Reducing Loss in Optical Switches for Quantum Interconnects

Marii Koyama[1], Michal Hajdušek[2], Shota Nagayama[2], Rodney Van Meter[3]

[1] Graduate School of Media and Governance, Keio University, Kanagawa, Japan

[2] Graduate School of Media Design, Keio University, Kanagawa, Japan

[3]Faculty of Environment and Information studies, Keio University, Kanagawa, Japan

{mia, michal, rdv}@sfc.wide.ad.jp, shota@qitf.org

Abstract

Optical switches are essential for modular quantum computing interconnects, but each 2×2 switch point adds insertion loss, circuit depth, and control complexity. This work studies hybrid optical switches whose outputs are split between Bell-state analyzer (BSA) ports for entanglement generation and full-permutation ports for inter-switch routing. By exploiting the pair-egress flexibility of BSA-bound photons, we derive scalable rearrangeably non-blocking designs with reduced switch count and depth. We analyze one-sided, middle, and two-sided BSA output arrangements, provide routing algorithms, and show that balanced two-sided BSA placement reduces both switch count and depth.

Motivation

Modular quantum computers route photons to Bell State Analyzers(BSAs), for entanglement distribution among nodes, or outward via inter-group links.

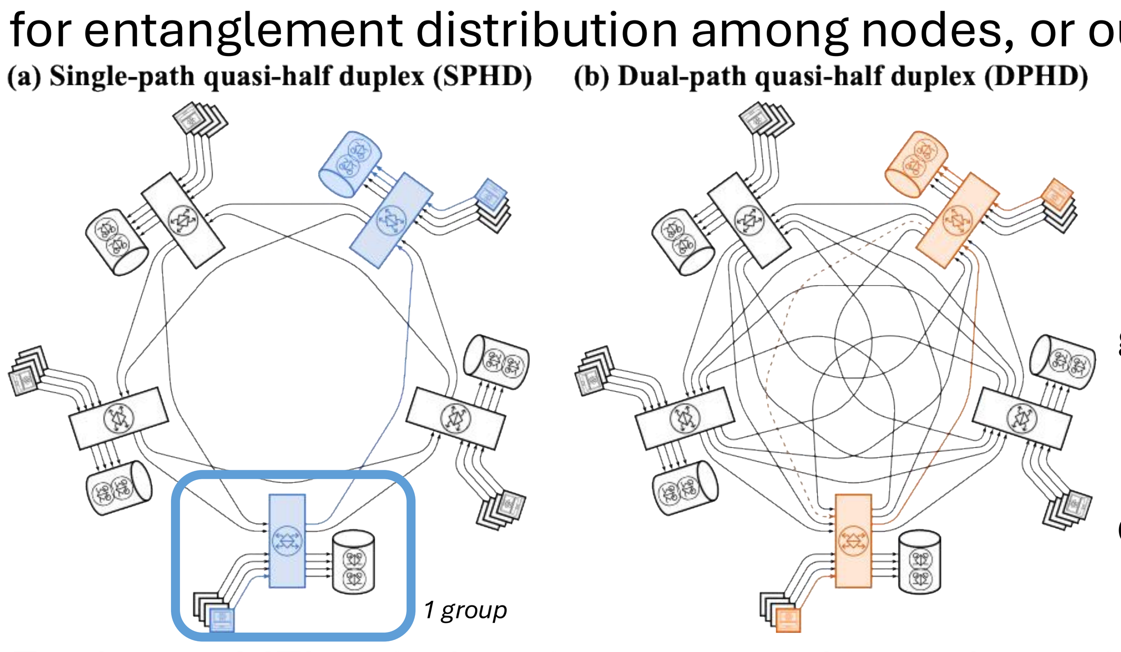

Fig 1: Q-Fly modular quantum interconnect architecture. Quantum nodes are organized into groups, and photons are routed through optical switches either to local BSA resources for entanglement generation or to inter-group links for other groups. Q-Fly figures used with permission from [1].

Each 2×2 MZI switch point traversed introduces insertion loss.
Thus, minimizing switch count *S* and depth *D* is essential for entanglement generation rate.
In previous work, full-permutation switch design[2] and all BSA-bound switch design[3] with minimal switch number has been proposed.
We aim to create a new design, combining the two ideas.

