Coplanar wire crossing in quantum cellular automata using a ternary cell

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Abstract: To date, ternary quantum-dot cellular automata (QCA) has been especially investigated and also is being advanced. Nonetheless, it should be possible to make interactions between binary QCA and ternary QCA circuits in order to have a versatile platform of designing. On the other hand, one of the most important concerns in QCA is minimising wire crossings because of low robustness caused by their manufacturing process and operational defects. In this study, a novel ternary-to-binary (and vice versa) converter is introduced firstly and a novel coplanar wire crossing scheme is proposed and presented afterwards. The latter scheme uses both kinds of binary and ternary QCA cells and provides a reliable crossover. Detailed circuit designs and results are presented to show correct functionality of the proposed circuits.

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1 Introduction

Complementary metal oxide semiconductor (CMOS) technology has whelmed digital system markets in recent decades. Wide range of devices and circuits designed and implemented on CMOS cannot be ignored. Many types of small gates to large and complex microprocessors have been manufactured based on this technology. There are still numerous investigations being done in this field which have focused on basic elements such as adders [1–3]. In spite of all advantages of this ubiquitous technology, it is facing issues and weakening points whereas dealing with very small scales. In fact, as CMOS technology enters submicron regime, physical limitations arise. At the first look, high density designs lead to thermal problems such as overheating the chip. Moreover, various leakage currents, difficult on-current and threshold voltage control, less reliability, more manufacturing cost, doping fluctuations and so on are some of the critical concerns to which close attention should be paid. Also, there are different limitations inside a MOSFET transistor. For instance, sub-threshold leakage current, which is related to the channel, is a serious source of power dissipation [4].

In order to meet Moore's law, the scaling-down trajectory should be continued at nano-scale level. In nano-scale design, classical physics rules are not enough because many phenomena could only be interpreted on the basis of quantum-mechanics. Several technologies at nano-scale such as nano-wire (NWs) transistors, carbon nano-tube (CNTs) transistors, graphene nano-ribbons (GNRs) transistors, single electron transistors (SETs) and quantum cellular automata (QCA) have been introduced. However, QCA is a promising technology which has a new approach to computation. In QCA, first introduced by Lent *et al.* in 1993 [5], the electrostatic charges interacting with each other with no electrical current, construct basic concepts. Several advantages of QCA, such as small size, high density, fast switching speed and very low power consumption [6, 7] have increased its attractiveness. More information on QCA will be presented in Section 3. Generally, many different designs including QCA have been investigated in terms of binary logic and multi-valued logic (MVL). MVL is presenting a significant perspective in the field of computation. It offers several advantages which should be considered. First, there is no possibility to describe real nature using binary states whereas most natural phenomena are inferred as many-state cases. Therefore fuzzy logic can be an ideal scenario in computations. Since there has been no perception of fuzzy logic in QCA yet, MVL can be a proper alternative in order to go closer to nature. MVL is an intermediate state between binary logic and fuzzy logic which can take the advantages of having multiple states. Second, denser computational circuits can be achieved using MVL. There are also other points which will be discussed in more details in Section 2.

There are two main achievements in this article; design of a novel ternary-to-binary converter and design of a novel coplanar crossover, as an application of the former design, in which both binary and ternary QCA cells are used. These designs have been exhaustively analysed and proved to function correctly.

The remainder of this paper is organised as follows. MVL basics and a relevant example are discussed in Section 2. In Section 3, QCA is mentioned generally and then ternary QCA is stated in Section 4. Materials related to the proposed converter are completely discussed in Section 5 and experimental results for the converter are demonstrated in Section 6. Afterwards, the proposed coplanar crossover is presented and verified in Sections 7 and 8, respectively. Finally, the paper is concluded in Section 9.

2 Multi-valued logic

In computations, MVL plays a key role because of its capabilities. Although main focus of designs is on binary logic and most of implemented devices work with binary data, the various advantages of MVL scenario which were stated in Section 1 cannot be neglected. Several applications of MVL designs have been introduced. For instance, one of the most usable fields of MVL systems is memory design. Here, a quick look is taken at basics of MVL. It has been shown that among the MVLs the 'ternary' logic is the simplest and the most efficient way of representing numbers [8]. Therefore a brief description of ternary logic is presented here. Two main operators in ternary logic are 'Min' and 'Max'. These operators correspond to 'AND' and 'OR', respectively. Truth tables of these two operators are shown in Table 1 [9]. Note that there can be different representations of values in ternary logic. Namely, {0, 1/2, 1}, {−1, 0, 1} and {0, 1, 2} can be considered. Here the former is considered.

There are three kinds of inverters in ternary logic called standard ternary inverter (STI), positive ternary inverter (PTI) and negative ternary inverter (NTI) [10]. Truth table of an STI is demonstrated in Table 2. There are several researches about MVL and especially ternary in CMOS technology such as various ternary-to-binary (and vice versa) converters [11], ternary gates [12], adders [13], ternary memory elements and even processor designs. Among these, looking at a converter can be more relevant to our work.

