Modeling Magnetic Quantum-dot Cellular Automata by HDL

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Abstract— **Quantum-dot Cellular Automata (QCA) is one of the emerging technologies that have been advocated to overcome the physical limitations of CMOS in the nano ranges. For QCA to be a viable alternative to CMOS in the decades ahead, tools and methodologies at physical and logic levels are urgently needed in support of all design phases. This paper presents an HDL based framework and related models to simulate and assess magnetic QCA (MQCA). The tool proposed in this paper extends a currently available tool for electrostatic QCA, thus adding new capabilities related to MQCA. In particular, the proposed tool (referred to as HDLM) is used to design and characterize both the functionally complete gate set and few specific structures that have proposed for the operation of MQCA. Models and functions are proposed for the MQCA cell and the building blocks. The proposed tool is finally used also to design a a novel n-input AND gate in MQCA; its characteristics are simulated and assessed, thus showing the effectiveness of the proposed tool to investigate MQCA.**

I. Introduction

Among the disparate emerging technologies that have been proposed to overcome the limitations of "end-of-the-roadmap" CMOS, Quantum-dot Cellular Automata (QCA) shows promising features to achieve both high computational throughput and low power dissipation. The QCA computational paradigm [1] [2] introduces highly pipelined architectures with extremely high speed (in the order of THz), while radically departing from the switch-based operation of CMOS. QCA manufacturability has been demonstrated both for metal-dot QCA [3] and molecular scale allowing room temperature operation. Recently, magnetic QCA (MQCA) based on Co nanomagnets has been analyzed [4], [5], [6], [7], [8]. The use of nanomagnets is very attractive, because MQCA can operate at room temperature, and has been shown to be easier to implement than the molecular implementation of an electrostatic QCA. Moreover, MQCA could also be integrated with other emerging technologies such as magnetic RAM for memory design. The clocking mechanism of MQCA is similar to electrostatic QCA; the use of abrupt switching in electrostatic QCA is unreliable [2] due to the possible generation of metastable states, so a quasi-adiabatic clocking scheme has been proposed to overcome the kink probability in QCA circuits [2]. For MQCA a three phases snake clock has also been proposed [9]. Finally, a technology-based solution has been proposed in [7] to stabilize the magnetization state of nanomagnets by adding biaxial anisotropy. This arrangement modifies the framework in which MQCA circuits can be designed, thus requiring further investigation into mechanisms (also at circuit level) to leverage the newly introduced functionalities.

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In addition to advances in cell manufacturing and fabrication, research at the higher circuit and system-levels has been pursued for QCA. Various QCA architectural solutions have been proposed, such as memories [10], [11] and microprocessors[12]. As for tools, QCADesigner [13] has been widely utilized by manual placing the electrostatic QCA cells on a two-dimensional layout and simulating their behavior. QCADesigner incurs in high computational penalties and is not suitable to design or simulate logic circuits of even medium complexity; therefore new environments suitable for CAD implementation must be devised for circuit-level QCA design. For these reasons both a SPICE level model [14] and a simple VHDL level model [15] have been proposed for similar nanomagnet based devices. [16] has introduced an HDL-based design tool (HDLQ) that allows to overcome the limitations of simulators like QCADesigner with respect to a circuit-level evaluation for electrostatic QCA. In this paper an HDL framework (and associated tool) based on [7] is proposed; its models are compatible with the HDLQ framework and allow to simulate the behavior of MQCA. It should be noticed that the modelization proposed in this work, based on [7] is valid until the underlying physical assumptions will be proven viable for the actual manufacturing of these devices. This framework utilizes different and novel models by which MQCA cells can be simulated and a circuit-level assessment can be pursued at reduced computational complexity compared with other (physically-based) simulators, such as OOMMF. HDL models for the MQCA cell as well as building blocks are proposed to ensure magnetization, clocking and signal propagation; functions and testbenches are also presented for the proposed CAD tool (denoted by HDLM). Moreover, the lazy AND and the dictator gates are modeled to ensure correct MQCA operation. The effectiveness of the proposed tool is further evidenced by the novel design presented in this paper for a n-input AND gate.