System model

BSA-bound outputs

Photon pair routed to any adjacent BSA slot.
Internal order irrelevant.

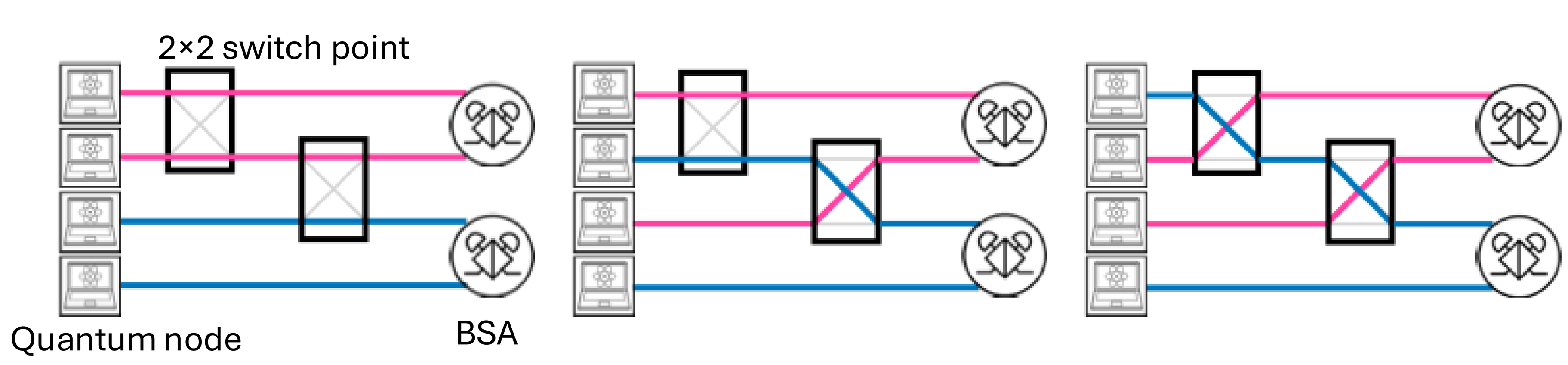

Fig 2: Example of an all BSA-bound output N=4 switching network design.
We need to send photons to the same BSA to generate entanglement between nodes.
There is a freedom of internal ordering and the assigned BSA, which reduces the switches needed compared to a full-permutation network.

Full-permutation outputs

Single photon routed to an exact specified output port.

We consider *N* inputs *N* outputs network with *k* BSA-bound outputs, and *N-k* Full-permutation outputs.

Considerations:

- Depth: The number of columns in the design. Maximal switch points number a photon may traverse.
- Switch count: The overall number of switch points in the switch.
- Rearrangeably non-blocking: Any routing request can be satisfied.
- Planar: The waveguides are placed parallel. For chip fabrication.

One-sided & Middle BSA design

Both arrangements achieve the same minimal switch count, proven tight via a worst-case lower bound argument:

