

Exploration of Quantum computing and communication blocks with IBM Qiskit

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Abstract

This manuscript provides a comprehensive exploration of quantum computing and communication's foundational elements, employing Qiskit—an open-source quantum computing framework. It delves into the simulation of fundamental quantum blocks and the intricacies of two-qubit entanglement, presenting findings through graphical analyses. The discussion extends to quantum logic gates, including X, Y, Z and CNOT. This study not only examines the construction and application of quantum circuits. The simulation with Qiskit programming presents the basic quantum circuits and its outcomes after measurement.

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1. Introduction

The inception of quantum communication can be historically linked to Albert Einstein's initial identification of "spooky action at a distance," a notion that was subsequently developed by notable scholars including Shamir and Blakley with their covert sharing system, Richard Feynman with his proposition for quantum information transmission, and Alain Aspect with his experimental confrontations with the Einstein-Bohr [1].

Recent developments in the domain of quantum mechanics have substantially enhanced the viability of quantum computing and communication. The present collection of scholarly work explores the fundamental quantum systems and their prospective implementations in

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established and developing quantum communication frameworks. A profound differentiation exists between classical and quantum information, which facilitates the development of the theoretical framework for a global quantum network [2]. The resilience of this network is additionally fortified by state-of-the-art developments in satellite quantum channels, which intrinsically provide protection against conventional eavesdropping techniques [3].

This study explores the field of quantum mechanics, namely the modelling of quantum components and quantum entanglement in two-qubit. The Qiskit framework [4-5] is used to enable these applications. The paper thoroughly analyses quantum logic gates, including X, Y, Z, CNOT, using graphical representations. It emphasises their programming complexities and their crucial significance in quantum circuit design such as BB84 protocol [6-7]. This paper divides in two sections, first section explains the basic blocks of quantum system. Second Section covers the discussion of results and simulation part.

2. Quantum blocks exploration

I. *Basics of Quantum*

A. QBIT

A qubit serves as a fundamental component of quantum information processing, akin to the role of a classical bit in conventional computing. A qubit, unlike a traditional bit, may concurrently represent both a 0 and a 1 state. A qubit is often represented as a quantum system with two possible states, such as the spin orientation of an electron or the polarisation state of a photon [8].

B. Superposition

The principle of superposition is a cornerstone concept in quantum mechanics. It posits that, similar to the way waves behave in classical mechanics, it is possible to combine two or more quantum states through a process known as “superposing”. Essentially, superposition enables a quantum system to exist in multiple distinct states simultaneously. This concept is mathematically represented by the superposition equation 1 and 2.

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \quad (1)$$

$$\alpha^2 + \beta^2 = 1 \quad (2)$$

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (3)$$

$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (4)$$

$$\begin{aligned} |+\rangle &= \frac{|0\rangle + |1\rangle}{\sqrt{2}} \\ |-\rangle &= \frac{|0\rangle - |1\rangle}{\sqrt{2}} \end{aligned} \quad (5)$$

C. Bloch sphere

It serves as a visual depiction of the state of a quantum system with two layers. The representation, first suggested by physicist Felix Bloch in 1946, provides a geometric framework for understanding the quantum states of these systems. The Bloch sphere is a unit sphere that represents the state of a system, with the system's state located on the surface of the sphere. The entity under consideration is a 3D sphere with a radius of 1, located precisely at the point of origin. The Cartesian coordinate system is used, whereby unique qubit form by each position on the sphere. The qubit state $|0\rangle$ is denoted by the apex of the Bloch sphere, whereas the qubit state $|1\rangle$ is represented by the nadir.

II. Entanglement

The phenomenon entanglement in Quantum in which particles, whether in pairs or groups, become interconnected in such a way that the state of one particle cannot be determined without taking into account the states of the other particles.

The link between the particles remains unchanged regardless of their distance, whether they are close together or far apart. Consequently, the actions of individual particles within an entangled ensemble are mutually reliant, regardless of any physical distance between them. Figure 1 and 2 depicts the block sphere and Entanglement model [9].

III. Quantum Logic Gate

A quantum logic gate is a specialized device created to perform a certain quantum operation on a group of qubits with precision. Quantum

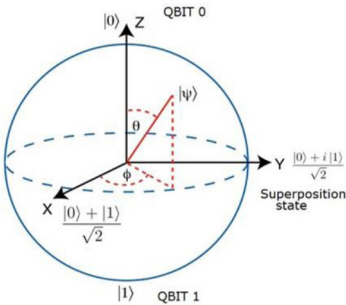


Figure 1
Bloch sphere

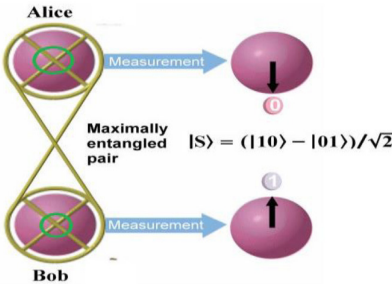


Figure 2
Entanglements between alice and bob

gates are essential elements of quantum computing that facilitate the manipulation, control, and measurement of the quantum state of a quantum system. Quantum computing often employs quantum logic gates, including the Hadamard gate, the CNOT gate, and the Toffoli gate. These gates are often known as Pauli gates [10].

