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Design and Implementation of Multi-Operative Reversible Gate for Even/Odd Parity Generators In Quantum Based Technologies

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Abstract

Quantum technology is graciously budding in nano-communication due to its properties and logical function, having the momentous prosperity of being reversible. It has gained an appeal to future-generation research owing to those sole aspects that may not be explored in the classical realm. A reliable nano-communication system utilizes varied error detection and correction techniques. Beyond low device density, authentic random number generation is a crucial issue in the cryptographic aspects of future communication architecture. To our knowledge, this is the innate study of an intriguing prospect: the design and implementation based on the lower level of power 'even/odd parity generator' using a single multi-operative reversible gate that has been achieved and functionally authenticated in the QCA nanotechnology, likewise in the IBMQ experience allied to quantum-based technologies. This breakthrough in nanotechnology and quantum-based technologies could have significant implications for blooming more efficient, secure communication systems in post-quantum cryptography.

Keywords: Multi-Operative; Reversible Circuit; Even/Odd Parity Generator; Nano-Communication; Quantum Technologies

1 Introduction

'Complementary metal-oxide semiconductor' logic is a highly viable technique for creating computing and communication devices. Quantum-dot cellular automata (QCA) are the preferred surrogate to CMOS technology for making integrated circuits at the nanoscale level. QCA technology presents numerous benefits over CMOS, such as increased circuit densities, quicker processing speed and reduced power usage. In addition, the productive nature of nanotechnology and VLSI fabrication mutually depend on each other's growth. The drive for high-performance digital circuits in the nanoscale is allied to the CMOS paradigm. Quantum-based technology has sparked researchers to explore new approaches to computing and circuit design [1]. It necessitates a reliable and efficient nanostructure, such as QCA, that can replace CMOS and provide faster processing speeds with minimal power consumption at extreme thicknesses[2, 3].

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QCA devices enable current-free information flow [2], resulting in high-density circuits with fast switching speeds at room temperature. It attributes to their low energy usage, dissipation, and density of packaging, with the capability for THz-speed operation [4–6]. QCA was initially shown through Metal-Island use and can be implemented via semiconductor, molecular or magnetic means [7]. QCA devices work on quantum mechanics and charge quantization principles [2, 8]. The quantization of charge is fundamental in quantum mechanics and crucial to its operation. Quantum computing explores this occurrence for new computational devices with potential revolutionary capabilities in information processing [9–12].

This study explored the use of semiconductor-based QCA and quantum computing to enhance security in nano-communication. Our research examines the effectiveness of reversible gates in QCA and quantum computing, with potential implications for secure communication strategies in nanotechnology. The aim is to strengthen secure communication methods during the post-quantum era of cryptography by leveraging quantum effects for information processing and complex computations.

1.1 Preliminaries

QCA basics

In QCA, electron polarizations determine the logic state instead of voltage levels in CMOS technology. The fundamental unit of quantum cellular automata is the QCA cell, which utilizes quantum mechanics principles to enable efficient computation at the nanoscale. This cell contains four strategically positioned quantum dots arranged in a square formation, with two electrons enclosed within. Due to Coulombic repulsion, the electrons occupy antipodal locations in equilibrium. This arrangement of quantum dots serves as a suggested model for quantum computation, as it allows the execution of Boolean logic functions. The intricate states of the quantum dots enable the encoding and processing of information [2–8]. It is akin to traditional cellular automata (CA) and relies on tunneling,' a phenomenon in quantum mechanics, which enables information propagation through the system, allowing non-local interactions and state superposition and applications in computing and cryptography [2–12]. The movable electrons in binary QCA can tunnel between dots and form two stable polarizations, 'P'= +1 (as logic '1') and 'P'= -1 (as logic '0'), following Fig.1 of QCA cell operation [2, 13–19].