Here a quick look is taken at a CMOS binary-to-ternary converter [11]. In this work, a mixed transistor/gate circuit has been proposed which is shown in Fig. 1. There are *n* input binary signals, *k* intermediate control signals and *m* output ternary signals. This design is composed of two main parts, decoder and encoder logic networks. More details can be found in [11].

To concentrate on the work proposed in this paper, QCA and its relevant issues are discussed in the next sections.

3 QCA

Table 1 Truth tables of MIN and MAX

	A		
B	0	1/2	1
Min or AND			
0	0	0	0
½	0	½	½
1	0	½	1
Max or OR			
0	0	½	1
½	½	½	1
1	1	1	1

Table 2 Truth table of a standard ternary inverter

In	0	½	1
Out	1	½	0

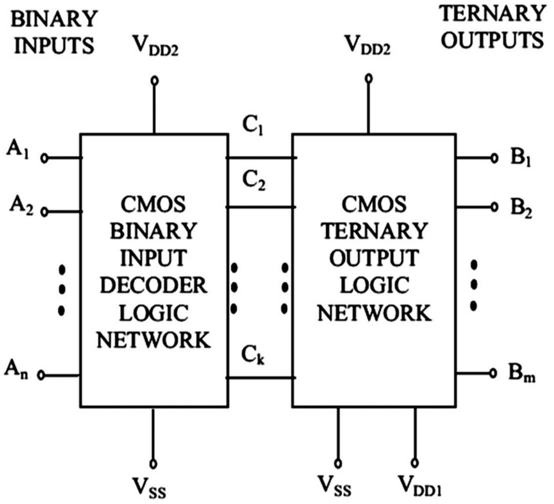


Fig. 1 *Diagram of a CMOS binary-to-ternary converter [11]*

As the name of QCA induces, there is a cellular structure for constructing primitives. A typical binary QCA (bQCA) cell, shown in Fig. 2, is comprised of four quantum dots and two mobile electrons. Owing to natural electrostatic interaction between charges of a cell, they prefer to locate at antipodal sites. Thus, they make two different polarisations; $P = -1$ and $P = +1$ corresponding to logic values '0' and '1', respectively. A bQCA cell is mostly set such that there is a distance of 20 nm between centres of two adjacent dots. Also, quantum dots with diameter of 10 nm [14] are assumed.

Two fundamental points are greatly under focus in QCA. One of them is electrostatic interaction which is the natural behaviour between charges. In fact, attraction and repulsion among different and same charges construct this concept. This phenomenon causes binary QCA cells to get two certain configurations which were discussed above. Electrostatic interaction between a dot in cell *i* and each dot in cell *j* is computed as follows [15]

$$E_{ij} = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_i q_j}{\left|r_i - r_j\right|} \tag{1}$$

where ε_0 is vacuum permittivity, ε_r is the substance relative permittivity which is assumed to be 1 for vacuum, q_i is charge of a dot in cell *i*, and $|r_i - r_j|$ implies the distance between dots of two cells. It should be noted that charge of a dot can be either negative or positive according to electron presence or absence in that dot. Considering the point that a QCA cell must be totally neutral, background positive charge of dots, mentioned in [5], can be obtained using $2/D$ electron charge, where D is number of dots.

Another concept is called kink energy and refers to potential energy which is computed for two neighbouring

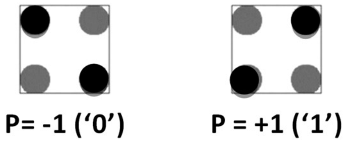


Fig. 2 *Two different polarisations of a bQCA regular cell*

cells i and j, based on electrostatic interaction, as follows [16]

$$E_{\text{kink}}^{i,j} = E_{\text{opposite state}}^{i,j} - E_{\text{same state}}^{i,j} \tag{2}$$

3.1 QCA applications

Since QCA introduced, many circuits were proposed and simulated in binary logic. In fact, different logic gates, adders, multipliers, memories and so on have been designed using QCA. There is also a basic microprocessor, Simple 12 [17], designed in QCA and its dataflow is also described. Many of these circuits have advantages like smaller size and faster speed over their CMOS counterparts. Besides, some works have been newly accomplished on cell minimisation such as [18, 19]. Additionally, a new paradigm has been introduced in QCA which refers to a methodology for multistage interconnection networks (MINs) using QCA [20]. Alongside, MVL system can be perceived better in QCA because of its nature. Meantime, properties of an MVL-based circuit cannot be achieved easily in conventional circuits and this fact highlights the excellence of nano-based technologies. Thus, focus is on the field of ternary QCA (tQCA), a practical kind of MVL QCA, which takes the advantages of MVL designs mentioned formerly.

4 Ternary QCA

Because of several advantages of computation in MVL with respect to binary logic, many efforts are being made on QCA MVL circuits. As mentioned before, ternary logic is the most practical one among MVL systems, so a brief background is brought.

4.1 tQCA cell

tQCA cell was firstly introduced by Bajec *et al.* in 2006 [21]. In [22] they presented a 110 × 110 nm cell which has eight quantum dots and two mobile electrons that can tunnel between quantum dots (Fig. 3*a*). Quantum dots have a diameter of 10 nm. It should be noted that only four states can occur for electron positions because of the natural interaction between charges. These four states, named *A*, *B*, *C* and *D* are depicted in Fig. 3*b*. For each state, a corresponding logic value can be considered.

