LOSS-TOLERANT ALL-OPTICAL QUANTUM COMPUTING ARCHITECTURE USING PARITY-STATE-ENCODED MULTIPHOTON QUBITS

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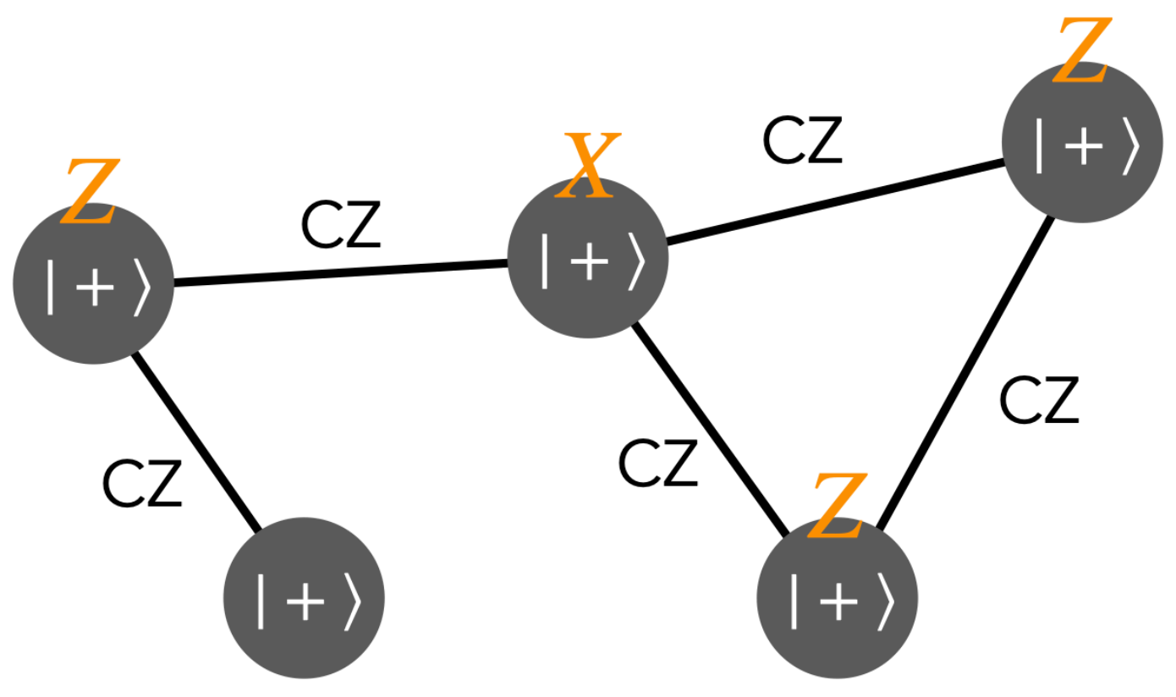
Seok-Hyung Lee,[1] Srikrishna Omkar,[2] Yong Siah Teo,[1] and Hyunseok Jeong[1]*
[1]Department of Physics and Astronomy, Seoul National University, Seoul, Republic of Korea
[2]ORCA Computing, Toronto, Canada

서울대학교
SEOUL NATIONAL UNIVERSITY
SQuIS
Seoul National University
Quantum Information Science Group

SUMMARY

- Measurement-based quantum computing (MBQC) in linear optical systems
  → Promising for near-future quantum computing architecture
- Nondeterministic nature of entangling operations & Photon losses
  → Hinder the generation of resource states and introduce errors during MBQC
- We propose a **linear-optical MBQC protocol using the parity state encoding** to overcome these problems**.**
- It is shown to be **highly photon-loss tolerant and resource-efficient**.
- For realistic error analysis, we introduce a **Bayesian methodology to track errors caused by nonideal entangling operations**.
- We show that our protocol is **advantageous over several other existing protocols**.

