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PAPERS

Energy estimation of QCA circuits: An investigation with multiplexers

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Quantum-dot Cellular Automata (QCA) is a rival to complementary-metal-oxide-semiconductor (CMOS)-based technology and one of the most cutting-edge nano-scale technologies. The multiplexer is a fundamental component in the fields of nano communication and nano computation. The investigative item of this article is the QCA multiplexer, and a handful of the best multiplexers were chosen as samples for the current experiment. The QCA layouts were designed in the QCADesigner-2.0.3 simulation engine environment, and the best one was reported after successfully experimenting on a total of eight samples. The co-ordinate-based energy was estimated using QCADesigner-E (QDE), and the non-adiabatic energy waste was investigated using QCAPro. According to the coordinates-based technique, the overall energy waste of the best energy-saving QCA multiplexer is 5.90 meV, with an average energy loss per cycle of 0.537 meV. Another approach, QCAPro-based, was used to estimate the energy loss at three different levels of tunneling at a constant temperature, yielding an overall energy loss of approximately 12 to 15 meV for the energy-efficient multiplexers..

K e y w o r d s: energy estimation, multiplexer, QCA circuits, QCADesigner, QCADesigner-E, QCAPro

1 Introduction

In recent times, the most frequently used CMOS technology also faces some physical limitations at nano scales [1]. These flaws are intended to be addressed by QCA technology. QCA technology is quickly emerging nanotechnology and an immediate successor of CMOS technology. In contrast to CMOS technology, QCA technology has a tera-hertz operation speed and is transistor-free [2]. The main benefits of QCA technology have low power consumption, great speed, and higher density [1]. A QCA cell is at the heart of this technology, and all logic circuits are built using them, much like a building is built with bricks. A QCA cell may be made in four distinct ways: metallic, semiconductor, magnetic, and molecular [3]. The use of various methodologies to estimate the energy dissipation of QCA technology is a current trend in QCA-based research. Several attempts have been made to build or implement QCA-based logic circuits, such as combinational circuits, sequential circuits, and other computing circuits. Section 3 has been devoted to a thorough analysis of the QCA multiplexer literature because it serves as the foundation for the current work. On a lighter side, the current research examined the energy dissipation of basic QCA multiplexers for each QCA coordinate and each cell, where each coordinate works as an energy bath and the essential factor for each cell is a non-adiabatic interaction. After successfully experimenting on a total of eight samples, the optimal energy dissipating QCA layout was reported. QCADesigner [4] simulation engine environment was used for the implementation of layouts. The tool QCADesigner-E (QDE) [4, 5] was used to estimate the co-ordinate-based energy, while the tool QCAPro [6] was used to study the non-adiabatic energy dissipation. Multiplexers energy has been estimated through a series of experiments. The outputs were successfully confirmed after designing all experimental items in the QCADesigner 2.0.3 tool. Then, using QDE software, the calculation of energy dissipation was completed successfully. Each QCA cell has been given a set of coordinates and is treated as an energy bath. Following this experiment, energy estimation using another popular tool, QCAPro, was successfully completed. In the case of the QCAPro energy analysis, non-adiabatic clocking interaction acts as the major function. The primary goal of this article is to understand both methodologies for a single entity.

We give an overview of QCA technology and a brief theory of digital multiplexers, as well as existing works on QCA multiplexers and gaps. Discusses the simulation tools utilized in the analysis and depict the experimental object layout as well as simulation results. After the energy calculation analysis, we compare results and discuss future scope.

2 Overview of QCA technology

The cornerstone of QCA technology is a square shaped QCA cell which consists of four quantum dots positioned

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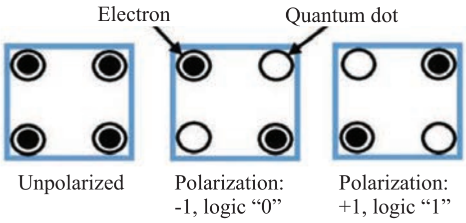


