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Optimization of quantum networks using novel non-blocking optical switches

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ABSTRACT

Quantum switching is a new topic in optic networks. The present study investigated 2×2 and 4×4 optical quantum switches. The design and routing of a butterfly network using a 4×4 non-blocking quantum switch is also examined. In addition to comparing unidirectional and two-directional butterfly networks using 2×2 and 4×4 quantum switches for the number of gates, network cost, and delay, a 4×4 non-blocking quantum switch was also analyzed.

1. Introduction

Quantum computation [1–3] is a new method of data processing based on quantum mechanics that results in strange and powerful events in the context of quantum. Recent advancements in nano-quantum topics have increased their applications for the design of logic and invertible circuits. Decreasing circuit cost and power consumption limits circuit design for common connection structures; thus, integrating quantum structures and classic circuits has been proposed to remove these limitations. Quantum features such as parallelism, superposition, and quantum entanglement have become important physical resources in many computations. Domains for applications such as optics have increased with the incorporation of the superior characteristics of this data over classic data.

Switching networks in the presence of quantum data has been studied extensively. These networks are defined by structures and algorithms similar to classic switching networks. Their input is the superposition of quantum information packets that form the structure of the network using gates, copying, and moving packets. The packets are transferred to their respective inputs. Complexity, blocking, packet routing, and other features of classic networks are similarly defined for quantum networks. Most models define classic switching networks that can be defined and implemented in quantum switching networks as well [4].

Shukla and Oruc [5] was the first to design a quantum switch using quantum gates. The use of quantum parallelism is required for a non-blocking interconnection network; to date, no models have investigated circuit synthesis. The present study introduces a 2×2 quantum switch (including input-output) with an optimized structure that decreases constant inputs and garbage outputs that play no key role in switch function. The mechanism of the switch, because of the high volume of computations in the sub-network of the butterfly network, can be extended to a network with larger dimensions.

In networks made of common switches, the probability of blocking is high. A quantum switch is composed of quantum invertible gates for which blocking is eliminated by superposition of input packets in the outputs. The 4×4 non-blocking quantum switch defined by Sue et al. 2006 [6] includes more inputs and outputs than previous models and was used in this study to create a network with more inputs and outputs. A butterfly network was also designed using 4×4 non-blocking quantum switches. Chen [7] has discussed this switch in more detail elsewhere. The present study provides an optimal model that improves circuit synthesis and decreases circuit cost.

In the rest of the paper, Section 2 summarizes the subject matter. Section 3 investigates 4×4 non-blocking quantum switches. Section 4 describes the design of butterfly networks using 4×4 non-blocking quantum switches. Section 5 compares the results. Finally, Section 6 concludes the paper.

2. Background

2.1. Multistage interconnection network

Multistage interconnection networks (MINs) connect inputs and outputs of a network by switching stages; each network stage

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and each connection between two adjacent stages of switches specifies the network connection and its feature [8]. A Banyan network is a group of interconnecting networks that has only one path out of each input-output pair. A delta network is a subset of Banyan networks where k^n nodes are connected to one another through n stages of k × k switches with n/k switches at each stage. A butterfly network (omega) is a type of delta network [8].

2.2. Design and routing of butterfly

One feature of the delta network is the self-routing [9,10]. In these routings, intermediate switches independent from the source were selected based on the destination address. The routing algorithm was distributed and absolute; in classic topics, this feature is converted to a quantum equivalent.

These networks cross all channels and the data flow from the source to the destination is only switched. An N node MIN built with $k \times k$ switches can be represented as:

$$C_0(N)G_0(N/K)C_1(N)\ldots C_{n-1}(N)G_{n-1}(N/K)C_n(N) \tag{1}$$

where G_i is the ith stage, C_i is the ith connection, and $N=kn$. There are n stages. Each stage G_i consists of N/k identical $k \times k$ switches and is denoted as $G_i(N/k)$. Each connection C_i connects N right-hand side ports at stage G_i-1 to N left-hand side ports at stage G_i and is denoted as $C_i(N)$. Connection pattern C_i defines the topology of the one-to-one correspondence between adjacent stages G_i-1 and G_i, also known as a permutation [11].

2.3. Quantum gates

The indivisible unit of classical information is the bit, which can take a value of either 0 or 1. The corresponding unit of quantum information is the quantum bit or qubit. A qubit state is a vector in 2D complex Hilbert space. The elements of an orthonormal basis for this space are represented as $|0\rangle$ and $|1\rangle$. A qubit can also exist in the superposition of 0 and 1 states. In general, a qubit's state can be written as $|x\rangle=a|0\rangle+b|1\rangle$ where a,b∈C and $|a|^2+|b|^2=1$.$|x\rangle$ is also represented as $|x\rangle=[ab]^T$. Measurement of a qubit is either state $|0\rangle$ or state $|1\rangle$ with probability $|a|^2$ and $|b|^2$, respectively. The state of a system with multiple qubits can be written using the tensor product of the individual state vectors [1,12].

