization, spin, or any other physical entity which we would like to use to describe the system. Any two diagonally opposite states on the Bloch sphere in fig. 1, form an orthogonal basis which describe the qubit, and any two orthogonal lines through the origin define two mutually unbiased bases. Pure states lie on the outer shell and mixed states inside [4].

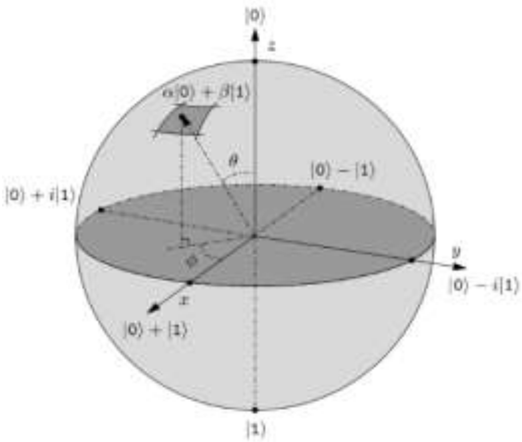

Fig. 1. Bloch-sphere [4].

Analogous to conventional computers, Quantum computers use the qubits instead of bits to store data and perform computations. Generation of an efficient and stable qubit is a primary step for quantum computing.There are various trapping system to trap the qubit in a controlled quantum state like penning trap which uses combination of electric and magnetic fields to trap the qubit. Paul or quadrupole trap uses a time-dependent electric field to trap the qubit.Currently different companies are using different techniques to trap the ion or atom to represent a qubit, to store data and perform quantum computing and communication. Companies like IBM, Google, and Rigetti Computing, are using superconducting circuits cooled to temperatures colder than deep space to trap the qubit. Other, company like IonQ uses electromagnetic fields on a silicon chip in ultra-high-vacuum chambers to trap individual atoms.

III. PREPARATION OF QUBITS

The qubit, also known as quantum bit, is the basic unit of quantum information, which corresponds to the basic information unit in classical theory bit [5]. The state of a classical bit is 0 or 1, but the state of a qubit is described by a linear combination of computational basis states 0 or 1 state, corresponding to Dirac notation $|0\rangle$, $|1\rangle$ respectively, usually called superposition and can be represented as: $\psi = \alpha|0\rangle + \beta|1\rangle$, where α, β are complex numbers and both satisfy normalization conditions such that $|\alpha|^2 + |\beta|^2 = 1$, [6]. The beam

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splitter has four input ports and four output ports. As the name suggests it can be used to split the light of two input ports, a and b, into two output ports, a_0 and b_0. The different types of interference effects produce in a beam splitter is shown in table 1 [4].

	$\|\psi_{ab}\rangle$	$\overset{B}{\longleftrightarrow}$	$\|\psi_{a'b'}\rangle$
1	$\frac{1}{\sqrt{2}}(\|01\rangle + i\|10\rangle)$		$i\|01\rangle$
2	$\frac{1}{\sqrt{2}}(\|01\rangle - i\|10\rangle)$		$\|10\rangle$
3	$\|01\rangle$		$\frac{1}{\sqrt{2}}(i\|01\rangle + \|10\rangle)$
4	$\|10\rangle$		$\frac{1}{\sqrt{2}}(\|01\rangle + i\|10\rangle)$
5	$\|11\rangle$		$\frac{i}{\sqrt{2}}(\|02\rangle + \|20\rangle)$
6	$\frac{1}{\sqrt{2}}(\|02\rangle - \|20\rangle)$		$\frac{1}{\sqrt{2}}(\|20\rangle - \|02\rangle)$
7	$\|20\rangle$		$-\frac{1}{2}\|20\rangle + i\frac{1}{\sqrt{2}}\|11\rangle + \frac{1}{2}\|02\rangle$
8	$\|02\rangle$		$\frac{1}{2}\|20\rangle + i\frac{1}{\sqrt{2}}\|11\rangle - \frac{1}{2}\|02\rangle$
9	$\frac{1}{\sqrt{2}}(\|02\rangle + \|20\rangle)$		$i\|11\rangle$