Fig. 1. QCA cell

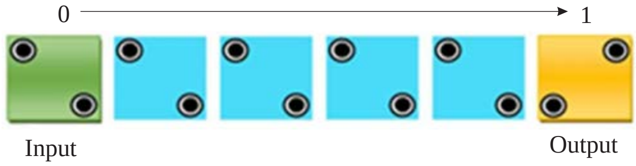


Fig. 2. QCA wire

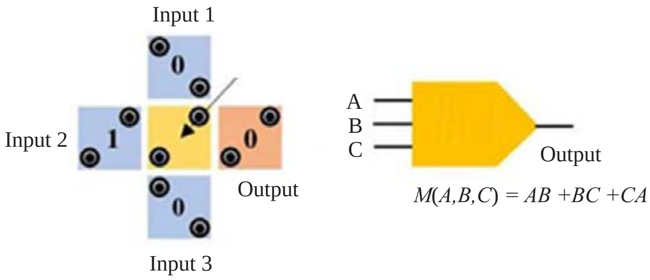


Fig. 3. Majority voter or majority gate

at the vertices of a square to produce potential barriers, [1]. Two electrons, which are isolated by these walls, tunnel between these dots due to the quantum mechanical tunneling mechanism, [3]. According to Coulombs rule, to keep a long-distance, these two electrons will always try to take over the vertices of a square which results in making two configurations that are relatively stable, [7]. Each configuration is referred as a polarization state which is denoted by binary bits 0 and 1, as illustrated in Fig. 1, [1]. An array of QCA cells is called a QCA wire, [8]. QCA wire is an alignment of QCA cells in a series, in which the input polarization is transferred from one cell to the next till the output cell, [7]. As we can see in Fig. 2, the reflection of the input polarization at the output cell. Five cells are required to made majority voter (MV) or majority gate, which is another essential component that consists of three inputs and one output, [8]. A driver cell is put in the middle, as depicted in Fig. 3. The majority gates Boolean expression is

$$M(A,B,C) = AB + BC + CA\,. \qquad (1)$$

In Fig. 3, A, B, and C are input lines of the majority gate, and $M(A,B,C)$ denotes the output, which is a function of three inputs. Basically, if any of the inputs are set to polarization -1, it behaves like a 2-input AND gate, and when any of the inputs are set to polarization +1, it behaves like a 2-input OR gate. Therefore, one majority gate functions as an OR/AND gate depending on the specific values of the inputs. Fig. 4 depicts a NOT gate or inverter, where two cells are aligned in a diagonal layout with output polarization opposing the input polarization, [7]. As an aside, the three various types of QCA inverters that are frequently used for the circuit designs are shown in Fig. 4. All the above-mentioned entities, namely the QCA cell, QCA wire, majority gate (OR/AND gate), and QCA inverter, are the primary building blocks of QCA technology.

The dissemination of information in QCA technology between the QCA cells is protected by the employment of an appropriate clock signal. The primary function of the clock is to control the inter-dot barriers by the establishment of an electric field in the adjacent cells [9]. In the QCA clocking system, there is a 90-degree phase difference between each of the four phases, [9]. Switch, hold, release, and relax are the four phases of a clock signal, as represented in Fig. 5. Based on the input polarization, cells become polarized during the switch phase of the clock, and it holds in the polarized state until the clock phase stops, [9]. Under the release phase, cells become unpolarized or adjust their polarization, and during the fourth phase of the clock, that is relaxation phase, cells attain null polarization, [9]. To make sure that the flow of information is proper, an appropriate clock flow is required in QCA circuit designs.

