Memory-assisted Bell measurements for high-performance entanglement distribution based on multiplexed cavity QED systems

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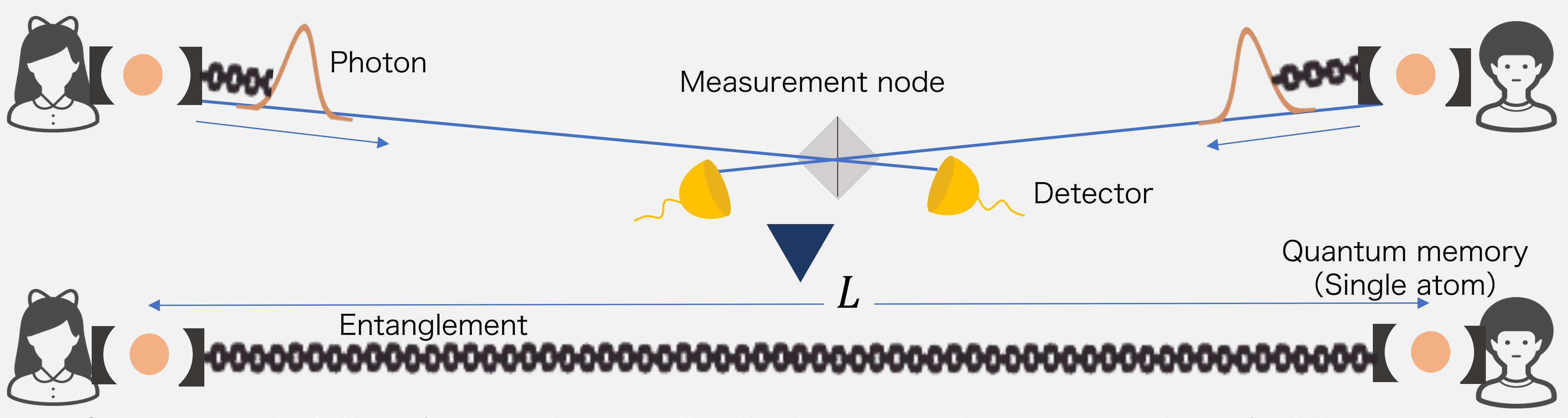
1. Back ground

Entanglement distribution with direct transmission



Success probability of entanglement distribution

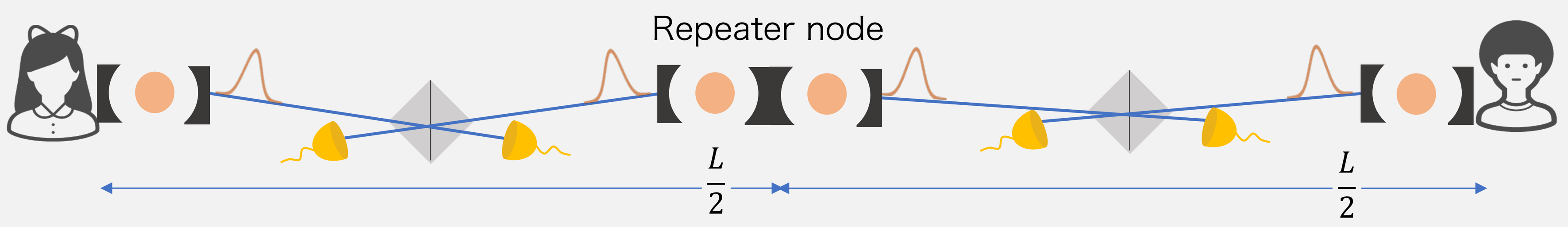
$p \propto \exp\left(-\frac{L}{L_{att}}\right)$