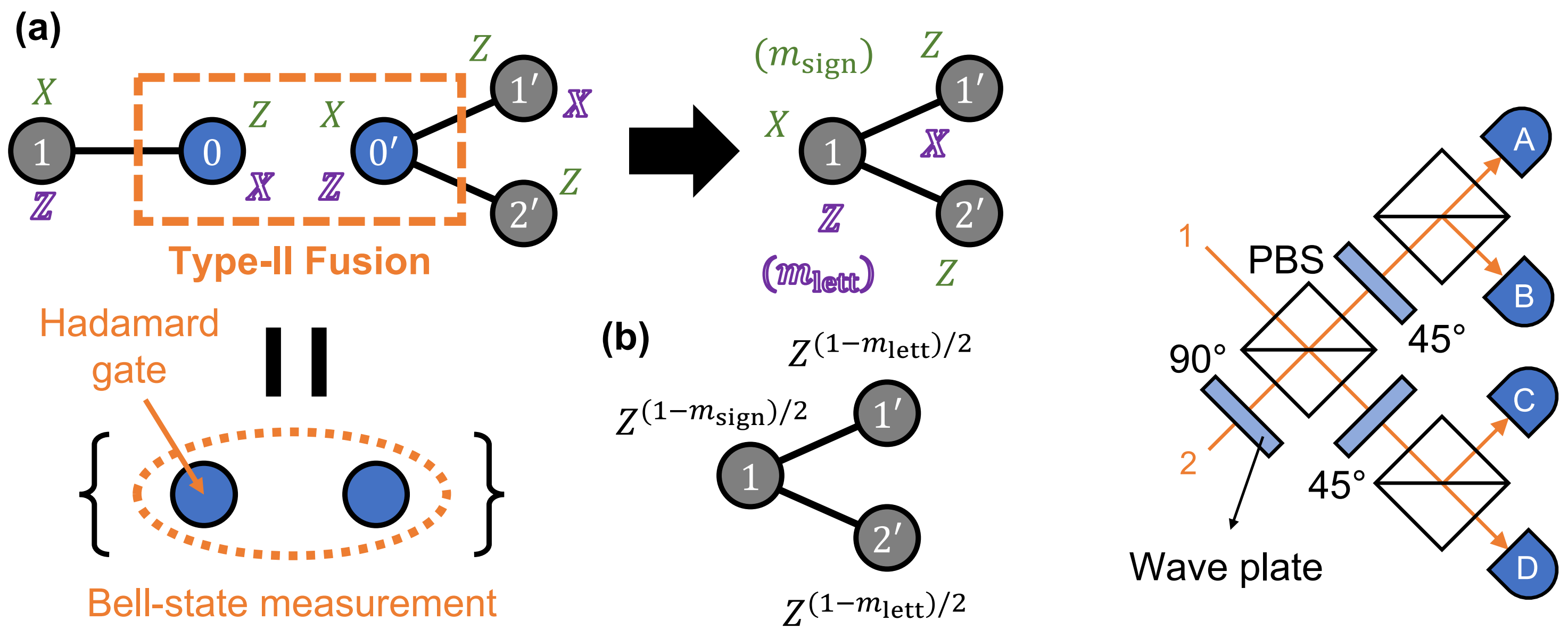
BACKGROUND



- **Graph state** $|G\rangle$ for a graph G
  - For each vertex v,

$$S_v|G\rangle := \left(X_v \prod_{v'\in N(v)} Z_{v'}\right)|G\rangle = |G\rangle$$