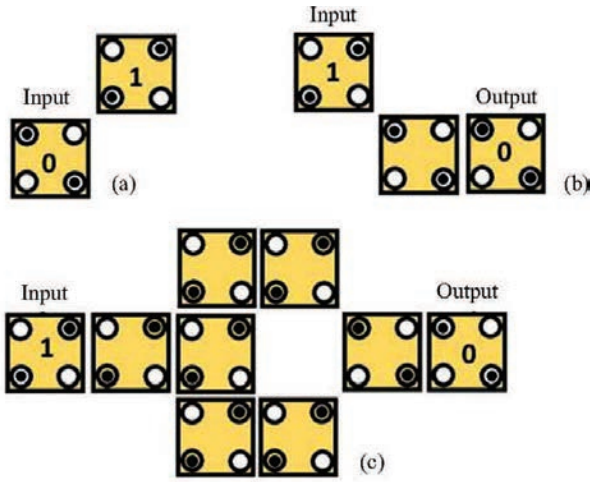


Fig. 4. QCA NOT gate

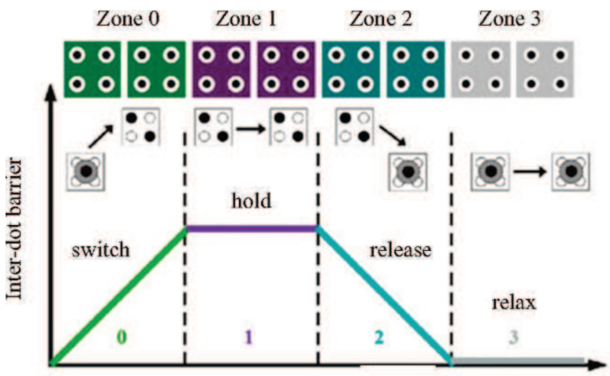
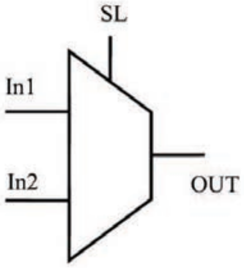


Fig. 5. QCA clocking



SL	IN1	IN2	OUT
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

Fig. 6. Truth table of 2:1multiplexer

3 Former works and gaps

The multiplexer (MUX) is essential for developing nano-computing and nano-communication fields because it picks a single path from numerous input channels. A 2:1 MUX is the simplest module of a digital multiplexer, which consist of two input lines, one output line, and a single select line, for this

$$OUT = IN_1 \cdot \overline{SL} + IN_2 \cdot SL\,, \tag{2}$$

hence, if the select line $SL = 0$ then the multiplexer selects IN_1, and if $SL = 1$ is 1, it selects IN_2.

The symbol of 2:1 MUX is shown in Fig. 6. and (2) is comes out from the shown logic table.

Numerous studies are linked to QCA multiplexers; however, this work will focus on a few prominent designs released in the previous few years. Recently [10] a single-layer 2:1 QCA MUX with ten cells and higher-order circuits was developed. The power dissipation of higher-order circuits in was measured using the QCAPro tool; however, power analysis of 2:1 MUX is absent in [10]. In [11] authors used the QDE and QCAPro tools to calculate the energy dissipation of a 2:1 multiplexer. They also estimated the stated multiplexer's cost functions. Another piece of similar work which again examined the energy dissipation and cost of a multiplexer is [12]. A high-performance, straightforward 2:1 MUX without a majority gate or wire crossing was proposed by Khan and Arya for the year 2022 [13]. However, the described multiplexer in [13] should have a cell with a fixed polarization of -1, instead of +1, which is a layout error. Two layouts of 2:1 multiplexer were used QDE to calculate the energy dissipation in [14]. The designs have excellent scalability. To develop a random-access memory, there was described a modest 2:1 QCA multiplexer in [15]. However, the arrangement of input-output and the layouts symmetry is not very impressive. In [16] hypothesized and computed kink energy using a simple multiplexer was presented. A novel multi-layered MV32 gate approach for QCA-based layout design and created new QCA multiplexers was suggested in [17]. Authors in [18] identified faults of QCA multiplexers, proposed a fault tolerant QCA multiplexer, and estimated the power. The suggested design comprises 27 cells, which is a very high level of cell complexity. Another, recently presented several ultra-efficient multiplexers and showed that they were superior to previous designs, [19]. Further there were suggested a few efficient multiplexers and demonstrating effectiveness by utilizing a variety of characteristics such as clock delay, circuit complexity, size, and so on, [20]. Finally, the effect of temperature on a newly proposed multiplexer was investigated in [21].

Together with a few simple QCA multiplexers, predicting that the designs would be important in the field of nano communication, was presented, [22]. The effectiveness of a modular-based QCA multiplexer design approach was demonstrated in [23] , using the synthesis of configurable logic blocks, [23]. However, the proposed 2:1 MUXs cell complexity was as high as 23.

However, energy estimation is certainly explored in existing studies, leaving a gap in the QCA literature. However, there are two alternative ways to estimate the energy in QCA circuits, none of the available designs in the literature help to comprehend both processes for a single item. If each cell is seen as an energy bath, then during operation under the assigned clock cycle, there is also coordinate-to-coordinate or cell-to-cell energy transfer in addition to non-adiabatic energy loss during the switching step. Because of this, it is necessary to study the energy estimations for each estimating technique on a particular QCA circuit, in this case, the QCA multiplexer, to perform a thorough examination.

4 Simulation tools

The QCA circuits are designed, and the outputs are checked using the tool QCADesigner 2.0.3, which is a popular QCA layout design simulation engine. QCADesigner 2.0.3 make user enables to identify the two simulation modes, that is, bistable approximation and coherence vector mode. For coordinate-based energy estimation of the design, an advanced tool called QCADesigner-E or QDE is utilized, which works in the coherence vector mode. In the non-adiabatic energy measuring method, another technique, QCAPro and QCADesigner 1.0.1 was utilized to estimate the energy.

