QQCAsim: a new simulation tool for quaternary logic in QCA technology

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Abstract

Quantum-dot cellular automata (QCA) technology is one of the candidate technologies to replace CMOS in multi-valued logic (MVL) circuit designs, to overcome the problems of binary systems. One of the advantages of MVL systems is that they can process more information. Some techniques are essential to simulate and evaluate new multi-valued designs and their performance. This article introduces a new software platform for simulating Quaternary QCA (QQCA) circuits that can be run on computers on Windows and Linux computers is powerful and can run simulations with high accuracy. The presented tool provides the results in two formats. The first format is waveform and the second one is truth table. The presented software has a user-friendly interface that allows users to easily implement their QQCA circuits. Furthermore, the electrostatic energies for all cases in which the basic gates assume four values are determined and the step-by-step simulation process is described. The basic NOT, AND, and OR gates have already been simulated and validated by the relevant software.

Keywords: Multi-Valued Logic (MVL), Quaternary QCA, QQCAsim, polarization states, Hamiltonian matrix

1. Introduction

By scaling CMOS transistors, some problems, such as high leakage current and low threshold voltage, emerge. Therefore, alternative technologies, such as CNTFET, FINFET, and Quantum-dot cellular automata (QCA), have been proposed to resolve these problems [1-8]. One of the alternative technologies that have received more attention is QCA technology. A reason that makes QCA interesting is its proximity to the concept of fuzzy logic, which is believed to be implemented in the future using multi-valued logic (MVL) QCA systems [8,9].

By increasing the levels in multi-valued systems, information can be compressed into a smaller number of bits. This means that more information can be transmitted in multi-valued systems than in a binary system with a smaller number of data transmission paths (wires) [4, 5, 9].

In Ref. [10], D, T, and JK flip-flops have been investigated using Quaternary reversible gates. The results in [10] show that by increasing the levels, more information is processed and also reduces the complexity of the circuit design [10].

Each proposed technology requires a standard by which computer-aided design (CAD) tools can be designed. In QCA technology, some standards, such as clock operation, application method, and gate design methodology, are of particular importance in designing CAD tools. The QCA designer tool has been provided for simulating binary logic, and TQCAsim software has been developed by the QCA research team at IAUCTB for simulating ternary logic circuits [4, 5].

In this study, for the first time, a quaternary QCA (QQCA) simulation tool whose polarization is calculated based on quantum measurements is investigated. This software can simulate QQCA gates and circuits based on the model proposed in [8]. Moreover, in this study, the performance of QQCAsim software is reviewed.

This tool is based on the .NET framework and the C # programming language. The innovation in the processing engine of the software called "Inputs to Output Cell to Cell Follow (IOCCF)" is unlike the processing engines of other software in this field, and provides processing by propagating information from input to output. All other cells in the processing path are processed using intelligent routing.

2. QCA technology

The QCA technology is a new technology that can be examined from two aspects [4, 5, 8]. The first is the quantum view by which polarization, Hamiltonian matrix, and power dissipation in a cell can be calculated [8, 9]. The second aspect deals with determining the external electrostatic effect, which is the operation principle in the QCA technology [4, 5, 11-17].

Based on the calculations in QCA technology [8, 9], polarization states of QCA cells are used for quantum measurement. Equation 1 shows a quantum measurement.

$$P_k = -\langle \delta_{zk} \rangle \tag{1}$$

To date, the QCA technology has been presented for binary, ternary, and quaternary [4-6, 8-9, 16-23] systems. In this technology, each cell is made up of a few electrons and quantum dots enclosed in a square, and the electrons cannot leave the square. In calculating the polarization, the number of electrons is of special importance. In binary, ternary, and quaternary QCA structures, the numbers of required electrons (particles) are one, two, and three, respectively [8].

Using quantum measurement, the polarization in a binary system is {-1.1}, in a ternary system is {-2,0,0,2} (in previous articles the wrong polarization {-1,0,0,1} has been used), and in a quaternary system is {3,-3,-1,1,3} [8, 9].

Each binary QCA cell consists of four potential wells and two electrons [24, 25]. Figure 1 (a) shows the polarization in the binary QCA cell. Also, TQCA cells are composed of eight potential wells and two electrons, which creates four stable states with eight potential wells and two electrons, which is the repeated zero state ({-2, 0, 0, 2}) [4]. Figure 1 (b) shows the polarization in the Ternary QCA cell.

As mentioned, the purpose of this study is to present a simulator for simulating QQCA cells and circuits. In the structure of a QQCA system, three electrons (particles) exist. The QQCA simulation tool is based on the model presented in Ref. [8]. The reason for using a two-layer structure for the cell presented in Ref. [8] is to achieve stability although the properties of this cell allow implementing it in one layer. Figure 2 shows the QQCA cell and its polarization [8].

QCA technology has received attention due to its high response speed and reduction of circuit dimensions with this technology [24, 25]. In the construction of a QCA cell, electron beam lithography with the double layer resists is used on Si or Si/SiO2 substrate, and also quantum dots are deposited on an aluminum substrate [26]. Because of the increasing progress of semiconductor device manufacturing technology, QCA technology can be implemented.
In the construction of this technology, the technology of making devices less than 10 nm is needed. The methods of making semiconductor devices less than 10nm can be used some method such as field emission scanning probe (FE-SP) [27], plasmonic lithography [28], electron beam lithography using polymethylmethacrylate (PMMA) resist [29], and extreme ultraviolet (EUV) interference lithography [30]. It is also mentioned in [8, 31] that the QQCA cell can be implemented in one layer using input and output drives.
The clock in QQCA is similar to the clock in binary QCA and has four zones: switch, hold, release, and relax, which are used to control and transfer information simultaneously. Figure 3 shows the clock in QQCA [8].

3. Energy in QQCA

Energy in QCA technology has two forms of intracellular energy and extracellular energy [4, 5, 8]. Intracellular energy includes internal electrostatic energy, ground-state energy, and kink energy [8]. External cellular energy contains only external electrostatic energy, which is the

basis of QCA cell operation. As mentioned in the previous section, for the stability of the QQCA cell, the cell is presented in two layers [8]. Equation 2 calculates the external electrostatic energy in each layer.

$$E_{ij} = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\sum_{i=0}^{m}\sum_{j=0}^{n}\frac{q_i q_j}{d_{ij}}$$

(2)

In calculating the external electrostatic energy, the electrons of each layer must first be labeled in two neighboring cells and the distance between them must be calculated. Figure 4 shows the labeling system in each layer of the QQCA cell.

The external electrostatic energies in the first layer are denoted by *Ee11*, *Ee12*, *Ee13*, and *Ee14*. Moreover, *Ee11* and *Ee12* represent similar labels, while *Ee13* and *Ee14*, represent dissimilar labels. By specifying the electrostatic energy of similar and dissimilar labels in equation 3, the amount of energy in the first or ternary layer can be calculated [8].

$$E_{t_{TQCAlayer}} = \left(E_{e11} + E_{e12}\right) - \left(E_{e13} + E_{e14}\right)$$

(3)

In the second layer, the situation is similar to the first layer, and the external electrostatic energy for the distances between the electrons is represented by *Ee21, Ee22, Ee23*, and *Ee24*. Additionally, *Ee21* and *Ee22* represent similar labels, while *Ee23* and *Ee24*, represent dissimilar labels. By specifying the electrostatic energy of similar and dissimilar labels in Equation 4, the amount of external electrostatic energy in the second or binary layer can be calculated [8].

$$E_{t_{bQCAlayer}} = \left(E_{e21} + E_{e22}\right) - \left(E_{e23} + E_{e24}\right)$$

(4)

After calculating the external electrostatic energy in both layers, the total external electrostatic energy for two neighboring cells can be calculated by algebraically summing the energies of each layer. Tables 1 to 4 show the electrostatic energy values for two neighboring cells, NOT gate, AND gate, and OR gate, respectively.

