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On the Development of Multi-Input Multi-Output Nano Digital Circuits for Molecular Medicine

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***Abstract*—There is an increasing interest in the development of nano digital circuits for molecular medicine. Several authors have analyzed some human body operations as equivalent to simple nano gates and their connections. The objective of this paper is to suggest an approach by which any human body function can be represented in the form of truth table. The Boolean expressions corresponding to these tables are realized with the help of nano digital circuits. Nano circuits can be realized using quantum-dot cellular automata (QCA) logic. This logic is implemented by Verilog representation. This representation is then converted into majority gates which lead to the nano digital circuits. This paper gives an approach by which multi-input multi-output Boolean functions are realized by nano digital circuits. Essentially, the approach is the design, simulation and implementation of various biosensors using nano technology.**

***Keywords*-Nano circuits; digital design; majority gates; molecular medicine ; quantum-dot cellular automata (QCA).**

I. Introduction

Several authors have recently taken interest in the design of biosensors. Biosensors form an important role in human body. Some authors have represented biosensor functions with the help of logic gates. N. Tamara *et al.* [1] suggested a biosensing system represented by a truth table. W. Joseph and E. Katz [2] suggested another biosensing system. The truth tables consider the digitized values of input-output variables under consideration. The first biosensor explained in [1] is an assembly of a four-enzyme-coupled system that includes four inputs, acetylcholine, butyrylcholine, oxygen and glucose and producing NADH as the output signal. They also derived the equivalent logic circuitry for this system. Similarly, for the second biosensor system in [2], there are four different chemical input signals (oxygen, glucose, acetaldehyde and NADH) and one output (pH). Most of the authors have represented a multi-input and single output design.

QCA majority gate and an inverter can be considered as the basic logic devices for any QCA circuit [4]–[7]. Any complex Boolean function can be represented in majority expression. With the help of QCA majority gate and inverter any majority expression can be implemented in QCA. Several techniques are available in literature to convert the Boolean function to majority logic. Reduced-unitized-tables [8], K-maps [9] and Shannons decomposition principles [10] are some of the popular techniques. However, these methods are limited for a single output.

In this paper we suggest an approach in which multi-input multi-output systems can be taken instead of a single output. Multiple boolean functions with multiple outputs are taken for the design and these functions are first converted to majority expression. The different systems are implemented with lesser number of majority gates by combining the common gates. Recently, Amjad and Singh [3] suggested a new approach for designing a nano digital circuit for any multi-input single-output Boolean function using QCA technology. In this paper, an extended work is done to use this technique to design multi-input multi-output systems.

This paper is organized as follows. Section II gives the background material for quantum cellular automata. The methodology followed for multi-input multi-output QCA design is explained in Section III. Section IV gives the molecular applications of the proposed method. Some concluding remarks are given in Section V.

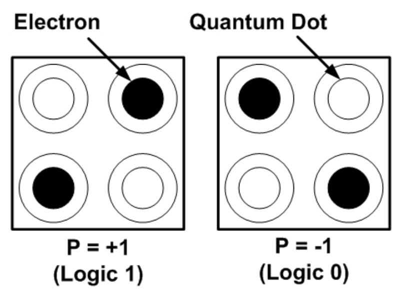

Figure 1. QCA cell with electrons indicating possible polarization.

II. Background Material

A. QCA Cell

QCA cell is the basic element in QCA. This cell contains four quantum dots. Each cell takes only two electrons. The binary states are determined by the location of electrons in the cell as shown in Fig. 1

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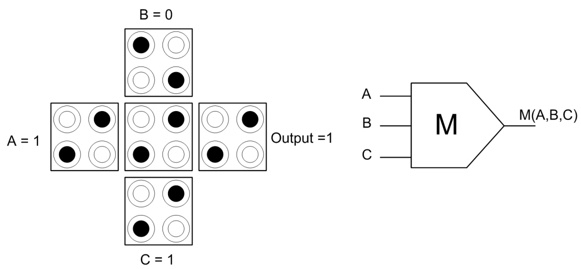

Figure 2. QCA majority gate.

