Designing quantum-dot cellular automata circuits using a robust one layer crossover scheme

Sara Hashemi, Keivan Navi

Department of Electrical and Computer Engineering, Shahid Beheshti University, G.C., Tehran, Iran
E-mail: navi@sbu.ac.ir

Published in *The Journal of Engineering*; Received on 3rd November 2013; Accepted on 2nd February 2014

Abstract: Quantum-dot cellular automata (QCA) is a novel nanotechnology which is considered as a solution to the scaling problems in complementary metal oxide semiconductor technology. In this Letter, a robust one layer crossover scheme is introduced. It uses only 90° QCA cells and works based on a proper clock assignment. The application of this new scheme is shown in designing a sample QCA circuit. Simulation results demonstrate that using this new scheme, significant improvements in terms of area and complexity can be achieved.

1 Introduction

To date different coplanar quantum-dot cellular automata (QCA) crossover schemes have been introduced [1–4]. The first structure which is shown in Fig. 1a is implemented using 90 and 45° QCA cells [1]. This crossover scheme has a high sensitivity to manufacturing faults and needs a high precision for QCA cell placement [2, 5]. The presented solutions in [2–4] are implemented using only 90° QCA cells. The coplanar crossover scheme in [2] (as shown in Fig. 2*b*) uses an eight-phase clocking mechanism with three types of clock signals (normal, crossing and converting signals). In this scheme, four-phase shifted versions of the normal clock signal are used for general logic flow in QCA cells *a*, *c*, *p* and *r*. A crossing signal is used in QCA cell *x* and two-phase shifted versions of the converting signal are required in QCA cells which are shown by *b* and *q*. Regarding this structure, it is clear that this crossover scheme leads to a QCA circuit with a complex clocking mechanism. The crossover scheme in [3] and its clocking waveforms are shown in Figs. 1*c* and *d*. This solution in contrast to the previous scheme [2] uses only four regular clock signals. As shown in Fig. 1*c*, the horizontal wire is segmented into two parts. All of the four clock signals must be elapsed at the left segment, whereas the QCA cells of the right segment are controlled by the clocking signal *C*2. At the first clock cycle, the input signal *B* propagates to the 'output' *B* (at $T = 1$ all of the QCA cells of the vertical wire *B* are in the switch phase). At clock cycle 5, the input signal *A* has been propagated to QCA cell *x*. This cell is in the hold phase and drives the QCA cells of the vertical wire *B* which are in the switch phase (the input *B* has been considered unpolarised at this time). Finally, at $T = 6$ the input signal *A* is propagated to the right using the QCA cells of the vertical wire (at this time, the QCA cells of the right side of the vertical wire are in the switch phase, whereas the QCA cells of the vertical wire *B* are in the hold phase). However, as mentioned in [3], in this crossover scheme, the input signals *A* and *B* are only applied during the first clock cycle and then removed (the input *B* is considered unpolarised at $T = 5$). If this condition is not satisfied at clock cycle 5, the input signal *A* cannot correctly be transmitted to the vertical wire *B*. Regarding this condition, this scheme is not suitable for pipeline structure of QCA circuits.

Based on the Landauer clocking mechanism, four clocking zones can be used to design QCA circuits [5]. The schematic of a QCA wire composed of four clocking zones is shown in Fig. 2*a*. Each of these clocking zones is comprised of a group of QCA cells which are controlled by the same QCA clock. The four QCA clock waveforms [5] are shown by Fig. 2*b*. As shown in this figure, in each of the clocking zones, four clock phases can occur; a switch, a hold, a release and a relax phase. During the switch phase, the input cells affect the unpolarised QCA cells and some values are reached. In the hold phase, the polarisation of QCA cells is locked for transmission to their neighbouring cells. During the release phase, QCA cells lose their values. Finally, the relax phase means that QCA cells are completely unpolarised [5]. As shown in Fig. 2*b*, there is a 90° phase delay between clocking zones. For example, there is a 180° phase delay from the first clocking zone (zone0) to the third one (zone2). Regarding these phase delays, two routing elements with simple structures were introduced in [6]. These elements are constructed using five QCA cells and are used to implement two edges and straight crossings in a QCA programmable switch matrix (PSM) interconnection element [6]. These elements also can be considered as a suitable solution for crossing wires in a QCA circuit.