4. Simulator design

To design and implement CAD tools for QQCA circuits, the C# programming language was used under the Microsoft .Net Framework 4.8 in the Microsoft Visual Studio 2019

programming environment. This software was designed with a very user-friendly interface, so the user can more easily design QCA circuits.

The results of the circuit in Ref. [8] confirm the proper operation of the QQCAsim software. QQCA cells in QQCASim software are based on quantum calculations. This cell is proposed due to stability in the design of basic gates in two layers, which can be implemented in one layer as well [8]. New features such as cell-to-cell, clock-to-clock, and state-to-state processing are also added to the software for easier troubleshooting of the designs. Figure 5 shows the flowchart used to design the CAD tool for QQCA.

4.1 Design modeling

In the modeling and implementation of QQCAsim software, a 40×30 matrix has been used to increase the speed of the software. Each cell in the QQCA design can be considered an input cell, output cell, intermediate cell, communication cell, or a cell with fixed polarization. In this software, colors represent cell states. The input cell is in blue, the output cell is in yellow, and the cell with fixed polarization is in orange. The color of the intermediate cells depends on the clock zone. For the intermediate cell, the clock zones, 0, 1, 2, and 3 are in green, purple, phosphors, and white, respectively. Figure 6(a) shows the colors of QQCA cells in the input, output, and fixed cell modes. Figure 6(b) shows the color of the intermediate cells in different clock zones.

Before the simulation, the user must specify the cell state (input, output, fixed, and intermediate) and select the associated symbol. Then, the user has to assign the appropriate clock value to the selected cell, and finally, press the Start simulation button. Accordingly, the software begins the simulation and displays the truth table and waveform of the designed circuit to the user for different input modes. Figure 7 (a) shows the cell type and clock selection window. Figure 7 (b) shows the simulation step and modes, such as state-to-state and clock-to-clock.

4.2 Simulation process

The simulation begins by setting the values of the input cells, and the polarity of the intermediate and output cells is determined based on the calculation of energy between the cells. The next steps of the simulation are as follows:

- Determining the list of input and output cells used to obtain the truth table, and showing the waveform used to find intermediate cells.
- Determining the input loop to the input cells; in this step, each input cell can obtain the polarization {-3, -1, 1, 3} or {A, B, C, D}.
- Determining the intermediate cell polarization using external electrostatic energy.

4.3 Processing window (processing priority)

The proposed software uses a new method to calculate the polarization in QQCA cells. In the proposed method, the center of the processing window is placed on the desired cell and the effects of adjacent cells on the central cell are calculated separately. Moreover, a 3×3 and a 5×5 window can be chosen for processing, and a 40×30 window is used for the Crossover design. Figure 8 shows 3×3 and 5×5 processing windows.

The 3×3 window only determines the effect of adjacent cells, which are one unit away from the central cell (processed cell), and ignores the effect of farther cells. For example, if the software is set to the 3×3 window, the distance between two wires passing each other should not exceed the size of a cell. As another example, if the processing is set to the 5×5 window, the interaction of the two wires cannot be ignored, unless the distance between the two wires exceeds two cells.

The processing priority is determined based on the radial distance of the central cell from the adjacent cells and their clocks. Accordingly, the closer distance between an adjacent cell and the central cell and a unit difference in clock zones lead to a higher processing priority. Figure 9 shows the processing priority for the two examples.

The software also presents the following new processing features that can be used to troubleshoot the designed circuit:

- Cell-to-Cell processing: to evaluate cell-to-cell data propagation
- Clock-to-Clock processing: to check the release of data on a clock-by-clock basis
- State-to-State processing: to view cell mode simultaneously
- Next move processing: to display the next move in seconds
- Displaying cell options in which the following items can be selected: label, clock, or the calculated value and energy.

Figure 10 shows the simulator settings and the cell options.

5. Results

The results of the presented simulator are given in two formats. In the first format, the results are presented in the form of truth table, and the second format, in the form of waveform. The truth table and waveform are presented based on the number of inputs and the polarizations that an input receives. Figures 11 (a), (b), and (c) show an example of a gate circuit, its truth table, and its waveform, respectively. These results were presented by Akbari et al. [8].

Using the measurements in Microsoft Visual Studio 2019 programming environment, QQCA AND and OR gates were evaluated by the software on two different machines which shows the results in Table 5.

6. Conclusion and future studies

Each new concept requires specific methods to prove its proper performance. In this study, a new CAD tool for designing quaternary gates and circuits based on QCA technology was presented. This software was designed based on both the external electrostatic energy calculations and the calculations presented in previous studies. In this simulation software, the results were presented graphically in the forms of truth table and waveform. Although the proposed QQCA software is in its initial stage, we intend to improve its efficiency in each upcoming version so that several new values can be set in more comprehensive software in the future.

Our research team has developed comprehensive software to simulate ternary and quaternary circuits in QCA technology. Moreover, we try to expand the software to be able to include different QCA structures (BQCA, TQCA, etc.) in the comprehensive software to design circuits with different structures and to integrate these structures. We always try to improve the performance of the software for QCA enthusiasts in future releases of the software.

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Figures:

Figure 1. (a) Binary Quantum-dot cellular automata (QCA) cell presented in [4], (b) Ternary QCA cell presented in [4]