This paper is organized as follows: Section 2 provides an overview of magnetic QCA; in Section 3, the basic principles of the proposed framework and tool (denoted as HDLM) are described. In Section 4, the HDL model of a MQCA cell is introduced in detail. Section 5 presents the functional model used in the HDL simulation for the MQCA building blocks. Some of these blocks (wire, majority voter) are similar to the electrostatic implementation, while others

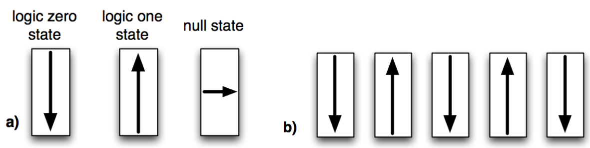

Fig. 1. **a)** Bistable feature of a MQCA cell **b)** MQCA binary wire

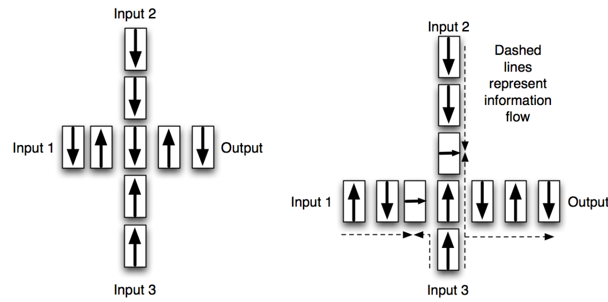

Fig. 2. **a)** MQCA majority gate **b)** MQCA majority gate with uneven legs

(the lazy AND and the dictator gate) are specific to an MQCA implementation. Section 6 introduces a novel n-input AND gate that exploits the characteristics and functionality of MQCA; this also shows the effectiveness of the proposed tool to investigate new gates while establishing at functional level its operational features. Conclusion is provided in the last section.

II. Review of Magnetic QCA

Quantum-dot Cellular Automata (QCA) operates on a computational paradigm based on the interactions of a set of bistable cells. The two stable states of a cell leads to a straightforward correspondence with the logic (boolean) values of zero and one. Figure 1.a) shows the two stable states of a magnetic QCA (MQCA) cell (also referred to as nanomagnet). A MQCA cell can also assume a metastable null state: while in the logic (zero and one) states, the magnetization is aligned to the vertical axis (which has a stable energy level), the magnetic field in the metastable state is aligned horizontally and does not interact with neighboring cells (therefore, corresponding to a functionally null state).

Logic operation and signal propagation are performed in two steps in MQCA [7]. In the first step, all nanomagnets are aligned along their magnetically hard (lithographically short) axes by applying a global external magnetic field. In the second step, the external field is removed. If an input is imposed, then the dipole field alignment between neighbors pushes them out of their metastable state and induces an antiparallel magnetization state. Therefore, the behavior of a horizontal line of MQCA cells, can be seen as a chain of inverters propagating the signal by successive operation (inversion) of the input value. Figure 1.b) shows the state of a chain of nanomagnets (binary wire) in its stable state.

Similarly to the kink occurrence in electrostatic QCA, the cascade propagation in a horizontal wire may fail when the number of MQCA cells is increased [5]. To overcome this limitation, one of the most commonly used solutions requires the partition of the MQCA circuit into small zones driven by a suitable clock circuitry [8]. [7] has proposed a solution to this problem; it introduces a hard axis stability by adding a biaxial anisotropy term to the net magnetization energy of each nanomagnet. Simulation performed using the OOMMF simulator [17] has shown that this technique allows to correctly propagate a signal even if up to 30 nanomagnets are used. In the simulations, the input is transferred through 30 nanomagnets in 3 ns, corresponding to a propagation time through a single magnetic QCA cell of approximately 100 ps. While a horizontal wire of nanomagnets tends to align in an antiparallel configuration, the vertical wire tends to align in parallel. Therefore, the horizontal wires invert the signal, while the vertical wires perform no inversion.

The basic logic gate for MQCA is still the majority voter and works in a similar fashion as for electrostatic QCA, i.e. the output cell assumes the configuration of the majority of the inputs (Figure 2.a)). Together with the inversion provided by the antiparallel magnetization, this forms a functionally complete gate set.

