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Quantum Cryptography and Quantum Key Distribution Protocols: A Survey

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Abstract— **Quantum cryptography renders a cryptographic solution which is imperishable as it fortifies prime secrecy that is applied to quantum public key distribution. It is a prominent technology wherein two entities can communicate securely with the sights of quantum physics. In classical cryptography, bits are used to encode information where as quantum cryptography i.e. quantum computer uses photons or quantum particles and photon's polarization which is their quantized properties to encode the information. This is represented in qubits which is the unit for quantum cryptography. The transmissions are secure as it is depended on the inalienable quantum mechanics laws. The emphasis of this paper is to mark the rise of quantum cryptography, its elements, quantum key distribution protocols and quantum networks.**

Index Terms— basis, classical cryptography, photons, polarization, quantum cryptography, quantum key distribution protocol, qubits, quantum networks, states

I. INTRODUCTION

The principle of uncertainty could be used for cryptography was first devised by Stephen Wiesner, a physicist in 1969 [1]. Thus the hatching of quantum cryptography took place which has given a promising concept to many cryptographers. One of the ideas of [1] was expanded to propose a method for quantum public key distribution i.e. QPKD under the principles of quantum mechanics which is verifiably secure [2]. Bennet and Brassard who had collaboration with Stephen Wiesner were proposed the first QPKD in 1984 and is familiarized as the BB84 protocol [4].

Quantum cryptography is a prominent technology wherein two entities can communicate securely by implementing the sights of quantum physics. QPKD commences with the transmission of photons which are prepared in four quantum states randomly, relating to two mutually conjugate bases [1], rectilinear and diagonal. The rectilinear basis has two states i.e. polarizations namely 0° represented horizontally and 90° represented vertically. The diagonal basis 45° and 135° [1] [4].

The transmissions are secure as it is depended on the inalienable quantum mechanics laws. The two predominant constituents of quantum mechanics i.e. the principle of Heisenberg Uncertainty and the principle of photon polarization are the foundations of quantum cryptography. The Heisenberg Uncertainty principle defines that the observer simultaneously cannot measure two physical properties which are related with each other [4].

In regard to this definition, two examples are referred 1) the example which is customarily specified is, where for a particle P, the position A and the momentum B of P cannot be calculated simultaneously. 2) The measurement of a photon cannot be done simultaneously in rectilinear basis and diagonal basis [1] [2]. If done, it randomizes the other. The principle of photon polarization defines that the replica of qubits cannot be made as per theorem of no-cloning [1] [3]. It was recognized that photons were used for transmitting the information instead of storing it which was the major revolution in the area of quantum cryptography [5].

Section 2 gives an outline about Quantum Cryptography. Section 3 discusses about the probability of a photon transmitted and produced. Section 4 explores about quantum key distribution protocols. Section 5 discusses about quantum networks. Section 6 outlines about recent contributions in this area. Finally section 7 gives a conclusion and future enhancement.

II. QUANTUM CRYPTOGRAPHY

A. Polarization of Photon

The photon is polarized in one of the bases to represent a bit known as a qubit. A 0° polarization of photon in the rectilinear

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basis or 45° in the diagonal basis is used to represent a binary 0. A 90° polarization in the rectilinear basis or 135° in diagonal basis is used to represent a binary 1 as shown in figure 1 [11].