Typically, as in [21], *A*, *B*, *C* and *D* are denoted as 0, 1, 1/2 and ½, respectively. Also, they are assumed as 0, 1, -1 and -1, respectively, in some references such as [22] in order to have a balanced system. However, here the former is considered.

4.2 Some definitions

In QCA designs, there are three types of cells according to their positions in the circuit and what they perform [21]. These three categories are as below:

- *Driver cells* which are inputs of circuits and are located at the borders of a design. These cells typically have a fixed polarisation using an external electric field.
- *Internal cells* which are inside a design and perform data transmission.
- *Target cells* which are also at the borders of a design and can be considered as outputs.

An important convention for ternary QCA is that state *D* is only allowed for internal cells [21]. In the field of tQCA there are some works such as basic elements [8], a memorising cell [22] and interconnection schemes [23].

5 Proposed novel converter

Valuable advantages of ternary logic have been pointed in several studies. In the field of QCA, this fact has been investigated and some schemes have also been proposed. However, tQCA is premature and needs to be studied more. In some situations a bQCA/tQCA co-design can achieve better results since advantages of both types can be exploited. According to this, there is a substantial need for creating an interaction between tQCA and bQCA circuits. Also, when it is necessary to evaluate operation of a ternary circuit in binary form, there will be a need for such a converter or interface. Here we propose a novel ternary-to-binary converter which can also play the role of an interface. In CMOS technology, some efforts, as in [11], have been made to design such a converter but no such sample has been considered in QCA.

In QCA, the following general advantages of this converter can be mentioned:

- Designing circuits using both bQCA and tQCA elements in order to gain more density and other advantages of such a design.
- Using ternary output in the form of binary logic in order to evaluate the results of a tQCA circuit and comparing with bQCA circuits.
- Generating a new perspective for future complex designs.

It will be stated that our proposed converter is capable of working in reversed direction. In other words, the proposed converter will be a binary-to-ternary converter as well.

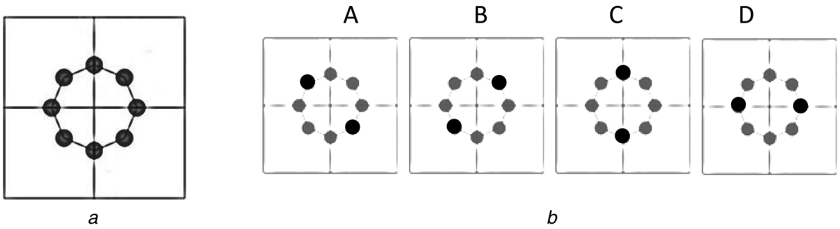


Fig. 3 *Quantum dots*

a tQCA cell
b four possible configurations of a tQCA cell

Table 3 Inputs and outputs of the converter

Input state (ternary)	*A*	*B*	*C*	*D*
output value (binary)	00	11	01	10

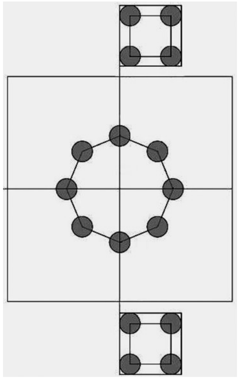


Fig. 4 *Primary design of the converter*

5.1 Scenario

In design of a ternary-to-binary converter, some scenarios can be mentioned. In this paper, a scenario which is demonstrated in Table 3 is used. In this scenario, since four input states can be interpreted in two bits, a 2-bit output for each input state is defined. In other words, the ternary-to-binary path is assumed here.

On the other hand, two viewpoints can be taken into account. First, the real size of bQCA cells can be ignored and both kinds of cells can be considered in the size of tQCA cells. Second, all cells can be considered with their real size. In the former case, there are some weak points. It is not worth, increasing the size of bQCA cells since it is not wise and useful from area point of view. Besides, in spite of simplicity of this design, applying input where no noise is imposed on output cells is not feasible (the outputs are prone to noise). Thus, here we consider the case of cells with their real size.

5.2 Proposed designs

To have a precise design with true dimensions and distances, an accurate design is provided here. A primary design is illustrated in Fig. 4. In this design there are one tQCA cell as input and two bQCA cells as outputs on the opposite sides of the tQCA cell. This design is actually a basic design and seems to work correctly. However, it is not evaluated thoroughly since it has a shortcoming. In the case of embedding this design in a large circuit, preceding cells which propagate data signal up to the tQCA cell can unexpectedly affect the bQCA output cells and then designer needs to take this effect into account to prove correct signal propagation. Thus, for a more precise case, the primary design has been improved, leading to the final proposed design, and its functionality has been evaluated exhaustively.

In the new design, the two output bQCA cells are positioned on the two adjacent sides of the tQCA cell, allowing input signal on the other side of tQCA cell in a diagonal pattern. In fact, in final design (Fig. 5), input cells preceding the tQCA cell are farther from the output (bQCA) cells comparing to the primary design. In order words, there is a wider chance of positioning preceding input cells adjacent to the tQCA cell so that noise effects (inter-cellular effects between preceding cells and bQCA cells) can be decreased remarkably.