[7] has addressed the behavior of majority gates with legs of unequal length. The input that arrives earlier at the majority gate of Figure 2.b) imposes the magnetization on the center cell (crossing) of the majority gate. This may generate the wrong output and propagate an erroneous result also toward the other legs of the crossing. Figure 2.b) shows the propagation of the information from the input nearest to the crossing towards the other inputs and to the output. A metastable (null) state is still present in those nanomagnets that have an equal distance from the inputs. To address the issues related to this race condition in the signals of the majority gate, [7] has proposed two functional blocks:

1) *Lazy AND:* this gate acts as an AND gate when the output is supposed to be a logic zero. When the gate should output a logic 1, it generates no output, i.e. the value of its output cell is in the metastable (null) state.
2) *Dictator (majority) gate:* this is a modified majority gate, in which the two vertical inputs (i.e. labeled 1 and 3) have a weaker coupling to the center nanomagnet (the nanomagnets are separated by a longer distance). It can only change the output provided all inputs agree; otherwise, the output toggles only once the value coming from the input labeled 2 reaches the center nanomagnet.

A	B	output
0	0	0
0	1	0
1	0	0
1	1	z

TABLE I
Truth table of lazy AND gate

The lazy AND gate is physically realized by adding some extra nanomagnets (orthogonally placed with respect to the original direction) to block the magnetization corresponding

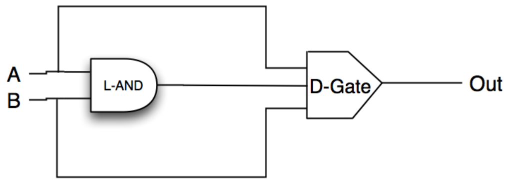

Fig. 3. AND gate realized with dictator and lazy gates

to the logic one value. The truth table of the lazy AND is given in Table I. If one of the inputs is zero, then the output is zero; otherwise the output remains in the metastable state (denoted as z, in analogy with the high impedance state of CMOS technology). Note that by this truth table, the arrival order of the inputs is irrelevant. For example, assume that the A input signal arrives first: if A is zero, then the output is zero regardless of the value of B. However, if A is one, the gate will wait for the arrival of the input signal on B to decide whether the output must toggle to zero, or remain in the metastable state.

For the dictator majority gate, the order in which the inputs arrive is important. Assume that the two vertical inputs and the single horizontal input, are available; let the horizontal input be defined as *dominant,* i.e. the distance of the horizontal nanomagnet from the center nanomagnet is smaller than the distance for the vertical nanomagnets. However, the magnetization of only one vertical input is not sufficient to toggle the majority gate. The vertical inputs can impose the value to the majority gate only if they arrive first and are identical. If only one vertical input reaches the center nanomagnet, or the vertical inputs are in disagreement (different values), then the gate remains in the z state. The horizontal input is capable of imposing the magnetization to the gate if the gate is still in the metastable state when the horizontal signal arrives. Using the lazy and the dictator gates, new and different logic gates can be designed; these gates are insensitive to the propagation delay of the signals. Figure 3 shows an AND gate that is insensitive to the order of arrival at its inputs.

III. HDL Framework

The complexity of low level physical simulations induces to introduce more usable simulation models such as already proposed at SPICE-like level in [14] or at VHDL level in [15], in which a VHDL model for domain-wall based (not single-domain devices) has been proposed. This paper proposes a novel HDL-based framework (with associated tool) by which MQCA can be assessed by simulation. The tool of the proposed HDL framework is referred to as HDLM due to its compatibility of a previous tool proposed by the same authors and applicable to electrostatic QCA design [16]. Modeling in HDLM relies on two components.

- A model for the MQCA cell as related to the unique features of this technology (such as magnetization) and its interaction with immediate neighboring cells.
- The models for some basic building block for designing MQCA circuits. These building blocks include the majority voter as well as few gates that are specifically used to alleviate some of the problems incurred in signal propagation using MQCA.

HDLM is compatible with HDLQ [16] because it uses similar principles and data structures; this permits to utilize primitives as models for characterizing the cell and circuits, while changing the mode of operation from Coulombic interactions (for electrostatic QCA) to magnetization (for MQCA).

Similarly to [16] the model is realized by using a Verilog HDL description of MQCA. The comparative advantages of such an approach are as follows.

1) OOMMF is not suitable to simulate circuits (even of modest size) due to the complexity of the equations involved for the MQCA cells.
2) The overall design process is highly simplified when an HDL description is used. Moreover, as HDL is widely used in the digital design community, many tools are available and compatible with such languages and description.

Therefore, a Verilog description can be used to model the basic MQCA cell, and the structures described in the previous section, i.e. the lazy AND and the dictator gates. HDL modeling allows to leverage the presence of an event driven simulation, so for example the occurrence of transitions on a neighboring cell induces an event, and the evaluation of the next state in the cells. Consequently, by introducing a delay in updating the output of a cell, a cascade of switching events, as expected in a nanomagnet array can be generated to model MQCA.

IV. HDL Model of a MQCA cell

This section describes the model for the behavior of a magnetic QCA (MQCA) cell as introduced in the previous section. In HDLM, a MQCA cell requires a different characterization from the electrostatic cell of HDLQ. In particular, different functions must be utilized in the model to capture the magnetic properties of MQCA.

A. I/O Interface

For a MQCA cell, we must define an I/O interface, i.e. a model by which cell interactions occur among neighboring cells in the layout. In HDLM, this interface is characterized by the following features.

- Four inputs corresponding to the North, South, East, West (N,S,E,W) directions;
- The inputs corresponding to the application of the external magnetic field that provides the metastable state;
- An output corresponding to the value assumed by the cell itself.

While the N and S directions contribute to the cell magnetization in a parallel manner, the E and the W directions contribute in an antiparallel manner. Directional inputs and the output can assume three values, corresponding to the logic (zero and one) and to the metastable states (i.e. the z value).

Finally, the external magnetization field is considered to act as a clock signal and can assume a zero or one value.

- If the clock signal is one, the output of the cell is z, regardless of the value of the other inputs.
- If the clock value is zero, then the Verilog model evaluates the magnetization of the cell by using a magnetization function based on the values seen at the directional inputs N, S, E, W.

B. Magnetization

To evaluate the magnetization of the cell, a function converting the binary value to a magnetization value is used. The function *bin2mag* is given by

$$bin2mag = \begin{cases} +1 & \text{if } x = 1 \\ 0 & \text{if } x = z \\ -1 & \text{if } x = 0 \end{cases} \quad (1)$$

The function *bin2mag* permits to evaluate the magnetization of a cell by adding the magnetization values of the vertical inputs and subtracting the magnetization values of the horizontal inputs using the following equation

$$output(N,S,E,W) = bin2mag(N) + bin2mag(S) - (bin2mag(E) + bin2mag(W)) \quad (2)$$

The last step of this computation is the inverse conversion from the magnetization to the binary representation that follows from (1). This step is referred to as reverse conversion and the *mag2bin* function is used.

C. Propagation and cell placement

To emulate the propagation delay through the nanomagnets, the output receives the computed value within a specified delay (set to a default value of 100 ps). The use of the magnetization function closely resembles the physics behavior. It has a high level of flexibility because it can be used to provide weights to the inputs (as discussed in a later section when the model of the dictator gate will be described).

Placement and connection between cells are performed as follows: the nanomagnets are placed on a grid layout, such that each magnet can have at most four neighbors, one for each direction. The directional inputs (N,S,E,W) are connected to the output of the corresponding neighbor, if present. If no cell is present in that direction, then the corresponding input is connected to a fixed z value. Finally, all cells are connected to a specific clock signal. The use of a clock signal is utilized to define the so-called clocking zones, similarly to [9].