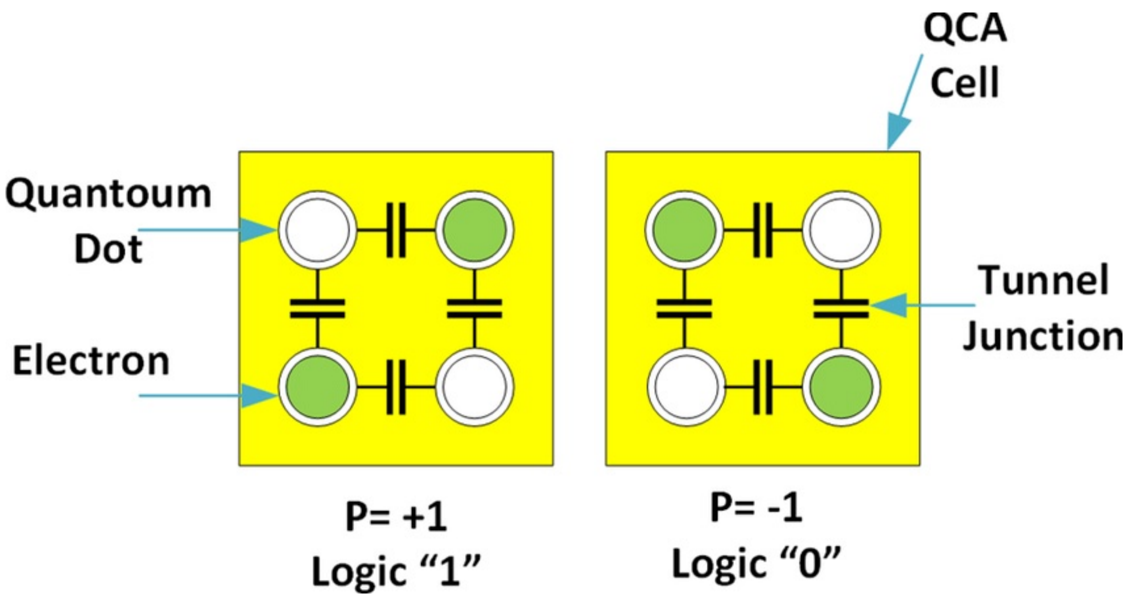


Figure 1: Illustration of two stable stem cell states in a QCA cell using four quantum dots (logic '1' on the left hand and logic '0' on the right) [15].

Coulombic interactions between neighboring cells enable information to flow without electron transfer, resulting in minimal power dispersion. In a series QCA cells, each cell can rearrange its polarized status in accordance with the abutting cell to create the information flow [15–17]. The 'QCA wire', 'Inverter' (I) and 'Majority Voter' (MV) serve as the fundamental and logical building blocks in any QCA circuit design. Their versatile nature facilitates the efficient conception of logical circuits in the QCA framework [3, 8, 18, 19]. The 'MV' acts as a two-input AND gate for any fixed input at the '-1.00' polarization, as a two-input OR gate for '+1.00' polarization [20]. QCA, or Quantum-dot Cellular Automata, is a nanotechnology-based computing paradigm that utilizes the principles of quantum mechanics. In BQCA cell operation, binary information is represented by manipulating and interacting with tiny semiconductor particles called quantum dots. These cells are arranged in a grid-like structure and governed by the laws of quantum physics. The use of QCA in secure nano-communication for post-quantum cryptography has gained attention recently [4, 16–20].

Reversible logic in quantum-based technologies

The primary goal of VLSI is achieving low-power design. With each bit of information lost, conventional irreversible logic circuits release 'KTln2' joules of heat energy, where 'K' stands for Boltzmann's constant and 'T' indicates the absolute temperature throughout the estimation [9]. Bennett's research [10] indicates that KTln2 joules of energy in reversible logic processing cannot be lost. Power-saving reversible logic circuit design is essential for quantum-based technologies, as energy dissipation causes information loss, making it a fruitful area of research [14, 21–26]. The inclusion of reversibility improves QCA effectiveness. Reversible circuit methodology takes precedence in QCA, quantum computing, and DNA computing [16, 27–29]. Quantum technology employs reversible gates like 'Fredkin', 'Toffoli', 'Feynman', and 'Peres Gate' as embellished in [22–30].

Definition 2.2.1:*"If a reversible gate has k inputs and therefore k outputs, Input Vector Iv is mapped with output vector Ov such that mapping is bijective, i.e. the one-to-one mapping between Iv and Ov. The corresponding reversible gate is known as the RLG k*k gate"* [31].