Table: 1. The different types of interference effects in a beam splitter

To prepare a qubit we need a quantized and coherent system consisting of two levels. Such system can be realized using the energy levels of an atom, the spin of particles, or any other degree of freedom. There are different ways to produce entangled qubits. Let's take a look on different ways of representing the qubits one by one:

3.1. Polarization qubit

The most popular method to produce a qubit is the polarization of the electrical field. The polarization can be H/V (horizontal/vertical), D/A (diagonal/ anti-diagonal), or R/L (right/left circular), forming three mutually unbiased bases. A simple qubit has the form $|\psi\rangle = \alpha\,|R\rangle + \beta|L\rangle = \alpha\,|0\rangle + \beta|1\rangle$. Polarized qubits are very simple to encode and decode using half-wave plates, quarter-wave plates, and polarizing beam splitters, but are problematic to transport over fibers [4].

3.2. Phase qubit

The phase is the most commonly used representation for the qubit in faint-pulse quantum cryptography. The phase is naturally chosen to encode the information to overcome the problems using polarization in optical fibers. The phase-qubit is prepared and analyzed using interferometers and phase-modulators. The photon coherence length needs to be longer than the path-length mismatch between the different arms of the interferometers [4].

3.3. Dual-rail qubit

In this method the qubit is encoded in two spatially different modes, such that a single photon exists in a superposition of being in either mode. Sometimes it is also called a bosonic qubit. The qubit is prepared by a semi-transparent mirror, or beam splitter. The photon in each mode is attributed the value 0 or 1, according to the notation $|n_0 n_1\rangle$, where n denotes the number of photons in each arm (mode). Thus, the two modes define a single qubit system, which has the form $|\psi\rangle = \alpha|01\rangle^{t_1} + \beta e^{i\phi}|01\rangle^{t_2} = \alpha\,|0\rangle + \beta e^{i\phi}|1\rangle$ [4].

3.4. Continuous-time qubit

This type of coding is usually associated with entanglement between two systems, so called energy-time entanglement, and was first proposed by Franson [1989]. It consists of two unbalanced Mach-Zehnder interferometers. The coding uses the phase information to encode the information similar to phase-qubits. When detecting two energy-time correlated photons in precise coincidence, one cannot determine which way either of them took in the interferometers. Therefore, the two paths, long-long and short-short, will interfere (the long-short and short-long cases will not produce coincidences). Depending on the phase, the photons will come out in either port of the last beam splitters, in correlation [4].

3.5. Spatial qubit

Spatial qubit can be obtained through the higher orders of transverse Hermite-Gaussian (HG_n, m) and Laguerre-Gaussian (LG_p, m) modes, which both contain an infinite set of orthogonal modes. The mathematical structure of these modes, indexed by {n, m} and {p, m}, respectively [4].

3.6. Frequency qubit

The method of frequency multiplexing has made a strong impact on classical communication, and in the case of a qubit it would imply the encoding of one frequency $|\omega_1\rangle$ as $|0\rangle$ and another frequency $|\omega_2\rangle$ as $|1\rangle$, where ω_1 and ω_2 are the sidebands of a center frequency ω_0. The photon-pairs generated by spontaneous parametric down conversion will have quantum correlations in frequency (entanglement), which makes it a suitable basis for qubits, or even qudits [4].

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IV. QUANTUM GATES

To make simple to understand the working of quantum gates, let's first take an overview on classical gates then we will discuss about Quantum gates. The classical gates are the building blocks of classical computers. A gate is used to implement binary operations and perform computation using Boolean algebra on binary inputs. NOT, AND, OR, NOR, XOR etc. are some examples of traditional gates. For example, NOT gate inverse the input and provide at output. If we give 1 at input of NOT gate it will give 0 at output and vice versa. In quantum computation the situation is quite different, because qubits can exist in superposition of 0 and 1. The set of allowable single qubit operations consists of unitary transformations corresponding to 2 × 2 complex matrices U such that $U^{\dagger}U = 1$. The corresponding action on a single qubit is represented in a circuit shown in fig. 2.