L_{att} : Fiber attenuation length

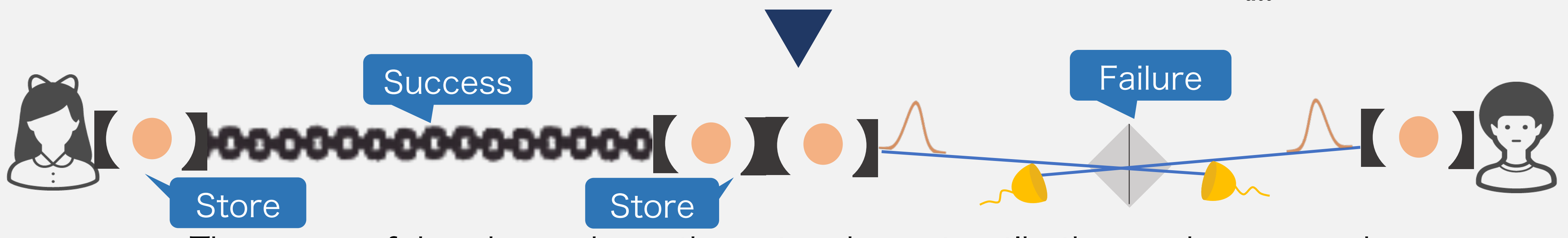
Average number of trials

$1/p \propto \exp\left(\frac{L}{L_{att}}\right)$

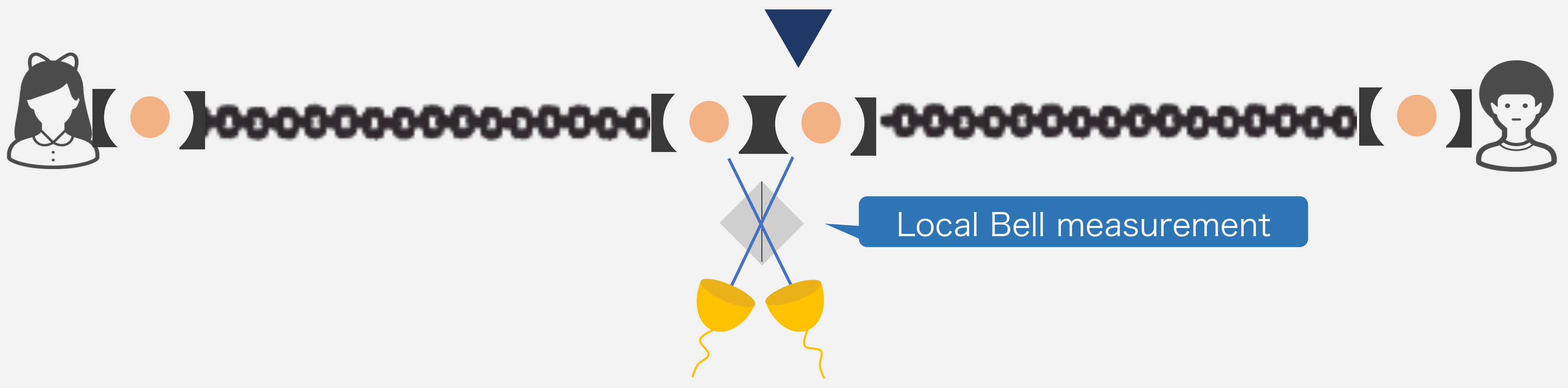
Entanglement distribution with quantum repeaters



Success probability of entanglement distribution : $p_2 \propto \exp\left(-\frac{L}{2L_{att}}\right)$



The successful node can keep the entanglement until other nodes succeed.

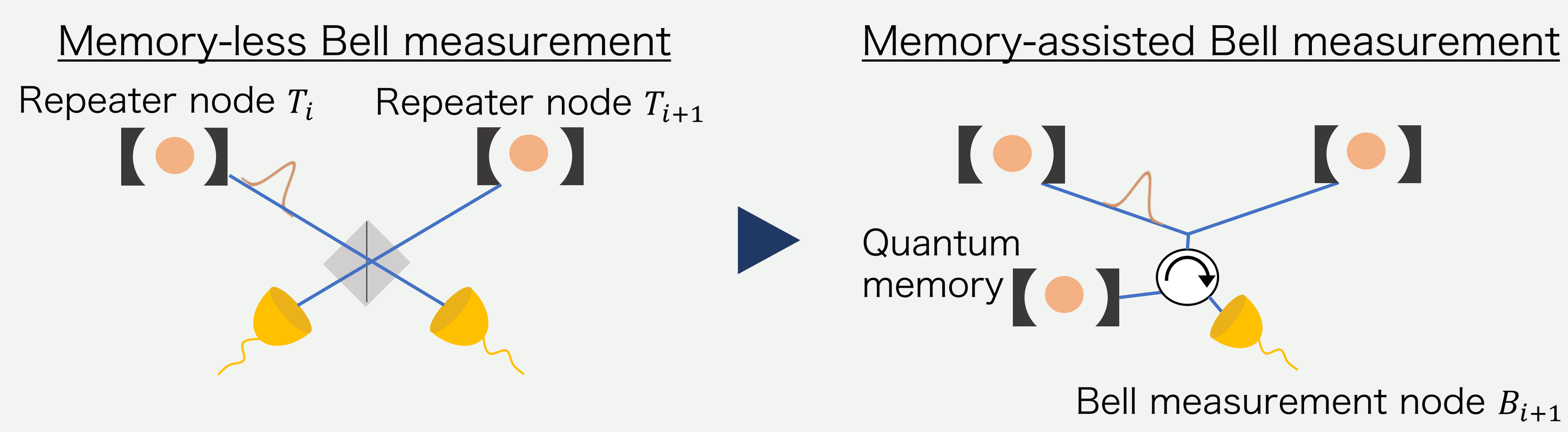


Average number of trials : $1/p_2 \propto \exp\left(\frac{L}{2L_{att}}\right)$

2. Our proposal

Our idea

Improve the first Bell measurement with quantum memories



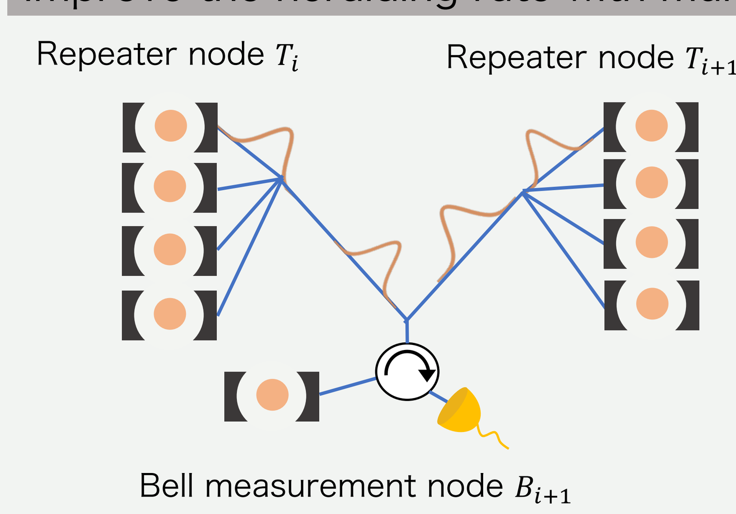
Success only when both photons arrive without loss.

Bell measurement node can store success events.

Drawback: Additional errors from infidelities of additional controls and dephasing of atoms in Bell measurement nodes.

Improvement with similar idea is demonstrated in quantum key distribution experiments using SiV center[1,2].

Improve the heralding rate with multiplexing cavity QED systems



Multiplexing can reduce the effect of dephasing errors of the protocol.

When T_i and T_{i+1} have many memories, the frequency of trials increases.
→ Decreased waiting time for T_i and relax the effect of dephasing error.

High-performance multiplexing of cavity QED systems is demonstrated in nanofiber cavities [3,4].

Main contribution

Optimize parameters of cavity QED systems for the memory-assisted Bell measurement

Evaluate the optimal performance of entanglement distribution with realistic cavity QED systems

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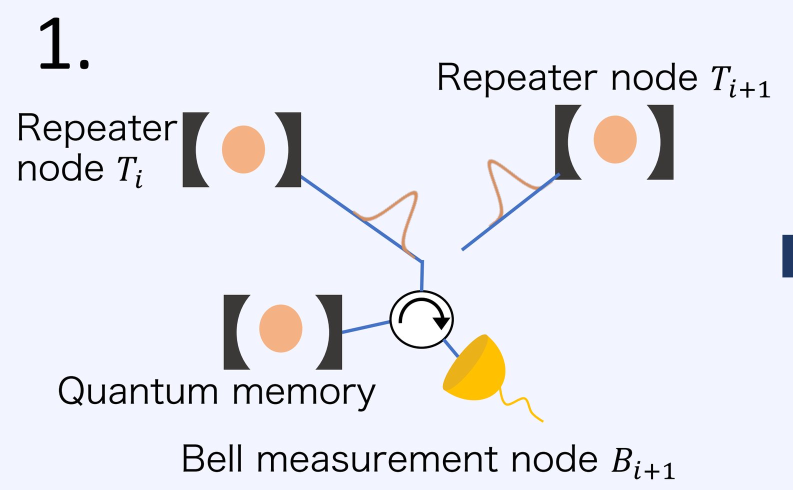
Extend the limits of entanglement distribution with quantum repeaters using available technology

Show multiplexing of cavity QED systems can improve the entanglement distribution

3. Protocol detail

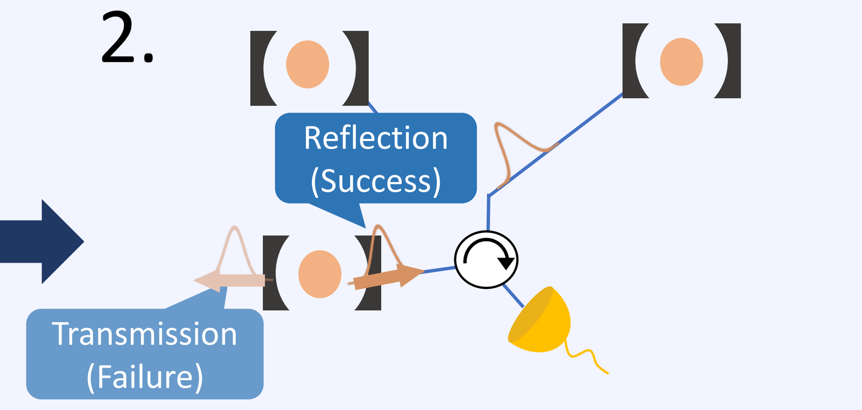
We designed a protocol to reduce the effect of dephasing

1.



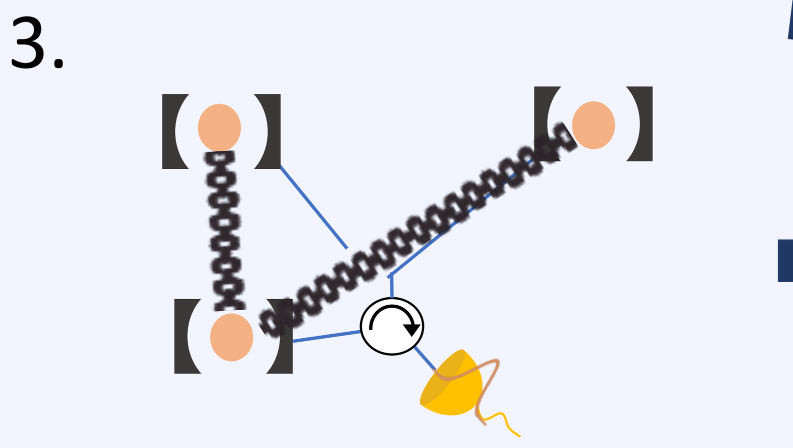
Nodes T_i and T_{i+1} emit a single photon entangled with its atom.
Bell-measurement node receives photons from T_i.