The optimal use of reversible circuits is essential for the efficient operation of quantum computers, requiring physical and logical reversibility. Reversible gates are essential in quantum computing, preserving information by ensuring unique outputs for each input and vice versa. This property allows for backward computations and minimizes energy consumption and heat dissipation in quantum circuits [21–23, 31].

Quantum gates and fundamentals: IBMQ experience

Quantum gates are a crucial component of reversible circuits in quantum computers. Several quantum gates are commonly used in quantum computing, including the "Pauli-X" gate (or 'NOT' gate), "Hadamard" gate, "phase shift" gate, 'Controlled-NOT' gate ("Feynman" or 'CNOT'), "Toffoli" gate ('CCNOT') and the "Swap gate", "RZ gate" and so on [32–35]. Each quantum gate has distinct mathematical qualities that allow it to perform explicit action on qubits on the quantum mechanics platform. Quantum gates can be combined to form complex quantum circuits that enable the manipulation of qubits and the execution of quantum algorithms and circuits. Now, using the equations (1), (2), (3), and (4), look into several widely used gates of quantum computing.

1. The simplest elementary gate is 1×1 'NOT' gate. The "Pauli-X" gate or the bit-flip gate is the quantum equivalent of the classical NOT gate, represented by the unitary matrix, as shown in Eq. (1) [33, 36]:

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

2. A quantum gate that generates a uniform superposition of two basis states in one qubit is known as a "Hadamard" gate. It means $|0\rangle$ is converted to $\frac{|0\rangle+|1\rangle}{\sqrt{2}}$ and $|1\rangle$ to $\frac{|0\rangle-|1\rangle}{\sqrt{2}}$. The matrix representation of the 'Hadamard' gate [35, 37–39] is as shown in Eq. (2).

$$H = \frac{1}{\sqrt{2}} \times \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{2}$$

3. The two-qubit "Swap" gate exchanges the states of the two concerned input qubits. The matrix expression is as given by Eq. (3) [34, 37, 38]:

$$SWAP = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

4. 4) A "Rz" gate refers to a diagonal single-qubit rotation operator, which can be implemented in hardware through frame modifications involving z-axis rotations at an angle of 'θ' (measured in radians) [39, 40]. The matrix representation of the "Rz" gate is as given by Eq. (4).

$$Rz(\theta) = \begin{bmatrix} e^{-i\frac{\theta}{2}} & 0 \\ 0 & e^{i\frac{\theta}{2}} \end{bmatrix} \tag{4}$$

Quantum computing uses quantum bits, utilizing quantum mechanics principles, for faster computations, enabling breakthroughs in communication, cryptography, and optimization, which have the potential to revolutionize those fields significantly [32–37]. IBM has developed IBM Quantum Experience (IBMQ) software and cloud-based services to enable researchers, educators, and developers to design quantum algorithms, run them on quantum hardware, and simulate their performance on classical computers [34–38]. Furthermore, IBM Quantum Experience features Qiskit [36, 37], an open-source quantum software toolkit. It consists of various modules with tools to create and manipulate quantum circuits, algorithms implementation, and execution on IBM's devices or simulators. IBM Quantum Experience has been designed to make quantum computing more accessible and facilitate research into the technology's capabilities and limitations.

In practice, QCA and quantum computing increase the security of nanotechnology by optimizing RAM cells, implementing quantum-resistant encryption algorithms, and constructing nanoscale sensors and detectors for secure communication and detection of security breaches or unauthorized access. A few academic efforts have focused on designing multi-operative reversible gates for secure nano-communication circuit applications, including parity generators and parity checkers in quantum-based technologies amid the post-quantum era outlook.

2 The Proposed Designs

The schematic building block and logical representation of the proffered 3×3 Multi-operative Reversible Quantum logic gate (MRQ-gate) are depicted in Fig. 2a and 2b.

