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Published

2014

Conference Title

2014 IEEE INTERNATIONAL SYMPOSIUM ON CIRCUITS AND SYSTEMS (ISCAS)

Version

Accepted Manuscript (AM)

DOI

10.1109/ISCAS.2014.6865513

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Conference Paper *in* Proceedings - IEEE International Symposium on Circuits and Systems · June 2014

DOI: 10.1109/ISCAS.2014.6865513

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A Novel Approach to Perform Reversible Addition/Subtraction Operations Using Deoxyribonucleic Acid

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Abstract

Reversible logic transforms logic signal in a way that allows the original input signals to be recovered from the produced outputs, has attracted great attention because of its application in many areas. Traditional silicon computers consume much more power compared to computing systems based on Deoxyribonucleic Acid (DNA). In addition, DNA-based logic gates are stable and reusable. In this paper, we propose a new approach for designing DNA-based reversible adder/subtractor circuit; it's possible to perform addition and subtraction operations using single circuit representation. We first merge the properties of addition and subtraction operations. Then, we demonstrate reversible DNA-based addition and subtraction operations. Our proposed DNA-based reversible addition/subtraction circuit is faster than the conventional one due to parallelism and replication properties of DNA strands. It also requires less space because of compactness of DNA strands. In addition, the DNA-based adder/subtractor circuit needs low power as the formation of DNAs consumes a small amount of energy. Finally, the comparative results show that the proposed DNA-based system requires $m+3.2^n$ *DNA signals, but in existing system, it requires* $m.2^n$*, where m is the size of extra tags and n is the total number of bits. Besides, the run time complexity of proposed system has* $O(1)$ *while the existing system has* $O(mln_2n)$*.*

Keywords- *Reversible Logic, DNA and DNA Bases, DNA Annealing, Reversible Logic Gates, DNA Computing, Addition, Subtraction.*

I. Introduction

In 1994, Adleman has solved the *Hamilton Path Problem* with 7-vertices using DNA [1]. The information inside the DNA are stored as a code made by four chemical bases: *Adenine (A)*, *Guanine (G)*, *Cytosine (C)* and *Thymine (T)*. The bonding between two bases of DNA happens between complementary bases, *A* with *T* and *C* with *G*, form base pair units [2]. There are also some non-natural bases like *Xanthine (X)*, *Pseudouridine (Ψ)* and *N(2)-Dimethylguanosine (D)* are complimentary to *Adenine(A)*. Scientists all over the world are now trying to exploit these unique features of DNA to make future computational system to overcome the present limitations of traditional silicon computers, also looking for the additional uneven features of DNA as well. It has been found that Watson-Crick hydrogen bonding is not the only way of interaction between the nucleobases in DNA. Rather, some other important H-bonding interactions between nucleobases are *Hoogsteen* and *Haschemeyer-Sobell* interactions, aid to generate bonding between the natural bases and some non-natural bases [3]. Among the non-natural modified bases, some are *Inosine (I)*, *Xanthosine (X), Pseudouridine (Ψ), 1-Methylguanosine* (m^1G), *N(2)-Dimethylguanosine (D)*. These modified bases are found to modulate some inherent functions of DNA like structural stability, temperature tolerance etc.

Reversible logic was introduced with a view to minimize the energy loss of a circuit. According to Landauer, in irreversible circuits, every bit of information loss generates *KTln2* Joules of energy, where *K* is the *Boltzmann* constant of $1.38\text{x}10^{-23}$ J/K and *T* is the operating temperature [4]. According to Bennet, zero energy dissipation would be possible only if the network consists of reversible gates [5]. As, reversible logic provides one-to-one mapping between the input and output vectors and ensures that the number of input vector is equal to the number of output vector. So, the mapping between input vector and output vector reduces the information loss.

Followings are the main advantages of using DNA-based computations over the existing silicon-based computations:

- Data density of double strands DNA will be one base per square nanometer and it will be over one million Gbits/square inch, where data density of typical high performance hard drive is about 7 Gbits per square inch [6-9].
- Base pair complementation gives a unique error correction mechanism as like RAID 1 array [10].
- As many copies of the enzyme can work on many DNA molecules simultaneously. It can work in a massively parallel fashion [11].
- DNA is a stable molecule that never suffers from any changes (mutation) unless it faces harsh (very high temperature, corrosive agents etc.) environment [19].
- Logic gates based on DNA can be preserved for a very long time (more than a decade) by maintaining and varying temperature [12], [13].