2.



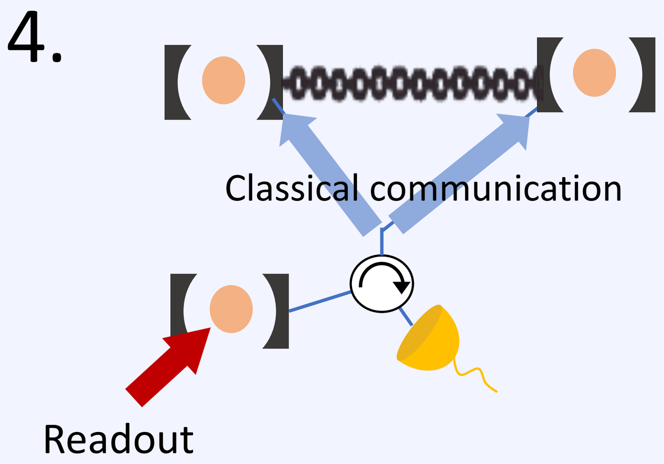
When a photon from T_i arrives at B_{i+1}, the photon is reflected by cavity depending on the atomic state at B_{i+1}. Detection of photo-detector heralds the entanglement between atoms of T_i and B_{i+1}. B_{i+1} starts receiving a photon from T_{i+1}.

3.



Similarly, B_{i+1} receives a photon from T_{i+1} and three atoms are entangled.

4.

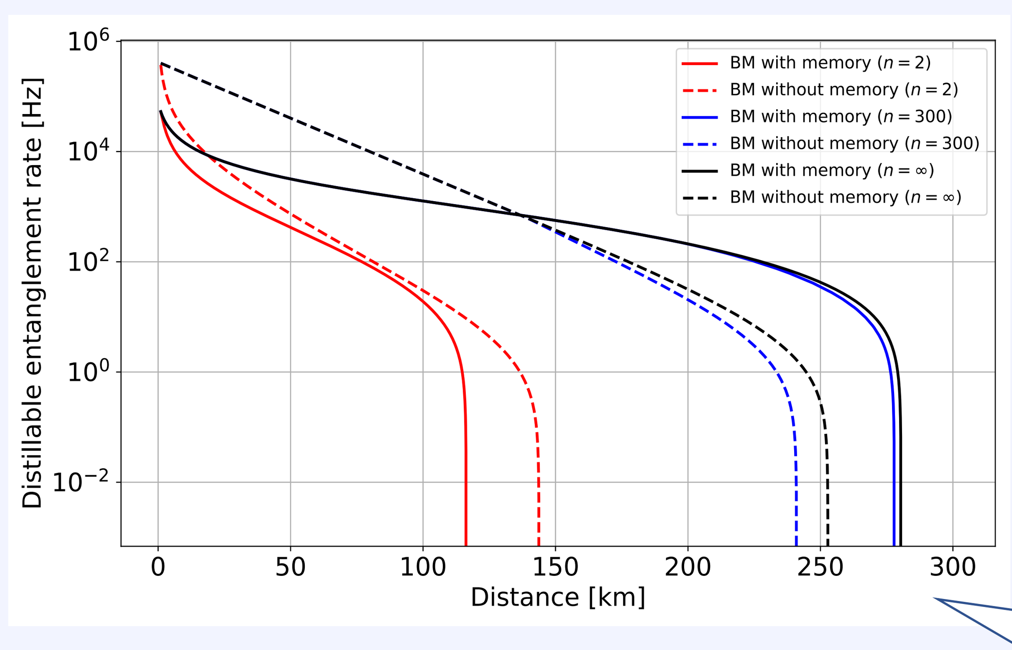


Node B_{i+1} measure its atom and announce the outcome, and two atoms result in Bell state.