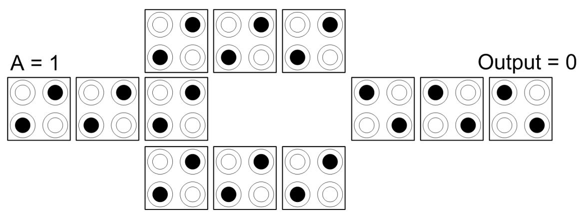

Figure 3. QCA Inverter.

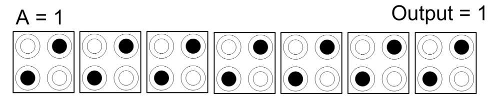

Figure 4. QCA wire.

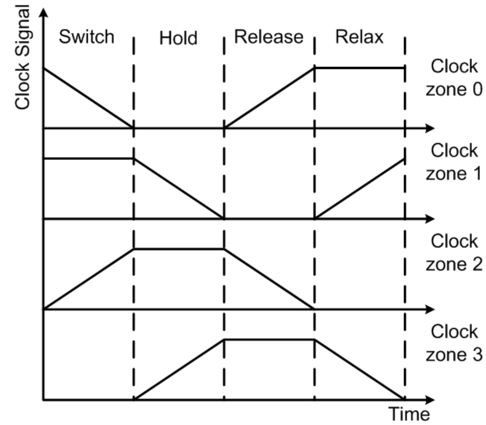

Figure 5. QCA Clocks and its four phases with difference of 90^0.

B. QCA Devices

The QCA logic devices are QCA majority gate, QCA inverter and QCA wire. A QCA majority consist of three-input and one output. Fig. 2 shows simple diagram of a QCA majority gate. The function of majority gate is to get the output logic 1 when the majority of inputs are 1. Otherwise, the output is logic 0. The majority gate function is given in (1). Simple diagram of a QCA inverter is shown in Fig. 3.

$$M(A, B, C) = AB + AC + BC \tag{1}$$

A QCA wire is a group of cells. These cells are placed to each other as shown in Fig. 4. The direction of signal flow goes from left to right cell.

In QCA majority gate, by fixing one of the three inputs as logic 0, the function of majority gate will be AND gate, and fixing one input as logic 1 the function of majority gate will be OR gate as shown in (2) and (3) respectively.

$$M(A, B, 0) = AB \tag{2}$$

$$M(A, B, 1) = A + B \tag{3}$$

C. QCA Clock

In QCA there are four different stages. These stages are clock 1, clock 2, clock 3 and clock 4. Each of these clocks has four phases with a difference of 90^0 [11] as shown in Fig. 5. These phases namely switch, hold, release, and relax [5] that depicted in Fig. 6 . The first purpose of using these clocks is to power the automata. The second purpose is to control direction of data flow. The data flow direction is determined by the state of cell and its state neighbors. In the first phase, which is switch, the cell is polarized based on the neighbor's state. During the whole phase, the cells retain its polarization. Finally, in the release and relax phases, the cells are unpolarized [12].

III. METHODOLOGY

The steps for the proposed algorithm are given below:

1) Write down Boolean functions in the form of minterms from the requirement of multi-input multi-output biosensor systems truth tables.
2) Realize each Boolean function with XOR and AND gates using XOR-AND minimization chart given in [13].
3) Simplify each XOR-AND Boolean function to all its possible simplified functions by utilizing XOR property ($\overline{f} = 1 \oplus f$).
4) Convert the simplified XOR-AND Boolean functions into majority gate expression [3].
5) Reduce the number of inverters [3].
6) Choose majority expression from each output functions in such a way that the total number of majority gates is minimum. Then implement this reduced multi-output functions in QCA.

A. Example

Consider two systems have the following Boolean functions:

$$F_1 = AB + \overline{B}C \tag{4}$$

$$F_2 = AB + \overline{AB} \tag{5}$$

This Boolean function is implemented as follows:

1) The Boolean function in minterms expression is given below:

$$F_1 = \sum(1, 5, 6, 7) \tag{6}$$

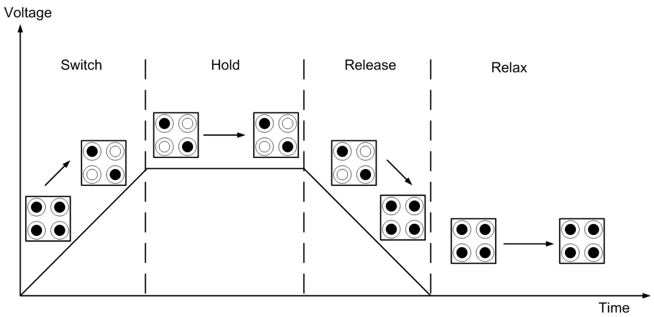

Figure 6. Four phases of a QCA clock.

Table I
XOR-AND MINIMIZATION CHART FOR F_1 AND F_2

F	Minterms ABC	1	A	B	C	AB	AC	BC	ABC
F_1	001				1		1	1	1
	101						1		1
	110					1			1
	111								1
	(✓) or (x)	x	x	x	✓	✓	x	✓	x
F_2	000	1	1		1	1	1	1	1
	001						1	1	1
	110					1			1
	111								1
	(✓) or (x)	✓	✓	✓	x	x	x	x	x

$$F_2 = \sum(0,1,6,7) \tag{7}$$

2) Converting the Boolean functions given in (6) and (7) to the XOR-AND Boolean functions form using minimization chart is shown in Table I. From this table, the equivalent XOR-AND function is given in below:

$$F_1 = C \oplus AB \oplus BC \tag{8}$$

$$F_2 = 1 \oplus A \oplus B \tag{9}$$

3) The all possible simplified XOR-AND functions are given below:

$$F_1 = AB \oplus \overline{B}C \tag{10}$$

$$F_2 = \overline{A} \oplus B \tag{11}$$

$$F_2 = A \oplus \overline{B} \tag{12}$$

4) By converting (10), (11) and (12) to majority expressions, they are obtained as shown in (13), (14) and (14) respectively. It can be noted that (11) and (12) will give the same majority expression.

$$F_1 = M(M(\overline{M(A,B,0)}, M(\overline{B},C,0),0), \\ M(M(A,B,0), \overline{M(\overline{B},C,0,0)},1) \tag{13}$$

Table II
TRUTH TABLE FOR SYSTEM A

Acetylcholine	Butyrycholine	Oxygen	Glucose	NADH (F_A)
0	0	0	0	0
0	0	0	1	1
0	0	1	0	0
0	0	1	1	1
0	1	0	0	0
0	1	0	1	1
0	1	1	0	1
0	1	1	1	0
1	0	0	0	0
1	0	0	1	1
1	0	1	0	1
1	0	1	1	0
1	1	0	0	0
1	1	0	1	1
1	1	1	0	1
1	1	1	1	0

Table III
TRUTH TABLE FOR SYSTEM B

Oxygen	Glucose	Acetaldehyde	NADH (F_A)	pH(F_B)
0	0	0	0	0
0	0	0	1	0
0	0	1	0	0
0	0	1	1	0
0	1	0	0	0
0	1	0	1	0
0	1	1	0	0
0	1	1	1	1
1	0	0	0	0
1	0	0	1	0
1	0	1	0	0
1	0	1	1	0
1	1	0	0	1
1	1	0	1	1
1	1	1	0	1
1	1	1	1	1

$$F_2 = M(M(A,B,0), M(\overline{A},\overline{B},0),1) \tag{14}$$

5) For function (13), the further reduction of inverters number is not possible. The reduced inverters function for (14) is given below:

$$F_2 = M(M(A,B,0), \overline{M(A,B,1),1)} \tag{15}$$

6) These functions given in (13) and (15) can be implemented in QCA. The block diagrams for majority functions in (13) and (15) are shown in Fig. 7.

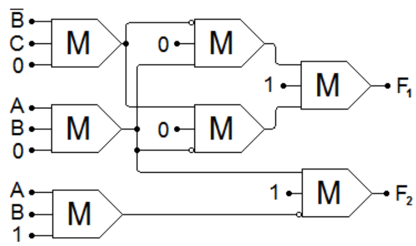

Figure 7. Majority gate implementation of F_1 and F_2.

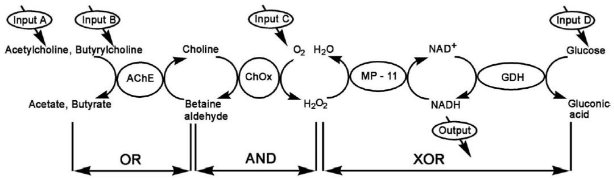

Figure 8. Scheme describing the operation of concatenated logic gates based on four coupled biocatalysts [1].

IV. Molecular Application

In this section, we suggest the proposed technique for the following applications in molecular medicine:

System A: Assembly of a Four-Enzyme Logic System Producing NADH as the Output signal

Consider the system having the truth table given in Table II. The truth table considers the digitized values of the variables under consideration. This system is an assembly of a four-enzyme-coupled system that includes four inputs, acetylcholine, butyrylcholine, oxygen and glucose and producing NADH as the output signal as shown in Fig. 8. This is discussed by N. Tamara in [1].

System B: Multigate/Multisignal Processing Enzyme Logic System Producing pH as The Output Signal

Consider the biosensing system having the truth table given in Table III. The truth table considers the digitized values of the variables under consideration. This system contains of three enzymesalcohol dehydrogenase, glucose dehydrogenase, and glucose oxidase. This was designed to process four different chemical inputs signals (NADH, acetaldehyde, glucose and oxygen) as shown in Fig. 9. This is discussed by W. Joseph in [2].

These systems are implemented as follows:

1) From the truth tables, the minterms expressions of system A and B are

$$F_A = \sum(1, 3, 5, 6, 9, 10, 13, 14) \tag{16}$$

$$F_B = \sum(7, 12, 13, 14, 15) \tag{17}$$

Figure 9. Multigate/multisignal processing enzyme logic system producing in Situ pH changes as the output signal [2].

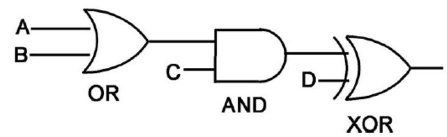

Figure 10. The equivalent logic circuitry for the concatenated four-enzyme system [1].

The equivalent logic circuitries for system A and B are shown in Fig. 10 and Fig. 11.

2) Converting the Boolean function in (16) to the XOR-AND Boolean function form using minimization chart is shown in Table IV, where the inputs are:

- $A - acetylcholine$
- $B - butyrycholine$
- $C - oxygen$
- $D - glucose$

and the output

- $F_A - NADH$

The second Boolean function of system B in (17) is converted to the XOR-AND Boolean function form using minimization chart as shown in Table V, where the inputs are:

- $C - glucose$
- $D - oxygen$
- $E - acetaldehyde$
- $F_A - NADH$

and the output is

- $F_B - pH$

From Table IV and Table V, the equivalent XOR-AND functions are given as:

$$F_A = D \oplus AC \oplus BC \oplus ABC \tag{18}$$

$$F_B = CD \oplus DEF_A \oplus CDEF_A \tag{19}$$

3) The simplified XOR-AND functions are:

$$F_A = D \oplus AC \oplus \overline{A}BC \tag{20}$$

$$F_A = D \oplus BC \oplus A\overline{B}C \tag{21}$$

$$F_B = CD \oplus \overline{C}DEF_A \tag{22}$$

Table IV
XOR-AND MINIMIZATION CHART FOR SYSTEM A

Minterms $ABCD$	**1**	A	B	C	D	AB	AC	AD	BC	BD	CD	ABC	ABD	ACD	BCD	$CDEF_A$
0001					1			1		1	1		1	1	1	1
0011											1			1	1	1
0101										1			1		1	1
0110									1			1			1	1
1001								1					1	1		1
1010							1					1		1		1
1101													1			1
1110												1				1
(✓) or (x)	x	x	x	x	✓	x	✓	x	✓	x	x	✓	x	x	x	x