Figure 2. (a) Quaternary QCA (QQCA) cell presented in [8], (b) symbolic form of Quaternary QCA (QQCA) [8], and (c) polarization of Quaternary QCA (QQCA) [8]
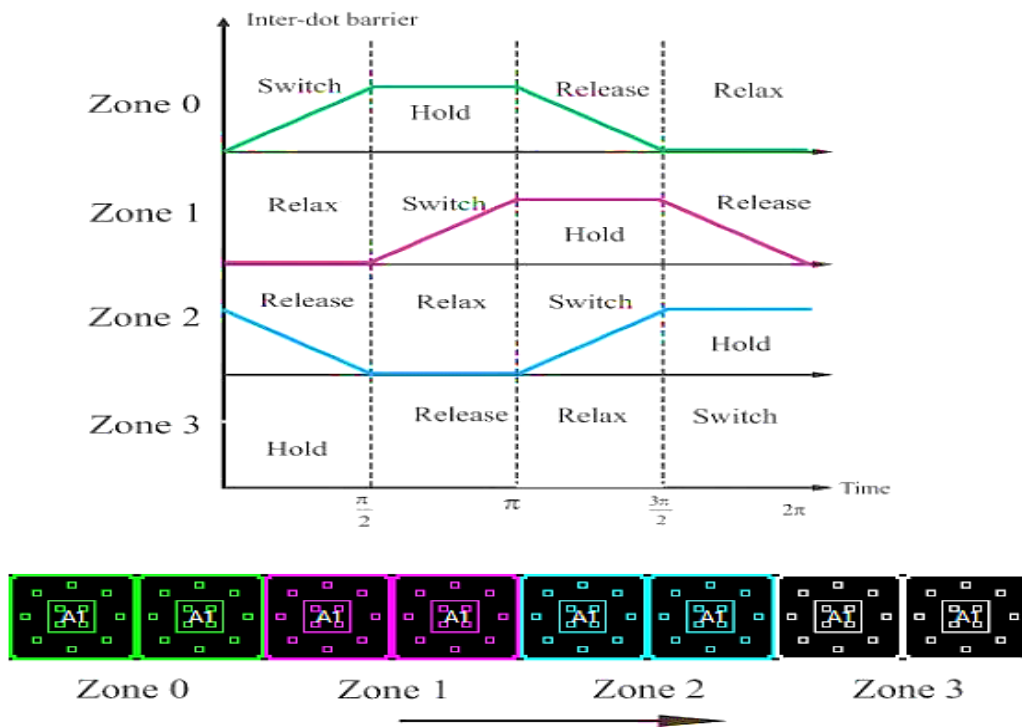
Figure 3. Clock in Quaternary QCA (QQCA) [8]
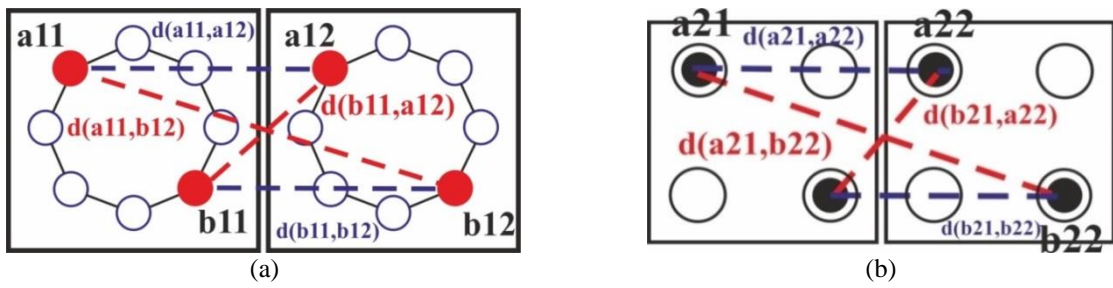
Figure 4. Distance between two Quaternary QCA (QQCA) cells [8] (a) in the first layer (ternary layer) and (b) in the second layer (binary layer)
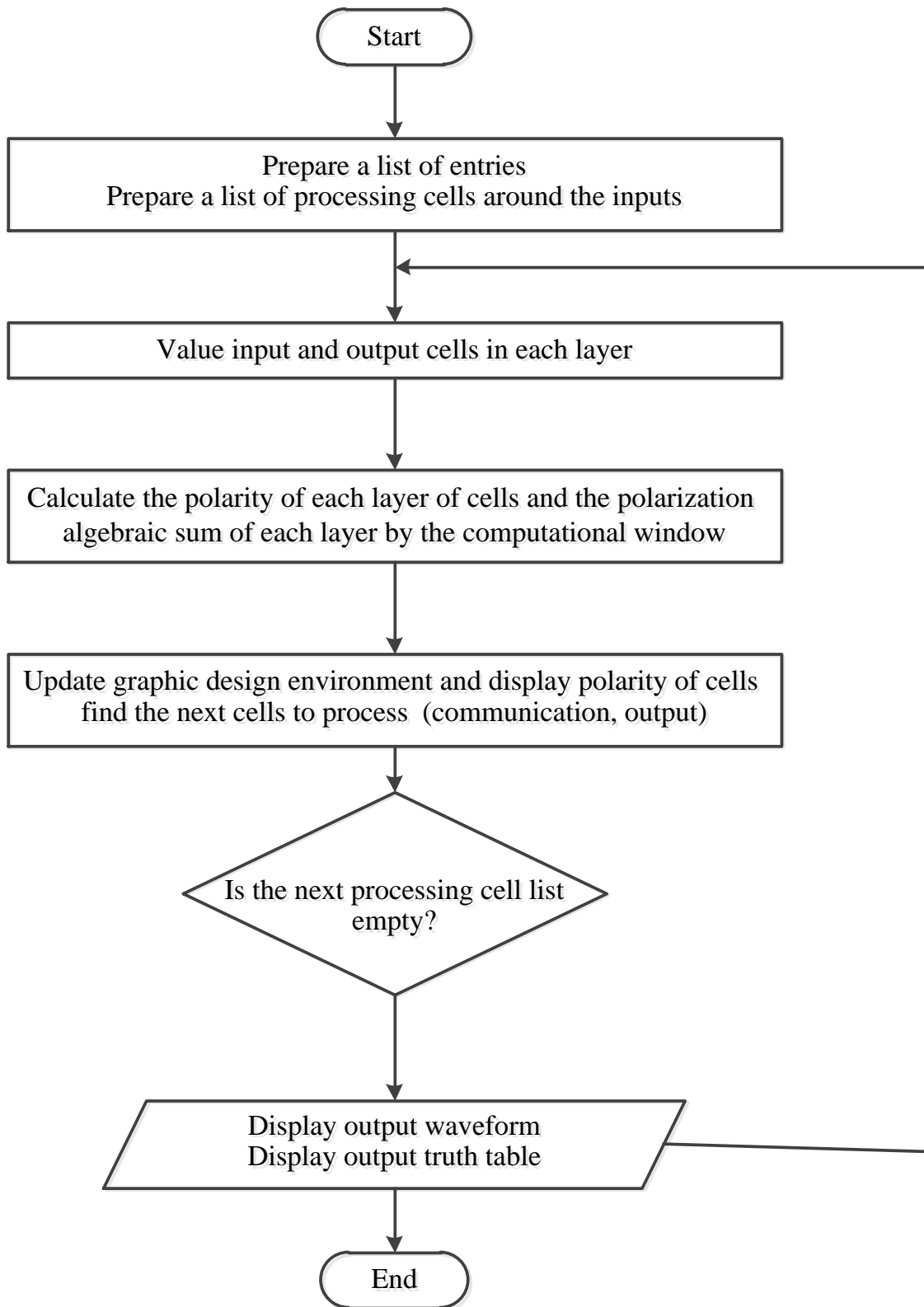
Figure 5. Simulation flowchart of the software