5 Experimental unit

The top eight 2:1 QCA multiplexers suggested in [10], [13-16], [19-20], and [22] have been chosen as experimental samples of current work after a thorough review of the literature. The experimental units that were chosen had a cell complexity of less than 20. A better one in terms of better energy efficiency is reported here after the experiments are completed.

The layout design of all selected multiplexers was discussed in this section of the current article using QCA technology, and the QCADesigner-2.0.3 tools were utilized by employing the coherence vector simulation mode.

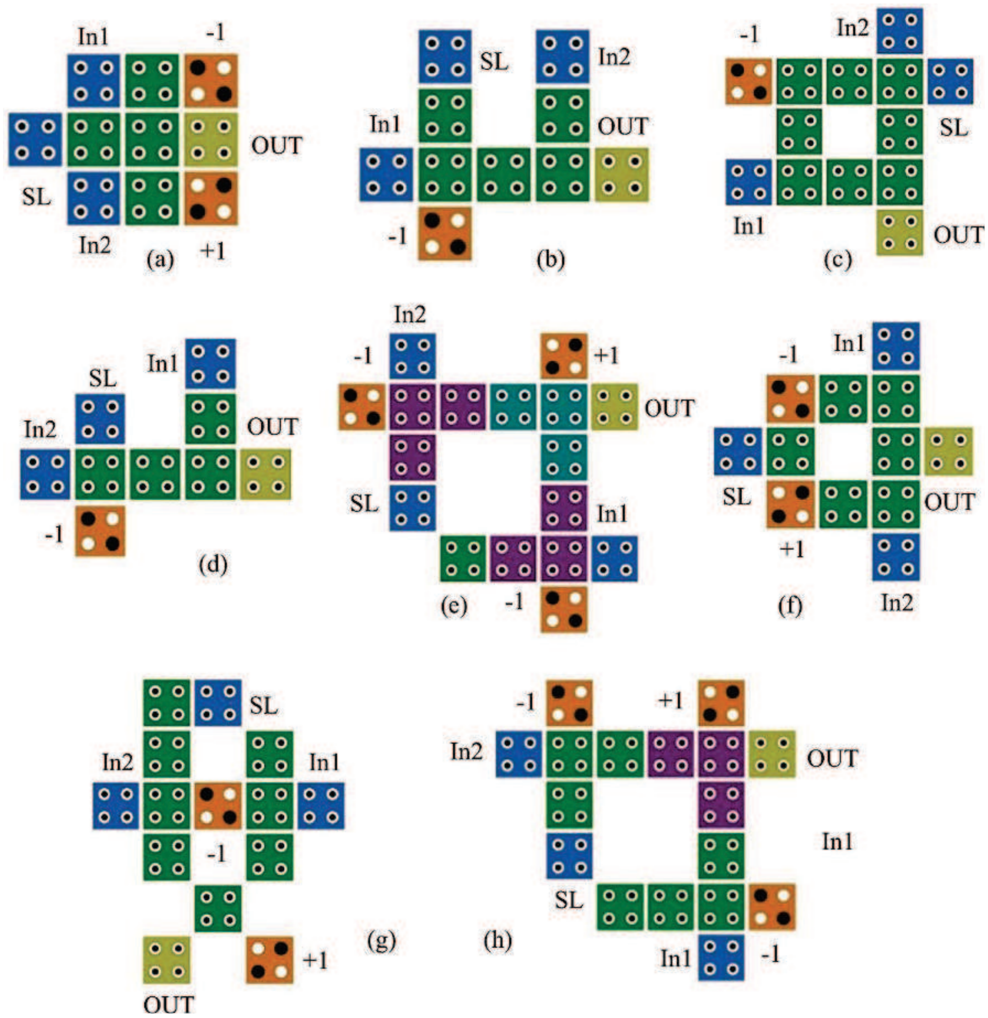


Fig. 7. QCA multiplexer designed using qcadesigner-2.0.3 layout: (a) – [10], (b) – corrected [13], (c) – [14], (d) – [15], (e) – [16], (f) – [19], (g) – [20], and (h) – [22]