$D = N$

$$S = \frac{N(N-1)}{2} - \frac{k^2}{4}$$

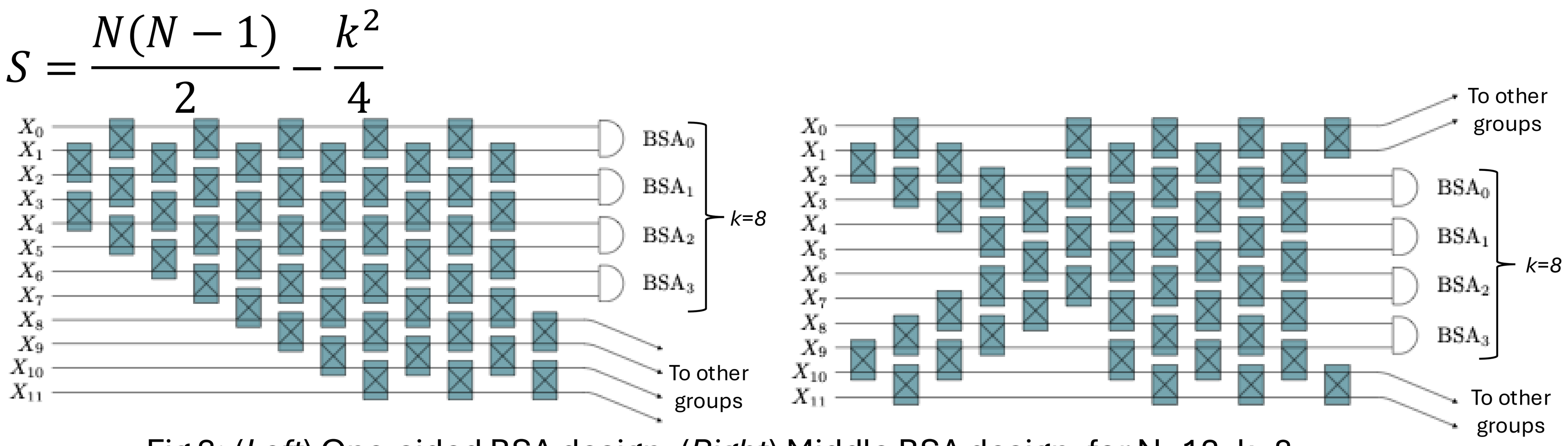

Fig 3: (*Left*) One-sided BSA design. (*Right*) Middle BSA design, for N=12, k=8.
Both designs have the same switch count and depth.

Two-sided design

Splitting BSA ports across both edges of the full-permutation region(*a* top ports, *b* bottom ports, *k=a+b)* gets a brickwork construction with lower depth. When *a=b*, it yields fewer switch counts than the previous designs.

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

$$S = \left\lceil\frac{D}{2}\right\rceil\left\lceil\frac{N-1}{2}\right\rceil + \left\lfloor\frac{D}{2}\right\rfloor\left\lfloor\frac{N}{2}\right\rfloor - \begin{cases} \frac{a(a-b)}{4} & (a>b) \\ \frac{k}{4} & (a=b) \end{cases}$$

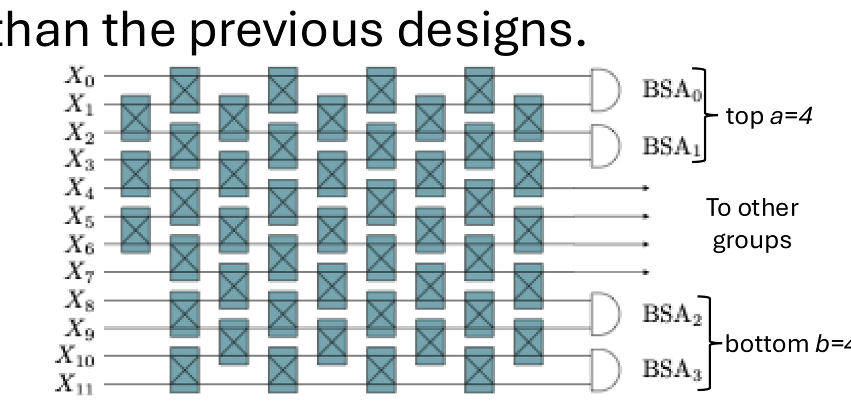

Fig 4: Two-sided BSA design, for N=12, k=8 (a=b=4).