The state of a qubit can be transformed using quantum gates and circuits [13]. These gates are unitary transformations (and are reversible) acting on a fixed number of qubits. Reversibility implies that the corresponding input is uniquely determined given the output of a gate. A common one qubit gate is the Hadamard gate. The transformation matrix for this gate is:

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{2}$$

It transforms states $|0\rangle$ and $|1\rangle$ as: $|0\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)$ and $|1\rangle \xrightarrow{H} \frac{1}{\sqrt{2}}(|0\rangle-|1\rangle)$. A Hadamard gate puts a qubit in state $|0\rangle$ or $|1\rangle$ into an equal superposition of $|0\rangle$ and $|1\rangle$. Other common quantum gates for manipulating qubits are controlled quantum gates (controlled Hadamard or controlled-NOT gate) [1]. A controlled gate becomes active depending on the state of some control qubits. Fig. 1 shows one such gate, the controlled-controlled-NOT (CC-NOT) gate has two control qubits (c_1 and c_2).

This gate does the following operation

$$|c_1\rangle\,|c_2\rangle\,|X\rangle \xrightarrow{\text{CC-NOT}} |c_1\rangle\,|c_2\rangle\,|(c_1.\bar{c}_2)\oplus X\rangle \tag{3}$$

i.e., it inverts X when $C_1=1$ (solid circle) and $C_2=0$ (open circle). This can be extended to quantum gates with multiple control qubits. The present study uses NOT and Hadamard gates with multiple control qubits in the quantum switch.

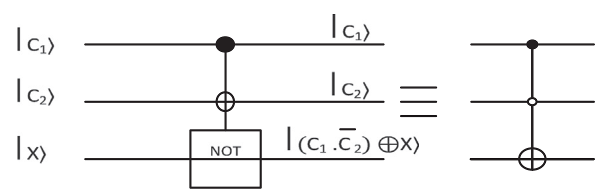

Fig. 1. A Controlled-Controlled NOT(CC-NOT) quantume gate.

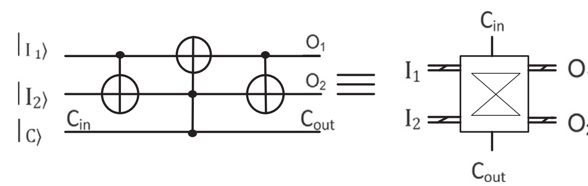

Fig. 2. the structure of 2 × 2 quantum switch.

2.4. Structure of 2 × 2 quantum switch

The basic building block of a quantum switch is a quantum gate, or switch gate [5]. The first main block in the structure of a quantum switch is a 2 × 2 controlled swap gate (Fredkin gate) consisting of two Feynman gates and one Toffoli gate (Fig. 2).

This is a $(2n+1)$ qubit-controlled quantum gate with one control qubit and two n-size sets of target qubits, each set representing a packet of size n. If the control qubit is a set in state $|1\rangle$, the gate interchanges the two sets of target qubits; if the control qubit is in state $|0\rangle$, it leaves them unchanged. The state of the control qubit is $|c\rangle$, the states of the two sets of target qubits are strings $|x\rangle=|x_1\ldots x_n\rangle$ and $|y\rangle=|y_1\ldots y_n\rangle$, respectively, where C, x_i, y_i ∈{0,1}, $i=1..n$, the function of this gate can be written as

$$|c\rangle\,|x_1\ldots x_n\rangle\,|y_1\ldots y_n\rangle \to |c\rangle\,|u_1\ldots u_n\rangle\,|v_1\ldots v_n\rangle \tag{4}$$

where $u_i=\bar{c}x_i+cy_i$ and $v_i=\bar{c}y_i+cx_i$. It can be easily verified that the gate can fulfill its functions depending on the state of the control qubit

$$|0\rangle|x\rangle|y\rangle \longrightarrow |0\rangle|x\rangle|y\rangle,\ |1\rangle|x\rangle|y\rangle \longrightarrow |1\rangle|y\rangle|x\rangle, x,\ y\in\{0,\ 1\} \tag{5}$$

The switch gate superposes the packets contending for one output of a 2 × 2 switch and route the superposition to that output. For example, if the control qubit of the gate is set in an equal superposition of states $|0\rangle$ and $|1\rangle$ then the action of the gate is:

$$\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)|x\rangle|y\rangle \longrightarrow \frac{1}{\sqrt{2}}(|0\rangle|x\rangle|y\rangle+|1\rangle|y\rangle|x\rangle) \tag{6}$$

Equal superposition (probability of observation = 1/2) of packets x and y is created at both the outputs. Both terms within the parenthesis contain x and y. If packet x is observed at one output, then packet y will be observed with certainty at the other output and vice-versa [14]. There are two modes of gate function: cross and through. Regulating the status of the switches in the cross or through modes depends on the value of the bit address in the information package (Fig. 3).

For example, at the ith stage of a Banyan network, a packet having the ith most significant address bit $a_i=0$ is routed to the upper output of the 2 × 2 switch and a packet having $a_i=1$ is routed to the lower output. The input packets of a 2 × 2 switch at the ith stage are in contention for an output link, if the ith most significant bit addresses of them are the same (Fig. 4). The purpose of the quantum switch is to remove this blocking so that the two contending packets can be routed in parallel on the same link using quantum superposition [5].

A simple design for a 2 × 2 quantum switch was given by