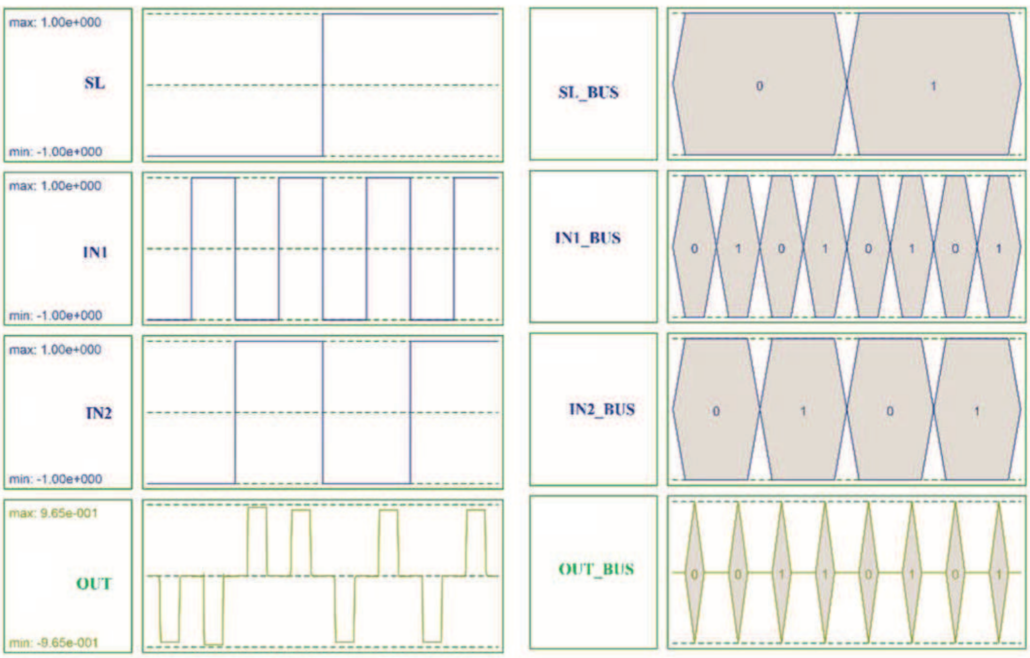


Fig. 8. Simulation outputs of target MUX

Table 1. QDE energy analysis table, all values are in meV

Design	Total energy loss	Error in total energy loss	Average energy loss	Error in avg. energy loss
[10]	8.71	-0.936	0.792	-0.0851
[13]	10.70	-1.150	0.976	-0.1040
[14]	5.90	-0.587	0.537	-0.0534
[15]	6.50	-0.689	0.591	0.0627
[16]	11.20	-1.160	1.020	-0.1060
[19]	6.43	-0.657	0.584	-0.0597
[20]	8.16	-0.854	0.742	-0.0777
[22]	12.00	-1.250	1.090	-0.0113

5.1 Design: layout

The top eight 2:1 QCA multiplexers reported in [10], [13-16], [19-20], and [22] have been selected from the literature as experimental items. Figure 7 demonstrates the equivalent circuit layouts of QCA of experimental objects. Cell complexity was less than 20 in the experimental units that were selected. From Fig. 7, it is illustrated that the two input lines of a 2:1 MUX are represented as IN1 and IN2, one select-line denoted as SL, and one output line represented with OUT.

5.2 Simulation results

QCADesigner 2.0.3 tool environment and the coherence vector simulation modes were used to accomplish the layout design steps. At 2 Kelvin, the temperature is to be constantly held throughout the design stage, and the Euler approximation method is used. The clock has a high value of 9.8e-022 Joule and a low value of 3.8e-023. For all the samples, the produced outputs have been evaluated, and Fig. 8 displays the simulation outputs. With the help of the previously mentioned truth table, the simulation output may be inspected, as illustrated in Fig. 6.

When "SL" = 0, "IN1" determines the output, and "IN2" has no effect; for example, "OUT" = 0 only when the select line "SL" = 0 and input line "IN1" = 0; and "OUT" = 1 only when the select line "SL" = 0 and input line "IN1" = 1. And when the select line "SL" = 1, input line "IN1" has no effect on the output, and input line "IN2" determines the outcome; for example, the outcome from the 2:1 MUX is "OUT" = 0 when the select line "SL" = 1 and input line "IN2" = 0; and when select line "SL" = 1 and input line "IN2" = 1, then the outcome from the 2:1 MUX is "OUT" = 1, as illustrated in Fig. 8(a). In Fig. 8(b), input lines are labeled "IN1_BUS" and "IN2_BUS," select line is labeled "SL_BUS," and the output line is labeled "OUT_BUS". A 0.5-clock cycle delay is noticeable in both output choices.