So, from the above discussion we can understand the DNA-based reversible operations require less space and it has self error-recovery capability. Moreover, it also gets parallelism and faster read-write capability.

The organization of this paper is as follows: Section 2 represents the prior knowledge associated with our proposed methods; Section 3 introduces the relation between 0/1 logic and DNA-based logic. Section 4 presents the concept of merging addition and subtraction operations, also, describes our methodology; besides, Section 5 depicts the comparative analysis. Finally, we conclude this paper with overall significances of our work with future possibilities.

II. Basic Definitions and Properties

In this section, we present the basic definitions and ideas related to reversible logic and DNA computing.

A ***k*×*k* reversible gate** is a *k*-input and *k*-output circuit that produces a unique output pattern for each possible input combination [15]. Let the input and output vector be I_V and O_V, where $I_V = (I_1, I_2, ..., I_k)$, $O_V = (O_1, O_2, ..., O_k)$, $I_V \leftrightarrow O_V$. Fig 2.1 shows a $k \times k$ reversible gate. One bit inverter is a 1×1 reversible gate. Unused outputs of a reversible gate are known as ***garbage outputs***, are only used to maintain the reversibility. When a *Feynman Gate* (FG) is used for *Ex-OR* operation of two inputs, extra output *P* is added, this additional output is known as garbage output [15]. A ***3×3 Toffoli gate*** realizes $P = A$, $Q = B$, and $R = AB \oplus C$, where *A*, *B*, *C* are inputs and *P*, *Q*, *R* are outputs [14]. Similarly, A ***3×3 Fredkin gate*** realizes $P = A$, $Q = A'B \oplus AC$ and $R = A'C \oplus AB$, where *A*, *B* and *C* are inputs and *P*, *Q* and *R* are outputs [15].

DNA is the deoxyribonucleic acid. Two chains of DNA are in a right handed double helix. The strands are joint by hydrogen bonding between the bases of opposite strands, to form the base pairs [2]. ***DNA Denaturation,*** also known as DNA melting, is the process by which *dsDNA* (double-stranded) unwinds and separates into single strands through the breaking of *H-bonds* between the bases and becomes *ssDNA* (single-stranded). Both terms are used to refer to the process as it occurs when a mixture is heated, although "*DNA Denaturation*" can also be referred to the separation of DNA strands induced by chemicals like urea. In DNA replication, DNA denaturation occurs among DNA and it transforms into single-stranded DNA. On the other hand, ***DNA Renaturation*** or annealing means the formation of *dsDNA* (double-stranded) from *ssDNA* (single stranded) with the help of base pairing by making H-bonds to make a complementary sequence. This term is often used to describe the reformation of complementary strands that were previously separated by heat (thermally denatured) or by use of some chemicals (chemically denatured). In final step of DNA replication, "*DNA Renaturation*" or annealing, also known as hybridization occurs by complementary bases formed using *H-bonds*. The *5'-end* designates the end of the DNA or RNA strand that has the fifth carbon of the deoxyribose or ribose at its terminus where a phosphate group is attached. The *3'-end* designates another end of the DNA or RNA strand and is so named due to its terminating at the hydroxyl group of the third carbon in the sugar ring.

III. Relation Between 0/1 Reversible Logic and DNA

Several existing DNA-based designs have proposed the relationships between 0/1 logic with DNA logic [10], [16], [17]. However, existing DNA-based design [17] shows cleaver approach to encode 0/1 logic using two types of single DNA strands, one for input bit and another for operand bit. Also, in design [16], reversible *Toffoli* gate is realized using different DNA strands for control inputs and target inputs of *Toffoli* gate where control input signals are constructed using the dinucleotides *5'-AG* and *5'-CT* representing bit 1 and 0, respectively. The target inputs are constructed with *5'-ΨA* and *5'-UA* as bit 1 and 0, respectively. Similarly, the final outputs are constructed using mixer of *3'-AU, 3'-AD, 3'-AT* and *3'-AX* representing bit 1, 1, 0 and 0, respectively.

IV. Proposed DNA-Based Adder/Subtractor Circuit

A half-adder circuit performs addition operation between input variables A and B, equations of the summation and carry are as follows: $Sum = A \oplus B$, $Carry = AB$. Similarly, full-adder circuit performs addition operation for input variables A, B and C, however, equations of summation and carry are as follows: $Sum = A \oplus B \oplus C$, $Carry = AB \oplus AC \oplus BC = C(A \oplus B) \oplus AB$. Unlike adder circuit, a half-subtractor circuit performs subtraction operation between input variables A and B. Here, equations of borrow and difference are as follows: $Diff = A \oplus B$, $Borrow = \overline{A}B$. Similarly, full-subtractor circuit performs subtraction operation for input variables A, B and C. Thus, equations of borrow and difference are as follows: $Diff = A \oplus B \oplus C$, $Borrow = \overline{A}B \oplus \overline{A}C \oplus BC = C\ \overline{(A \oplus B)} \oplus \overline{A}B$. In fact, addition and subtraction operations are only differ for *Carry* and *Borrow*. Since *Carry* and *Borrow* signals are not being required at one time, we can easily merge these signals using one *exclusive-or* operation. The overall representation is depicted in Fig. 4.1. Four reversible DNA-based *Toffoli* gates with one DNA-based *Fredkin* gate are used to construct the proposed adder/subtractor circuit, (the university of *Toffoli* gate makes possible to realize any composite circuit). First, it calculates AB and $\overline{A}B$; then, it performs $A \oplus B$. Finally, it generates *Carry/Borrow.* There are seven inputs with one control signal, S_0 for *Fredkin* gate and three outputs (*Add/Sub*, *Carry/Borrow* and S_0) with four garbages. To construct the DNA-based adder/subtractor circuit, we adopt the procedure, technical parameters of existing method [16]. As like that work, two single stranded DNA (*ssDNA*) molecules are used here as control inputs and another is used as target input. The final output is produced using two control input signals and generated with pre-designed *ssDNA* segments which binds with the target input and make it double stranded (*dsDNA*). Here, we propose the slightly modified pre-designed DNA segments with a *Poly-A* tail, it helps this segment to get more molecular weight compared to the target input and this modification is necessary for the effective execution of operations. The two control inputs with the target input are represented by a string of bits where each bit is represented by a *dinucleotide* (two consecutive nitrogenous base of DNA). As like the previous work [16], control inputs, target input and final output are encoded in the same way (not shown here). The non-natural bases are used to make the design more efficient in terms of performance. Also, it is used to modulate the final output signals. After performing the operations, there are unchanged two input signals (two *ssDNA*) and one output signal (one *dsDNA*, consists of control input signal with a larger predesigned oligo). This *dsDNA* is denatured for separation of the smaller strand by capillary electrophoresis. This smaller strand is again ready to be annealed with the modified input strand (having poly A tail and inosines, I, binds with all the bases and indicates no value after binding with the bases and used here for blocking one bit). Meanwhile, all other things are transferred to storage for reusing. This double strand is now ligated with another input (two base pairs long double strand DNA fragment that adds either 1 or 0 bit signal) on the opposite site of flanking *Poly-A* nucleotide tail. This ligated double strand is the output for the first round of addition/subtraction operations. To make sequential circuit, it is necessary to form all input in single stranded form. To fan-out third output of proposed gate, a unique tag is used in target input. As a result, third output is formed in partially double strand where left part with unique tag is double stranded (representing output) and right part is single stranded (equivalent to output forming in control input) which will be used to fan-out.

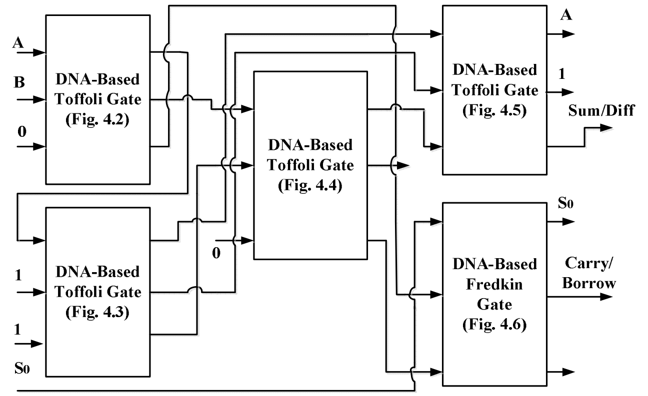

Fig. 4.1: Block diagram of the Hybridization process of the proposed DNA-based system for Addition/Subtraction Operation.

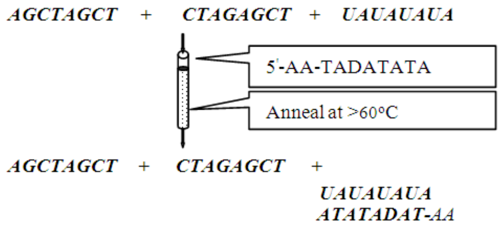

Fig. 4.2: DNA Hybridization of logical *AND* operation using DNA-based *Toffoli* gate.

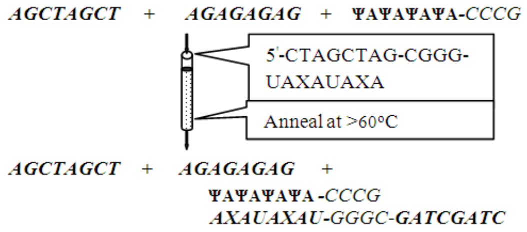

Fig. 4.3: DNA Hybridization of logical *NOT* operation using DNA-based *Toffoli* gate.

Later figures (Fig. 4.2-Fig. 4.6) show the sequential operaitons of proposed DNA-based half-adder/subtractor. Fig. 4.2 shows the operations of DNA-based *Toffoli* gate performing AB, where first input A represents 1010 and B represents 0110; the target output represents 0010 by using 3′ single strand DNA bases, then, it is fed into final *Toffoli* gate. Similarly, Fig. 4.3 shows the performing $\overline{A}$ operation, where final output is 0101, also represented by 3′ single strand DNA bases, it is fed into middle *Toffoli* gate. Again, in Fig. 4.4, $\overline{A}B$ operation is performed using outputs of first and second *Toffoli* gates, produces 0100 represented by 3′ *TCTCGATC* which is fed into final *Toffoli* gate to produce *Carry/Borrow* signal.

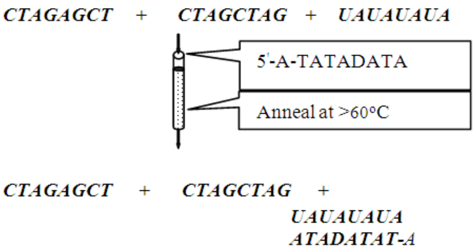

Fig. 4.4: DNA Hybridization of logical AND operation between complemented and non- complemented literals using DNA-based *Toffoli* gate.

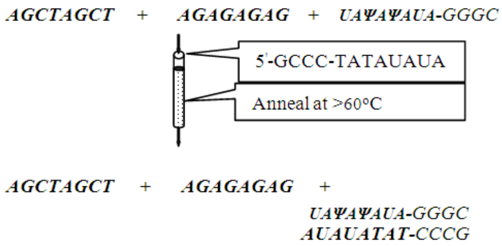

Fig. 4.5: DNA Hybridization of logical *Ex-OR* operation using DNA-based *Toffoli* gate.

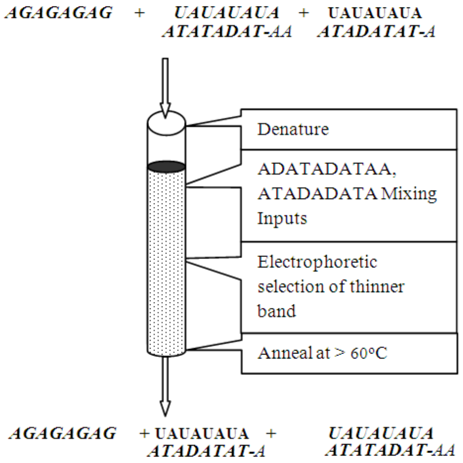

Fig. 4.6: DNA Hybridization of logical *Ex-OR* operation between two *ANDed* products using DNA-based *Toffoli* gate.