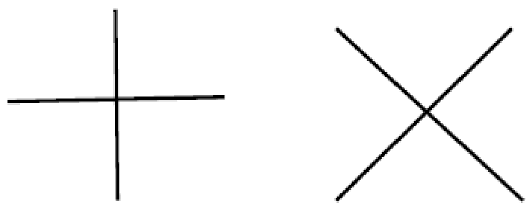


Fig. 1. Rectilinear and Diagonal bases

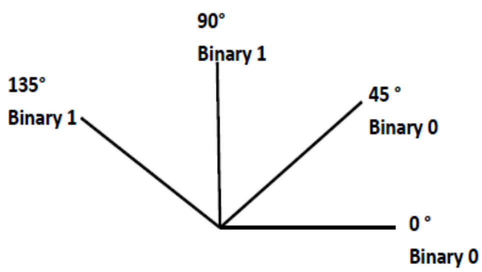


Fig. 2. Polarization of photons to represent bits

B. Representing Information- Qubits and quantum states

The underlying unit of quantum cryptography is qubit. It has two states, labeled as |0⟩ and |1⟩ (vertical bars | and angle brackets ⟩) and referred as a state, a ket or a Dirac notation named after its framer Paul Dirac who had instigated this notation in 1939 [1] [13].

A bit can be in the state 0 or 1 whereas a qubit can occur in the state |0⟩ or |1⟩. It can also occur in superposition state which is a linear combination of the states |0⟩ and |1⟩. A state can be labeled as $|\psi\rangle$. The state in superposition is noted as $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ where α, β are complex numbers [13].

Perhaps a qubit occurs in a superposition state |0⟩ and |1⟩, but this state cannot be measured. Certainly, when a qubit is measured, it will occur in the state |0⟩ or in the state |1⟩.

The probability of obtaining the state |0⟩ or |1⟩ qubit is the modulus squared of α, β respectively according to quantum mechanics laws. That is to represent the probability of obtaining $|\psi\rangle$ in |0⟩ state is $|\alpha|^2$ and the probability of obtaining $|\psi\rangle$ in |1⟩ state is $|\beta|^2$. The probability of getting result of a measurement is obtained by squaring the coefficients. The condition is $|\alpha|^2 + |\beta|^2 = 1$ [13].

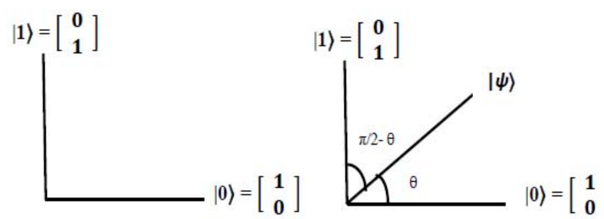
C. Classical and Quantum Computation

In classical computation the probability of observing state i is P_i, where $P_i \in R$, R is real number and $0 \le P_i \le 1$, $\sum P_i = 1$. In this, transition depends on probabilities and uses stochastic matrix. In quantum computation the probability of observing state S is $|a_s|^2$ where a is amplitude and $a_i \in$ complex number, $0 \le |a_i|^2 \le 1$, $\sum_i |a_i|^2 = 1$. In this, transition occur based on amplitudes. The quantum computation uses unitary matrix.

D. Interpretation of Quantum Mechanics

$\alpha\,|0\rangle + \beta\,|1\rangle$ is a state where $\alpha, \beta \in$ complex number. The state can also be written by stacking the two complex numbers $\begin{bmatrix}\alpha \\ \beta\end{bmatrix}$ which is a two-dimensional complex unit vector

$|0\rangle = \begin{bmatrix}1 \\ 0\end{bmatrix}$ where α=1, β=0 and $|1\rangle = \begin{bmatrix}0 \\ 1\end{bmatrix}$ where α=0, β=1



$|\psi\rangle = \cos\theta\ |0\rangle + \sin\theta\,|1\rangle = \begin{bmatrix}\cos\theta \\ \sin\theta\end{bmatrix}$ [1] [14].

E. Notations

1) $|0\rangle = |-\rangle$

2) $|1\rangle = |\,|\,\rangle$

3) $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) = |\,/\,\rangle$

4) $\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle) = |\,\backslash\,\rangle$

Notation 1 and 2 represents state 0° and state 90° in rectilinear basis respectively. Notation 3 and 4 are state 45° and state 135° in diagonal basis respectively [1].