Figure 6. (a) color representation of the input, fixed, and output cells and (b) color representation of intermediate cells in different clock zones
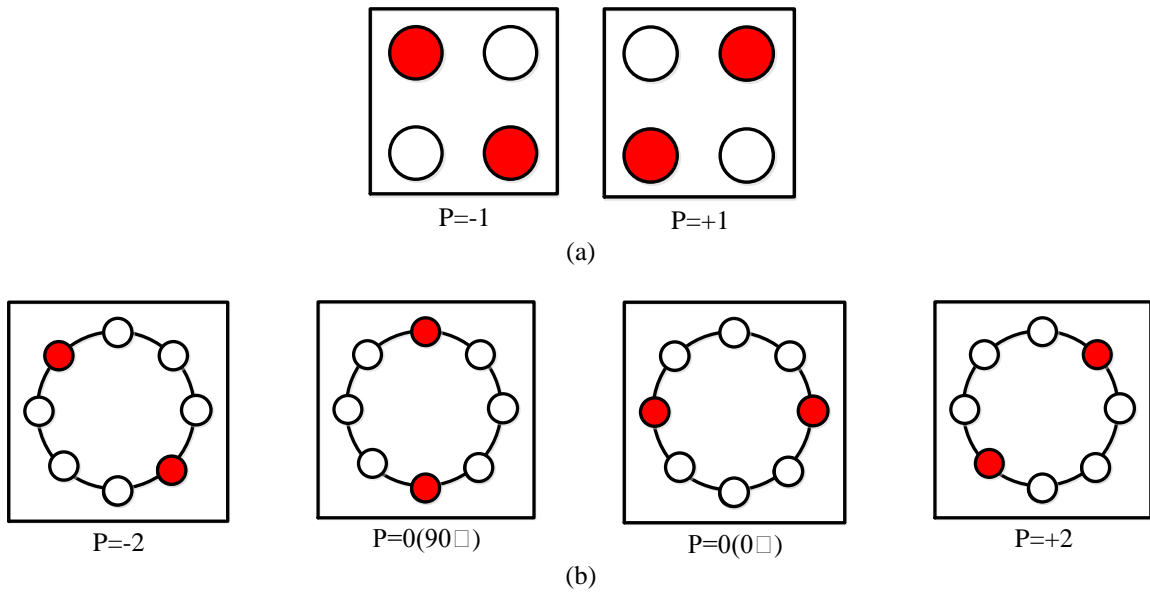
Figure 7. A view of (a) cell selection and (b) simulation properties windows

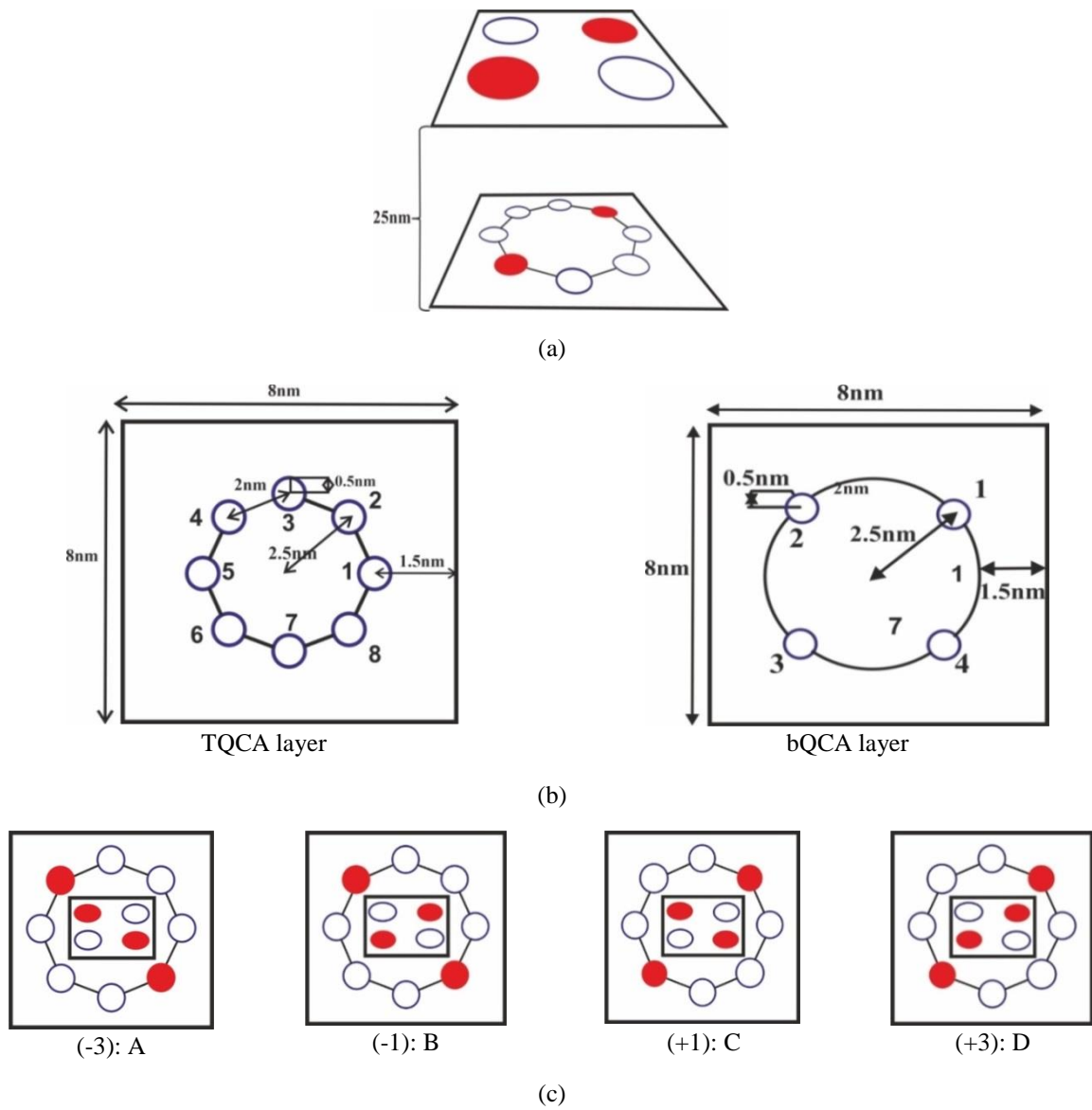**Figure 8.** (a) 3×3 and (b) 5×5 processing windows

Figure 9. Two examples of processing priority in QQCA software

**Figure 10.** Simulator settings and cell label

Figure 11. Designed sample of AND gate using QQCAsim software [8]; (a) schematic [8], (b) output waveform [8], and (c) truth table of the AND gate in Quaternary QCA (QQCA) [8]

P=-1   P=+1

(a)

P=-2   P=0(90□)   P=0(0□)   P=+2

(b)

Figure 1. (a) Binary Quantum-dot cellular automata (QCA) cell presented in [4], (b) Ternary QCA cell presented in [4]

(a)

(b)

TQCA layer

bQCA layer

(c)

(-3): A   (-1): B   (+1): C   (+3): D

Figure 2. (a) Quaternary QCA (QQCA) cell presented in [8], (b) symbolic form of Quaternary QCA (QQCA) [8], and (c) polarization of Quaternary QCA (QQCA) [8]
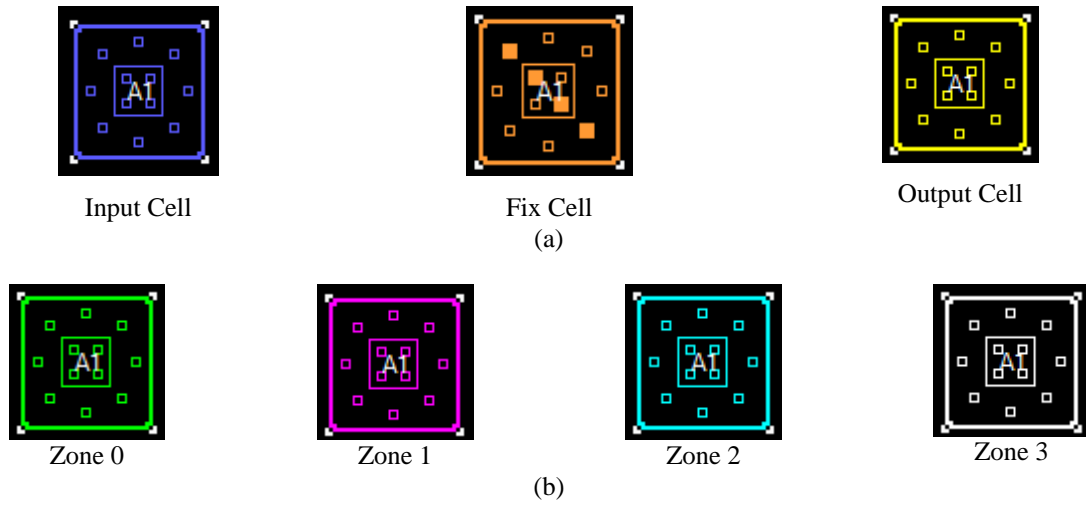
Figure 3. Clock in Quaternary QCA (QQCA) [8]