The two bQCA cells, as shown in Fig. 5, are numbered and are defined as most significant bit (MSB) and least significant bit (LSB). In this section only the schematic of the circuit was presented. Detailed evaluations and results are provided and discussed in Section 6.

6 Experimental results for the converter

In the field of ternary QCA, there has been no formal tool to simulate and analyse circuits. Instead, analytical methods such as intercellular Hartree approximation (ICHA) [14] are used to evaluate circuit functionality. Before going to experimental results, a significant concept is described in details here.

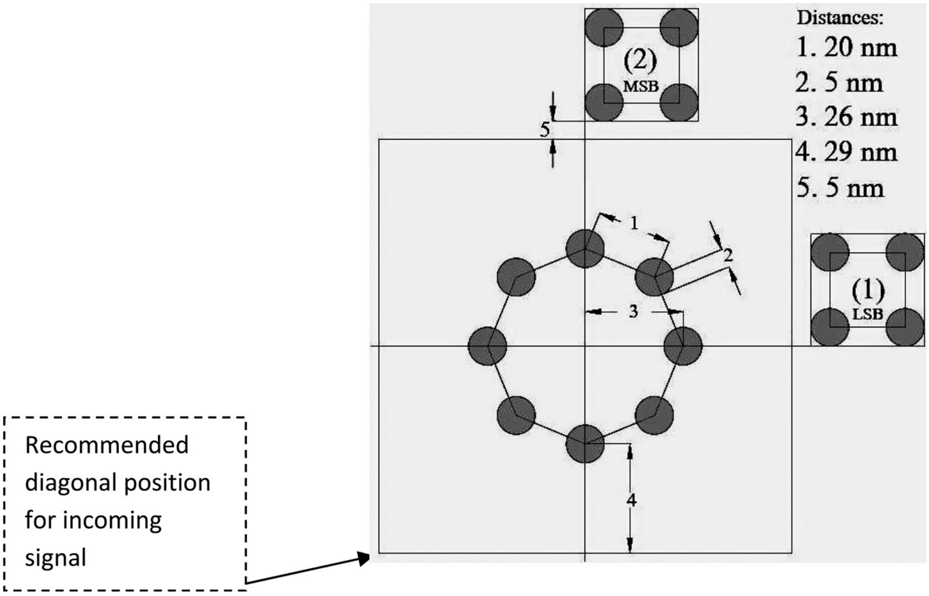
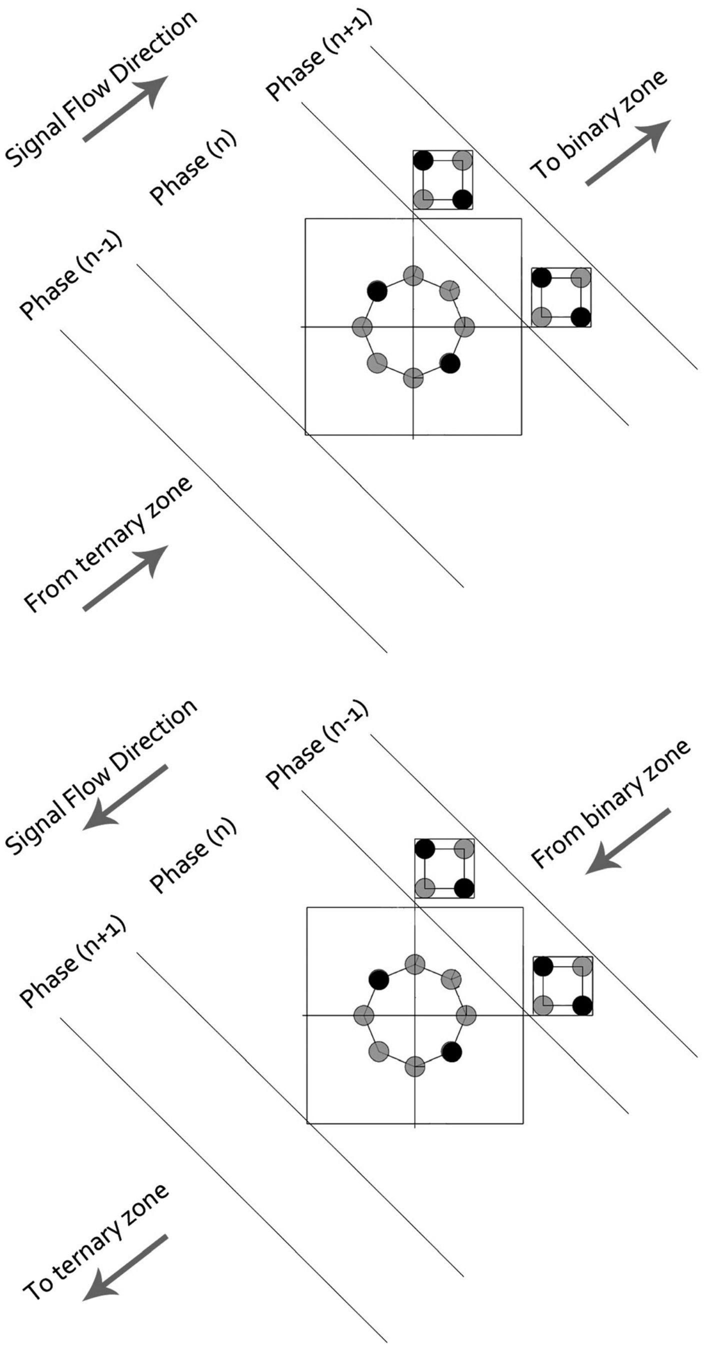