6 Energy estimation using QDE

For each QCA coordinate, recently developed QDE tool has been utilized for the energy dissipation of the multiplexer, which treats like bath of energies for each of them. The behavior of energy is represented throughout the course of a full QCA clock cycle. The QCA cell is depolarized at the start of the clock cycle, as we all know. To get the polarization, energy could be taken when the clock is encircled by the cells. At the end of the clock cycle, the cell came back to a state where polarization was eliminated. Also, energy is returned to the clock and expanded to the connected cells. In the environment, some portions of the allocated energy were also lost.

To begin with, the mathematical analysis of QCADesigner-E (QDE), considering each QCA cell as a soaking of energy (energy bath), with E_{bath} [5, 24] representing the overall amount of energy that gets transferred from the respective clock. Let E_{ev} be the energy transmitted from the cells to the surrounding environment. According to [5],

$$E_{\mathrm{bath}} = E_{\mathrm{ev}} \,. \tag{3}$$

Categorization of the loss of energy (or energy dissipation) can be done into three parts of which the first one has been already discussed and denoted as E_{ev}. Second is the transmission of energy from one cell to another (*ie* inter-cell) to an indication of the clock be E_{ck}. Lastly, the energy E_{io} is bounded by the QCA cells. The resultant of inward and outhcoming components of a series arrangement of QCA cells, [5]

$$E_{\mathrm{io}} = E_{\mathrm{in}} - E_{\mathrm{out}}, \tag{4}$$

is easy to interpret.

Evaluating the loss of energy, a minimal error can occur

$$E_{\mathrm{rr}} = E_{\mathrm{ev}} - (E_{\mathrm{ck}} + E_{\mathrm{io}}), \tag{5}$$

which, relating to the transmission direction, can be either positive or negative. For example, the possitive error means some of the energy is transported to the nearby environment [5, 24]. The energy dissipation in this work, considering eight multiplexers as samples, was calculated using this following approach.

6.1 Result of experiment using QDE

The list of used default parameters in QDE has been considered for the simulations. A total of 500000 samples were examined for each item simulation according

Table 2. QCAPro energy analysis table, all values are in meV

Design	Leakage energy loss			Switching energy loss			Total energy loss		
	$0.5E_K$	$1.0E_K$	$1.5E_K$	$0.5E_K$	$1.0E_K$	$1.5E_K$	$0.5E_K$	$1.0E_K$	$1.5E_K$
[10]	1.97	6.25	11.40	12.70	11.09	9.54	14.67	17.34	20.94
[13]	2.12	6.54	11.76	9.70	8.52	7.33	11.82	15.06	19.09
[14]	3.19	9.23	16.38	16.46	14.90	13.20	19.65	24.13	29.58
[15]	1.86	5.69	10.18	8.00	6.98	5.98	9.86	12.67	16.16
[16]	4.51	13.79	24.45	20.65	17.56	14.78	25.16	31.35	39.23
[19]	3.77	9.90	16.62	11.15	9.47	8.04	14.92	19.37	24.66
[20]	4.52	11.94	20.13	6.65	5.51	4.66	11.17	17.45	24.79
[22]	4.14	13.18	23.84	11.17	9.51	7.95	15.31	22.69	31.79