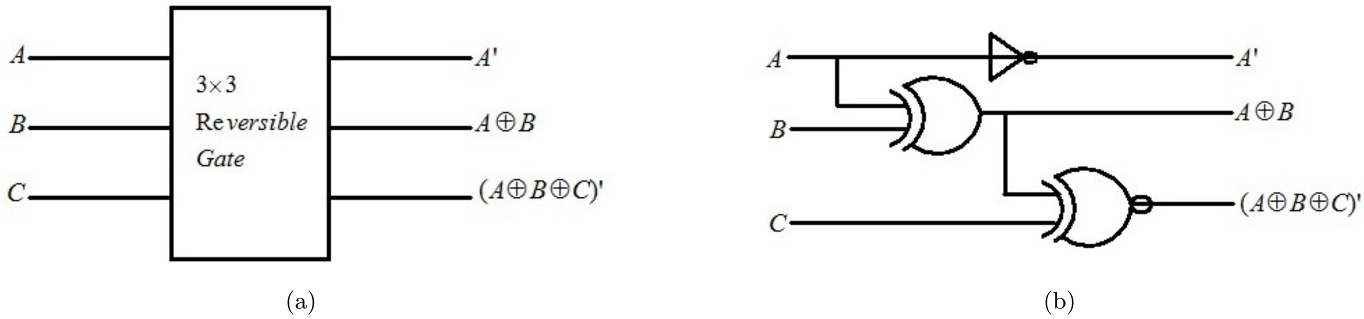


Figure 2: (a) Proposed schematic design of 3×3 reversible gate; (b) Planned logical diagram of 3×3 reversible gate.

The logical diagram illustrates the count of fundamental logic gates (one XOR, one NOT, and one XNOR) used in the proposed design. The output implementation count is needed to evaluate MRQ-gate fabrication complexity. Additionally, the evaluation approach assesses the fabrication complexity of the MRQ-gate by analyzing the output implementation count (as shown in Figure 2b), providing valuable insights into its overall hardware intricacy. The MRQ-gate design has minimal hardware complexity and considers the number of fabrication steps and efficiency by relying only on three fundamental logic gates: XOR, XNOR, and NOT operations within its framework. Indeed makes it a cost-effective potential design for large-scale quantum circuits for implementation in quantum-based Technologies.

As per the *definition 2.2.1*, a reversible gate has a unique and reciprocal correspondence among its input and output vectors. The MRQ-gate's encoding and input-output combinations are listed in Table 1, establishing and verifying its reversibility. The MRQ-gate mapping function, $IV(A, B, C) \rightarrow OV(A, B, C)$, is tested bijective by examining the correspondence between the input (IV) and output (OV) vectors (as referred to in Table 1). In due course, the QCA schematic layout and its simulation outcomes are exposed in Figures 3a and 3b. Likewise, a quantum computing approach using IBM QISKIT, illustrated in Figures 4a and 4b, can verify and confirm that the MRQ-gate satisfies the criteria for a reversible gate. This property makes the MRQ-gate a potential candidate for implementation in future quantum information processing systems.

Table 1: Truth Table of the Projected 3×3 Reversible Gate: Proof of Reversibility

A	B	C	A'	A XOR B	(A XOR B XOR C)'
0	0	0	1	0	1
0	0	1	1	0	0
0	1	0	1	1	0
0	1	1	1	1	1
1	0	0	0	1	0
1	0	1	0	1	1
1	1	0	0	0	1
1	1	1	0	0	0