Fig. 5 *Proposed design of ternary-to-binary converter*

Table 4 Total kink energy in five categories between input cell and output cell with the given output logic (*J*)

Category	Output cell number	Given output logic value	Input cell state			
			A	*B*	*C*	*D*
1	2	0	**−6.79983E − 32**	1.44133E − 31	−1.71366E − 31	9.52309E − 32
2	2	1	6.79983E − 32	−1.44133E − 31	1.71366E − 31	−9.52309E − 32
3	1	0	**−6.79994E − 32**	1.44133E − 31	9.52316E − 32	−1.71365E − 31
4	1	1	6.79994E − 32	−1.44133E − 31	−9.52316E − 32	1.71365E − 31
Electrostatic interaction between bQCA cells (*J*)						
5			‘00’	‘01’	‘10’	‘11’
			3.15851E − 32	−3.15851E − 32	−3.15851E − 32	3.15851E − 32



* This clocking assignment lets a ternary state transform to binary state.

* This clocking assignment lets a binary state transform to ternary state.

Fig. 6 *Concept of clocking and reversibility of the proposed converter*

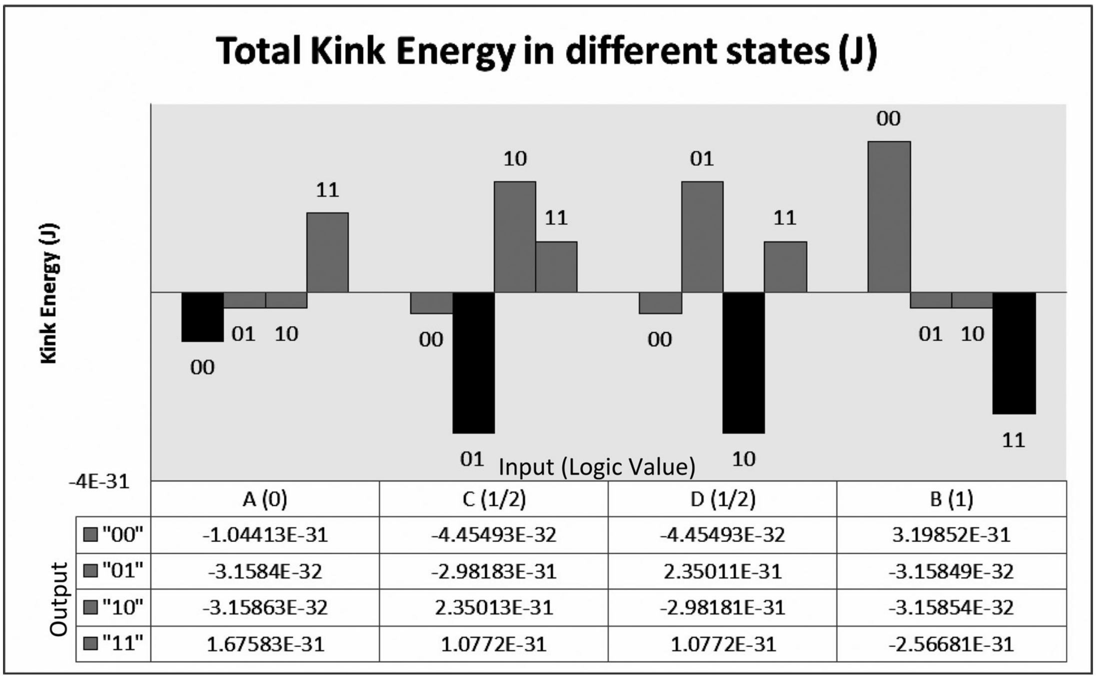


Fig. 7 *Total kink energy between all cells in different states*

In the field of QCA, there is a term called ground state. This term can be perceived for any QCA circuit element (a part of a big circuit) and refers to the lowest potential energy level of the whole element in a static manner. This lowest level of energy can be inferred as the most negative value of the potential energy of the element. In fact, for the proposed 3-cell converter there are four different ground states with respect to the four possible states of the input tQCA cell. Then, if we consider tQCA as input (because of ternary-to-binary conversion) and fix its state in any of the four states '*A*', '*B*', '*C*' or '*D*', the whole converter circuit will reach its lowest energy level naturally which is its ground state. It should be noted that all inter-cellular effects will be significant and must be taken into account. Regarding to this information, the computational steps are explained as follows.

