PhD Forum: Evaluating and Designing Routing Protocols for Reliable Distributed Quantum Systems

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Distributed Quantum Systems' