Critical Study on Quantum-Dot Cellular Automata (Qca)

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Abstract:
As a new paradigm in electronics for processing and transmitting data, cellular automata based on quantum dots is a fascinating development. The world has taken notice of this groundbreaking microscopic technology. Since the exact same units that are used to produce logic gates may also be utilized to generate cables conveying term logistics, QCA is preferable to other nanoscale digital design concept. In contrast to the limitations of current CMOS technology, the QCA enables operation at frequencies in the THz range and device integration densities roughly 900 times higher. According to the Semiconductor Industries Association's International Roadmap for Semiconductors, this is one of the nanotechnologies of the future (ITRS). As opposed to current flow, QCA cells communicate with one another via Coulombic interaction to perform logical operations and transfer data. The QCA layout takes advantage of emerging technologies like mobile ram and processor via wires. The concept of "storage on the fly" is a subset of "having to process," a broader framework. Information can be manipulated during signal transmission and reception thanks to the processing-by-wire (PBW) capability of QCA. Both the configuration of the cells in an MV and the so-called inverter chain exhibit PBW capabilities. This paper reflects overview of the investigation of Quantum-Dot Cellular Automata (QCA).

Keywords: Technologies, Polarization, Material System, Electron.

Introduction:

Nanocrystals, structures made of semiconducting like InAs/GaAs, are a frequent component of many electronic devices. These formations can be viewed as three-dimensional versions of photonic crystals. This means that energy quantization effects can be observed at distances hundreds of times greater than the lattice constant of the material system.

As a well, a quantum dot is easy to imagine. The energy needed for an electron to break free from a trapped state inside a dot is greater than what the electron itself can provide. The further energy that's required for an electron to leave a tiny dot, the more we can take use of particle physics. The next figure (1) from Konard walus et al. shows one such quantum dot (2004).

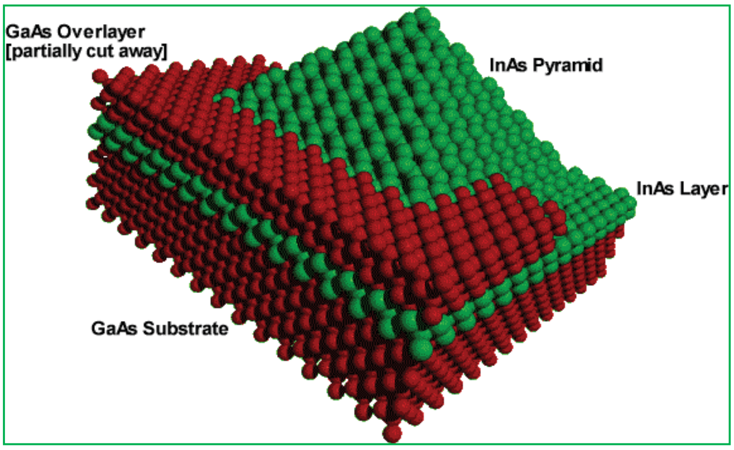


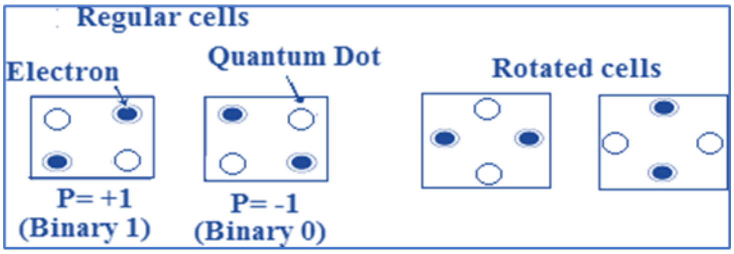
Figure 1: Example of An InAs/GaAs Quantum Dot Pyramid

QCA CELL:

A QCA cell, seen in Figure 2 as a square made up of four quantum dots, is the basic building block of a QCA circuit. It has been reported by Zhang et al. (2004) that the cell has two extra electrons that, with the help of a clocking mechanism, can tunnel between the various quantum dots. Because of their electrostatic repulsion, these electrons prefer to sit in the antipodal positions. The columbic repulsion is what allows one cell to communicate with its neighbour. As can be seen in Figure 2, the two electrons in the QCA cell can be arranged in two equivalent configurations, both of which are energetically minimum. P= +1 and P= -1 represent two distinct configurations of cells, respectively. Differentiation of cells into distinct layers. In the current composition of the QCA cell, the values P = +1 and P = -1

encode the binary code "1" and "0," respectively. In addition, there are rotating cells that each perform a unique purpose. Hence, the normal cell is unaffected by the usage of rotating cells for coplanar wire transfers.

Figure 2: The QCA Cell With Its Two Potential Polarisations



The cells of a QCA are laid out in a methodical fashion so that the planned gate and link architectures can be realised. Usually, QCA layouts are assessed with a concentration on the granularity of cell-to-cell communication.

The outlined boundaries around the cell serve solely as a means of differentiation between individual cells and do not represent any kind of real-world structure. Since electrons are fundamental constituents of quantum mechanics, they can tunnel through the spaces between the cellular dots. Electrons in neighbouring cells will communicate with one another. Hence, the polarisation of an individual cell is directly influenced by the polarisation of its surrounding cells. Figure 3 depicts a non-linear sensor dynamic model, showing the nature of this communication.

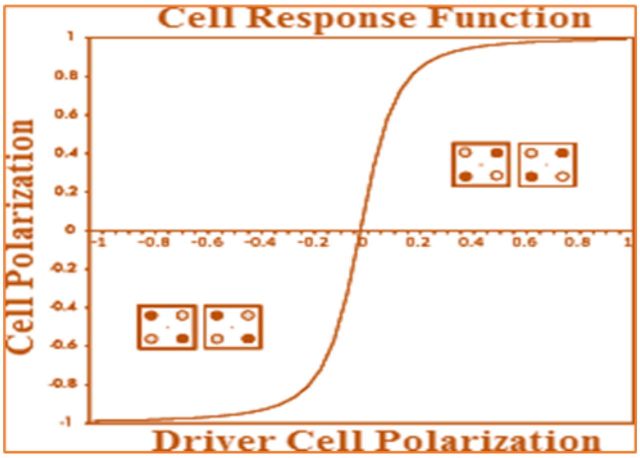


Figure 3: Communications Between Cells Non-Linear Power Parameters Defined

The polarisation of the first cell, which serves as the driver, is adjusted between -1 and 1. Polarization of its neighbour is depicted graphically as a result. Even if the driving cell's own polarisation isn't fully saturated, according to Konard walus (2004), it will nevertheless force a nearly complete polarisation in its next cell. As a result of this communication, neighbouring cells must coordinate their polarisation. By switching polarities in reaction to an input from a controller cell, a network of QCA cells can act as a wire to level of information.

The electrostatic energy of two cells (cell a and cell b, with respective polarizations P_a and P_b), are given by the Equation (1). The total energy of the two cells is calculated by the sum of the electrostatic energy between each of the four quantum-dots of cell a, (with charge q_i^a and location r_i^a) and each of the four quantum-dots of cell b, (with charge q_j^b and location r_j^a); both i and j range from 1 to 4, as there are 4 quantum-dots in each cell.

$$E^{a,b} - \frac{1}{4\pi\varepsilon}\sum_{i=1}^{4}\sum_{j=1}^{4}\frac{q_i^a q_j^b}{\left|r_i^a - r_j^b\right|} \tag{1}$$

$$E_{kink} = E^{a,b}_{p_2 \neq p_b} - E^{a,b}_{p_u = p_b} \tag{2}$$

QCA LOGIC GADGETS:

All the information we need to know about QCA logic devices has been laid out by Walus et al. (2004). As will be seen below, the QCA logic primitives consist of the QCA wire, QCA inverter, and QCA majority gate.

WIRES FOR QCA PROTECTED:

The wire is a horizontal row of QCA cells, and an electrostatic contact between neighbouring cells allows a binary signal to travel from input to output. The excess electrons, if any, will be situated on the diagonal if the cell has been charged with two. The columbic repulsion forces prevent them from locating in any other configuration. The electrons in the neighboring QCA will be polarized to the same position if one of the electrons in the first cell is on a given horizontal (logic 1).

The wires in Figure 4 and Figure 5 are examples of those built with either standard cells or rotating cells. In a 45˚ wire, the two polarisations of a binary signal alternate as the signal travels.

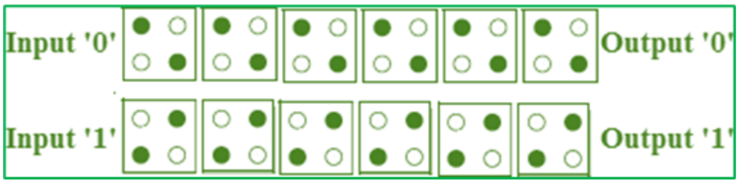


Figure 4: A QCA Wire at a Ninety-Degree Angle

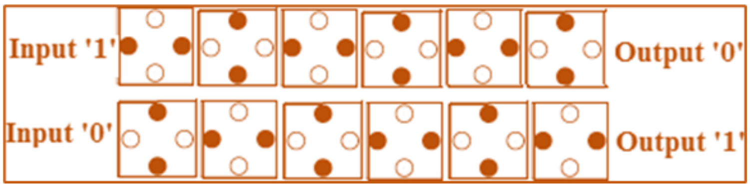


Figure 5: QCA Wire (45˚)

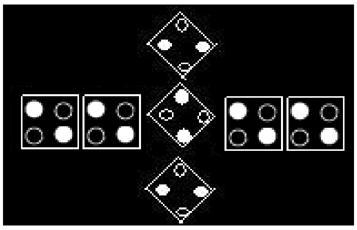


Figure 6: Wire Crossing

QCA wires have the unique ability to intersect in the level without diminishing the quantity sent on each wire, as seen in Figure 6. When the QCA wires are oriented differently, this property holds.

AN INVERTER FOR QCA CONVERTERS:

Due to interlayer interactions among neighboring cells, control devices can be built by merely reordering the cell lines in a sequence. The inverter, in instance, can be produced by arranging the cells so that only their corners touch (see Figure 7). Because quantum dots for various polarisations are misaligned across the cells, the electrostatic interaction is inverted. In other words, the information contained in cells 2-6 is transferred from cell 1. The electron pair in cell 7 talks to its neighbors in cells 5 and 6 to strengthen the columbic link and switch to the opposite polarization.

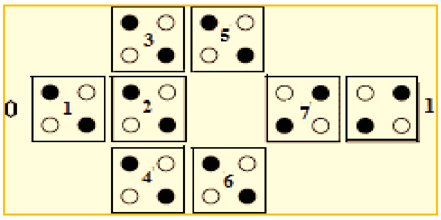


Figure 7: QCA Inverter

A MAJORITY-SUPPORTED QCA GATE:

One of the most basic building blocks of QCA logic is a three-input majority gate. It is composed of an A, B, and C input cell, a logic cell in the center, and an output cell. A logic operation with three inputs is carried out by the QCA majority gate. As a logical building block, the majority gate's purpose is

$$M(A,B,C) = AB + BC + CA \quad (3)$$

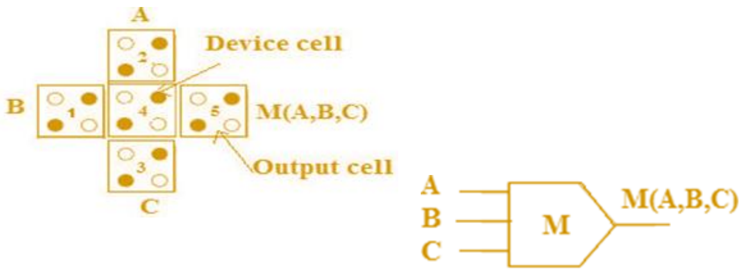


Figure 8: Design and Symbol for the QCA Majority Gate

Figure 8 depicts the schematic for a majority QCA gate. The core cell of the device, which makes up the majority of the device, will always adopt the polarisation of its neighbours because of its natural tendency to gravitate to a ground state. Given that the majority polarisation corresponds to the lowest energy state, it is natural for the device cell to move in that direction. The QCA majority gate can be used to create an AND gate or an OR gate by specifying the polarity of one input as logic "1" or logic "0," respectively.

$$M(A,B,0) = AB$$
(4)

$$\mathrm{M(A,B,1) = A + B}$$
(5)

NAND-NOR-INVERTER (NNI):

Investigations of NNI gate have been conducted by Pijush Kanti Bhattacharjee (2010). One such universal gate is the NNI gate. It may be used to implement logical functions and has a lower overhead for initialising variables when implementing the fundamental logic gates. When compared to other gates like the multiple-value (MV), exclusive-or (AOI), and inverter (NOT), the NNI gate requires very little real estate.

By setting one input to a constant value of 0 and the other to a constant value of 1, the majority gate can be used to implement the more familiar AND and OR gates. The MG lacks the ability to comprehend the logical NOT operation. MG, NOT is the full complement of available capability. So as to realise the logical NOT, designers need to adopt a different QCA cell configuration. Figure 9 depicts the Nand-Nor-Inverter gate, which is the consequence of implementing MG with the NOT function.

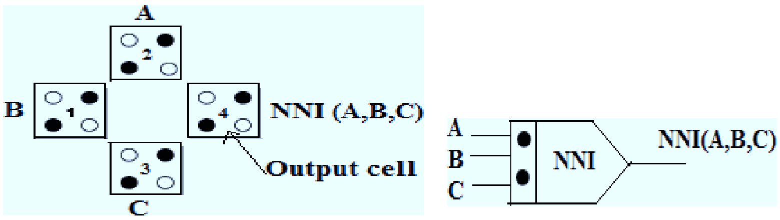


Figure 9: Symbol with QCA NNI Gate

Below is the NNI gate's truth table. If the other inputs are held constant, the NNI gate's output is dependent on input B. Only if both inputs are similar does the result match the inputs. Gates generate logic functions as,

$$\mathrm{NNI}(A,B,C) = M(A',B,C') = A'B + BC' + C'A' \tag{6}$$

Table 2: A NNI Gate Truth Table

A	B	C	NNI (A, B, C)
0	0	0	1
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	0

AND-OR-Inverter (AOI):

In 2005, Mariam Momenzadeh et al. suggested a comprehensive QCA gate. The gate has a maximum of seven cells, one input cell, one device cell, and two output cells. The gate is built from the basic 5-cell MV by attaching two additional inputs (cells A and C), which flip the center cell due to their vertical position. It is a global QCA gate that includes AND, OR, and INV operations, and it has better synthesis applicability. The truth table for the AOI gate reads as follows:

$$\begin{aligned} F &= DE + (D+E)(A'C' + A'B + BC'), \\ &= \mathrm{Maj}\left(D, E, \mathrm{Maj}\,(A', B, C')\right). \end{aligned} \tag{7}$$

In this case, Maj is the majority function for three inputs.

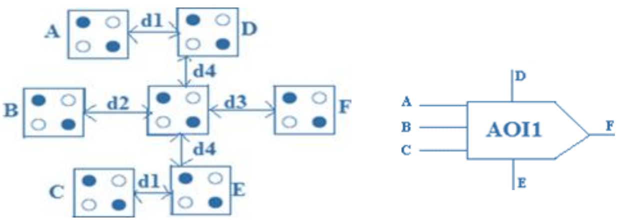


Figure 10: Outline of AOI Gates and Symbol

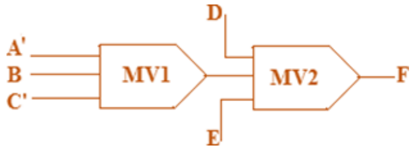


Figure 11: Relative Velocity (MV) AOI Gate

The AOI gate can be conceptualized as the formal amalgamation of two plurality electors (MV) with two complements inputs, as shown in Figure 11. (A and C). The AOI gate design features a pair of MVs nestled within one another.

FANOUT:

When one signal is received, multiple outputs will be generated. Each result is an exact duplicate of its respective input. In contrast to a majority gate, the FANOUT always lets the minority through. An example of a typical electronic circuit with a FANOUT is shown in Figure 12.

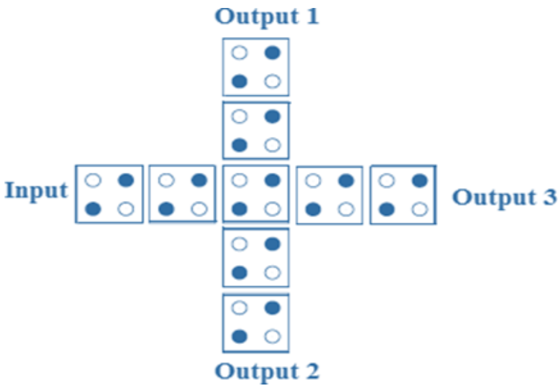


Figure 12: An Example of a QCA Fanout

STRUCTURE WITH A CROSSOVER:

There are two possible transitions presented by Walus et al. (2004). Coplanar crossovers and multilayer crossovers are both possible.

Placing a binary wire at 90˚ and an inverter chain at 45˚ allows you to cross two wires in a single plane. Due to the lack of a switching impact between the cables of opposite alignment, the crossing of the two frequencies remains unimpeded. Coplanar crossings are instances where two planes meet and then diverge.

Only one layer is used in Coplanar crossings, but two different types of cells are needed (regular and rotated). To avoid interference between the regular and rotated cells, coplanar wire crossings can be implemented using rotated cells. Because of this property, the coplanar crossover can send signals along either of the two cell wires. As can be seen in Figure 13, one wire is made up of normally oriented cells, while the other uses cells that have been rotated. When the intersection of two circuits is parallel, rotating units are utilized. You can acquire the genuine or the reverse of the input by choosing the link point from among the cells. The data in the horizontal wire would be able to make it across the chasm if the effect of the vertical wire, which is made up of the rotated cells, could be disregarded.

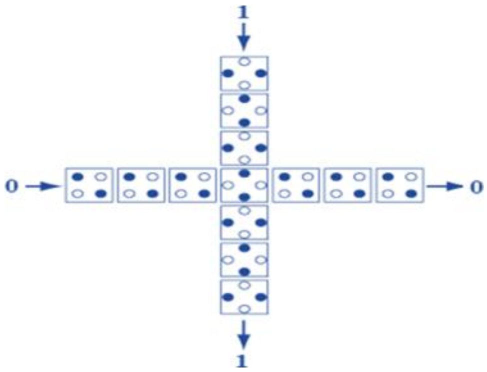


Figure 13 Coplanar Crossover

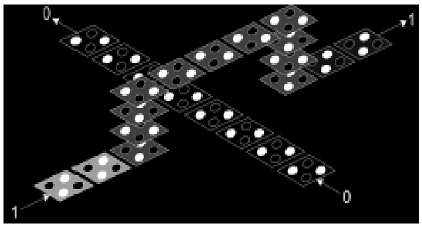


Figure 14 Multilayer Crossover

The horizontal cell spacing, E_{kink}, can be adjusted to achieve a perfect vertical match. Whereas in traditional CMOS microchips, aluminum levels are just utilized to communicate incompatible sections of the device, in CA, these successive layers can be used as dynamic circuit elements and contribute intelligence to the overall system.

QCA CLOCKING:

A reference signal (i.e., a clock) controls timing in VLSI systems, which is necessary for sequential circuits. QCA uses four distinct and periodic clocking phases to achieve the timing required by both combinational and sequential circuits. Information flow can be regulated, and real power can be gained, with clocking in QCA. The clock recovers signal energy that was dissipated into the surrounding environment.

Clock signals in QCA are produced by applying an electric field to the cells in order to either increase or decrease the tunnelling barrier between the dots in a QCA cell. It's possible for cells to switch between polarised and unpolarized states depending on the strength of the barrier between them.

Heumpil Cho et al. have provided an explanation for the clocking of QCA circuits (2007). A strategy distinct from CMOS is needed. The clock is the only source of electricity for the cells. As can be seen in Figure 15, there are a total of four clocking zones available for use when pumping data down a circuit. Each successive clocking signal is out of phase by 90 degrees with the previous one.

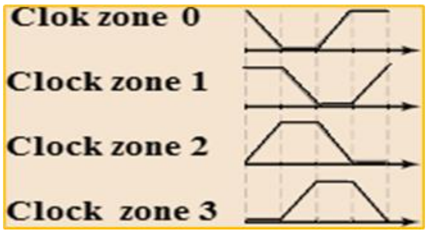


Figure 15: Clocking Zones for the QCA

It is possible to combine cells together into zones so that the field that influences each cell in the zone will be the same for all of the cells in the zone. A zone will go through these four phases as it cycles. Kyosun Kim et al. (2007) have provided an explanation of the four stages. Tunneling barriers in a given zone are increased to their maximum achievable height during the Switch phase. The cell's internal electrons may become vulnerable to the columbic charges of neighboring zones during this action. A high tunnelling barrier means that zones in the Hold phase will not transition to a new phase, but they will still have an effect on the zones in close proximity to them. The tunnelling barrier is lowered during the Release and Relax stages, and as a result, the zone will have less of an effect on other zones.

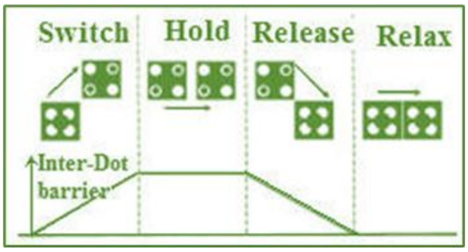


Figure 16: The Clock's Four Different Phases

Clock signals function as an "information pump," cycling across the circuit by causing cells linked to distinct clock phases to latch and unlatch data in rapid succession. Information traveling along a wire, for instance, will follow the direction of the clocking zones, which in this case, in this case, increases from left to right.

According to Walus et al (2003), various portions of the wire are connected to various clock signals. A wire that is connected to several distinct clock zones is depicted in Figure 17. A D-latch is a conceptual representation that may be used to define any group of cells that is tied to a specific clocking zone. Increasing clocking zones are represented by grayscale hues that get progressively darker.

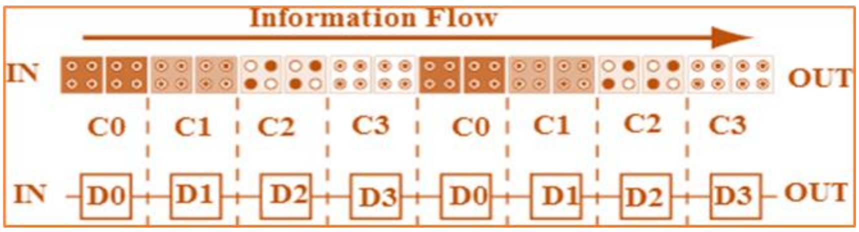


Figure 17: Clocked QCA Wire

The cells are in the latched phase, which is indicated by a low clock level. Cells are unfocused and unpolarized when the circuit is strong. When the data is strong, we are in this phase. According on whether or not the timer is going down or accelerating, the cells will be either attaching or unwinding during the pauses. What limits the shortened version size of the synchronization zone is the minimal feature size of the technology utilized to facilitate clocking.

QCA DESIGNER:

In order to evaluate the operation of QCA circuits, logic and circuit designers working with QCA need access to a simulation and design layout tool that is both quick and accurate. By providing a comprehensive collection of Computer Aided Design (CAD) tools, QCA Designer enables the designer to rapidly layout a QCA design. This is accomplished through the use of CAD. In addition, a number of different simulation engines make fast and precise simulation much easier. This is the first publically available modeling and design program for QCA, and it was developed by the ATIPS Laboratory at the University of Calgary. QCA Designer is capable of simulating the most complex QCA networks for the great majority of commonplace devices.

COMPUTER-BASED MODELING AND SIMULATION SYSTEM:

One of QCA Designer's features is a digital simulation engine that operates like a binary logic simulator. The engine treats each cell as either null, a logical one, or a logical zero. All that is needed to assure the right outputs are generated for a specific input set is to perform a design simulation with these three phases and the proper clock zones knowledge for every unit. By doing so, the logic designer can ascertain whether or not the QCA Designer-laid-out structure conforms to the desired logic function.

For the simulator to work, initial values must be given to the design's inputs. Then, just the cells that are about to swap are taken into account at each time shift. In the release and relax stages, the cell value is zero. In order to process cells that are on the verge of making a transition, values are assigned to them based on the polarisation of cells in their immediate vicinity and the QCA interaction rules.

A SIMULATOR FOR NONLINEAR APPROXIMATIONS:

The cell-to-cell response function is approximated nonlinearly, and this serves as the foundation for the simulation engine. Evidence suggests that the response function from one cell to another is nonlinear. Because of the approximation's assumptions, quantum mechanical correlations between cells are ignored. In an adiabatic transition, the system returns to a state very near to the ground one.

$$P_i = \frac{\frac{E_{i,j}^{k}}{2\gamma}\sum_j P_j}{\sqrt{1+\left(\frac{E_{i,j}^{k}}{2\gamma}\sum_j P_j\right)}} \quad (8)$$

Each cell's polarisation status is calculated by plugging its own polarisation state, P_i, into a formula for the polarisation of its neighbours, P_j. According to Walus, the circuit's frequency is determined y is the tunnelling potential, which is denoted by the symbol and is used to clock the circuit via the kink energy, which is denoted by the symbols $E^k{}_{i,\,j}$ and the energy cost, which is denoted by the symbols *i* and *j*. (2004).

MULTI-STATE MODELING AND SIMULATION SOFTWARE (BISTABLE SIMULATION ENGINE):

An improved simulation engine is needed so that we can run more precise simulations. Walus proposed the two-state model, which operates on the assumption that the cell is a straightforward binary system (2004). The following Hamiltonian (H_i) is proven to be constructible for this two-state system.

$$H_i = \sum_j \begin{bmatrix} -\frac{1}{2}P_j E^k_{i,j} & -\gamma_i \\ -\gamma_i & \frac{1}{2}P_j E^k_{i,j} \end{bmatrix}$$

(9)

Now we refer to the kink potential as Eki, j and it exists among cells I and j. The expense of maintaining the polarity of two cells in opposition is reflected in this kink energy. The degree of cellular polarisation, shown by the symbol P_j, is of paramount importance. The electron tunnelling energy in the cellular membrane is denoted *y*. The effective radius around cell *I* is what will be added up, and this can be determined beforehand. In the moment Wave function, we may determine the cell's mounted configurations in the capabilities provided by this Lagrangian. The Jacobi algorithm is used by QCA Designer to determine the Hamiltonian's eigenvalues and eigenvectors.

$$H_i \Psi_i = E_i \Psi_i$$

(10)

where H_i is the Hamiltonian given in Equation (3.9). Ψi is the state vector of the cell. E_i is the energy associated with the state. The algorithm sorts each of the states, Ψi, according to their respective energy, in ascending order.

This technique is not as effective as the nonlinear approximation, and as a consequence, the amount of time needed to run the simulation is increased. The model that this method is built on is much more accurate, which is one of the advantages of using this method.

It is necessary to define all of the simulation parameters before beginning the actual simulation. The bistable simulation engine was used for each of the simulations that were described in this thesis. All of the parameters make use of the default settings that QCA Designer supplies. The following parameters are utilised in the approximation of a bistable function:

Table 3: Variables of the Simulation Displayed in a Data Frame Style

Variables	**Values**
Cell Size	20 nm
Number Of Samples	12800
Convergence Tolerance	0.001000
Radius of Effect	65nm
Relative Permittivity	12.9
Clock High	9.8e-22J

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Clock Low	3.8e-23J
Clock Amplitude Factor	2
Layer Separation	11.5nm
Maximum Iteration Per Sample	10000

The following is a definition of each of the simulation's Variables:

Able to Accept Convergence

Each cell is converged by the simulation engine during each sample. The cycle should be activated when any layout cell's (old polarization - fresh polarization) is greater than convergence limitation for the experiment to end.

Efficacy Radius

Because cell connections diminish exponentially with the fifth value of cell length, you are not required to consider of every cell as an influence on each and every unit in the system. To discover its neighbours, each cell will first look thus far. This radius also includes your next-door neighbours.

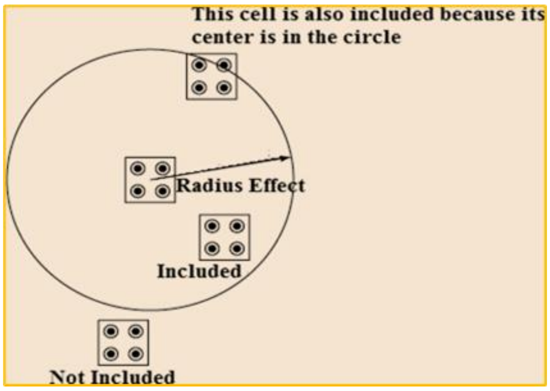


Figure 18: Cell Radius Impact

Intensity of Permitting Relationship

For simulation purposes, knowing the relative permittivity of the material is crucial. The default value for GaAs/AlGaAs is close to 12.9. The kink energy calculation necessitates this information.

Timekeeping Indicator

As can be seen here, QCA Designer's clock signal is derived as a hard-saturating cosine. Specifically, the tunnelling energy in the Hamiltonian is linked to the clock signal.

Time High and Time Low

Energy saturation points for the clock signal are shown by the low and high values of the clock. When time passes the cell door unlocks. In its depleted state, the cell locks.

Clock Shift

Offsets of any magnitude can be applied by schedule changes.

Adjusting the Amplitude of a Clock

The amplitude of the underlying cosine is reflected in the amplitude of the clock, which is calculated by multiplying (Clock High - Clock Low).

Separation into Layers

This controls the lateral distance between cells in multilayer QCA circuit simulations (nm).

Maximum Number of Repeats in Each Sample

If the model has not stabilized at the end of that number of test cycles, the experiment will forward to the next test sample.

QCA DESIGNER WINDOW:

The QCA layout editor and simulator is called QCA Designer. Figure 3.19 displays QCA Designer's primary layout design window.

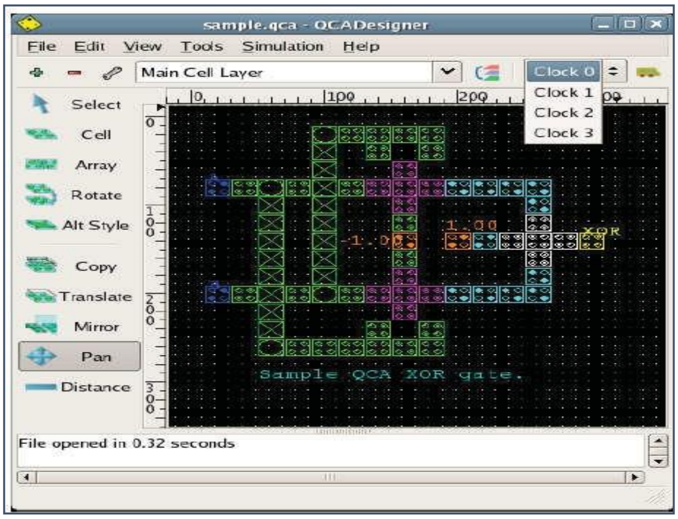


Figure 19: Designing with The QCA Designer's Layout Window

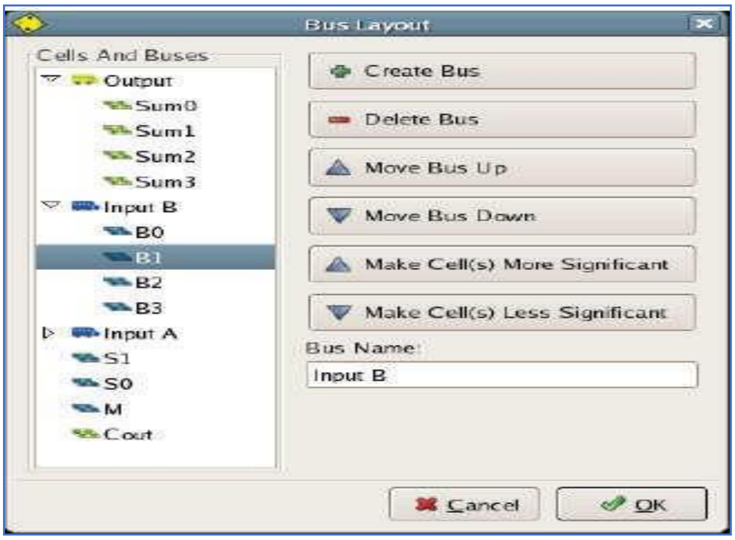
The physical facilities for editing the layout consist of:

- Generating a unique or many QCA cells with a typical distance (20 nm) comparable to the normal cell size (18 nm) plus the standard inter cell separation (20 nm) is an available (2 nm).
- QCA cell-specific clock signal setting is necessary for reliably operating synchronous circuits.
- Designing a multi-layer QCA layout with the necessary signal crossings.
- To achieve the necessary in-plane signal crossover, QCA cells must be drawn rotated by 90 degrees.
- Using the pattern depicted in Figure 3.20, we may visualize special cells (on via and crossover layers). The design as well as simulation results for cell in via and crossing architectures will seem unique, but they will function in the same way. In a standard diagram, a cell is represented by a square with four smaller circles inside; the orientation of the circle's changes depending on the cell's movement. Cells that function as vertical via interconnections between layers are depicted as circles within squares, while cells in crossover layers are depicted as squares with crosses within squares.

Figure 20: QCA Cell Style Norms Visually Identify Main Cell Layer Cells from Via and Crossover Cells.

- The purpose of using buses to organize I/O signals is to facilitate the naming of indications, the definition of simulation data points, and the analysis of simulation outcomes (see Figure 21).

Figure 21: QCA Designer's Bus-Based Grouping of Design Signals for the QCA



Designers of increasingly intricate layouts may find it helpful to organise inputs and outputs into buses for the sake of clarity and organisation. Buses are nothing more than labelled groups of inputs or outputs. The bus layout dialogue allows the designer to organise the design's inputs and outputs into buses. Input vectors can be chosen from a predefined list or generated dynamically during the simulation (Figure 22).

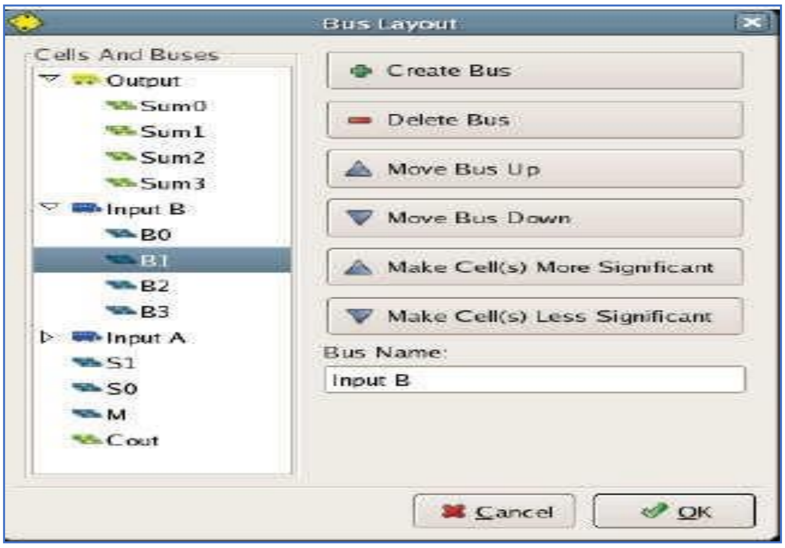


Figure 22: Inputs Pane for QCA Designer Simulations

The Coherence Vector Simulation Engine is one of two built-in simulation engines in QCA Designer; it is slower than the Bistable Simulation Engine but produces more reliable results. As can be seen in Figure 23, the waveform representation of the simulated data is used to display the results of the simulation.

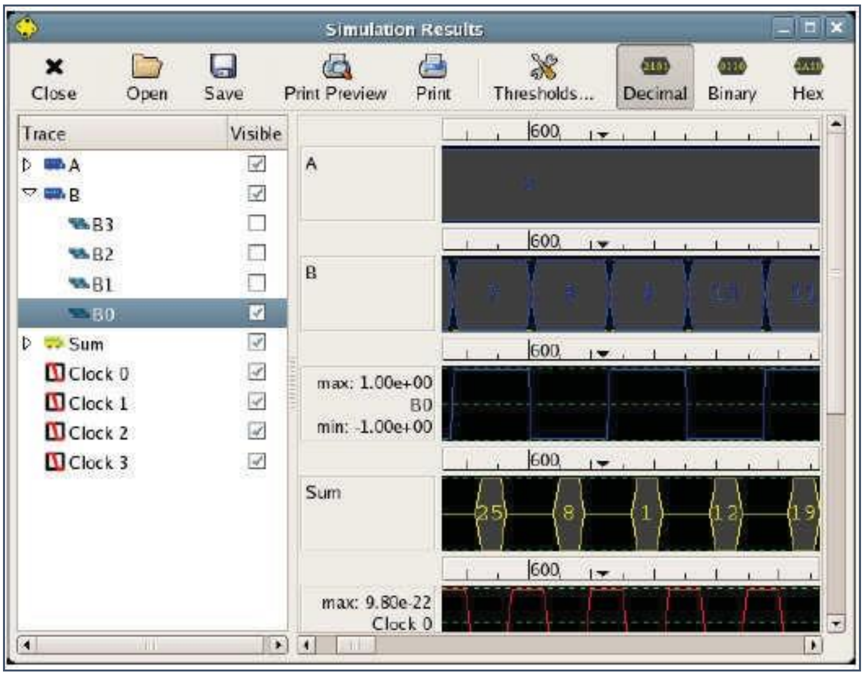


Figure 23: Display for QCA Designer Simulation Outcomes

Conclusion:

Cellular automata based on quantum dots represent an exciting new paradigm in electronics for data processing and transmission. This revolutionary tiny technology has drawn attention from all around the world. QCA is better than other nanoscale digital design concepts because the same units that are used to construct logic gates can also be used to generate cables conveying term logistics. The QCA allows device integration densities around 900 times greater and operates at frequencies in the THz range, which is not possible with existing CMOS technology. This is one of the nanotechnologies of the future, according to the Semiconductor Industries Association's International Roadmap for Semiconductors (ITRS). QCA cells use Coulombic interaction rather than current flow to exchange data and carry out logical operations with one another. Utilizing wires, the QCA configuration makes use of new technology such as mobile RAM and processors. Within the larger context of "having to process," the idea of "storage on the fly" is a subset. The processing-by-wire (PBW) function of QCA allows for the manipulation of information during signal transmission and reception. The so-called inverter chain and the arrangement of the cells in an MV both demonstrate PBW capabilities. Semiconducting structures such as InAs/GaAs are frequently seen in various electronic devices as nanocrystals. These forms can be thought of as photonic crystals in three dimensions. This indicates that at distances hundreds of times longer than the material system's lattice constant and energy quantization effects.

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