The Pauli gates are composed of the X, Y, and Z gates, which are single-qubit gates, together with the two-qubit controlled-NOT (CNOT) gate [11-12].

A. X gate:

The Pauli-X gate, often referred to as the NOT gate within the context of quantum computing, operates on a single qubit. Its function is encapsulated by a specific matrix representation.

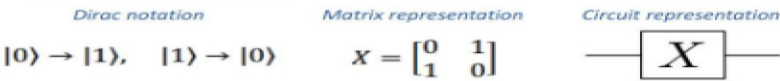


Figure 3
X Gate Symbol and formation

This matrix has the effect of inverting the value of a qubit. If the $|0\rangle$ state is the qubit state then, it will be flipped to the $|1\rangle$ state, and vice versa. This gate is the NOT Gate in quantum domain similar to classical NOT gate.

The Pauli X gate is also known as the bit-flip, NOT gate, or Pauli-X gate. IBM composer Pauli-X gate circuit shows Figure 3 and the outcomes are given in figure 4.

$$\text{---} \boxed{X} \text{---} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = |1\rangle \langle 0| + |0\rangle \langle 1|$$

Figure 4**X Gate with the superposition****B. Hadamard Gate**

The quantum Hadamard gate is a kind of quantum logic gate that enables the creation of quantum entanglement between two qubits. It is represented as a 2x2 matrix, which is applied to a qubit to produce a superposition state, which allows the qubits to become entangled [13]. Figure 5 and 6 present the Hadamard circuit and outcomes by the IBM Composer.

. It is represented by an H symbol and is sometimes referred to as the Hadamard transformation. The Single qubit gate category also contains the Hadamard gate. that performs a unitary transformation. This transformation is given by:

$$\text{Hadamard} \quad \text{---} \boxed{H} \text{---} \quad \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Figure 5**Hadamard Gate symbol and presentation****C. Qubit with Y Gate**

The Pauli Y gate is the phase changing gate, is essential for introducing phase changes in quantum computing operations. It is one of the Pauli gates, along with the X and Z gates. A rotation of a qubit's state is achieved by an angle of $\pi/2$ around the Y-axis on the Bloch sphere. Its operational essence is captured by a specific matrix representation.

$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \quad \text{---} \boxed{Y} \text{---}$$

Figure 6**Y Gate symbol and presentation**

The Performance of Pauli Y gate operation on a qubit can be expressed as: $Y|\psi\rangle = i|\psi\perp\rangle$

where $|\psi\rangle$ is the qubit's initial state and $|\psi\perp\rangle$ is the qubit's flipped state. This means that the quantum Pauli Y gate flips the phase of the qubit's state.

D. The Pauli Z gate

In the field of quantum computing, the gate is a kind of operator that operates on a single qubit. This gate is alternatively referred to as a phase gate or phase-flip gate. The procedure inverts the polarity of the state's wave function and may be used to make changes in phase. The Pauli-Z gate is a quantum gate that operates on a single qubit and is often used in quantum computing.

It is categorized among the three single-qubit Clifford gates, along with the Hadamard gate (H) and the phase gate (S). The Pauli-Z gate performs the π radians rotation on Bloch sphere about the Z-axis. It is also recognized as the σ_z gate or the phase-flip gate [8].

IV. GHZ Stage

The GHZ (Greenberger-Horne-Zeilinger) state is a quantum state that is entangled and involves three or more qubits. It is an extension of the well-known Bell states, which consist of two qubits. The GHZ state has great significance in the field of quantum computing and quantum communication protocols owing to its distinct features, namely in showcasing non-local interactions among qubits.

$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|0\rangle^{\otimes n} + |1\rangle^{\otimes n}) \quad (6)$$

3. Results and Discussion

Figure 7 shows the single bit representation system and its outcome in Qiskit simulation programming. Entanglement of qubits quantum circuit and its simulation show in figure 8 where two column represents the 00 and 11 value for entanglement condition. X gate simulation is shown in figure 9. Where 0 qubit inverts in output side.