Recently, another coplanar crossover scheme has been introduced [4]. This scheme works same as the presented elements in [6]. The only difference is the clocking zone of the middle QCA cell. In [6], the middle QCA cell is not connected to the QCA clock, whereas in [4] a QCA clock is assigned to this cell. As shown in Fig. 2*c*, the crossover scheme in [4] uses two different clocking zones with a 180° phase delay to crossover wires. In Fig. 2*c*, when the QCA cells of zone0 are in the switch and hold phases, the QCA cells of zone2 are in the release and relax phases; therefore the QCA cells of zone0 cannot be affected by QCA cells of zone2 and vice versa. In the next section, the robustness of this scheme is investigated and it is changed to obtain a robust structure against sneak noise paths.

2 Robust QCA crossover scheme

In [7, 8], the robustness of the basic coplanar crossover scheme (Fig. 3*a*) is investigated. The results demonstrate that the input signal of the vertical wire can affect the output of the horizontal wire and this leads to incorrect operation of the crossover scheme. Based on calculations [7], the kink energy between QCA cells {*A*1, *C*2}, {*A*2, *C*2} and {*A*3, *C*2} is zero and therefore the polarisation of QCA cells *A*1, *A*2 and *A*3 do not affect the polarisation of QCA cell *C*2. Unfortunately, the kink energy between the cell pairs {*C*2, *A*} and {*C*2, *X*} is non-zero and these cells (*A* and *X*) affect the polarisation of QCA cell *C*2 [7]. This results in sneak noise paths and the noise is conducted from input signal *Sv* to QCA cell *C*2 [7]. It is worth mentioning that these sneak noise paths can lead to incorrect operation when small QCA blocks are used to design larger QCA circuits. To solve this problem, as shown in Fig. 3*b*, in a robust crossover scheme the horizontal QCA cells on the right side of the vertical wire are controlled

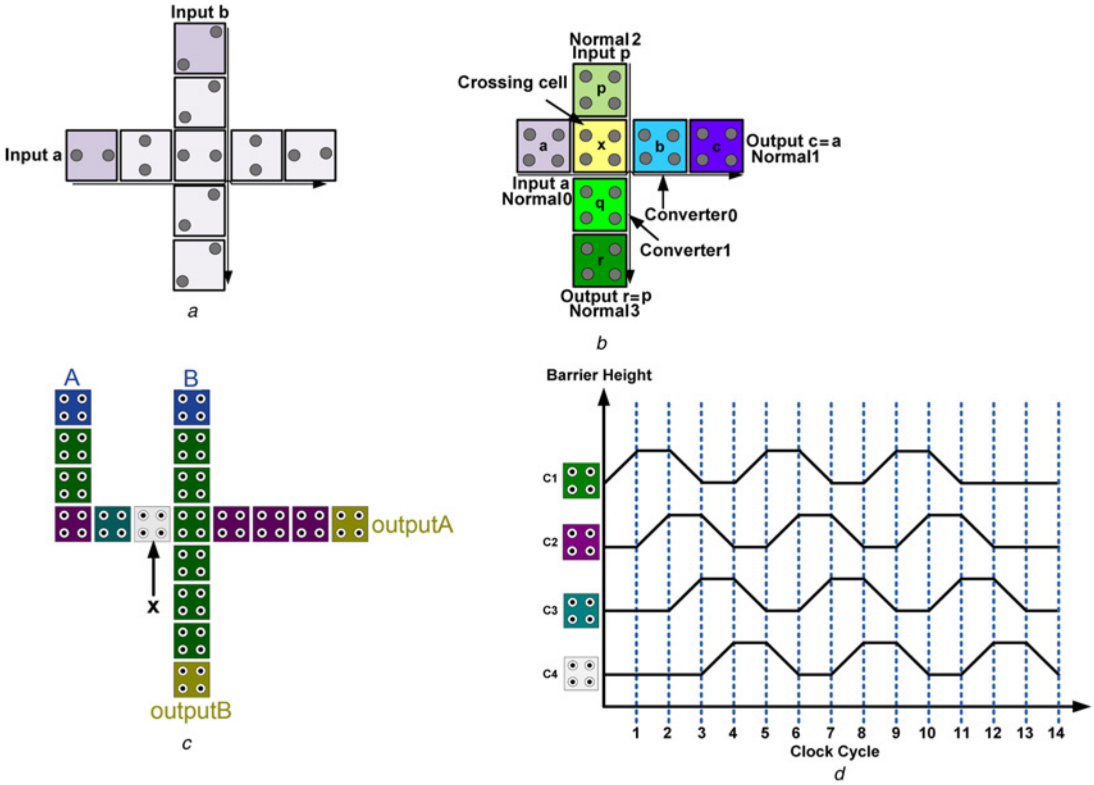

Fig. 1 *First structure*
a Basic coplanar crossing scheme constructed using 90 and 45° QCA cells [1]
b Coplanar crossing scheme constructed using only 90° QCA cells presented in [2]
c and *d* Coplanar crossover scheme in [3] with its clocking waveforms

using a QCA clock which has a 90° phase delay with the cells on the left side of the vertical wire [7, 8]. Using this proper clock assignment, during the switch phase of QCA cells *A* and *X* (controlled using clock0 in Fig. 3*b*), the QCA cells *C*2, *C*3 and *Z* are in the relax phase and they are not affected by the vertical wire. During the switch phase of clock1, the QCA cells *C*2, *C*3 and *Z* are affected by QCA cell *C*1 and the noise from cells *A* and *X* (the QCA cells *C*1, *A* and *X* are in the hold phase). In this condition, the polarisation of QCA cells *C*2, *C*3 and *Z* eventually settle down to the input signal *Sh*. In fact, using this proper clock assignment the input signal *Sh* does not arrive to the output no later than any noise signal and this leads to a robust QCA crossover scheme against sneak noise paths.

In this section, robustness of the coplanar crossover scheme in Fig. 2*c* against sneak noise paths is investigated and a robust structure is introduced. Based on Fig. 4*a*, it is clear that this scheme same as the basic design (Fig. 3*a*) is vulnerable to the sneak noise paths. As shown in this figure, the output QCA cells of the horizontal wire

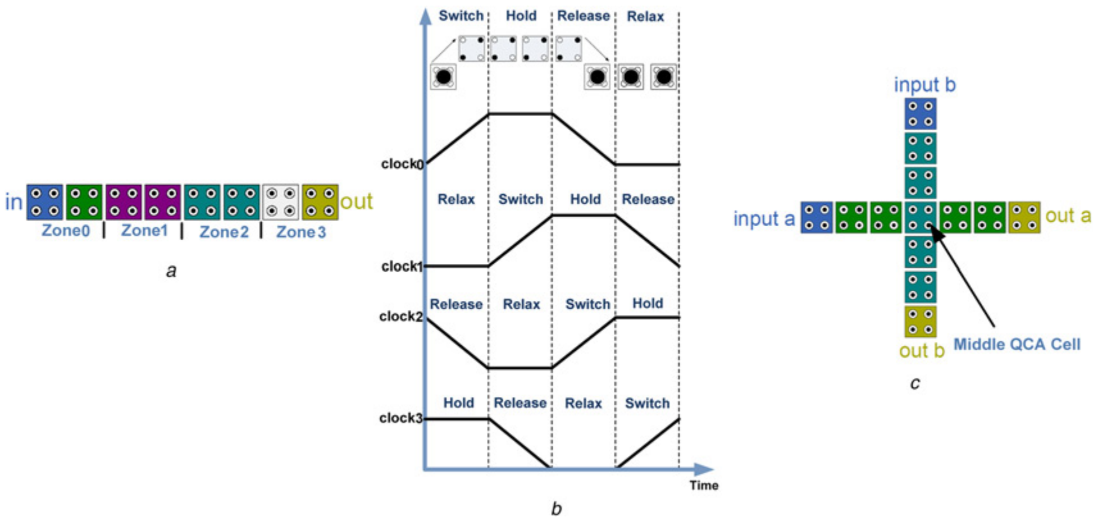

Fig. 2 *Coplanar crossover scheme*
a QCA wire constructed using four clocking zones
b Landauer QCA clocking waveforms [5]
c QCA crossover scheme in [4] which works same as the routing elements in [6]