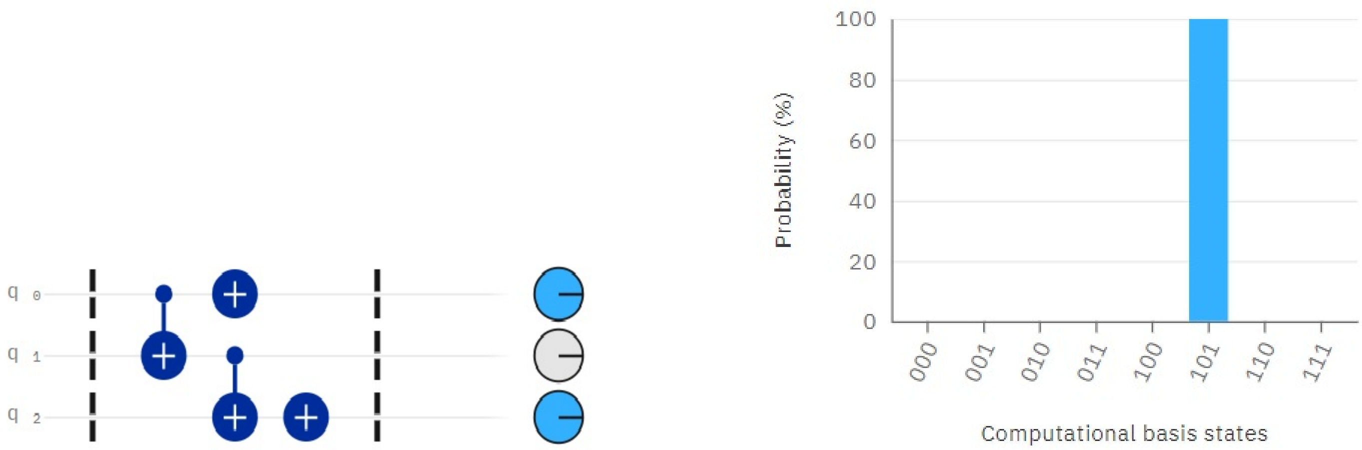
2.1 Quantum Technologies and Design Approaches: Simulation Tools and Result

In this section, the design and implementation of our intended Multi-operative Reversible Quantum (MRQ) circuit has been realized in an energy-efficient QCA framework along with IBMQ Experience [36] to authenticate its functionality. Accordingly, the QCA schematic layout adopting QCADesigner 2.0.3 [13] as well as its simulation outcomes are exposed in Figures 3a and 3b. Afterwards, a quantum computing approach using IBM QISKIT design for that proposal computes and illustrated in Figures 4a and 4b

(a) (b)

Figure 3: (a) Schematic QCA layout of the projected 3 × 3 reversible circuit;(b)Simulation results of designed 3 × 3 reversible circuit

These demonstrate the effectiveness of our proposed method in achieving reversible quantum computing with an energy-efficient QCA framework and functional authentication through IBMQ Experience. Overall, these results provide strong evidence for the feasibility and practicality of implementing the intended simple MRQ circuit in real-world quantum computing and open up new possibilities for secure nano-communication applications with improved energy efficiency and functionality.



(a) (b)

Figure 4: (a) The IBMQ schematic layout of the projected 3 × 3 reversible circuit; (b) The probable 3 × 3 reversible circuit's computational output in IBMQ configuration.

3 Application of Multi-Operative Reversible Gate in Quantum-Based Technologies for Even/Odd Parity Generators

This study presents a cutting-edge multi-operative reversible quantum ('MRQ') module that offers an innovative approach and potential applications in quantum-based technologies that are required in designing fundamental components of secure nano-communication systems such as 'Even/Odd Parity bit Generator.' The proposed approach introduces a simple reversible gate that operates at multiple levels that can improve and enhances security for quantum-based technologies at the nanoscale.

3.1 Proposed design and results of even/odd Parity bit generator using MRQ

Now consider 'A', 'B', and 'C' as intended message bits consigned via a communication medium. To generate the parity bit [41–43] 'P$_{E-O}$', simply one XOR, afterwards one XNOR maneuver, and contrariwise, is recommended. Thus, amid two reversible MRQ gates in a simple cascade connection, a three-bit 'even/odd' parity generator circuit can effortlessly be attained, as shown in Figure 5, where first, the 'MRQ' turns out the XOR of the inputs 'A' and 'B' along with one garbage expense as the complement of input "A.".