V. HDL Models of MQCA building blocks

HDL simulation models are presented in this section; MQCA building blocks such as a wire, the majority gate and specific structures that have proposed for MQCA (lazy AND and dominant majority gate), are assessed and evaluated.

```
MQCAcell Q02(nocell, v[1][2], nocell,       in, v[0][2], clock); //input 1
MQCAcell Q12(nocell, v[2][2], nocell,  v[0][2], v[1][2], clock); //wire
MQCAcell Q22(nocell, v[3][2], nocell,  v[1][2], v[2][2], clock); //wire
MQCAcell Q32(nocell, v[4][2], nocell,  v[2][2], v[3][2], clock); //wire
MQCAcell Q42(nocell, v[5][2], nocell,  v[3][2], v[4][2], clock); //wire
MQCAcell Q52(nocell,  nocell, nocell,  v[4][2],     out, clock); //output
```

Fig. 4. Verilog code of a MQCA wire

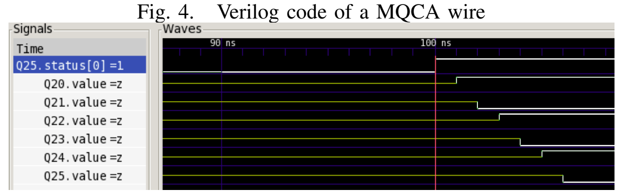

Fig. 5. Waveform of MQCA wire

A. MQCA binary wire

The binary wire is a well known block of the QCA functional paradigm. It is composed by a series of adjacent MQCA cells and allows the propagation of the information through the nanomagnets. Figure 4 shows the Verilog code of an horizontal MQCA wire. The MQCA cells making up the wire have been indexed with x and y coordinates in the two-dimensional grid as layout. The signal connecting the output of a cell to the input of its neighbor is defined as a bi-dimensional wire. The output of the cell (with coordinates (x,y)) is connected to the signal $v[x][y]$, while the west inputs are connected to $v[x-1][y]$ and the east input is connected to the $v[x+1][y]$ signal. The simulation starts by initially imposing an external magnetic field, corresponding to clock='1', therefore forcing the z value to all cells. After the clock is lowered, the signal starts propagating in the west-east direction by the concatenation of events as triggered by the change in state of the neighboring cell located in the west (W) direction. Figure 5 shows its waveform. Each output change occurs with the allowed switching time of a nanomagnet; currently this is set to the defaulted value of 100 ps delay, as reported in [7]. The wire behaves like the cascading effect of a domino chain; after all cells are magnetized, the wire remains in a steady state until a new clock rising event erases the attained state.

B. MQCA majority gate

A further building block that is modeled in HDLM is the majority gate. Figure 6 shows its MQCA layout; its inputs are positioned in the North, South and West directions, while the output is in the East direction. The vertical inputs are non inverting, i.e. only the horizontal input is inverting. In Figure 6 all inputs have the same length and therefore they have the same delay. The waveform in Figure 6 shows the inputs, the values of the MQCA cells carrying the input values to the majority gate and the MQCA cells making up the wire that carries the computed value to the output. The signals arrive to the cell labeled Q22 at the same time, as expected for a correct functionality of the majority gate. Moreover, similarly to the binary wire case, the waveforms show that also for the majority voter a change in the inputs will not affect the computed value after the cells attain their final value.