In this work, using (1), electrostatic interaction between charges is calculated exhaustively for all possible states. Note that if we consider absolute distances between cells in (1), and also calculate summation of the values for all charges between two cells, we will achieve the kink energy (in Joules). In more details, there are three cells in this design which divide our calculations into five categories. In the first category, input tQCA cell and cell '2' (assumed as 0) are taken into account. In the second category, input tQCA cell and cell '2' (assumed as 1) are considered and so on. An important point to mention is the last category where electrostatic interactions between the two output bQCA cells must be considered since they can affect each other and may change the output value. Therefore all four possible states of the two bQCA cells are examined as the 5th category and the results show that output values of the converter are still correct and reliable. Detailed results are listed in Table 4. These results are also proving correct functionality of our proposed design. According to (1) and regarding to the results in Table 4, it can be concluded that the more negative value of energy the less electrostatic repulsion (or potential energy) between cells, leading to ground state. In order to conclude the results using Table 4, three values must be added together. For example in the case of 'A' as input tQCA cell state and given '00' as output, the three bold values of Table 4 must be added together. This analysis can be generalised to other input cell states and final results can be obtained. Also, Fig. 7 presents a better view of the results. Let us consider an example below.

As mentioned before, in order to interpret values of Table 4, it should be noted that the more negative value the less potential energy between the two considered cells, leading to a stable state (ground state). Thus, negative values will be candidate to construct ground states. For instance, in categories 1 and 2, interaction between input cell holding state 'A' and output cell '2', implies that if input ternary cell is in state A, the output binary cell '2' will have the logic value of '0'. Moreover, similarly in categories 3 and 4, interaction between input cell holding state 'A' and output cell '1', implies that if input ternary cell is in state 'A', the output binary cell '1' will have the logic value of '0'. Finally, it can be concluded that if input cell is in state 'A', output result will be '00'. Similarly, all the states can be interpreted and Table 3 is then verified correctly. Final candidates are shown in black columns in Fig. 7. Since all calculations have been performed exhaustively in ground-state and in a static manner, it can be concluded that this design can work in reversed direction. In fact, we have a binary-to-ternary converter here as well. Reversibility which refers to the fact that outputs can be constructed through inputs in a reversible circuit [24–26] is shown in this work. Of course, the concept of reversibility here is strongly dependent on clocking assignment. Because it is the clocking that makes the circuit operates and also defines its propagation direction. To show the concept of clock phases in the proposed design and clarify the reversibility of the converter, Fig. 6 is illustrated.

Based on the proposed converter, a novel coplanar crossover is presented in Section 7 as an application of the converter. In the meantime, there are some important tips about the characteristics of the proposed converter which

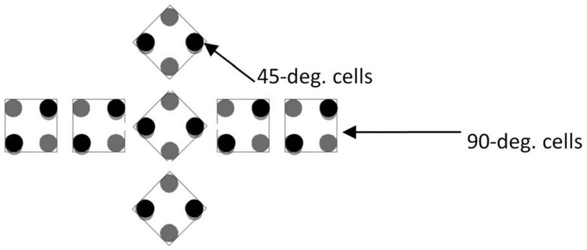


Fig. 8 *Typical QCA coplanar crossover [27]*

will be generalised to the next proposed design and will be discussed in details.

7 Proposed novel coplanar crossover

In many QCA designs, wire crossings are unavoidable. There are two wire crossing options in QCA; coplanar crossover and multilayer crossover. Coplanar crossover is a fascinating part of QCA which enables designer to cross two wires within a single physical layer. In Fig. 8, a typical coplanar crossover is demonstrated.

This kind of crossover (coplanar) is more practical since multilayer crossover is not likely to be manufactured easily. However, coplanar crossing is more prone to failure because of environmental conditions and noises. However, generally, design trends are focused on coplanar crossover because of manufacturing issues and even some works have been carried out on crossover fault tolerance and wire crossing minimisation [28–31]. As mentioned in [32], among basic elements of QCA designs, coplanar crossover is the most susceptible one. Indeed, because of manufacturing and also operational defects it can easily fail. Thus, a novel coplanar scheme is proposed here. This scheme exploits both kinds of QCA cells in a spectacular pattern. As shown in Fig. 9, the proposed coplanar crossover contains two input bQCA cells, one internal tQCA cell and two output bQCA cells. It should be noted that in order to have a monolithic design, quantum dots with the diameter of 10 nm are assumed and hence there is a centre-to-centre distance of 20 nm between adjacent dots inside a cell. The tQCA cell has dimensions of 110 × 110 nm.

The arrows in Fig. 9 show the signal propagation direction. Different grey-scale levels on middle cells demonstrate clocking scheme. In fact, the two input bQCA cells are assumed to have fixed polarisations. In the first phase, the tQCA cell is affected by input cells and then the two output bQCA cells are affected by the tQCA cell in the next phase. This clocking scheme which assumes the conventional four-phase clocking idea, defines the path for signal propagation. This design has two major advantages which are summarised here. First, there is no need to manufacture large amount of rotated bQCA cells and therefore the effect of manufacturing defects will be alleviated. It can be seen from Fig. 9 that all cells before and after the tQCA cell are regular cells and only one tQCA cell is located in the middle. Second, the input and output signals are separate enough that they cannot easily affect each other unexpectedly and thus noise effects are decreased. Here, we just presented a diagram-based description of the proposed design. All electrostatic interactions have been exhaustively calculated and correct functionality of the design is proven in the next section. Also more detailed strong points of the proposed design is explained below.