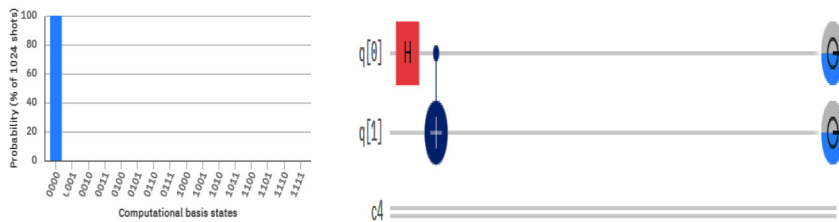


Figure 7

Qubit 0 representation in (a) circuit (b) in Outcome of qiskit

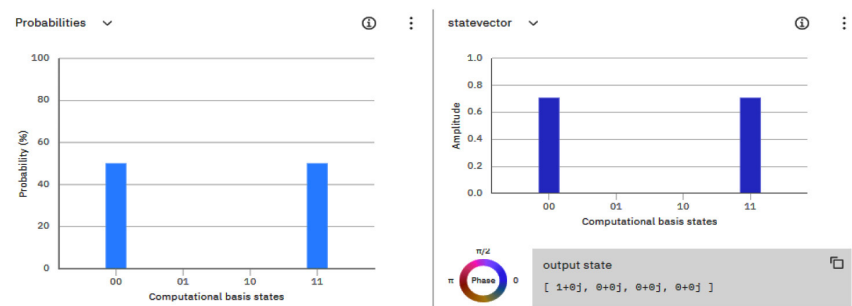


Figure 8
Two qubit Entanglement state output

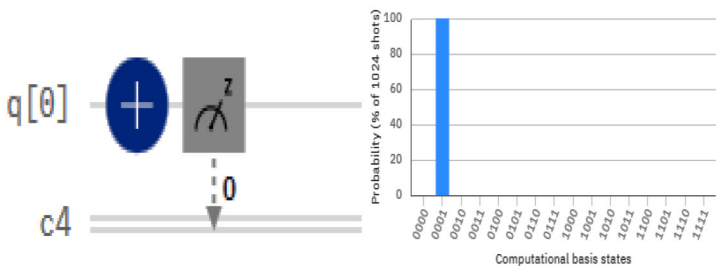


Figure 9
Qubit with X Gate

Hadamard Gate simulation setup and output in normal and phaser form given in outcome of simulation as shown in figure 10 and 11.



Figure 10
Qubit with Hadamard Gate

Figure 12 gives the simulation setup of Y gate and its outputs show the phase variation in superposition stage. Z gate will interchange the qubit in superposition stage and also phase as verified by the simulation in figure 13 and 14. GHZ Quantum circuit design is given in figure 15 with use of Hadamard Gate and CNOT gate and simulation shows the input

superposition stage and outcomes after measurement is obtained in form of three-bit (000 and 111) entanglement as shown in figure 16.

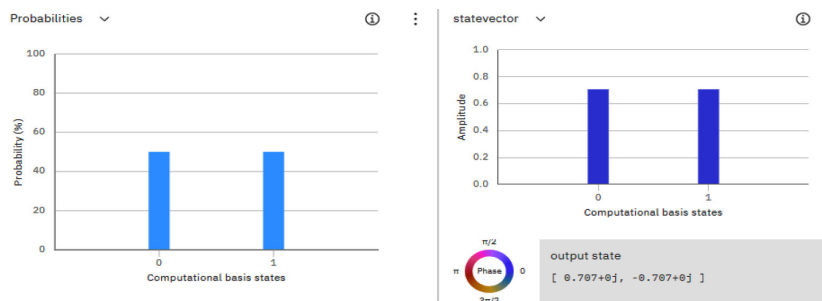


Figure 11
Qubit with Hadamard Gate



Figure 12
Qubit simulation with Y Gate



Figure 13
Superposition state 's Qubit with Z Gate



Figure 14
Superposition state 's Qubit with Z Gate



Figure 15
Entanglement of three qubit (GHZ State)

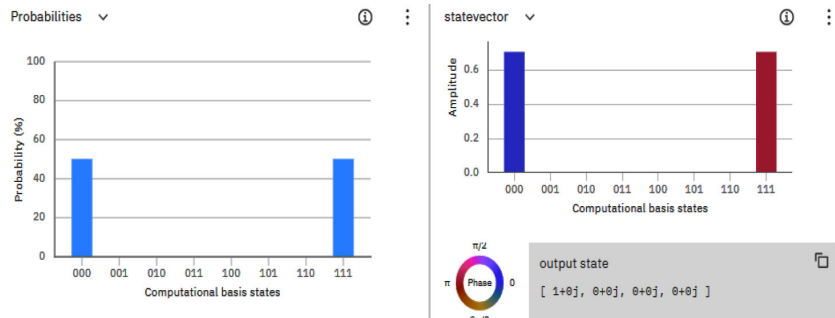


Figure 16
Entanglement of three qubit (GHZ State)

4. Conclusion

The article discusses fundamental notions such as basic words, basic logic gates, and potential entanglement circuit principles. The Qiskit programming and simulation tool is used to mimic the behaviour of these block and fundamental terms in quantum circuit design for quantum computing and communication, such as QKD and quantum error correction. The simulation output is displayed in graphical form to

facilitate the understanding of the underlying phenomena. The advent of open-source software programming, like Qiskit, facilitates the comprehension and execution of quantum communication protocols and algorithm design in a straightforward and comprehensive way.

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