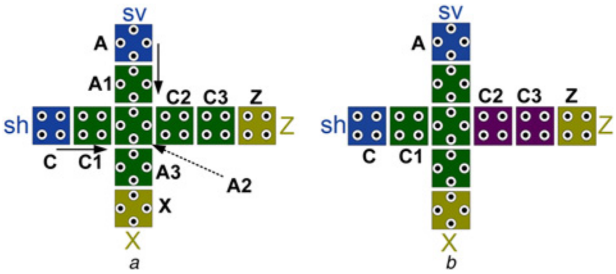

Fig. 3 *Robustness of the basic coplanar crossover scheme*
a Basic coplanar QCA crossover scheme
b Robust crossover against sneak noise paths [7, 8]

Table 1 Kink energy between QCA cells in Fig. 4*a*

QCA cells		≃Energy, J
*B*1	*A*1	-0.08×10^{-23}
	*A*2	-2.11×10^{-23}
*B*2	*A*1	-0.96×10^{-23}
	*A*2	-3.03×10^{-23}

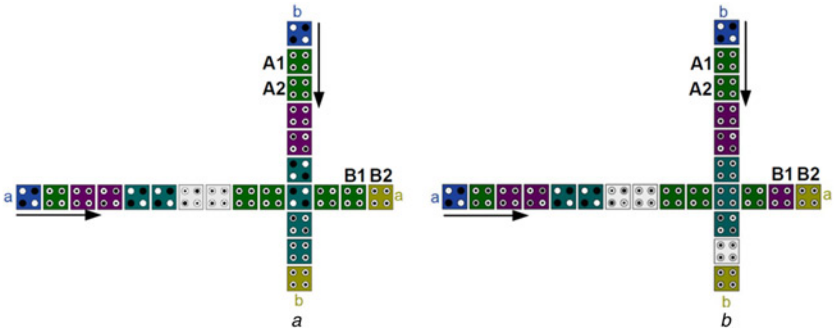

Fig. 4 *Output QCA cells of the horizontal wire*
a Coplanar crossover scheme in [4]
b Robust crossover scheme against sneak noise paths

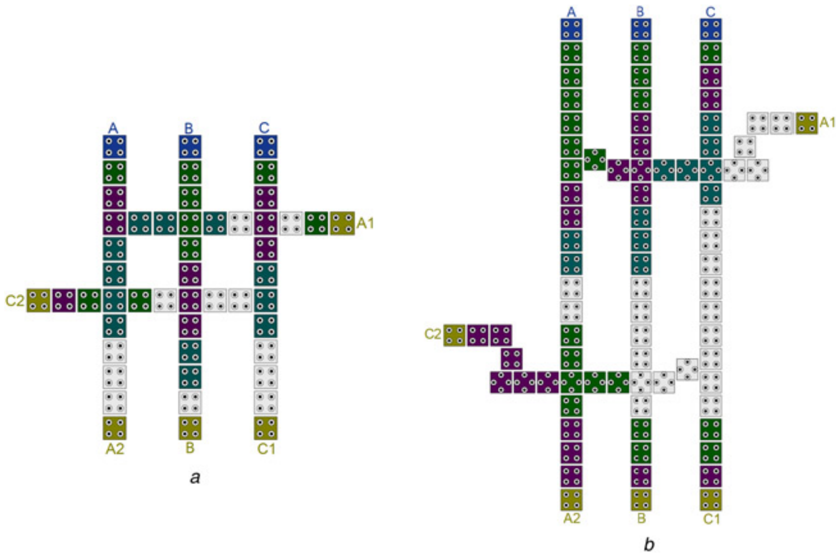

Fig. 5 *Application of the new crossover scheme*
a QCA circuit constructed using the new robust coplanar crossing scheme
b QCA circuit constructed using the coplanar crossing scheme in Fig. 3*b*