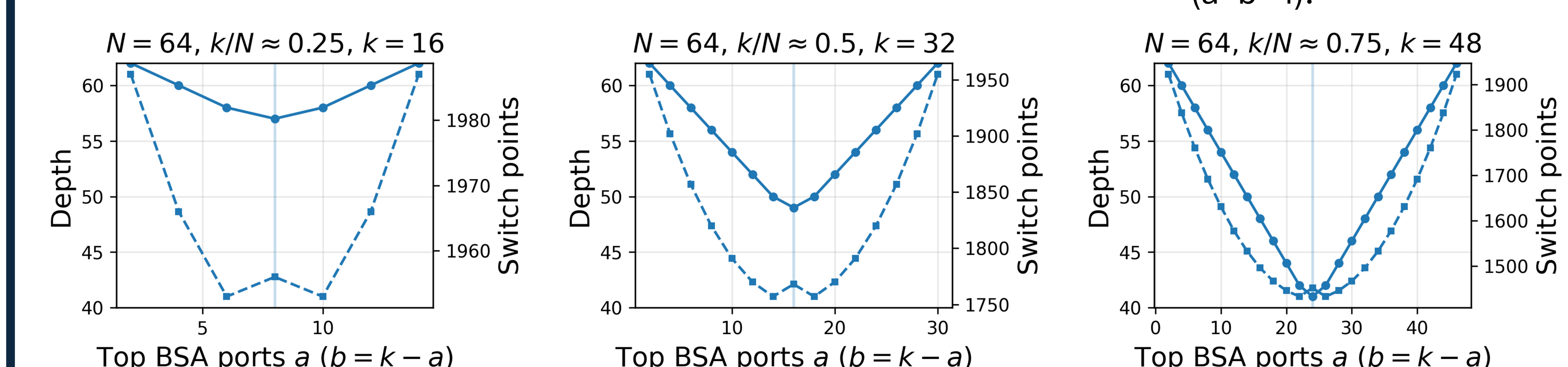

Fig 5: Graph showing the depth and switch count per different *a,b* and *k/N* ratio, for N=64.
Solid line represents depth and dashed line represents switch points.

Design Comparison

The table compares switch count and depth across full-permutation routing[2], full-BSA routing[3], and the proposed BSA aware layouts.

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

For Q-Fly group switches with fixed radix N, increasing the number of groups g raises the inter-group port count I(g), shrinking the BSA port budget B(g), increases maximum switch depth.

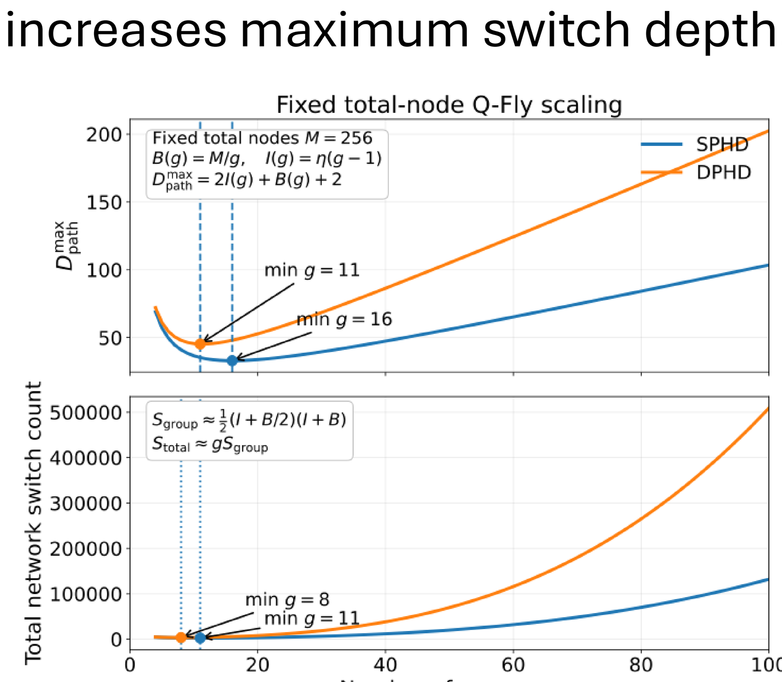

Fig 6: Relation between maximum switch depth a photon can pass, total switch count, and number of groups g, for a fixed total number of nodes over the whole network, M = 256.
SPHD uses a single inter-group path between each pair of connected groups, whereas DPHD uses two inter-group paths to provide additional routing flexibility at the cost of more ports and switches.
An optimum in switch depth exists around g = 16 (single-path) and g = 11 (dual-path). For switch count the optimum exists around g = 11 (single-path) and g = 8 (double-path).

Conclusions

- Hybrid BSA/full-permutation outputs allow smaller switching networks than full-permutation routing.
- Balanced two-sided BSA placement reduces switch count and depth.
- In Q-Fly style group switches, there is a trade-off between the optimal depth and switch count for fixed total node size.
- Future work: optimization of group size and BSA placement, scheduling, adjusted optimal switch designs for η>1.

References

[1] D. Sakuma et al., "Q-fly: An optical interconnect for modular quantum computers," arXiv preprint arXiv:2412.09299, 2024

[2] C. Clos, "A study of non-blocking switching networks," Bell System Technical Journal, doi:10.1002/j.1538-7305.1953.tb01433.x

[3] Marii Koyama et al., "Optimal switching networks for paired-egress bell state analyzer pools," QCE24, doi:10.1109/QCE60285.2024.00219.

Marii Koyama ・ mia@sfc.wide.ad.jp ・ Keio University SFC ・ JST Moonshot[JPMJMS226C] and [JPMJMS2061]