Figure 4. Distance between two Quaternary QCA (QQCA) cells [8] (a) in the first layer (ternary layer) and (b) in the second layer (binary layer)
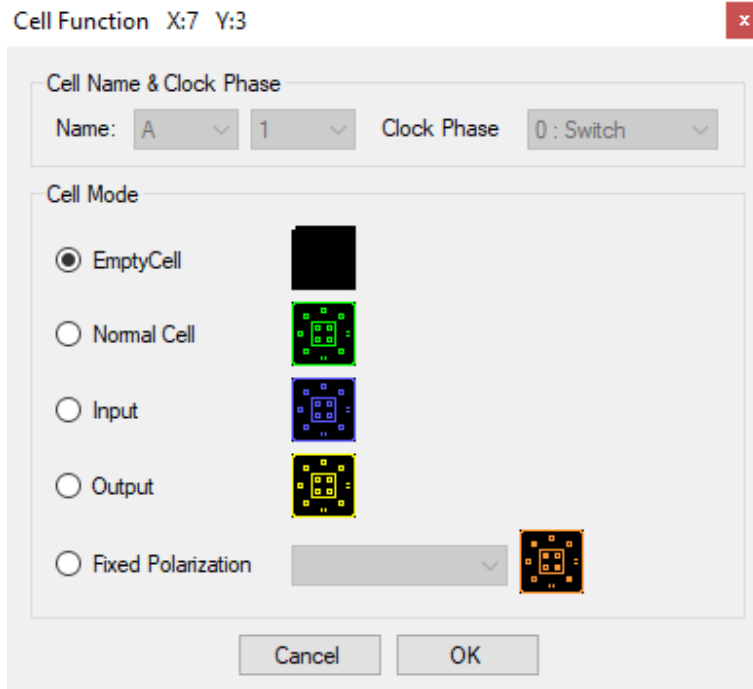
```
                          ┌─────────┐
                          │  Start  │
                          └─────────┘
                               │
                               ▼
        ┌──────────────────────────────────────────────────┐
        │              Prepare a list of entries            │
        │   Prepare a list of processing cells around the inputs │
        └──────────────────────────────────────────────────┘
                               │
                               ▼
        ┌──────────────────────────────────────────────────┐
        │        Value input and output cells in each layer  │
        └──────────────────────────────────────────────────┘
                               │
                               ▼
        ┌──────────────────────────────────────────────────┐
        │   Calculate the polarity of each layer of cells and the polarization │
        │   algebraic sum of each layer by the computational window │
        └──────────────────────────────────────────────────┘
                               │
                               ▼
        ┌──────────────────────────────────────────────────┐
        │   Update graphic design environment and display polarity of cells │
        │   find the next cells to process  (communication, output) │
        └──────────────────────────────────────────────────┘
                               │
                               ▼
                       ◇ Is the next processing cell list
                           empty? ◇
                               │
                               ▼
        ╱──────────────────────────────────────────────╱
        │          Display output waveform              │
        │          Display output truth table           │
        ╱──────────────────────────────────────────────╱
                               │
                               ▼
                          ┌─────────┐
                          │   End   │
                          └─────────┘
```

Figure 5. Simulation flowchart of the software

Input Cell   Fix Cell   Output Cell
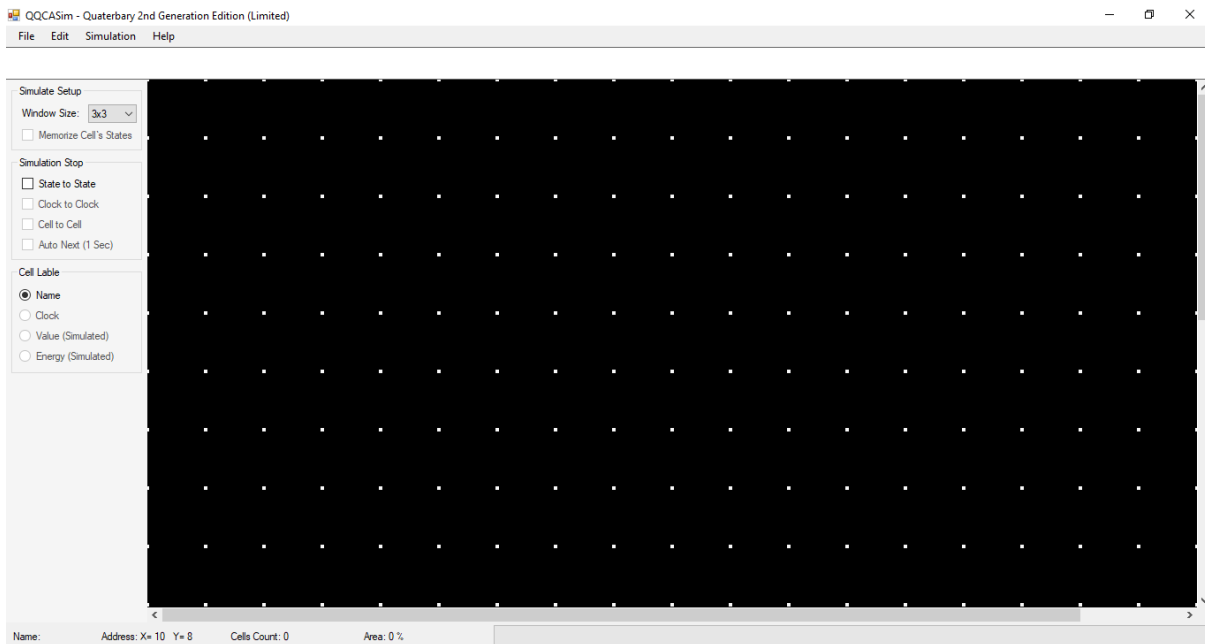
(a)

Zone 0   Zone 1   Zone 2   Zone 3

(b)