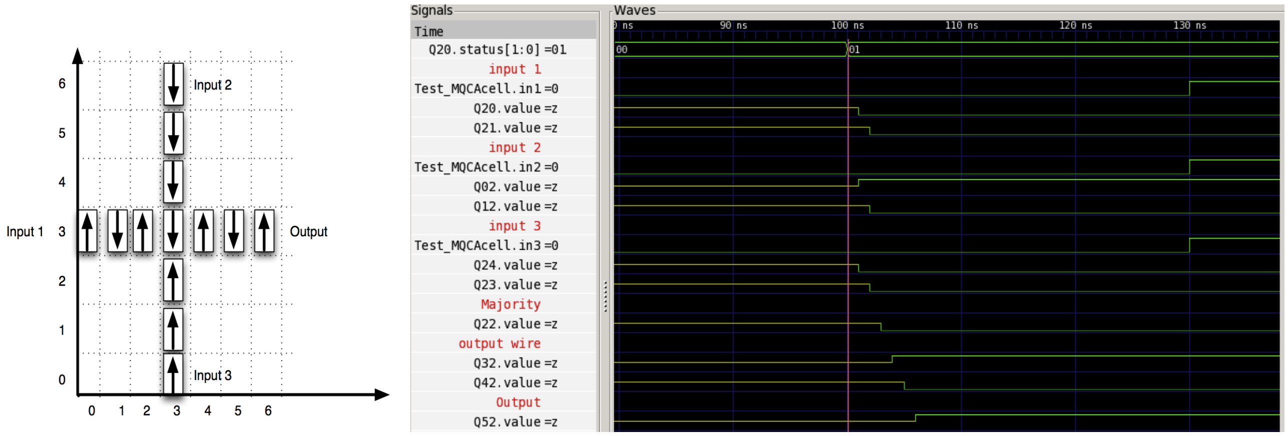

Fig. 6. Layout and Waveform of a MQCA majority gate

C. MQCA specific blocks

The following describes the extension of the functionality of the proposed simulation model in HDLM to MQCA specific blocks (the lazy AND and the dictator gates) as presented in a previous section.

1) Lazy AND Gate: The lazy AND gate can be constructed from the majority gate by employing two modifications. The first modification consists of setting one of the inputs to the logic zero value to achieve an AND function with the remaining two inputs. The other modification is related to the computation of the *mag2bin* function. As per the implementation of the lazy gate, the nanomagnet that computes the AND function can assume only a zero or z value, so the *mag2bin* function must be modified as per the following equation:

$$mag2bin = \begin{cases} 0 & \text{if } M < 0 \\ z & \text{if } M \geq 0 \end{cases} \quad (3)$$

The lazy AND gate can therefore be constructed as a MQCA cell with one of the input whose value is fixed to 0 and the *mag2bin* function modified as in (3).

2) Dictator Gate: The dictator gate can be considered as a modification of the majority gate. This gate is a majority gate that has vertical inputs at a distance further away than expected. Therefore, the interaction between the vertical inputs and the center of the majority gate is weaker. This behavior can be simulated by adding a weight in the magnetization function as given previously in (2). As in accordance with [7], only when the vertical inputs have the same logic value, then it is possible to impose a value to the output of the gate. So, when only one of the inputs is defined, or the two inputs have different values, then the output of the gate is in the z state. The modified magnetization function is given as follows

$$output(N,S,E,W) = 0.5 \cdot bin2mag(N) + 0.5 \cdot bin2mag(S) - (bin2mag(E) + bin2mag(W)) \quad (4)$$

This function produces a value with magnitude greater than 0.5 when either the horizontal input is set, or the two vertical inputs have the same value. The corresponding *mag2bin* function can be expressed as follows:

$$mag2bin = \begin{cases} 0 & \text{if } M < -0.5 \\ z & \text{if } -0.5 \leq M \leq 0.5 \\ 1 & \text{if } M > 0.5 \end{cases} \quad (5)$$

The above described models have been implemented in Verilog and therefore can be used to simulate circuits as well as different gates as presented in the next section.

VI. A NOVEL N-INPUT AND GATE IN MQCA

In this section it is shown that the MQCA specific building blocks introduced in the previous section together with HDLM can be used to design a novel MQCA gate, namely a n-input AND gate. By leveraging the functional characteristics of MQCA with the lazy AND gate, a compact implementation of a n-input AND gate can be designed. This gate consists of two blocks.

- A block made of multiple lazy AND gates;
- A block that resolves the output magnetization when all inputs are 1.

The first block works similarly to a wired AND gate, multiple lazy AND outputs are connected onto a single output wire (Figure 7 for n=7). This makes the layout similar to a wired AND; so when at least one input is 0, then the correspondent lazy AND output will dominate the magnetization on the output wire (because the other outputs will be in the so-called z state). When all inputs are equal to 1, then the wired output remains in the z state; this condition is resolved by the second block referred to as the resolution block. The resolution block has as inputs the multiple lazy AND gate output and an additional input (denoted as "the longest input wire" in Figure 7). It generates as output a 1 if the additional input is 1 and the other input is z, 0 otherwise. This block is therefore made of the longest input wire and the output wire. As for the order of arrival of the inputs, the n-input lazy AND gate has no constraint (being composed of 2-input lazy AND gates) whereas the second block has to be designed such that the signal propagating on the longest input wire must always arrive after the result of the lazy AND wired function. This constraint can be accomplished by using a snake shaped wire such as the one depicted in Fig. 7. All inputs are placed in the W direction, while the output is on