(*B*1 and *B*2) in the switch phase are affected by the QCA cells of the vertical wire which are in the same phase (QCA cells *A*1 and *A*2). The values of the kink energy between QCA cells can demonstrate this problem. The kink energy [7] between QCA cells *A*1, *A*2 and *B*1, *B*2 is presented in Table 1 (the kink energy can be considered as the difference in energy between two cells which have an opposite polarisation and those same two cells with a same polarisation [7]). In this table, the kink energy is calculated using the four possible interaction patterns between a pair of QCA cells (the length of each cell has been considered equal to 18 nm and there is a space of 2 nm between each of the two neighbour QCA cells). Based on these results, it is clear that the kink energy between QCA cells

Table 2 Comparison results of the proposed structures in Figs. 5*a* and *b*

Design types	Complexities (QCA cells)	Area, μm^2	Maximum delay (clock cycles)
new design in Fig. 5*a*	50	0.06	1.5
presented design in Fig. 5*b*	84	0.13	1.5

J Eng, 2014, Vol. 2014, Iss. 3, pp. 93–97
doi: 10.1049/joe.2013.0177

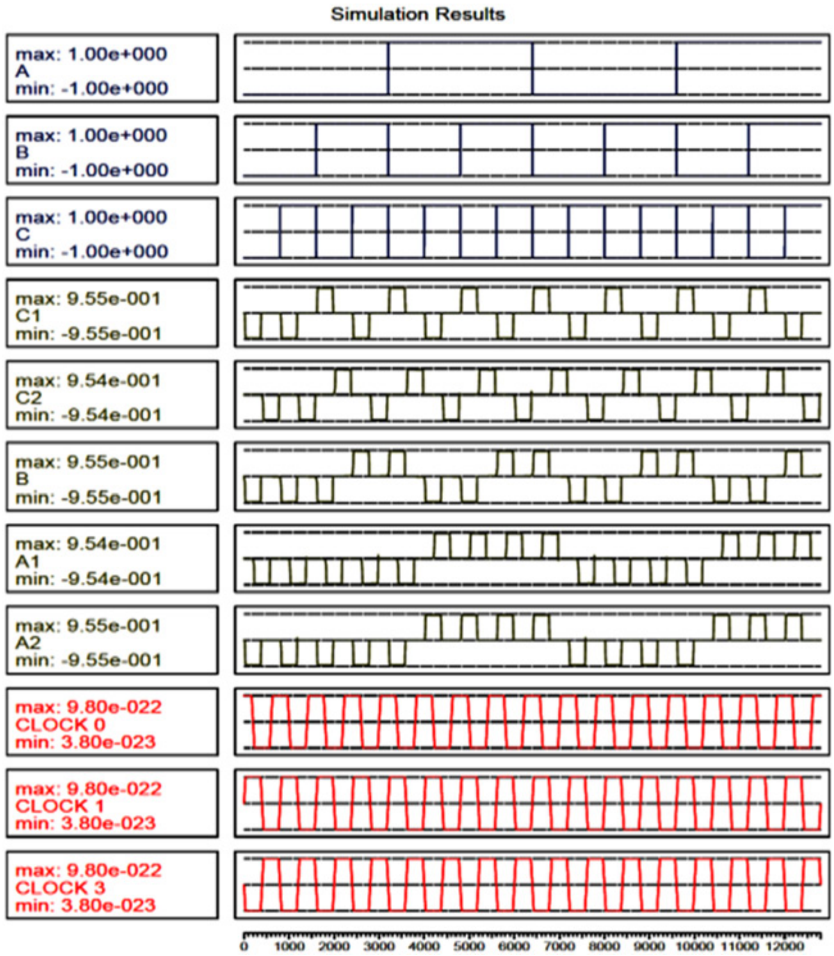

Fig. 6 *Simulation results of the proposed structure in Fig. 5a*

$A1$, $A2$ and $B1$, $B2$ is not zero. In other words, the polarisation of the horizontal outputs is affected by QCA cells of the vertical wire which are in the same clocking zone. To solve this problem, an additional clocking zone (with a 90° phase delay) must be added to the output of horizontal wire (Fig. 4*b*). In this case, same as the presented robust design in Fig. 3*b*, the horizontal input does not arrive after the noise signals. In this structure, when the QCA cells $A1$ and $A2$ are in the switch phase the horizontal outputs ($B1$ and $B2$) are in the relax phase and therefore the vertical wire does not affect the horizontal outputs. In addition, it is clear that an additional clocking zone (clocking zone 3 in Fig. 4*b*) must be added to the output of the vertical wire. This is done due to the fact that by adding a clocking zone to the horizontal wire, the output QCA cells of the horizontal and vertical wires are positioned in two clocking zones with a 90° phase delay (clocking zones 1 and 2 in this example). It is clear that in this case, the output QCA cells of the vertical wire in the switch phase (positioned in clocking zone 2) are affected by QCA cells of the horizontal wire which are in the hold phase ($B1$ and $B2$ which are positioned in clocking zone 1). To solve this problem, the output QCA cells of the vertical wire are positioned in a clocking zone which has a 180° phase delay with the outputs of horizontal wire (clocking zone 3 in Fig. 4*b*).