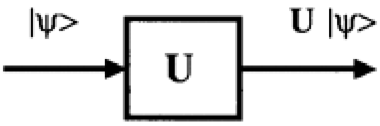

Fig. 2. Circuit representation [7].

Some quantum gates have classical analogues, but many do not. For example, the operator $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ is the quantum equivalent of the classical NOT gate, and serves the function of interchanging spin up and spin down. In contrast, the operation $X = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ rotates the phase of the wave function by 180 degrees and has no classical equivalent [7].

Some examples of Quantum gates are Pauli-X gate, Pauli-Y gate, Hadamard gate, and Phase gate etc. These gates act on a single qubit but CNOT gate or controlled NOT gate acts on two qubits. Fig. 3. and fig. 4. show the Dirac notation and matrix representation of X-gate respectively [8].

$$|0\rangle \rightarrow |1\rangle,\ |1\rangle \rightarrow |0\rangle$$

Fig. 3. Dirac Notation of Pauli X-gate

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Fig. 4. Matrix representation of Pauli X-gate

The working of Pauli X-gate on a general qubit state can be represented as, $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, $X|\psi\rangle = \alpha|1\rangle + \beta|0\rangle$. Hadamard gate is the most important gate in quantum computing. Hadamard Gate operation is just a rotation of the sphere above the Y axis by 90 degree, followed by a reflection in the xy plane. This gate is also known as a square-root of NOT gate and is used to put qubits into superposition. Hadamard gate, which on a single qubit acts as $\hat{U}_H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, $\hat{U}_H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$, where $\hat{U}_H|1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$.The input states may also be represented by polarization states of a photon (like, vertical and horizontal) by sending a photon beam through, a horizontal polarization filter ($|0\rangle$) or a vertical polarization filter ($|1\rangle$).The Hadamard gate transforms a state 0 or 1 in a halfway between this state and its negation. However, two subsequent applications of the Hadamard gate are not equal to the NOT gate but to the identity gate, which shows that the Hadamard gate is the inverse of itself. On an initial two-qubit state the Hadamard transform has the form $\hat{U}_H \otimes 2|00\rangle = \left(\frac{|0\rangle_1 + |1\rangle_1}{\sqrt{2}}\right)\left(\frac{|0\rangle_2 + |1\rangle_2}{\sqrt{2}}\right) = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$, [8-9].

CNOT gate operates on two qubits. Where the first operator in each product acts on the control qubit and the second on the target. If the bit on the control line is 1, the function is to invert the bit on the target line. The symbol and functional table is shown in fig. 5. The CNOT operation has something in common with the classical XOR gate. If the control qubit is in the state $|0\rangle$then the target qubit is unchanged, but if it is in the state $|1\rangle$then the Bloch vector for the target qubit is rotated through π radians about the x-axis. The quantum nature of the CNOT operation is its ability to create entangled states of a pair of qubits [9].

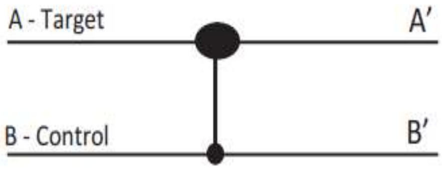

Fig. 5. Symbol of CNOT gate along with function table [9].

V. QUANTUM SUPERPOSITION AND ENTANGLEMENT

The quantum communication and computing are totally govern by two quantum mechanical phenomenon, entanglement and superposition.

5.1. Quantum Entanglement

A pair or group of particles is entangled when the quantum state of each particle cannot be described independently of the quantum state of the other particle. The quantum state of the system as a whole can be described. For example, two particles are created in such a way that the total spin of the system is zero. If the spin of one of the particles is measured on a certain axis and found to be anticlockwise, then it is guaranteed that a measurement of the spin of the other particle along the same axis will show the spin to be clockwise [12]. In classical circuit theory, the controlled-not gate, or XOR, creates correlations between the two input bits. A target input bit value of 0 will come out with the same value as the control bit, 0 or 1. What is unique for the corresponding quantum gate (CNOT) is that it also accepts superposition states, allowing to perform calculations on qubits. In quantum computation this effect can be used to create entanglement [4].