1) Four States of polarization of photons

$$1)\ |—\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 1\,|\,x\,\rangle + 0\,|\,y\,\rangle$$

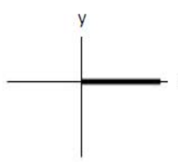
$$2)\ |\,|\,\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = 0\,|\,x\,\rangle + 1\,|\,y\,\rangle$$

$$3)|\,/\,\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} = \frac{1}{\sqrt{2}}|\,x\,\rangle + \frac{1}{\sqrt{2}}\,|\,y\,\rangle$$

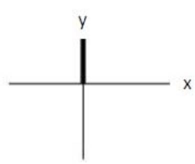
$$4)|\,\backslash\,\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix} = \frac{1}{\sqrt{2}}|\,x\,\rangle - \frac{1}{\sqrt{2}}\,|\,y\,\rangle$$

2) Representation of states

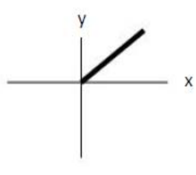
$|—\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 1\,|\,x\,\rangle + 0\,|\,y\,\rangle$



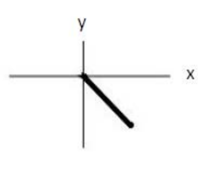
$|\,|\,\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = 0\,|\,x\,\rangle + 1\,|\,y\,\rangle$



$|\,/\,\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} = \frac{1}{\sqrt{2}}|\,x\,\rangle + \frac{1}{\sqrt{2}}\,|\,y\,\rangle$



$|\,\backslash\,\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix} = \frac{1}{\sqrt{2}}|\,x\,\rangle - \frac{1}{\sqrt{2}}\,|\,y\,\rangle$



III. Probability of a Photon- Transmitted in One Angle and Produced in Same/ Other Angle

A. Probability of a photon transmitted and produced in same basis and state

The probability of an unpolarized light transmitted through vertical polarizer or basis which is produced again in vertical polarizer is 100%. This is due to the polarizer is in the same direction of light which is polarized.

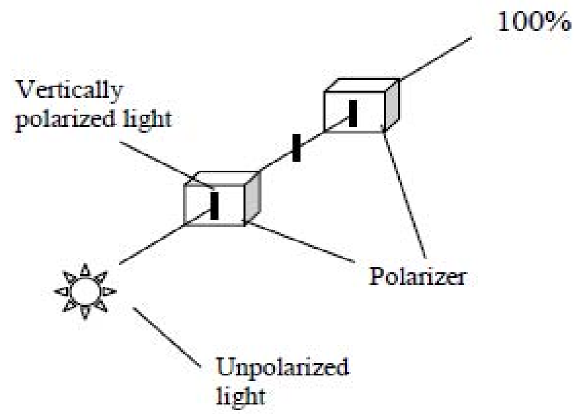


Fig. 3. An unpolarized light transmitted through vertical polarizer and produced in vertical polarizer

B. Probability of a photon transmitted and produced in same basis but prepared in different states

The probability of an unpolarized light transmitted through vertical polarizer prepared at an angle 90° of rectilinear basis and produced in horizontal polarizer at 0° of rectilinear basis is 0%.

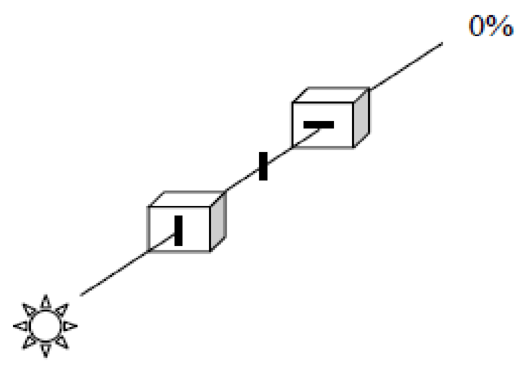


Fig. 4. An unpolarized light transmitted through vertical polarizer and produced in horizontal polarizer

C. Probability of a photon transmitted and produced in different basis

The probability of an unpolarized light sent through vertical polarizer and trying to produce at 45° diagonal basis is 50%.