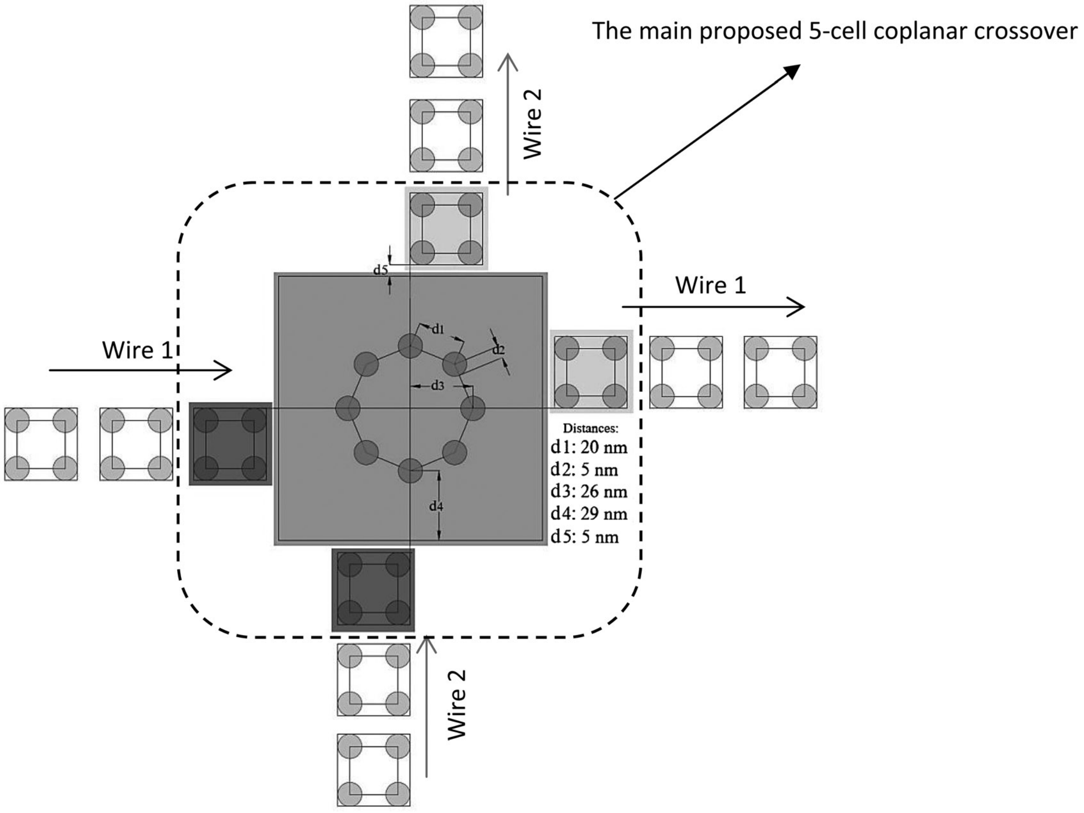


Fig. 9 *Proposed coplanar crossover which works in two clock phases*

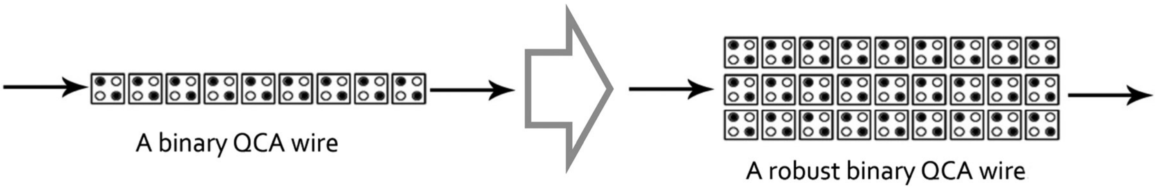


Fig. 10 *Simple sample of the concept of redundancy used in QCA*

7.1 Design advantages

Here is some more information on the design advantages (especially from the viewpoint of robustness) in details.

In the field of robustness, two major issues can be mentioned. First, we can point to the concept of redundancy. One of the conventional methods of making a circuit more robust and even fault-tolerant is redundancy. In QCA, this concept is also used mostly in the form of adding high number of adjacent cells in a wire (or other elements) leading to a bigger design at the expense of having a reliable design. For example one can propose a robust wire as shown in Fig. 10.

Similarly, here we propose a bigger coplanar crossover in comparison with conventional coplanar crossover. However, there is a trade-off such that we have used a single tQCA cell rather high number of bQCA rotated cells. Therefore input and output cells are far enough from each other so that unexpected effects between them are alleviated and finally this leads to a more robust design. This fact can also be seen through numerical results.

From the viewpoint of simulation results, it should be said that according to Fig. 7 (for the proposed converter and also generalised for both proposed designs) there is a considerable distance between the value of the selected state (shown in black column) of the design and other states. For example in the case that the tQCA has state 'C' and bQCA cells has the logic value '01', the darkened result is much more negative comparing to other collocated results (i.e. '00', '10' and '11'). This fact can highlight the certainty of the results and also reliability of the proposed designs.