Figure 6. (a) color representation of the input, fixed, and output cells and (b) color representation of intermediate cells in different clock zones
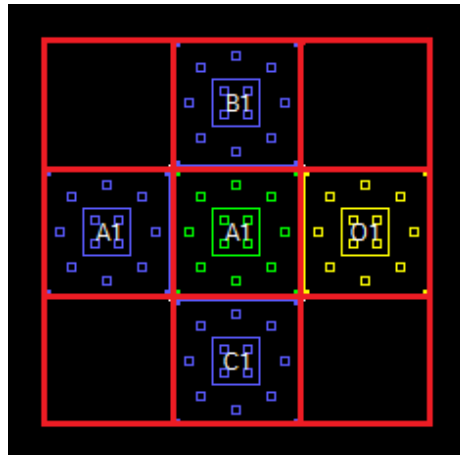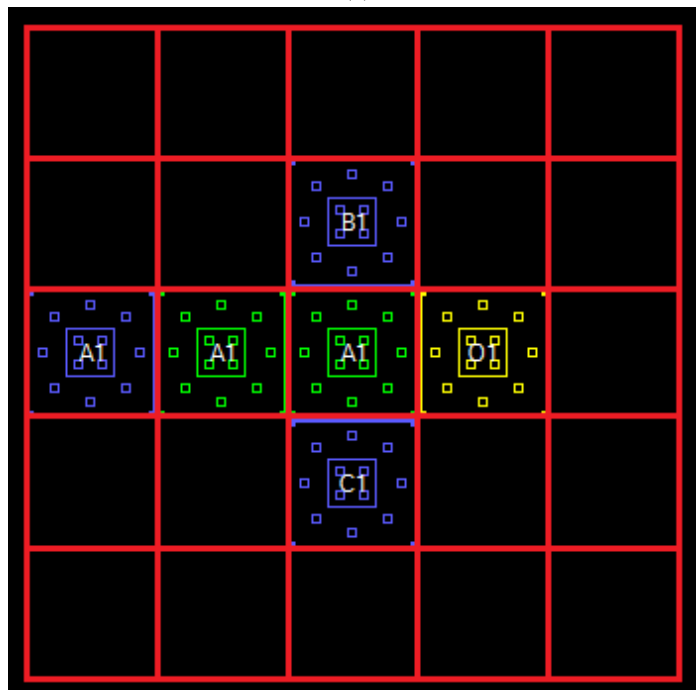
(a)

(b)

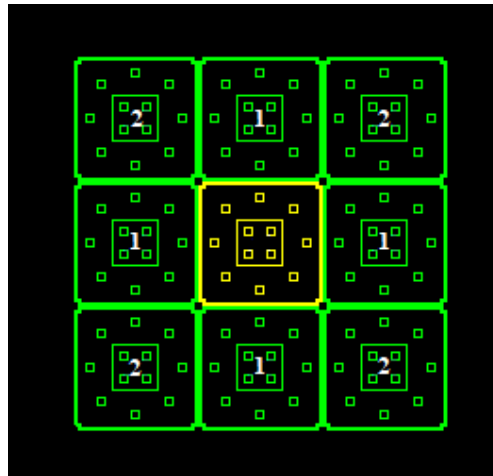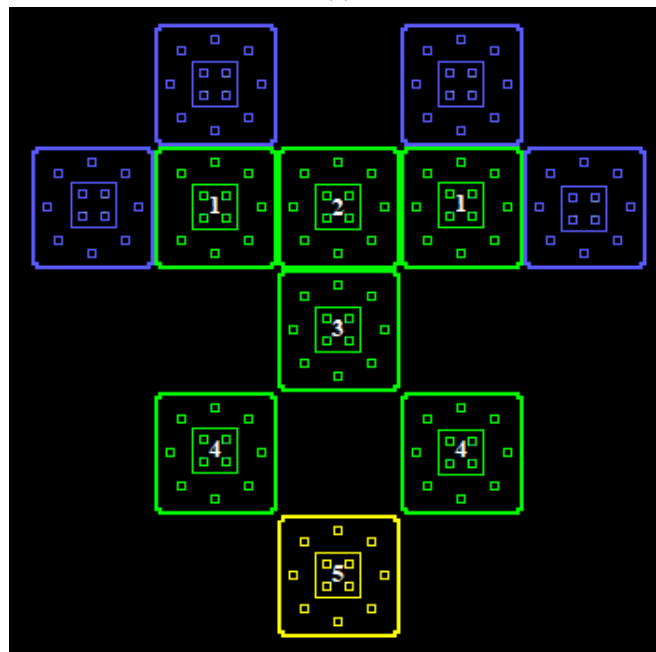**Figure 7.** A view of (a) cell selection and (b) simulation properties windows

(a)

(b)

Figure 8. (a) 3×3 and (b) 5×5 processing windows

(a)

(b)

Figure 9. Two examples of processing priority in QQCA software

Figure 10. Simulator settings and cell label

(a)

(b)

(c)

	I> B1	I> C1	O> O1
1	A	A	A
2	B	A	A
3	C	A	A
4	D	A	A
5	A	B	A
6	B	B	B
7	C	B	A
8	D	B	B
9	A	C	A
10	B	C	A
11	C	C	C
12	D	C	C
13	A	D	A
14	B	D	B
15	C	D	C
16	D	D	D
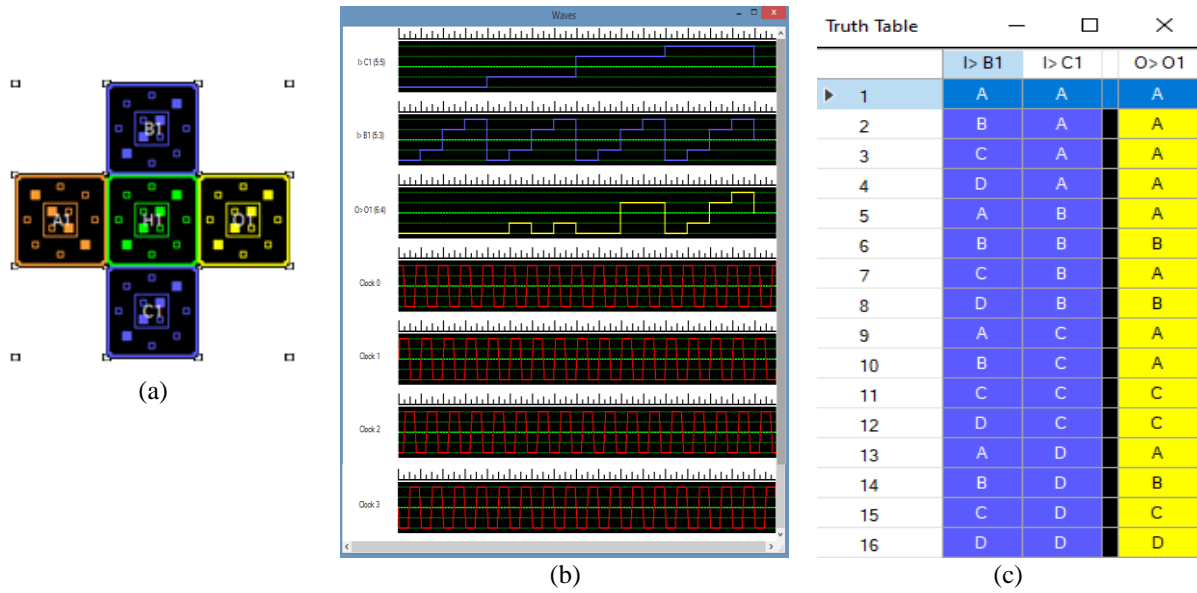
Figure 11. Designed sample of AND gate using QQCAsim software [8]; (a) schematic [8], (b) output waveform [8], and (c) truth table of the AND gate in Quaternary QCA (QQCA) [8]

Tables:

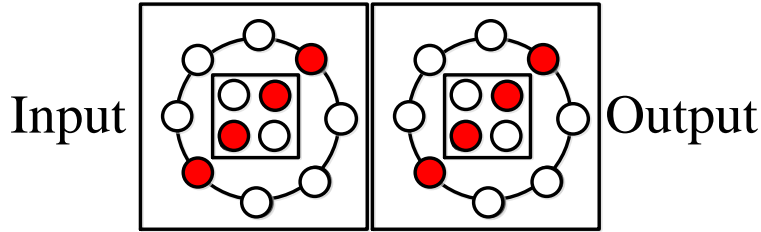**Table 1.** The output of two-cell effect and final results