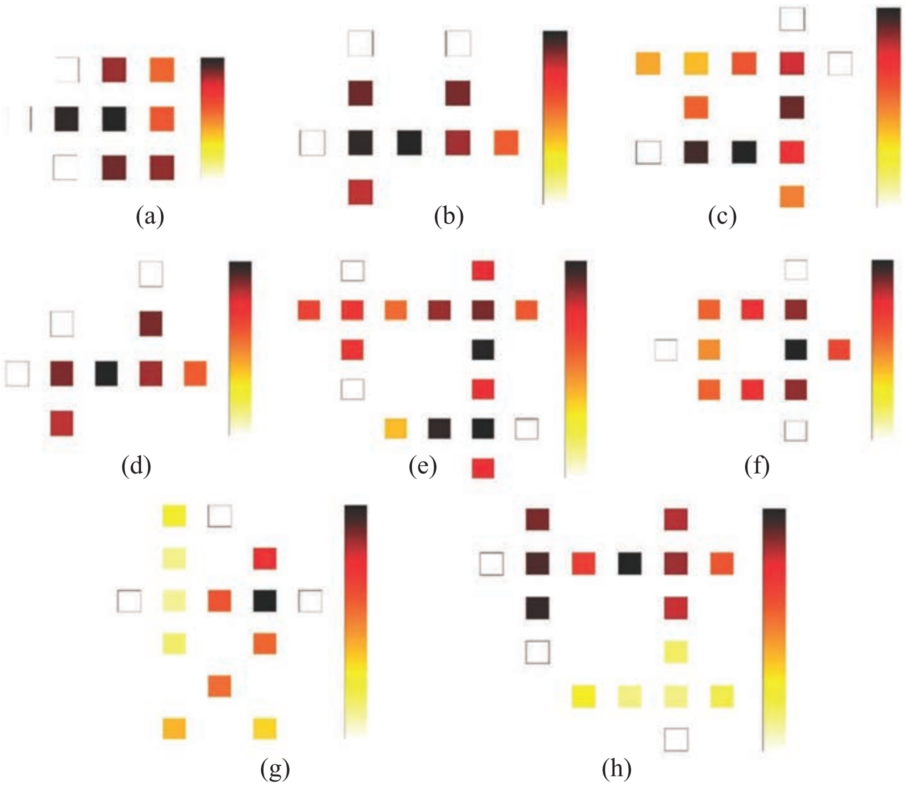


Fig. 9. Energy hotspots of multiplexers using QCAPro at $\gamma = 0.5\,E_{\mathrm{K}}, (T = 2K)$: (a) – [10], (b) – [13], (c) – [14], (d) – [15], (e) – [16], (f) – [19], (g) – [20], and (h) – [22]

to QDE, with coherence vector as the simulation mode. The total energy dissipation and the average energy dissipation of all the eight units are tabulated in Tab. 1. According to this, the most efficient multiplexer in terms of total energy dissipation is reported in [14], which is 5.90 meV (error = -0.587 meV). The multiplexer reported in [14] shows good average energy efficiency, and the value is 0.537 meV (error = -0.0534 meV). In addition, the layouts described in [15] and [19] are also good performers.

7 Energy estimation using QCAPro

Here, the energy estimation is based on non-adiabatic switching [6]. The expectation energy value is represented and expressed with the help of the Hartree-Fock approximation [6] where estimated energy is anticipated. It is expressed as

$$E = \langle H \rangle = \frac{\hbar}{2}\vec{\Gamma} \cdot \vec{\lambda}, \tag{6}$$

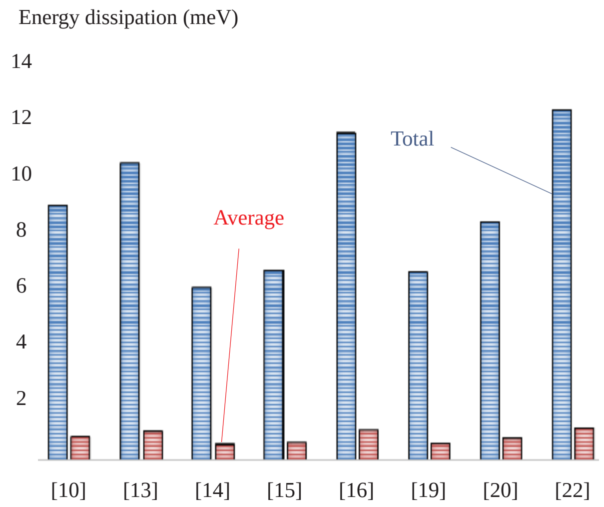


Fig. 10. Comparison of energy dissipation according to QDE

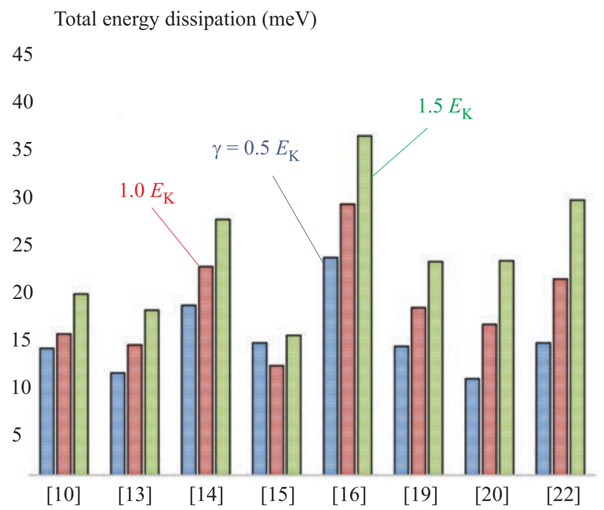


Fig. 11. Comparison of energy dissipation according to QCAPro

where $\hbar$ is the reduced Planck constant, $\vec{\Gamma}$ denotes a tri-dimensional energy vector, and $\vec{\lambda}$ represents the coherence vector [6]. Now the instantaneous power is

