Reducing Loss in Optical Switches for Quantum Interconnects

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***Abstract*—Modular quantum computing architectures require switching network that route photons to either Bell State Analyzers(BSAs) for entanglement generation or to inter-group link requiring full-permutation routing. The switching network is constructed by 2×2 switch points. Each optical 2×2 switch introduces insertion loss, increases circuit depth and adds control complexity, this raises the importance to minimize both switch count and network depth.**

The poster studies rearrangeably non-blocking scalable switching networks for shared BSA interconnects on planar waveguides. We look into the fact that BSA-bound photons only need to reach adjacent BSA ports as pairs, while photons routed to inter-group links require exact output ports. This pair flexibility reduces the switch resources needed compared with full-permutation routing.

I. Introduction

Scaling quantum computers beyond single devices requires modular quantum architectures, where quantum nodes are connected through photonic links. Architectures such as Q-Fly [1] and quantum data center designs [2] organize nodes into hierarchical groups, with photons routed to either BSAs within a group for entanglement generation, or outward to inter-group links. In planar photonic integrated circuits, we route photons with 2×2 elementary MZI switch points acting on adjacent waveguides. Every switch point that a photon traverses introduces insertion loss. Thus, minimizing switch count and network depth is crucial for entangelement generation rateand system scalability.

Previous work on non-blocking optical networks was either aimed at classical networks focusing on full-permutation routing [3], [4], or at a single switch network with BSA port outputs only [5] requiring paired-egress routing. However, current architecture proposals for quantum data centers utilize hybrid optical switches, where both types of routings are necessary. It is thus crucial to devise optimal designs for these hybrid optical switches. In this work, we characterize rearrangeably non-blocking hybrid switches in terms of their switch cost and depth. We introduce three different designs and discuss their use within the Q-Fly architecture.

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II. System Model

We consider an $N \times N$ switching network of N parallel waveguides. We use 2×2 switch points operating on adjacent waveguides, with two states BAR and CROSS. In BAR state, the two photons pass straight through. In the CROSS state, the photons exchange waveguides. We do not allow passive waveguide crossing, due to planar fabrication constraints. Output ports are divided into two sets: k BSA-bound outputs connected to $k/2$ BSAs, and $N-k$ full-permutation outputs, requiring exact port assignment. Fig.1 illustrates the three switch designs considered in this work. A routing demands specifies $k/2$ photon pairs to BSA outputs and $N-k$ single photons to exact full-permutation ports. The network must be rearrangeably non-blocking, thus, for every valid demand, a valid switch configuration exists.

We evaluate designs on switch count S, the total 2×2 switch points, and depth D, the number of switch columns, which is equal to the maximum switches a photon can traverse.

III. Minimal Switch Construction

One-sided and middle BSA arrangements: For both arrangements, we prove that the minimum switch count is,

$$S_{min}(N,k) = \frac{N(N-1)}{2} - \frac{k^2}{4}.$$

We prove this value is the lower bound by considering the worst case demand requiring this many switches and a construction achieving it. Both arrangements have depth $D = N$.

Two-sided BSA arrangements: We consider another design of placing BSA ports at the top a waveguides, and bottom b waveguides of the full-permutation region($k = a + b$). This construction creates a brickwork construction with depth:

$$D = \begin{cases} N-b, & a > b \\ N-b+1, & a = b \end{cases} \tag{1}$$

By removing unnecessary switches in the brickwork constructions, we achieve the switch count of,

$$S = \lceil D/2 \rceil \lfloor (N-1)/2 \rfloor + \lfloor D/2 \rfloor \lfloor N/2 \rfloor - \begin{cases} \frac{b}{2} \cdot \frac{a-b}{2}, & a > b \\ a/2, & a = b \end{cases}$$