Quantum entanglement is a crucial element in establishment of the entangled network structure of the quantum Internet. In the quantum Internet, the quantum nodes share quantum entanglement among one other, which provides an entangled ground-base network structure for the various quantum networking protocols.In [10] Gyongyosi et al. have defined a method to achieve entanglement access control in the quantum Internet [10]. In [13] Nanxi Zou did a questionnaire and sampling survey on the application of Quantum Entanglement in Quantum Communication. A total of 230 staff from 15 Chinese companies were selected as the sample for investigation, he found that both the researchers of quantum communication theory and the operators of quantum communication technology all involve the application of quantum entanglement in the range of quantum communication. Fig. 6. shows the result ofinvestigation and analysis of quantum detection, calculation and information processing after quantum entanglement is put into use[13].

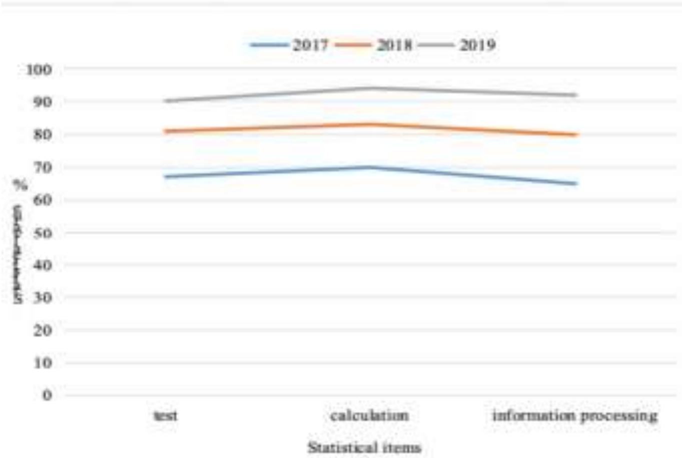

Fig. 6. Quantum Entanglement survey data. [13]

The important fact about the entanglement is that, once entangled, the particles preserves the quantum states even when they are separated wide apart. This gives a communication engineer to exploit the property well and use it to improve security and other aspects of communication [11]. There are four important maximally entangled states in the two-qubit space, called the Bell-states,

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are shown in Fig. 7. which are created from a product state using the circuit.

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

Fig. 7. Bell-states [4].

5.2. Quantum Superposition

At quantum level the particle experiences difficult to understand and very peculiar phenomenon, like superposition. A quantum particle can exist in multiple states simultaneously before the measurement. The feature of a quantum system is it exists in several separate quantum states at the same time. For example, electrons possess a type of intrinsic angular momentum called spin. In the presence of a magnetic field the electron can exist in two possible spin states, like spin up and spin down. Before the measurement the electron has a finite chance to exist in either up spin or down spin. Only after the measured the electron can possessa specific spin state.Superposition play a crucial role in quantum communication and quantum computing. In [14] James Bateman presented a robust method for the Creation of equal superposition in Rubidium for its implication in momentum sate Quantum computer. In such a device, information is stored in the momentum state of a collection of atoms [14]. A. Younes in [15] has described a method to hide specific quantum states using superposition to enhance the security of quantum communication. The proposed method is used to hide an encrypted message in a superposition during data transmission. He concluded that, if a message is hidden using proposed method and the eavesdropper applies direct measurement, then the message will be 100% safe. If the eavesdropper processes the superposition, the message will be 75% safe, and the communicating parties have a chance of 81.25% to detect the presence of the eavesdropping [15].

VI. QUANTUM COMMUNICATION APPLICATION

6.1. Quantum Teleportation

Information security is one of the main issue with conventional communication system. New techniques and models are needed to reduce the threat of data security. Quantum communication plays a major role in ensuring the risk of data lost and security. But the limitation of qubits to lose its entangled states due to noise present in the communication channels limits its application to short distance. Here quantum teleportation comes in play. Quantum teleportation is a landmark quantum communication protocol in the field of quantum information. In this process, quantum information which embedded in an unknown quantum state can be transmitted from a location to another with the assist of a shared entangled state between sender and receiver. A vital element during the execution of quantum teleportation is the preservation of the quantum channel which is assumed to be a maximally entangled pure state between Alice and Bob. The Bell 1 state is always the best quantum channel to complete quantum teleportation protocol no matter what the quantum noise environment is. Even we can get perfect quantum teleportation in case of common collective Pauli $\sigma_y$noise environment [16].