Table 2. NOT gate results for all states and final values

Table 3. Output results of AND gate for all states

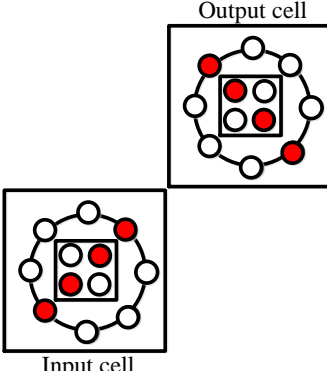**Table 4.** Output results of OR gate

Table 5. Evaluation of basic gates by the proposed software in two different systems

Table 1. The output of two-cell effect and final results

Input / Output

	Output cell in A state	Output cell in B state	Output cell in C state	Output cell in D state	Final result
Input cell in A state	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}}=0.392*10^{-20}$	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}}=1.748*10^{-20}$	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}}=1.748*10^{-20}$	$E_{t_{bQCA}}=1.552*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}}=3.104*10^{-20}$	$E_{t_{QQCA}}=0.392*10^{-20}$ Out state= A state
Input cell in B state	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}} = 1.748*10^{-20}$	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}} = 0.392*10^{-20}$	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}}=3.104*10^{-20}$	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}}=1.748*10^{-20}$	$E_{t_{QQCA}}=0.392*10^{-20}$ Out state= B state
Input cell in C state	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}}=1.552*10^{-20}$ $E_{t_{QQCA}} = 1.748*10^{-20}$	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}}=3.104*10^{-20}$	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}}=0.392*10^{-20}$	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}}=1.748*10^{-20}$	$E_{t_{QQCA}}=0.392*10^{-20}$ Out state= C state
Input cell in D state	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}} = 3.104*10^{-20}$	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 1.552*10^{-20}$ $E_{t_{QQCA}} = 1.748*10^{-20}$	$E_{t_{bQCA}} = 1.552*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}}=1.748*10^{-20}$	$E_{t_{bQCA}} = 0.196*10^{-20}$ $E_{t_{TQCA}} = 0.196*10^{-20}$ $E_{t_{QQCA}}=0.392*10^{-20}$	$E_{t_{QQCA}}=0.392*10^{-20}$ Out state= D state

Table 2. NOT gate results for all states and final values

Output cell

Input cell

	Output cell in A state	Output cell in B state	Output cell in C state	Output cell in D state	Final result
Input cell in A state	$E_{t_{bQCA}}= 0.2943*10^{-20}$ $E_{t_{TQCA}}= 0.2943*10^{-20}$ $E_{t_{QQCA}}=5.886*10^{-20}$	$E_{t_{bQCA}}=0*10^{-20}$ $E_{t_{TQCA}}=0.2943*10^{-20}$ $E_{t_{QQCA}}=0.2943*10^{-20}$	$E_{t_{bQCA}}= 0.2943*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}=0.5004*10^{-20}$	$E_{t_{bQCA}}=0*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}=0*10^{-20}$	$E_{t_{QQCA}}= 0*10^{-20}$ Out state= D state
Input cell in B state	$E_{t_{bQCA}}= 0*10^{-19}$ $E_{t_{TQCA}}= 0.2943*10^{-20}$ $E_{t_{QQCA}}=0.2943*10^{-20}$	$E_{t_{bQCA}}= 0.8029*10^{-20}$ $E_{t_{TQCA}}= 0.2943*10^{-20}$ $E_{t_{QQCA}}=1.0972*10^{-20}$	$E_{t_{bQCA}}= 0*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}=0*10^{-20}$	$E_{t_{bQCA}}= 0.8029*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}=0.8029*10^{-20}$	$E_{t_{QQCA}}=0*10^{-20}$ Out state= C state
Input cell in C state	$E_{t_{bQCA}}= 0.2943*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}=0.2943*10^{-20}$	$E_{t_{bQCA}}= 0*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}=0*10^{-20}$	$E_{t_{bQCA}}= 0.2943*10^{-20}$ $E_{t_{TQCA}}= 0.8029*10^{-20}$ $E_{t_{QQCA}}=1.0972*10^{-20}$	$E_{t_{bQCA}}= 0*10^{-20}$ $E_{t_{TQCA}}= 0.8029*10^{-20}$ $E_{t_{QQCA}}=0.8029*10^{-20}$	$E_{t_{QQCA}}=0*10^{-20}$ Out state= B state
Input cell in D state	$E_{t_{bQCA}}= 0*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}= 0*10^{-20}$	$E_{t_{bQCA}}= 0.8029*10^{-20}$ $E_{t_{TQCA}}= 0*10^{-20}$ $E_{t_{QQCA}}= 0.8029*10^{-20}$	$E_{t_{bQCA}}= 0*10^{-20}$ $E_{t_{TQCA}}= 0.8029*10^{-20}$ $E_{t_{QQCA}}= 0.8029*10^{-20}$	$E_{t_{bQCA}}= 0.8029*10^{-20}$ $E_{t_{TQCA}}= 0.8029*10^{-20}$ $E_{t_{QQCA}}=1.6058*10^{-20}$	$E_{t_{QQCA}}= 0*10^{-20}$ Out state= A state

Table 3. Output results of AND gate for all states

	Output cell in A state	Output cell in B state	Output cell in C state	Output cell in D state	Final result
In1=A In2=A In3=A	$E_{t_{bQCA}}= 0.919*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.262*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}=3.074*10^{-20}$	$E_{t_{bQCA}}= 0.919*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=2.65*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=3.462*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.262*10^{-20}$ Out state= A state
In1=A In2=A In3=B	$E_{t_{bQCA}}= 0.625*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}=1.968*10^{-20}$	$E_{t_{bQCA}}=2.534*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}=3.887*10^{-20}$	$E_{t_{bQCA}}=0.625*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=2.356*10^{-20}$	$E_{t_{bQCA}}=2.534*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=4.265*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=1.968*10^{-20}$ Out state= A state
In1=A In2=A In3=C	$E_{t_{bQCA}}= 0.919*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}=1.968*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}=2.78*10^{-20}$	$E_{t_{bQCA}}= 0.919*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}=3.453*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}=4.265*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=1.968*10^{-20}$ Out state= A state
In1=A In2=A In3=D	$E_{t_{bQCA}}= 0.625*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}=1.674*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 1.049 *10^{-20}$ $E_{t_{QQCA}}=3.583*10^{-20}$	$E_{t_{bQCA}}= 0.625*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}=3.159*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}=5.068*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=1.674*10^{-20}$ Out state= A state
In1=A In2=B In3=A	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}=1.884*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}=3.368*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=2.272*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=3.756*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=1.884*10^{-20}$ Out state= A state
In1=A In2=B In3=B	$E_{t_{bQCA}}= 1.602 *10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.945*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.816*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}= 3.333*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=3.204*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.816*10^{-20}$ Out state= B state
In1=A In2=B In3=C	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}=1.049*10^{-20}$ $E_{t_{QQCA}}= 1.59*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 3.074*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 3.075*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 4.559*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 1.59*10^{-20}$ Out state= A state
In1=A In2=B In3=D	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 2.651*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.049 *10^{-20}$ $E_{t_{QQCA}}= 2.522*10^{-20}$	$E_{t_{bQCA}}= 1.602 *10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 4.136*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 4.007*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.522*10^{-20}$ Out state= B state
In1=A In2=C In3=A	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=1.884*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=2.272*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=2.368*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=3.756*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=1.884*10^{-20}$ Out state= A state
In1=A In2=C In3=B	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=1.59*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=3.075*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=3.074*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=4.559*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=1.59*10^{-20}$ Out state= A state
In1=A In2=C In3=C	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 2.945*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 3.333*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 2.816*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 3.204*10^{-}$	$\boldsymbol{E_{t_{QQCA}}}= 2.816*10^{-20}$ Out state= C state