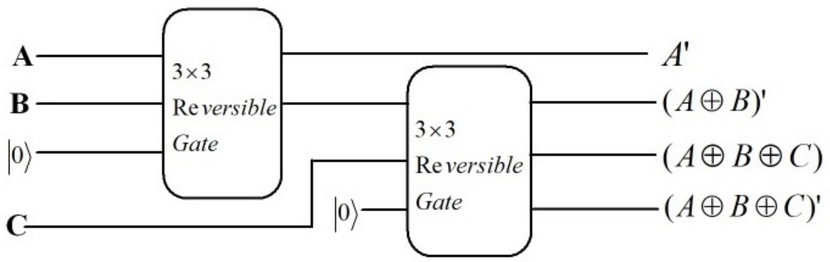


Figure 5: Logical illustration of the proffered 'even/odd' parity bit generator employing two projected multi-operative reversible quantum ('MRQ') modules.

The formed XOR-ed with 'A' and 'B' inputs of the first 'MRQ' is afterwards used as one of the inputs to the second 'MRQ'. The second 'MRQ' gives rise to the garbage value outputs as $(A \oplus B)$', $(A \oplus B \oplus C)$ and $(A \oplus B \oplus C)'$ will be the final corresponding yield bits of the even parity generator (EPG) and odd parity generator (OPG).

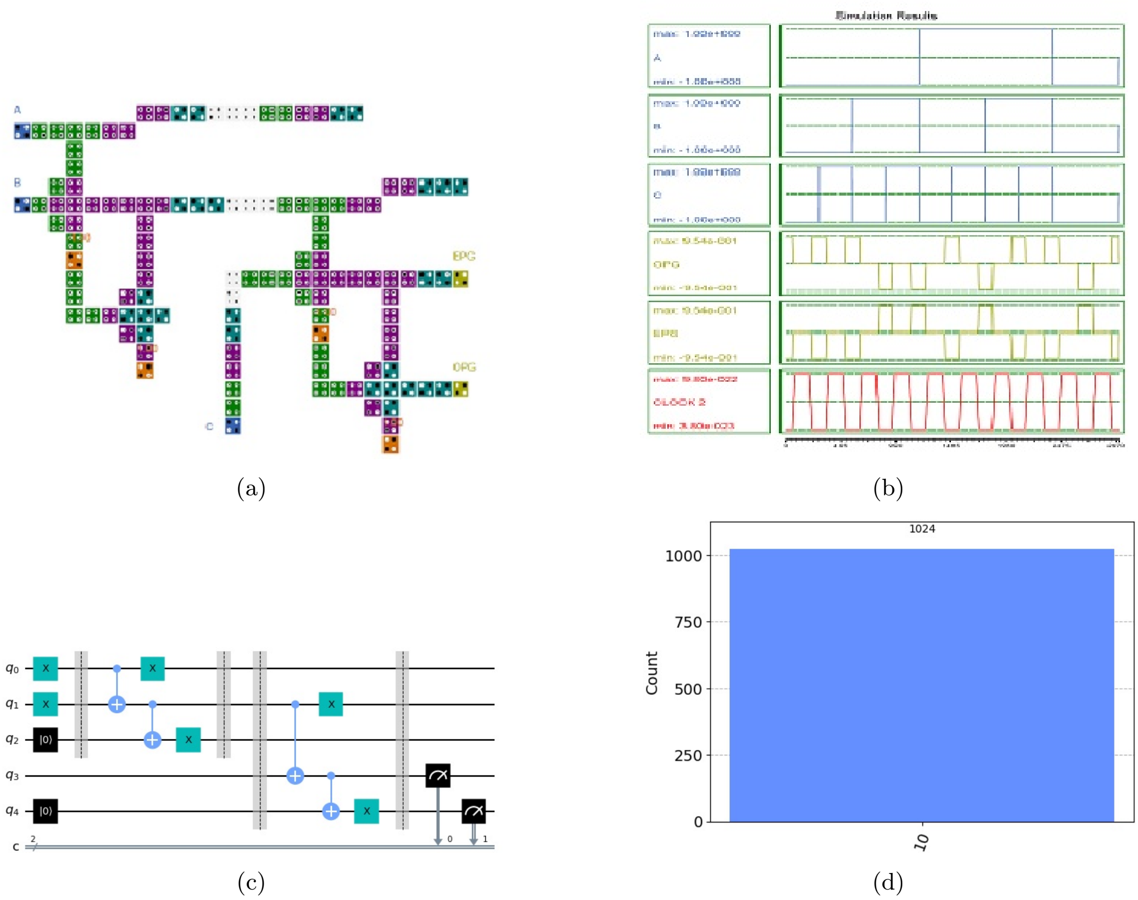


Figure 6: (a) QCA layout; (b) QCA simulation results for the intended 'even/odd' parity bit generator; (c) IBMQ schematic design of the intended 'even/odd' parity bit generator using the projected multi-operative reversible quantum ('MRQ') module; (d) Computational output in IBMQ of the planned 'even/odd' parity bit generator