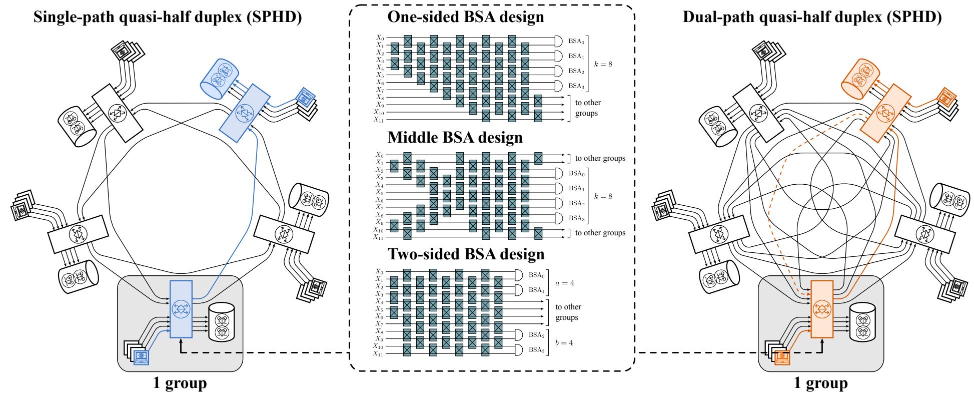

Fig. 1: Switch layout designs for Q-Fly group switches

(Center) The one-sided, middle, and two-sided BSA designs, each illustrated for an $N = 8, k = 4$ group switch. In the one-sided design, BSA outputs are concentrated at the top; in the middle design, BSA outputs are placed in the center of the port range; in the two-sided design, BSA ports are split across both edges. (Left) Single-path quasi-half-duplex (SPHD) topology, where each group connects to others via a single optical path. (Right) Dual-path quasi-half-duplex (DPHD) topology, which doubles the inter-group links for higher bandwidth and path redundancy. Figures of Q-Fly used with permission from [1].

Design	Switch count S	Depth D
Full-permutation [3]	$\frac{N(N-1)}{2}$	N
One-sided / middle BSA	$\frac{N(N-1)}{2} - \frac{k^2}{4}$	N
Balanced two-sided BSA	$\frac{(2N-k+2)(N-1)-k-2}{4}$	$N - \frac{k}{2} + 1$
singe-group switch design [5]	$\frac{N(N-2)}{4}$	$\frac{N}{2}$

TABLE I: Comparison of switch count and depth for the evaluated constructions.

IV. Evaluation

Analysis of Two-sided BSA design

For the two-sided BSA design, depth and switch count depend on how BSA ports are distributed between the top (a) and bottom (b). From Eq. 1, depth is minimized when $\min(a, b)$ is maximized, which occurs when $a \approx b$.

Switch count has similar characteristics. By comparing the switch count with different ratio cases, we can say that for fixed k, both depth and switch count are minimized near $a = b$.

Comparison of designs

We compare the three proposed designs. The two-sided design achieves lower depth than the other designs. In the balanced case of $a = b = k/2$ with even N, the switch count is also reduced for $(k - 2)(N - k - 2)/4$ switches, which is always positive when the full-permutation region contains more than two ports.

Application to Q-Fly architecture

We evaluate the two-sided BSA design implemented in a Q-Fly modular quantum interconnects. Let G be the number of groups, and B the number of BSA bound ports in one group switch. We write the number of inter group full-permutation ports as $I(G) = \eta(G - 1)$, where $\eta = 1/2$ corresponds to single-path quasi-half-duplex and $\eta = 1$ corresponds to dual-path quasi-half-duplex. The worst case switch depth under balanced two-sided BSA placement is $D_{\max} = 2(\eta(G - 1) + \frac{B}{2} + 1)$. This makes the bandwidth-depth tradeoff of topology choices also visible at the switch design level.

V. Conclusion

In this poster, we tackled the problem of minimizing optical loss in photonic switching network for quantum interconnects, motivated by the Q-Fly architecture and planar photonic integrated circuit constraints. We introduced the minimal switch count and depth for the one-sided and BSA in the middle arrangement. We then introduced a two-sided BSA design, which achieves lower depth than the previous two designs. We proved that both depth and switch count are minimized when the BSA ports are split evenly on both sides.

The Q-Fly evaluation shows that the worst-case switch depth, making the BSA port allocation and the single-path/dual-path topology choice directly visible at the switch design level.

These results provide a foundation for optical switch design in quantum interconnects. As future work, we consider closing the gap between the true minimum switch count for the two-sided arrangement, exploring adaptive BSA slot assignment strategies, and extending the analysis to different types of hierarchical topologies.

References

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