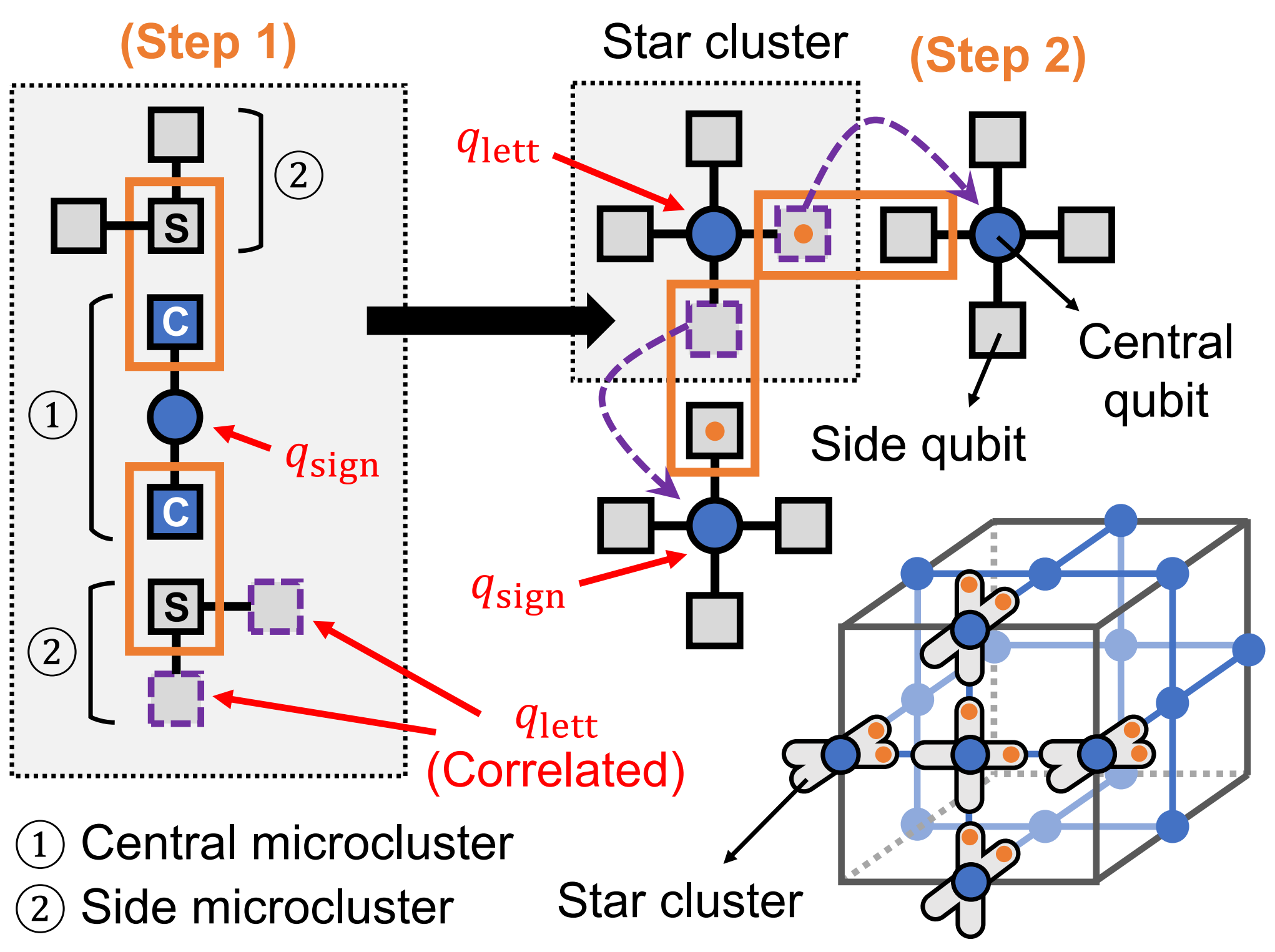
- **Measurement-based quantum computing (MBQC)** [1, 2]
  - Quantum computing done by **single-qubit measurements** on a **graph state**.
  - **Raussendorf-Harrington-Goyal (RHG) lattice** → Universal fault-tolerant MBQC
- **Type-II fusion** [3]: Hadamard gate + Bell-state measurement (BSM)
  - Combine two graph states