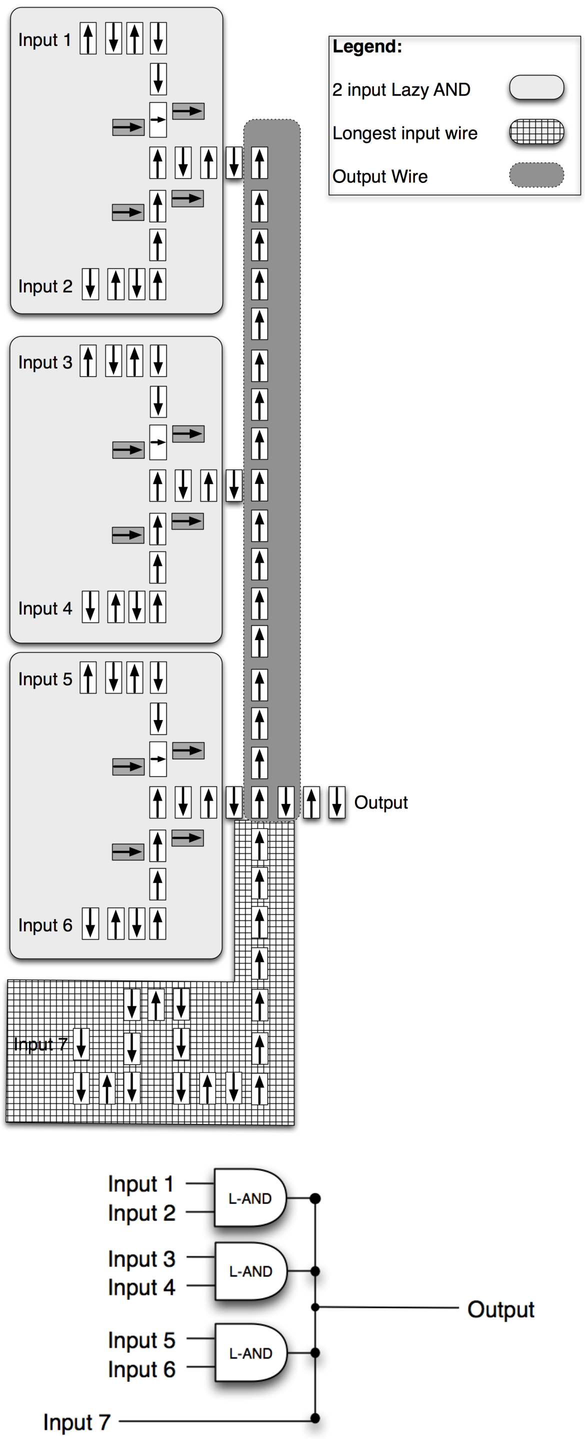

Fig. 7. Layout and schematic of a n-input AND gate

the E direction. The proposed AND gate has been described using the previously presented Verilog models and simulated to verify its correctness. The simulation results prove the functionalities of the proposed n-AND.

VII. Conclusion

This paper has presented a new framework for analyzing magnetic QCA; this framework has been implemented in HDL and a tool (HDLM) has been designed. In HDLM, the Verilog description has been implemented at nanomagnet level to leverage the event driven simulation engine ability of modeling a cascading propagation effect. Different weights are possible in HDLM to model the interaction between neighboring magnets, thus allowing the operation of MQCA specific functionalities (such as the Lazy AND and the dictator gates) to be evaluated. With the proposed tool is possible to model and simulate not only the typical QCA paradigm building blocks but also the specific gates that have been introduced for MQCA. Finally a novel MQCA gate (i.e. an n-input AND) has been introduced in this paper; the operation of this gate has simulated by utilizing HDLM. The proposed n-input AND gate exploits the novel characteristics of MQCA functional paradigm and have been assessed using the proposed tool.

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