Input	Output cell in A state	Output cell in B state	Output cell in C state	Output cell in D state	Final result
In1=A In2=C In3=D	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}=1.602*10^{-20}$ $E_{t_{QQCA}}=2.651*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 4.136*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}=2.522*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}=4.007*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=2.522*10^{-20}$ Out state= C state
In1=A In2=D In3=A	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 1.082*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 2.566*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=2.566*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=4.05*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 1.082*10^{-20}$ Out state= A state
In1=A In2=D In3=B	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 2.143*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=2.014*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.627*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.498*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=2.014*10^{-20}$ Out state= B state
In1=A In2=D In3=C	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 2.143*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 3.627*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}=2.014*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}=3.498*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=2.014*10^{-20}$ Out state= C state
In1=A In2=D In3=D	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}=3.204*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 3.075*10^{-20}$	$E_{t_{bQCA}}= 1.602 *10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 3.075*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}=2.946*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=2.946*10^{-20}$ Out state= D state

Table 4. Output results of OR gate

	Output cell in A state	Output cell in B state	Output cell in C state	Output cell in D state	Final result
In1=D In2=A In3=A	$E_{t_{bQCA}}= 1.048*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 2.521*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 3.075*10^{-20}$	$E_{t_{bQCA}}= 1.048*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}=2.65*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}=3.204*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.521*10^{-20}$ Out state= A state
In1=D In2=A In3=B	$E_{t_{bQCA}}= 2.110*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 3.583*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 2.522*10^{-20}$	$E_{t_{bQCA}}= 2.110*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}=3.712*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 2.651*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.522*10^{-20}$ Out state= B state
In1=D In2=A In3=C	$E_{t_{bQCA}}= 1.048*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 3.582*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 4.136*10^{-20}$	$E_{t_{bQCA}}= 1.048*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}=2.097*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 2.651*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}=2.097*10^{-20}$ Out state= C state
In1=D In2=A In3=D	$E_{t_{bQCA}}= 2.110*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}=4.644*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 3.583*10^{-20}$	$E_{t_{bQCA}}= 2.110*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 3.159*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 2.098*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.098*10^{-20}$ Out state= D state
In1=D In2=B In3=A	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$	$E_{t_{bQCA}}=2.025*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$	$\boldsymbol{E_{t_{QQCA}}}= 2.014*10^{-20}$ Out state= B state

Input					
	$E_{t_{QQCA}}= 3.498*10^{-20}$	$E_{t_{QQCA}}= 2.014*10^{-20}$	$E_{t_{QQCA}}= 3.627*10^{-20}$	$E_{t_{QQCA}}= 2.143*10^{-20}$	
In1=D In2=B In3=B	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 3.204*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.473*10^{-20}$ $E_{t_{QQCA}}= 2.816*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 3.333*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.602*10^{-20}$ $E_{t_{QQCA}}= 2.945*10^{-20}$	$E_{t_{QQCA}}= 2.816*10^{-20}$ Out state= B state
In1=D In2=B In3=C	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 4.559*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 3.075*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 3.074*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 1.59*10^{-20}$	$E_{t_{QQCA}}=1.59*10^{-20}$ Out state= D state
In1=D In2=B In3=D	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 4.265*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 2.534*10^{-20}$ $E_{t_{QQCA}}= 3.877*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.049 *10^{-20}$ $E_{t_{QQCA}}=2.78*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.049*10^{-20}$ $E_{t_{QQCA}}= 2.392*10^{-20}$	$E_{t_{QQCA}}= 2.392*10^{-20}$ Out state= D state
In1=D In2=C In3=A	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.498*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.627*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 2.014*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 2.143*10^{-20}$	$E_{t_{QQCA}}= 2.014*10^{-20}$ Out state= C state
In1=D In2=C In3=B	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 4.559*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.074*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 3.075*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 1.59*10^{-20}$	$E_{t_{QQCA}}= 1.59*10^{-20}$ Out state= D state
In1=D In2=C In3=C	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}= 3.204*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}= 3.333*10^{-20}$	$E_{t_{bQCA}}= 1.473*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.816*10^{-20}$	$E_{t_{bQCA}}= 1.602*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.945*10^{-20}$	$E_{t_{QQCA}}= 2.816*10^{-20}$ Out state= C state
In1=D In2=C In3=D	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}= 4.265*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}= 2.78*10^{-20}$	$E_{t_{bQCA}}= 2.534*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 3.877*10^{-20}$	$E_{t_{bQCA}}= 1.049*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.392*10^{-20}$	$E_{t_{QQCA}}= 2.392*10^{-20}$ Out state= D state
In1=D In2=D In3=A	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=4.05*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}=2.566*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=2.566*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=1.082*10^{-20}$	$E_{t_{QQCA}}=1.082*10^{-20}$ Out state= D state
In1=D In2=D In3=B	$E_{t_{bQCA}}=1.731*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.756*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 2.025*10^{-20}$ $E_{t_{QQCA}}= 3.368*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}= 2.272*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 0.541*10^{-20}$ $E_{t_{QQCA}}=1.884*10^{-20}$	$E_{t_{QQCA}}=1.884*10^{-20}$ Out state= D state
In1=D In2=D In3=C	$E_{t_{bQCA}}=2.025*10^{-20}$ $E_{t_{TQCA}}= 1.731 *10^{-20}$ $E_{t_{QQCA}}= 3.756*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}= 2.272*10^{-20}$	$E_{t_{bQCA}}= 2.025*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 3.368*10^{-20}$	$E_{t_{bQCA}}= 0.541*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 1.884*10^{-20}$	$E_{t_{QQCA}}= 1.884*10^{-20}$ Out state= D state
In1=D In2=D In3=D	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=3.462*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.731*10^{-20}$ $E_{t_{QQCA}}=3.074*10^{-20}$	$E_{t_{bQCA}}= 1.731*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 3.074*10^{-20}$	$E_{t_{bQCA}}= 1.343*10^{-20}$ $E_{t_{TQCA}}= 1.343*10^{-20}$ $E_{t_{QQCA}}= 2.686*10^{-20}$	$E_{t_{QQCA}}= 2.686*10^{-20}$ Out state= D state

Table 5. Evaluation of basic gates by the proposed software in two different systems

Machine	Gate	Simulation Time (ms)	Memory Usage (KB)
Intel® Core™ i7 3720QM 2.3GHz ~ 3.2GHz 8GB RAM Windows 10	QAND	307	59
	QOR	308	
Intel® Core™ i5-1135G7 2.40 GHz ~ 4.20GHz 8GB RAM Windows 10	QAND	101	
	QOR	103	

Biographies

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