BAYESIAN ERROR TRACKING FOR NONIDEAL FUSIONS

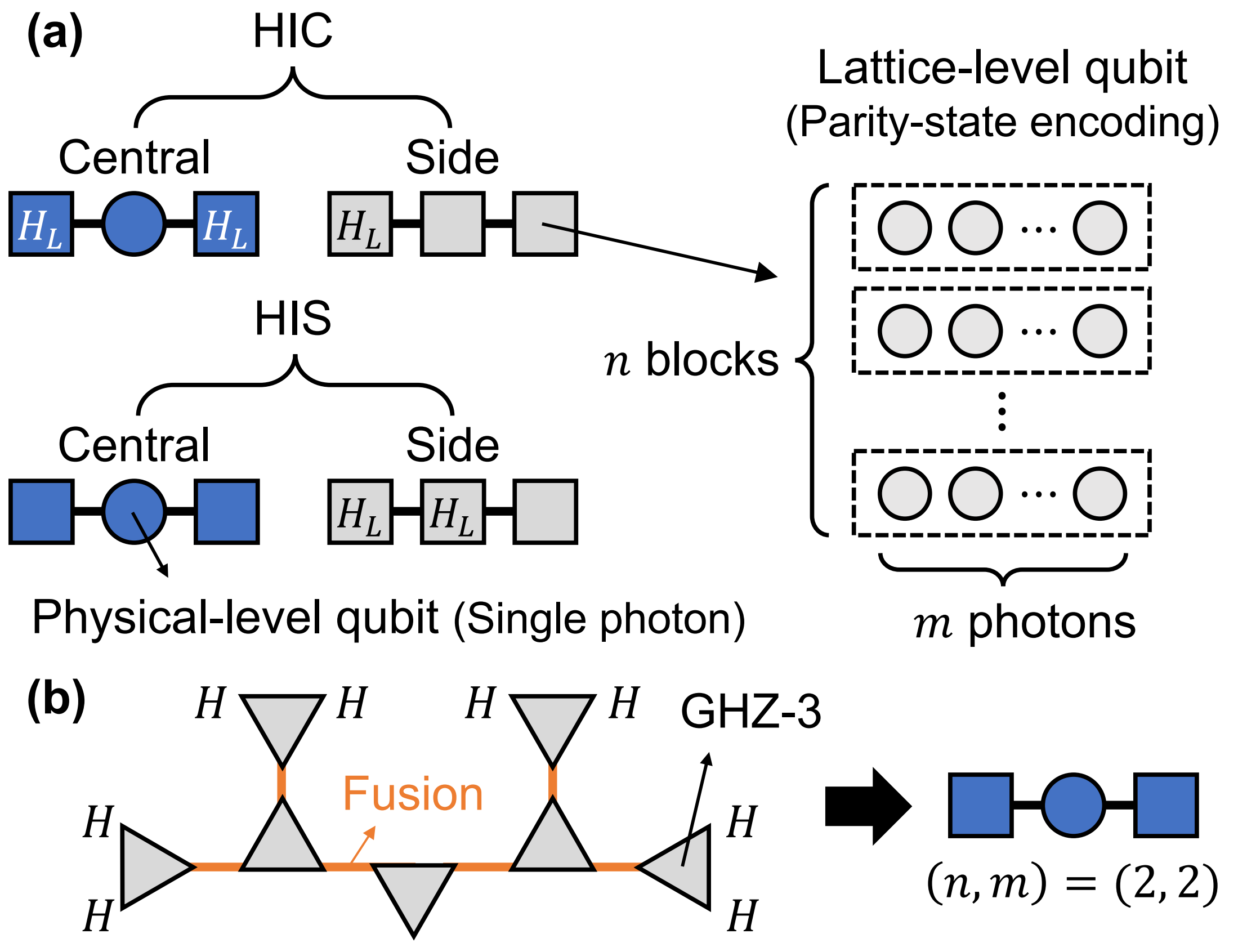
- **Ideal fusions are impossible** due to theoretical limitations & environmental noises.
- If **single-photon polarization qubits** are used,
  - A Bell-state measurement (BSM) can discriminate only $|\psi^\pm\rangle$.
    $|\phi^\pm\rangle := |0\rangle|0\rangle \pm |1\rangle|1\rangle,\ \ |\psi^\pm\rangle := |0\rangle|1\rangle \pm |1\rangle|0\rangle$
    (ϕ / ψ: "letter", ±: "sign")
  - When a BSM fails, m_{lett}: determined & m_{sign}: ambiguous
    → Randomly assign m_{sign}
  - **Equivalent to qubit 1 having a Z-error with a 50% chance**.
- In general,
  - A non-ideal BSM gives one of the multiple outcomes.
  - Calculate the posterior probability of each Bell state for the outcome with the **Bayesian theorem** → Select the most probable Bell state as the result.
  - Obtain the sign (letter) error probability q_{sign} (q_{lett}).
    → Propagate appropriately into nearby qubits.
- Enable **accurate and effective error simulations**
  - Qubits affected by unsuccessful fusions are locatable.
  - Error probabilities of individual qubits are used for adaptive decoding.