The other major issue is that reducing number of cells to be manufactured for a coplanar crossover causes to reduce the probability of occurring manufacturing defects. Hence, the proposed design will be more likely to feasibility and operability.

Table 5 Potential energy levels between the input cells and the tQCA cell (*J*)

	In			
Out	'*A*'	'*B*'	'*C*'	'*D*'
'00'	−1.35999E − 31	2.88266E − 31	−7.61337E − 32	−7.61337E − 32
'01'	0	0	2.66597E − 31	−2.66597E − 31
'10'	0	0	−2.66597E − 31	2.66597E − 31
'11'	1.35999E − 31	−2.88266E − 31	7.61337E − 32	7.61337E − 32

Table 6 Potential energy levels between the tQCA cell and the output cells added to inter-cellular effect of output bQCA cells (*J*)

	In			
Out	'00'	'01'	'10'	'11'
'*A*'	−1.04413E − 31	−3.1584E − 32	−3.15863E − 32	1.67583E − 31
'*B*'	−2.56681E − 31	−3.15854E − 32	−3.15849E − 32	3.19852E − 31
'*C*'	1.0772E − 31	2.35013E − 31	−2.98183E − 31	−4.45493E − 32
'*D*'	1.0772E − 31	−2.98181E − 31	2.35011E − 31	−4.45493E − 32

Table 7 Characteristics of both proposed designs

	Coplanar crossover	Ternary/binary converter
cell count	5	3
area, μm^2	0.0324	0.021
clock phase	2	1

8 Experimental results for the coplanar crossover

In order to prove correct functionality of the proposed scheme, physical proof using (1) is considered. As mentioned for the converter design, the method used in this work is based on ground-state concept in static manner. Note that this method has been already used and verified in [33]. Calculations can be divided into two categories. In the first category, written in Table 5, effects of the input bQCA cells on the tQCA cell are calculated. In the second category, demonstrated in Table 6, effects of the tQCA cell on the output bQCA cells and also inter-cellular effects of the output bQCA cells are calculated and both added together. Note that all values refer to potential energy level of the whole design (in Joules) in a given state. Since all calculations are analysed based on the definition of ground-state, it is concluded that the lower energy-level between cells the closer to ground state. Thus, the most negative values (shown in grey-scale in the tables) are our desired results. According to Table 5, it can be concluded that the tQCA cell accepts a certain configuration with respect to the effects induced by the two bQCA input cells. Table 6 shows that the two bQCA output cells are affected by the tQCA cell in the next clock phase. Overall, it is seen that two signals can pass the crossover flawlessly. At the end, characteristics of both proposed designs are summarised in Table 7.

8.1 Complexity and accuracy of the calculations

Since there are no formal simulator to be used for tQCA circuits to date, alternative methods have to be applied. In this work, all calculations were accomplished exhaustively

Table 8 Complexity of analytical computations for the proposed converter (number of operations)

ADD	MUL	DIV	Total
1312	724	704	2740
total number of distances measured: 144			

Table 9 Complexity of analytical computations for the proposed coplanar crossover (number of operations)

ADD	MUL	DIV	Total
3648	1648	1600	6888
total number of distances measured: 224			

manually through current accessible tools. Tables 8 and 9 show the large amount of computations done in this work.

It should be noted that all entries and calculations have been repeated several times to ascertain the correctness of the final results. However, this took a very long time and had an accurate procedure. Accordingly, it can be seen that the 3-cell converter design needs a long quantitative procedure to be proved. Moreover, the 5-cell crossover design has even a larger amount of calculations than those for converter design.

9 Conclusion and future works

In order to create a versatile design platform containing both bQCA and tQCA elements, there will be a need for providing the possibility of bQCA and tQCA interaction. Two major works have been done in this paper. First, a novel ternary-to-binary (and vice versa) converter was proposed in two stages, primary design and final design. Design advantages such as possibility of using the converter in complex circuits including both tQCA and bQCA, evaluation of ternary circuits using binary outputs, and so on were also stated. Second, a novel coplanar crossover was proposed which exploits both kinds of bQCA and tQCA cells. Two major advantages of this design, both referring to reliability, were mentioned. To validate the designs, exhaustive calculations were applied and behaviour of the circuits was analysed thoroughly in ground state according to total electrostatic interactions (kink energy). Based on the results, functionality of both circuits was approved. Finally, characteristics of both designs and also complexity of computations were presented.

Since the main field of this work is somehow premature, there are lots of options which can be chosen as the future works. Some of our trends are listed below.

- As mentioned in the context, there is no formal and public simulation tool to verify tQCA circuits. Hence, developing a new tool can be very helpful in the field of tQCA and even mixed bQCA/tQCA designs.
- To highlight strong points of the proposed designs on one hand and to verify them in large circuits on the other hand, some analytical procedure can be provided in the form of an auxiliary tool.
- Physical implementation of the two proposed designs can be investigated by cooperating with some researchers in the field of quantum physics.

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