Fioranelli et al. in [17] have proposed a hypothesis of quantum teleportation through biological wires, gravitational micro-bio-holes and holographic micro-bio-systems. They have considered the quantum information teleportation between cells, microbes and micro-bubbles. The biological systems like cells, bacteria, chloroplasts and other micro-organisms exchange quantum particles like electrons, photons and gravitational waves and they can have large distant information teleportation [17]. Hala et al. have presented a teleportation scheme for Controlled Quantum Teleportation.The new scheme can perform the controlled quantum teleportation using both GHZ and GHZ-like states as quantum channels. They confirmed that GHZ state is the best quantum channel when the network users cooperate to transmit the information from the sender to the receiver. They also proposed a situation where there is no evidence about the honesty of the controller or the third user. In such case, the GHZ-like state is the best quantum channel that can be used. Compared with the standard GHZ network [18].

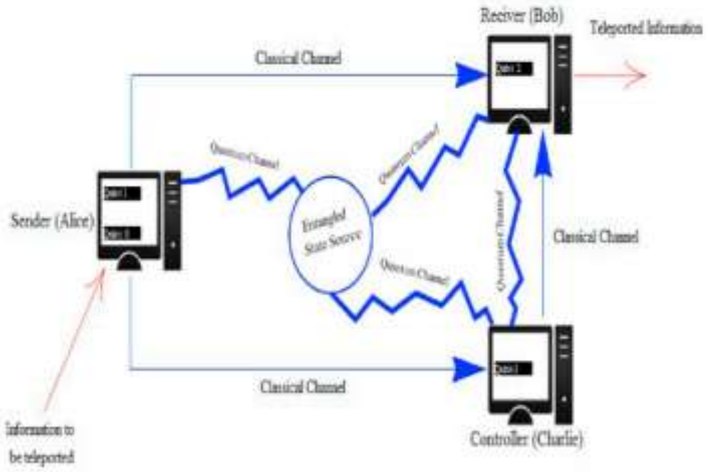

Fig. 8. A schematic diagram of the proposed teleportation scheme in [18].

6.2. Quantum Cryptography

In 1992 Bennet and Brassard designed the first rudimentary QKD apparatus since then, many systems, including systems built by Los Alamos, British Telecom, Johns Hopkins University, and IBM Almaden Research Center, have followed [19]. Cryptography is the practice and study of encoding and decoding secret messages to ensure secure communications. There are mainly two types of QKD schemes. One is the prepare-and-measure scheme, such as BB84 and the other is the entanglement based QKD, such as Ekert91 and BBM92. Quantum cryptography or quantum key distribution (QKD) applies fundamental laws of quantum physics to guarantee secure communication. It enables two legitimate users, commonly named Alice and Bob, to produce a shared secret random bit string, which can be used as a key to encrypt the message. There are two important aspects of QKD performance: key rate and maximal secure distance [20].

Quantum cryptography is a cryptographic technique based on quantum mechanics. It is usually referred to quantum key distribution since quantum mechanics is used to distribute an encrypted key not for transmitting data message between users. Encryption in quantum cryptography is done using quantum states called qubits. It is not possible to measure and clone the quantum states so that an eavesdropper cannot clone or measure the qubits. This technique require two type of channels ,quantum channel for secure transferring of key and classic channel for verification of key received [21]. The basic principle of QKD is, sender (such as Alice) transmit a string of polarised photons to receiver (such as Bob) using optical fibre as communication channel. The stream of polarized photons can represent ones and zeros, depending on the polarization of photons. For example, a vertically polarized (V) or photon having $+45^{\circ}$ state can represent 1 and a horizontally polarized (R) or photon having $+45^{\circ}$ state can represent 0. This string of polarized photons are nothing but qubits equivalent of bits in a binary system. At Bob end, the string of photons are passed randomly through beam splitter. Then Bob sends the obtained data to sender for its comparison. Alice compare with her own data and remove the photons which enter to the wrong beam splitter and finally the left sequence act as key which is used to encrypt message. A sequence to be act as key need to have bit error rate below the threshold value for secure transfer of message.