Table V
XOR-AND MINIMIZATION CHART FOR SYSTEM B

Minterms $CDEF_A$	**1**	C	D	E	F_A	CD	CE	CF_A	DE	DF_A	EF_A	CDE	CDF_A	CEF_A	DEF_A	$CDEF_A$
0001					1			1		1	1		1	1	1	1
0011											1			1	1	1
0101										1			1		1	1
0110									1			1			1	1
1001								1					1	1		1
1010							1					1		1		1
1101													1			1
1110												1				1
(✓) or (x)	x	x	x	x	✓	x	✓	x	✓	x	x	✓	x	x	x	x

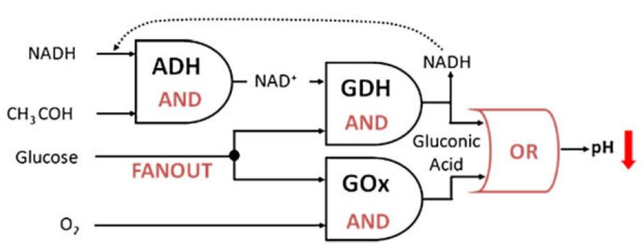

Figure 11. The equivalent logic circuitry for the biocatalytic cascade [2].

4) Convert (20), (21), and (22) to majority expressions as follows:

$$F_A = M(\overline{M(D, M(A, C, 0), M(M(\overline{A}, B, 0), C, 0))}, M(\overline{D}, M(A, C, 0), M(M(\overline{A}, B, 0), C, 0)), D) \quad (23)$$

$$F_A = M(\overline{M(D, M(B, C, 0), M(M(A, \overline{B}, 0), C, 0))}, M(\overline{D}, M(B, C, 0), M(M(A, \overline{B}, 0), C, 0)), D) \quad (24)$$

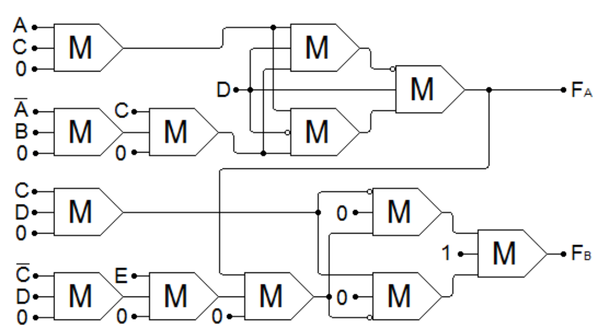

Figure 12. Majority gate implementation of F_A and F_B.

$$F_B = M(M(\overline{M(C, D, 0)}, M(M(M(\overline{C}, D, 0), E, 0), F_A, 0), 0), M(M(C, D, 0), \overline{M(M(M(\overline{C}, D, 0), E, 0), F_a, 0)}, 0), 1) \quad (25)$$

5) The above functions have no further reduction of inverters number.

6) By following the step 6 explained in section III, it is clear that from (23) and (24) there is no advantage of selecting one equation over the other. So we can choose (23) and (25). These functions can be implemented in QCA. The majority diagram of these functions is shown in Fig. 12.

V. Conclusion

The paper suggests the realization of multi-input, multi-output biosensor systems in the form of nano digital circuits. The suggested technique converts the requirements of multi-input multi-output biosensors as truth tables. The Boolean functions correspond to these truth tables are converted into majority gates expressions. These majority functions can be implemented in a digital nano circuit using QCA technology. The approach suggested here will lead to the multi-input multi-output biosensors functions into nano digital circuits. This will help in the simulation desgin and implementation of biosensors with nano digital circuits.

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