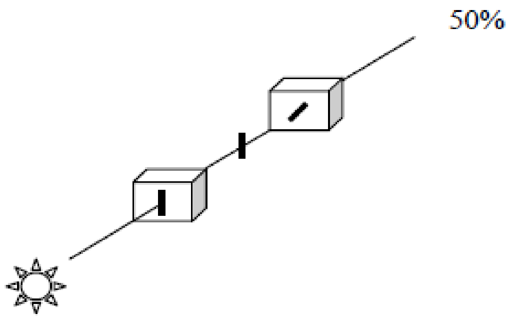


Fig. 5. An unpolarized light transmitted in vertical polarizer and produced in diagonal polarizer

D. Probability of a photon transmitted in one basis and produced at an angle

The probability of an unpolarized light sent through vertical polarizer and trying to produce through a polarizer which is at an angle **θ** in the vertical direction is $\cos^2\theta$ [1] [9].

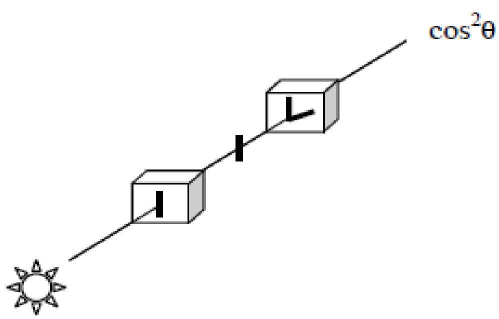


Fig.6. An unpolarized light transmitted in rectilinear polarizer and produced at an angle

IV. Quantum Key Distribution Protocols

A. BB84 Protocol

Bennet and Brassard proposed the quantum key distribution protocol for the first time in 1984 and familiarized as the BB84 protocol depended on Heisenberg Uncertainty principle. The components of BB84 protocol are two bases that are to specify rectilinear (R) and diagonal (D) and four states of polarized photons. A 0° polarization of photon in the rectilinear basis or 45° in the diagonal basis is used to represent a binary 0. A 90° polarization in the rectilinear basis or 135° in diagonal basis is used to represent a binary 1 [4] [11].

In QPKD, the communicating parties uses two communication channels namely a classical channel and a quantum channel. They transmit polarized single photons i.e. qubits on the quantum channel and the conventional messages on classical channel shown in figure 7. The following are the steps for secret key which is shared between two users.

1. The sender makes random bits in sequence manner and chooses random bases. He/she represents bits using polarized photons and sends the photons to receiver through the quantum channel.
2. The receiver measures each of them by choosing one of the two bases.
3. If the receiver selects the same basis as of sender's, then he/she will share the same binary information with sender, otherwise, with a different basis.
4. The receiver communicates this through the classical channel and sender tells receiver for which qubit he/she chose the same basis as he/she.
5. Both the parties will delete the bits which are of different bases and the other bits are the key known as sifted key [4].

Quantum Transmission															
Alice's Random bits	0	1	1	0	1	1	0	0	1	0	1	1	0	0	1
Alice's random sending bases	D	R	D	R	R	R	R	R	D	D	R	D	D	D	R
Photons Alice sends	/			\	—					—	—	\	/			\	/	/		
Random Bases as received by Bob	R	D	D	R	R	D	D	R	D	R	D	D	D	D	R
Bits as received by Bob	1		1		1	0	0	0		1	1	1		0	1
Public Discussion															
Bob reports bases of received bits	R		D		R	D	D	R		R	D	D		D	R
Alice says which bases were correct			OK		OK			OK				OK		OK	OK
Shared information			1		1			0				1		0	1
Bob reveals some bits at random					1									0	
Alice confirms it					OK									OK	
Sifted Key			1					0				1			1

Fig. 7. BB84 Protocol

B. B92 protocol

B92, a modified protocol of BB84 with two states. A photon polarization of 0° in the rectilinear basis is used to represent binary 0 and 45° in the diagonal basis is binary 1 [6].