QKD enable the transfer of data without any threat of eavesdropper. It has bright future in communication system, its beginning can be seen in different field. China is one of the country which demonstrated a stable and advanced QKD network over a large area. Li L L, Li J, Chang Y, et al. have presented QKD protocol based on a single particle and an EPR entanglement pair called as quantum TEQKD protocol. They analysed eavesdropping behavior for TEQKD and found at least a bit error rate of 62.5% due to involvement of intruder [22]. In traditional E- payment system after the selecting the items from E-shop portal, customer submits his credit or debit card information for paying the merchant. This payment system is not secure since any eavesdropper can act as customer by hacking information submitted by customer. In [21] the authors have proposed QKD along with visual cryptography and steganography to secure the transmission [21].

6.3. Quantum Dense Coding

Quantum dense coding extends from two-level entanglement to multilevel entanglement. Quantum dense coding transmits classical bits through quantum channel means only one qubit can transmit, while two kinds of classical information can be transmitted through quantum entanglement. The method is that the sender and the receiver each have a maximum entangled particle and are in a maximum entangled state. Because the two particles are entangled, any operation on one particle will affect the other particle, resulting in the formation of phase. This is called dense coding, which is also the simplest dense coding [13]. Dense coding is basically the reverse of teleportation. The dense coding protocol is depicted in fig. 9. Alice starts off with the entangled state $|\phi^+\rangle$ and sends only one of her both photons to Bob, which then applies a unitary transformation I, X, Y, or Z to the photon corresponding to the classical bit-values 00, 01, 10, and 11, thereby rotating the joint state to one of the four states $|\phi^+\rangle$, $|\phi^-\rangle$, $|\psi^+\rangle$, or $|\psi^-\rangle$. As the particle is sent back to Alice is carrying two bits of information that can be read off in a Bell-state analyzer. Thus, one bit is encoded in the qubit state value and the other bit in the phase between the qubit-states [4].

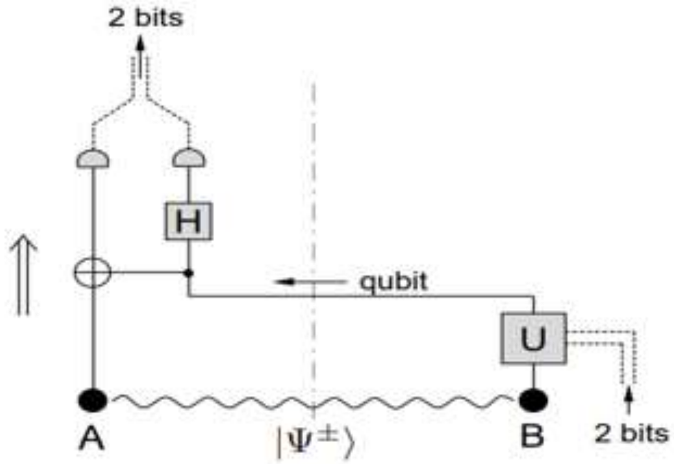

Fig. 9. Dense coding protocol. [4]

VII. CONCLUSION

When it comes to security and reliability, quantum communication and computation play an important role. The field has opened up new doors in communication and computing world and challenges the engineers and scientists to develop new theories and technique to improve and solve limitations of traditional communication. In this paper we explained the basics of quantum physics on which the quantum communication and computing is based on. We have also discussed the different method to produce qubits and explained some important quantum gates used to produce entangled qubits. Reviewed papers based on application of quantum communication which gives a glimpse of, how the future of the communication will look like? The current advancement and application of quantum communication and computing clearly show its bright future and beginning of new era in communication and computing field.

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