$$P_{\text{ins}} = \frac{\mathrm{d}E}{\mathrm{d}t}. \tag{7}$$

Note that this power is evaluated with three tunnelling levels at a constant temperature of 2K, and those tunnelling levels are given as $\gamma = 0.5\,E_{\mathrm{K}}$, $\gamma = 1.0\,E_{\mathrm{K}}$, and $\gamma = 1.5\,E_{\mathrm{K}}$. The default parameters of the tool have been utilized. Before doing the experiment in QCAPro, all the layouts were redesigned using the QCADesigner-1.0.1 tool as the tool QCAPro does not support any higher version of the layout design engine.

7.1 *Result of experiment using QCAPro*

When the temperature is fixed at 2K, the loss of energy for each of the multiplexers is searched using the tool QCAPro. Since the tool QCAPro does not support any higher version of the layout design engine, all of the layouts were recreated before doing the experiment in QCADesigner-1.0.1. Table 2 depicts the summary of QCAPro-based energy dissipations. The overall loss of energy of the best multiplexers are reported in [15] and [20], estimated as 9.86 meV and 11.17 meV at $\gamma = 0.5\,E_{\mathrm{K}}$. But at $\gamma = 1.0\,E_{\mathrm{K}}$ and $\gamma = 1.5\,E_{\mathrm{K}}$ the best performed multiplexer is reported in [15] as the loss is 12.67 meV and 16.16 meV respectively. Additionally, at higher tunelling levels, the design in [13] performs well. The energy hotspot of multiplexers during this experiment is shown in Fig. 9. In comparison to the light-colored cell, which exhibits fewer changes, the dark-colored cell reveals the most alterations, as shown in Fig. 9.

8 Comparison and discussion

QCA multiplexers have been used to understand both energy estimation procedures, and the results are different for both methods. Furthermore, a multiplexers quality can be assessed using any of the approaches because the aspect of the two-energy estimation is different. One energy estimation is based on the cell-to-cell interaction, and another one depends on the non-adiabatic switching. Figure 10 depicts the graphical up and downs of total energy and average energy components according to the QDE. The effective energy-efficient (total energy) designs are [14], [15], and [19], as shown in Fig. 10. The most energy-efficient design, nevertheless, is [14]. Figure]11 shows the energy dissipation values for all multiplexers according to QCAPro at 2K temperature for three different tunneling levels. Figure 11 shows that [13], [20] perform well at the lower tunneling level, whereas [13], [15] perform better at the higher tunneling level. It follows that the designs in [13], [14], and [15] are the three best designs that display good energy dissipation behaviors and might be useful in higher-order circuit design.

9 Conclusion and future work

A multiplexer is crucial in QCA circuits, especially in the domain of nano computing and nano communication. This study investigated the energy dissipation of multiplexers since energy estimation is a current trend in QCA research. There are two approaches to calculating the energy loss of QCA circuits. Given its simplicity and versatility in QCA-based computing, this article employs the multiplexer as an experimental entity. After successfully experimenting on a total of eight samples, superior QCA layouts were found. This work is significant since it is a comprehensive understanding of the work that looked for energy estimation using QCA coordinates (QDE) or non-adiabatic energy loss (QCAPro). The best performing design described in [14] dissipates total energy of 5.90 meV, according to QDE.

However, according to QCAPro, the designs in [13] and [15] are good performers, as 15.06 meV and 12.67

meV are the overall loss of energy of the projected multiplexers, respectively, at $T = 2K$ with a level of tunneling $1.0\, E_{\mathrm{K}}$. Additionally, the design in [20] also performs well. Therefore, it has been concluded that the basic multiplexer in [13], [14], and [15] are extremely energy efficient and could be used in more complex circuits. Shortly, this efficient 2:1 multiplexer could be used to develop higher-order multiplexers, and the energy dissipation could be determined.

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