The logical block illustration and simulation results of the intended 'even/odd' parity bit generator using two 'MRQ' modules have been functionally authenticated in QCA nanotechnology, likewise in IBMQ Experience as portrayed in Figure 5 and Figures 6a, 6b, 6c and 6d. In this work, we have considered the QCA realization concurrently with quantum computing simulation to authenticate the function and performance of the destined 'even/odd' parity bit generator and implementation employing 'MRQ'.

4 Accuracy Analysis and Discussion

This section analyses the accuracy and discusses the study findings and their implications for the current state of research. The proposal demonstrates the potential for producing an 'even/odd' parity bit generator deploying 'MRQ' modules in QCA and IBM Qiskit-like quantum-based technologies. The IBMQ computational output showed perfect accuracy (100%) and matched theoretical predictions for our planned 'even/odd' parity bit generator, as evident in Fig. 6 (d). The terminology 'Even/Odd' also merits this proposal to describe our module's ability to generate both types (even and odd) of parity bits together. This feature is favourable for applications that demand a concurrent generation of even and odd bits without processing delays. The proposed MRQ module-based technology aligns with computational output and theoretical predictions, offering the potential for practical applications in quantum computing. It reliably generates parity bits, reduces errors, and enhances data security, encryption methods, and faster solutions to complex challenges, which could have far-reaching implications for industries relying on data security and computational efficiency. Thus, our projected fruitful schemes in different quantum-based technologies show promising results for reliable and secure nano-communication systems and hold immense gist for multiple applications that meet the growing demands of modern technologies.

However, the proposed design of quantum-based technologies may face limitations and potential hurdles owing to their nanoscale nature, such as defect analysis, fault model development, testing, and the expensive lithography of QCA devices. As another option, scalability, noise, de-coherence, quantum error correction in quantum state measurement, hardware integration, signal synchronization, interconnectivity between components, and high computational cost are challenging tasks open to researchers to achieve robust, practical, fault-tolerant quantum circuits for real-world applications of quantum computing systems [20–22, 28–32, 44–46].

5 Conclusion and Future Works

In conclusion, our projected simple multi-operative reversible gate shows promising results for the effort of many more efficient and secure modules in future computing, nano-communication systems, and cryptographic applications. The research claims that the MRQ-gate design is a practical and cost-effective idea for large-scale quantum circuits since it only necessitates a few simple logic gates, resulting in little hardware complexity.

These findings also provide an opportunity for further academic exploration and development in the post-quantum era. Thus, future works could focus on exploring the potential of this module for large-scale circuits and its integration with other reversible and non-reversible modules to evolve an awe-inspiring 'Network-on-Chip' (NoC) or complex 'System-on-Chip' (SoC)-based nano-communication systems and post-quantum cryptography realization. Depending on the unique requirements of the end users, a single design may be beneficial in a variety of future secure nano-communication modules like "Even/Odd Parity bit Checker", "True Random Number Generator (TRNG)" and many others. It would also be interesting to compare the effectiveness and energy efficiency of the proposed reversible gate to other available choices. Scaling up and optimizing the proposed MRQ module with various quantum technologies could reveal its potential for fault-tolerant computing and more complex quantum tasks.

Declaration of Competing Interests

The authors declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution

Puspak Pain: Conceptualization, investigation, methodology, and writing - original draft, data curation, formal analysis; **Arindam Sadhu**: Conceptualization, methodology, software, visualization, data curation, writing, reviewing, and editing. **Kunal Das**: Visualization, investigation, software validation, supervision; **Maitreyi Ray Kanjilal**: Supervision; formal analysis, reviewing, editing.

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