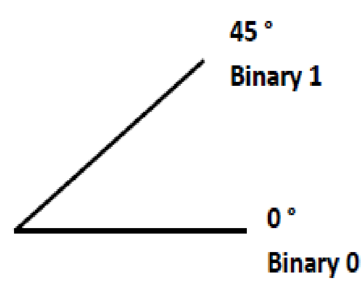


Fig. 8. B92 Protocol

C. Six-State Protocol (SSP)

SSP protocol shares the same steps of BB84 protocol except it allows three orthogonal bases to encode the bits which are required for communication between entities. Hence six states are used to represent the bits [7].

D. SARG04 protocol

The first phase of SARG04 protocol is identical to the first phase of BB84. It differs in second phase, where Alice announces a pair of nonorthogonal state. She uses one of them to encode her bit rather than announcing her bases directly. Alice and Bob verify for which bits they have corresponding bases. Bob will measure the exact state if he used the appropriate basis, otherwise he will not obtain the bit [8].

V. QUANTUM NETWORKS

A. The DARPA Quantum Network

The DARPA Quantum network is a quantum key distribution network with ten nodes that was set up in Massachusetts, USA and is in operational from 2004. The network was built by BBN Technologies [18] (Bolt, Beranek and Newman) funded by the US Defense Advanced Research Projects Agency (DARPA). It was collaborated with Harvard University, Boston University researchers. The DARPA Quantum network first undertook the implementation of traffic in the internet using QKD technology. BBN Technologies developed a QKD protocol stack which deserves in indicating two features. Firstly, it is applied on QKD protocols suite. Secondly, it has been designed in such a way to render the links of QKD from different research groups into DARPA Quantum network altogether with less difficulty, that is it can be easily plug in other QKD systems. The certainty of this model lies in Virtual Private Network (VPN) based quantum key distribution. In this network the key is used for the first time in IPSec based VPNs. It is used in processing of traffic and key agreement protocol [16] [17] [31].

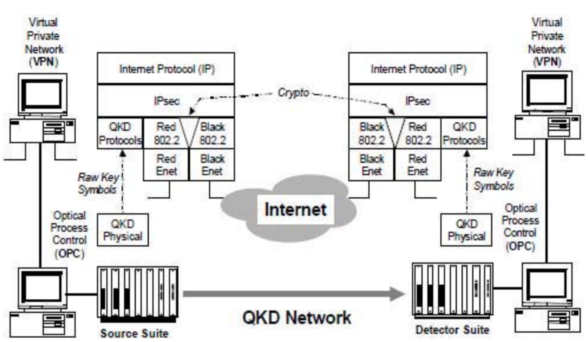


Fig. 9. VPN Network Quantum Cryptography [18]

B. The SECOQC Quantum Key Distribution Network

The SEcure COmmunication based on Quantum Cryptography (SECOQC) is a European project which was collective research attainment developed by 41 industrial and research organizations [19] [20] [21]. It was commenced in 2003 and took over between April 2004 and October 2008. The SECOQC offers networks with QKD with an emphasis on the prototype with trusted repeater [22]. The topology consists of 8 network links which are connected point-to-point. The operated version has been exhibited publicly in Vienna in the year 2008 where they discussed its architecture and functionality. The intrinsic technology used by them is three plug and play systems by ID Quantique [30] which was developed by a group of researchers. The SECOQC has prime networking agent known as SECOQC node module. The key distillation authentication for classical communication is provided by this module. Besides this, it manages communication channel between destinations in the network and secure key distribution between them [19] [20] [21].