Key point
Without waiting for T_i to succeed, T_{i+1} emits a photon.
This reduces the effect of dephasing by reducing the waiting time of T_i.

4. Result and Discussion

Comparison with memory-assisted and memory-less Bell measurement



Distillable entanglement rate $\geq R \times [1 - h(e_x) - h(e_z)]$ [5]

R : Noisy entanglement distribution rate

e_x : Bit flip error rate

e_z : Phase flip error rate

$h(x)$: binary entropy function

Pulse lengths are optimized according to the number of memories and node distance

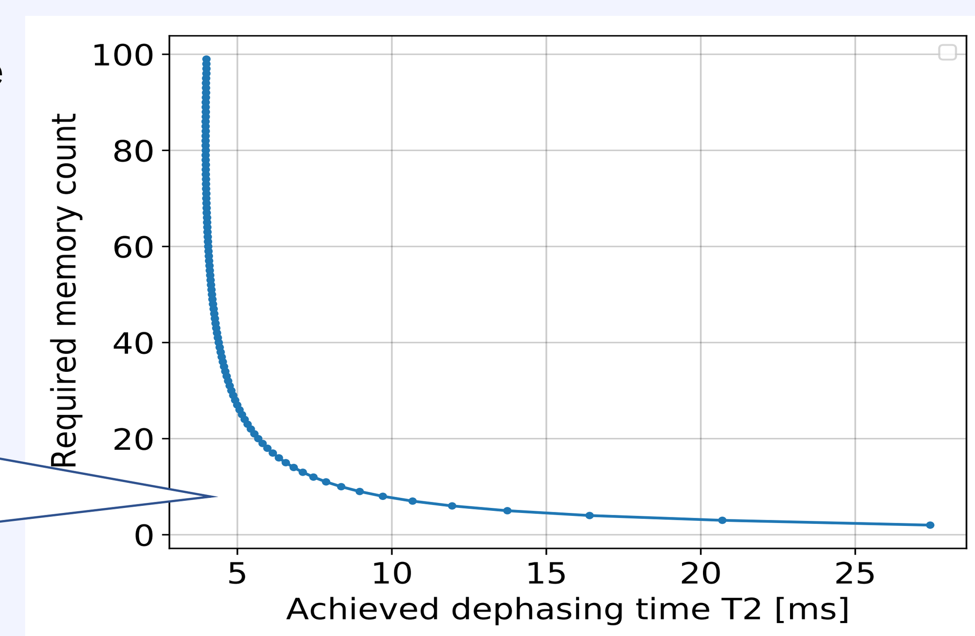
T_i and T_{i+1} have a sufficient number of memory, the memory-assisted Bell measurement shows higher rates in the long distance.

By increasing the number of memories, the memory-assisted Bell measurement can overcome the memory-less Bell measurement with the current parameters.

Achieved dephasing time T2 vs required memory count for advantage

We calculate the minimum dephasing time T2 required for the advantage of the memory-assisted Bell measurement at a certain distance.

When the dephasing time T2 is short, memory-assisted Bell measurements can show higher rates by increasing the number of memory.



Multiplexing of nanofiber cavities can improve performance and relax hardware requirements for advantage.

Reference:
[1]Bhaskar, Mihir K., et al. *Nature* 580.7801 (2020): 60-64.
[2]Nguyen, C. T., et al. *Physical Review B* 100.16 (2019): 165428.
[3]Kato, Shinya, et al. *Nature communications* 10.1 (2019): 1-6.
[4]Ruddell, Samuel K., et al. *Optics Letters* 45.17 (2020): 4875-4878.
[5]van Loock, Peter, et al. *Advanced Quantum Technologies* 3.11 (2020): 1900141.