As like previous gates, Fig. 4.5 represents $A \oplus B$, the Add/Sub operation, here, the produced 3′ single strand DNA represents 1100, which would be fed into full-adder/subtractor circuit. Finally, in Fig. 4.6, the selection operation of AB and $\overline{A}B$, means the *Carry/Borrow* produced by control signal S_0, 3′*AGAGAGAG* single strand DNA bases which is fed into *Fredkin* gate. Now, to construct DNA-based reversible full-adder/subtractor circuit, we can easily use two half-adder/subtractor blocks with extra exclusive-or operations.

V. Proposed Design Analysis

In our proposed design, we use four DNA-based *Toffoli* gates and one *Fredkin* gate to construct overall circuit. For three inputs, total number of synthesizing DNA bases is $4n$. In prior one [17], it had constraint of $m+2n \leq 20$, but this system has no such constraint. However, we need to construct $m+3.2^n$ DNA signals, (**n** is the total number of bits, **m** is the size of extra tags and 3 for considering inputs of *Toffoli* gate.) instead of $m.2^n$ [17]. We introduce 5 logic operations instead of 4 in prior design [17]. Also, a unit tag has to be generated for each operation which is not necessary in our proposed design. Besides, the probability of making new signal is $\frac{1}{2^n}$. Also, in [17], denaturing and renaturing of DNA was necessary to make the output signal. Comparing with another existing DNA-based addition and subtraction operations [18], our proposed design performs better as that design used complex biological steps, 5 steps for addition and 6 steps for subtraction. For addition and subtraction operatoins, complexity of our design is $O(1)$ instead of $O(mln_2n)$ [18]. We summarize these discussions into Table I to compare our proposed design with others.

Table I: Comparison Between Existing DNA-Based Systems and the Proposed System.

Parameters	Existing DNA-Based System [17]	Proposed System
Constraint	$m+2n \leq 20$	None
Required DNA signals	$m.2^n$	$m+3.2^n$
Total logical operations	4 logical operations	5 logical operations
Maximum number of making DNA signal	2^n signal	Probability is $\frac{1}{2^n}$
Process of DNA formation	Both denaturing and renaturing are required	Signals are used in renatured form
Probability of hydrolysis	Probability is high	Probability is low
Signal types	Uniform	Not uniform
Complexity of DNA formation	Less DNA bases are used, simple	Few more DNA bases are used, complex

Parameters	Existing DNA-Based System [18]	Proposed System
Biological operations	Consists of complex bio-logical operations	Consists of only renaturing and denaturing of DNA
Run time Complexity	$O(mln_2n)$	$O(1)$

Here, **n** is the total number of bits and **m** is the size of extra tags.

From Table I, although there are few flaws (including extra tags, generalization) in our system, we can easily conclude our proposed system will perform better than other existing DNA-based designs [17], [18].

VI. Conclusion

In this work, we realize the reversible adder/subtractor circuit using DNA-based inputs and outputs and the computations are performed using DNA. This study also aims to exploit some of these bases (X, Ψ and D) as well as natural bases to design a DNA-based composite circuit, they provide a broaden window of complementary to design the circuit. Also, some of these bases are used to modulate the final output signals by representing thyself mostly prioritized. So, whenever they are represented in output, the final signal will be the signal that they carried. This is one of the key characteristics of proposed DNA-based circuit. We also compare our proposed methodology with other DNA-based existing circuits. Since, to fan-out, extra bases are required, the demonstrated circuit outperforms the existing reversible logic gate in terms of speed, error correction, and power consumption. Unlike reversible logic gate, there is no use of silicon chip, only use of DNA bases. As a result, it is very faster [11] and lasts longer by maintaining and varying temperature [19]. Because of unchanging the input sequences, we get the reusability of it. Moreover, we also show that the proposed circuit has no constraint, requires fewer DNA signals and less complex in performing addition and subtraction operations than the existing DNA-based designs [17], [18].

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