An application of the new crossover scheme is shown in Fig. 5*a*. As shown in this figure, using the new scheme the input signals A and C are transmitted easily (the outputs of these signals are shown by $A1$, $A2$, $C1$ and $C2$). The structure of this circuit using the basic robust crossover scheme (Fig. 3*b*) is shown in Fig. 5*b*. Based on the proposed designs, it is clear that the new scheme leads to a very dense structure and is a suitable solution for designing robust QCA circuits (Table 2). The exhaustive simulations of the proposed structure (Fig. 5*a*) using the default parameters of both bi-stable and coherence vector engines of QCADesigner version 2.0.3 [9, 10] is shown in Fig. 6. It is worth mentioning that using both engines same results have been achieved which indicate the accuracy of the new crossover scheme. Regarding the proposed results, this scheme is a suitable solution for designing efficient and robust QCA circuits.

3 Conclusion

In this Letter, a robust one layer QCA crossover scheme was introduced. This design uses only 90° QCA cells and in contrast to its counterparts does not need a complex clocking mechanism. This scheme was used to design a sample QCA circuit. Simulation results indicate that using this scheme very dense structure and robust against sneak noise paths can be achieved.

4 References

[1] Tougaw P.D., Lent C.S.: ‘Logical devices implemented using quantum cellular automata’, *J. Appl. Phys. Am. Inst. Phys.*, 1994, **75**, pp. 1818–1824

[2] Devadoss R., Paul K., Balakrishnan M.: ‘Coplanar QCA crossovers’, *IET Electron. Lett.*, 2009, **45**, pp. 1234–1235

[3] Tougaw D., Khatun M.: ‘A scalable signal distribution network for quantum-dot cellular automata’, *IEEE Trans. Nanotechnol.*, 2013, **12**, pp. 215–224

[4] Shin S.H., Jeon J.C., Yoo K.Y.: ‘Wire-crossing technique on quantum-dot cellular automata’. Second Int. Conf. Next Generation Computer and Information Technology (NGCIT), 2013, vol. **27**, pp. 52–57

[5] Hänninen I., Takala J.: ‘Binary adders on quantum-dot cellular automata’, *J. Signal Process. Syst. (Springer)*, 2010, **58**, pp. 87–103
[6] Jazbec A., Zimic N., Bajec I.L., Pe’ar P., Mraz M.: ‘Quantum-dot field programmable gate array: enhanced routing’. Conf. Optoelectronic and Microelectronic Materials and Devices, 2006, pp. 121–124
[7] Kim K., Wu K., Karri R.: ‘The robust QCA adder designs using composable QCA building blocks’, *IEEE Trans. Comput. Aided Des. Integr. Circuits Syst.*, 2007, **26**, pp. 176–183
[8] Kim K., Wu K., Karri R.: ‘Towards designing robust QCA architectures in the presence of sneak noise paths’. Proc. Design, Automation and Test in Europe Conf. Exhibition, 2005, pp. 1214–1219
[9] QCADesigner Documentation [Online]. Available at http://www.qcadesigner.ca
[10] Walus K., Dysart T.J., Jullien G.A., Budiman R.A.: ‘QCADesigner: a rapid design and Simulation tool for quantum-dot cellular automata’, *IEEE Trans. Nanotechnol.*, 2004, **3**, pp. 26–31