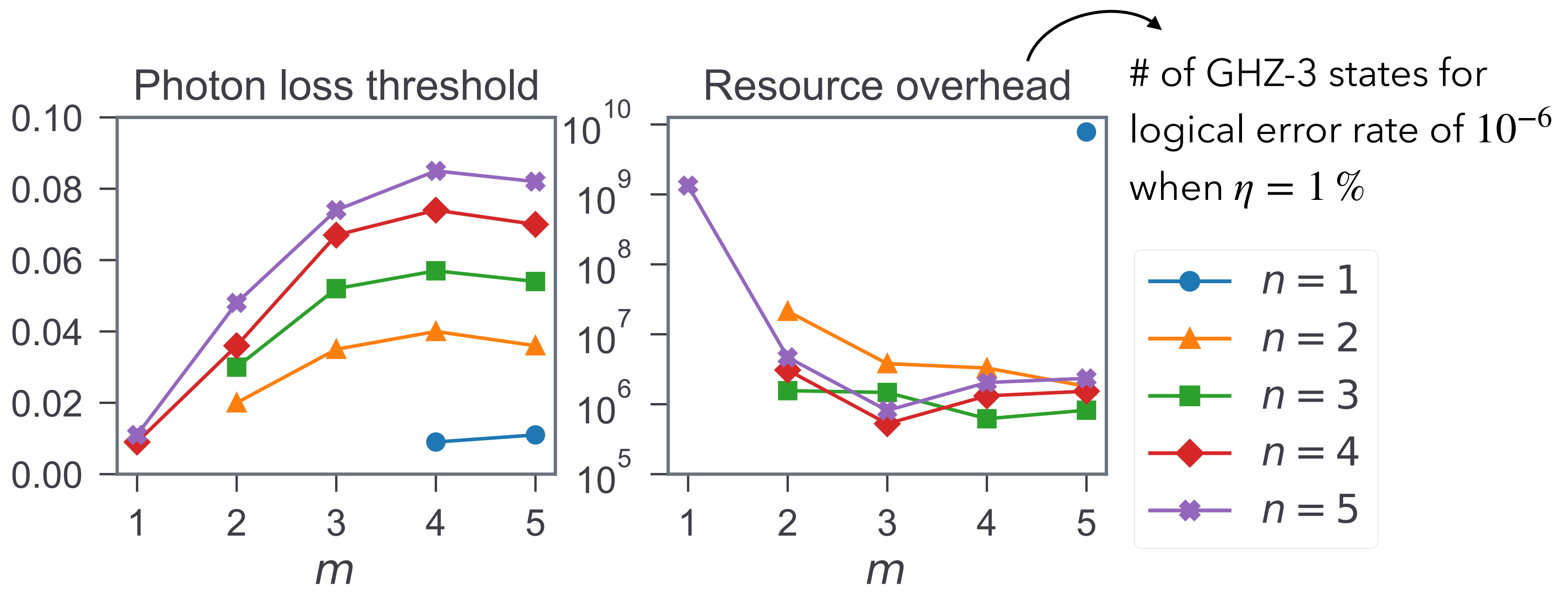
BUILDING AN RHG LATTICE



PARITY-STATE-ENCODING-BASED TOPOLOGICAL QUANTUM COMPUTING PROTOCOL

- (n, m) **parity state encoding**: $|0_L\rangle := |+^{(m)}\rangle^{\otimes n},\ \ |1_L\rangle := |-^{(m)}\rangle^{\otimes n}$,
  where $|\pm^{(m)}\rangle := (|H\rangle + |V\rangle)^{\otimes m} \pm (|H\rangle - |V\rangle)^{\otimes m}$
- **Concatenated BSM scheme** [5] is modified and used.
- Microclusters are generated by entangling multiple **3-photon GHZ states**.
  → Possible with linear-optical circuits, single-photon sources, and photodetectors.
- i.i.d. photon loss model with loss rate η





# of GHZ-3 states for logical error rate of 10^{-6} when $\eta = 1\,\%$

COMPARISON WITH OTHER APPROACHES

1. Using **single-photon qubits with fusions assisted by ancillary photons** [6–8]
   - Photon-number resolving detectors (PNRDs) that can resolve many photons (16 photons when $\eta = 1\,\%$) are required.
   - Ancillary states that are hard to generate with linear optics are required.
2. Using **simple repetition codes** [9]
   - Photon loss threshold $\lessapprox 1\,\%$ → Much smaller than that of our protocol.
3. Using **redundant tree structures on graph states** [10]
   - At least $\sim 2 \times 10^5$ photodetectors are required per data qubit, while our protocol requires $\sim 7 \times 10^4$ photodetectors.
     → About twofold improvement

CONCLUSION

- We addressed the problem of **overcoming the negative effects of nonideal fusions and photon losses** during linear-optical MBQC.
- We introduced a **Bayesian methodology for tracking errors** caused by nonindeal fusions, which enables accurate and effective error simulations.
- We proposed the **PTQC protocol** using the parity-state-encoded multiphoton qubits.
- PTQC has a **high loss threshold** of at most $\sim 8.5\,\%$ and requires 10^6 or less GHZ-3 states.
- We verified that PTQC is **advantageous over three other approaches** [6–10] in terms of fault-tolerance, resource overhead, or feasibility of basic elements.

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