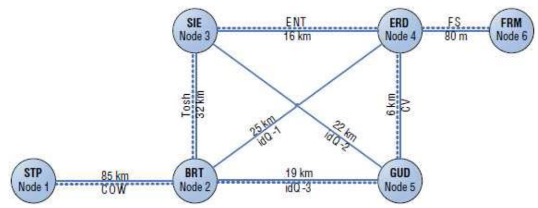


Fig. 10. The SECOQC network prototype topology [22]

C. Tokyo QKD Network

The Tokyo QKD network is a star network pattern linking various centers. It was launched on the day of the UQCC2010 conference (Updating Quantum Cryptography and Communications) in Tokyo. It comprises of 3 layers, 1) quantum layer, 2) the key management (KM) layer, 3) the communication layer. The first layer has devices with QKD functionality which generates keys. The KM layer collects and store the QKD devices and the communication layer ensures communications securely through the distribution of keys [23].

D. Hub and spoke network by Los Alamos National Laboratory

Los Alamos National Laboratory has developed a hub and spoke network and it was operating since 2011. The hub is used to route messages. Each node in the network has quantum transmitters. The quantum messages are received only by the hub. The communication commences when all the nodes issues a one-time pad which is received by the hub. This is used in secure communication over classical channel. This message can be routed by the hub to other node with other one time pad. This way, whole network will be secured [24].

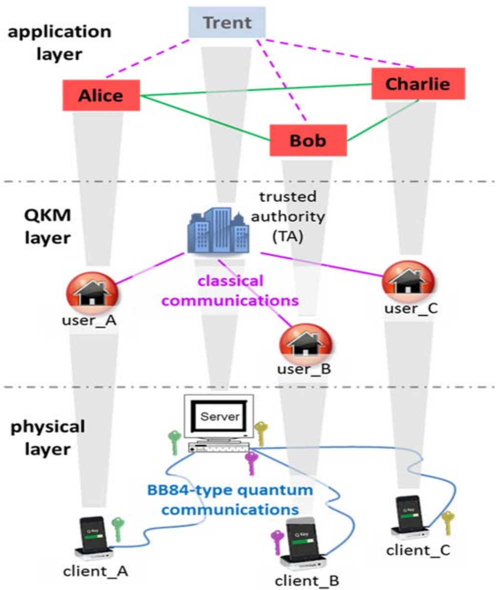


Fig. 11. Architecture of Network-centric Quantum Communications (NQC) [24]

VI. Recent Contributions

- In 2010, D-Wave, the Quantum Computing Company released first commercial system known as the D-Wave One quantum computer and in 2013 they released 512-qubit D-Wave Two system [32].
- For the first time, University of New South Wales research group designed a quantum logic gate using silicon in October 2015 [12][29].
- The scientists from IBM declared that there are two advancements in realizing practical quantum computer in terms of detecting and measuring quantum errors. They designed a new quantum bit circuit which can be scalable in April 2015 [25] [29].
- The researchers at University of New South Wales produced more precise qubits by wrapping them with a protective silicon shell. With this, the length of time to hold information has been increased which is a breakthrough and perhaps made quantum computers effortless to build 2014 [26] [29].
- A researcher group from ETH Zurich, University of Southern California, Google, Microsoft Research and University of California formulated how to assess and to measure quantum speedup in 2014 [27] [29].
- The U.S. National Security Agency (NSA) reported early in 2014 is running a research program to implement a quantum computer which is skilled in breaking encryption technique used in protecting different sectors [28][29].

VII. Conclusion & future work

The techniques adapted from classical computer science are applicable to quantum key distribution protocols is an appropriate sign that quantum cryptography is a rousing new area of research work. In this paper we endeavored to introduce quantum cryptography, quantum states. It explains about different quantum key distribution protocols. Quantum key distribution can be carried to a new direction using quantum gates. They can be used to implement quantum key distribution in a secure manner. In quantum computing especially the quantum circuit model of computation, the gate operates on number of qubits which are the building blocks of quantum gates. There is much more to describe about quantum cryptography.

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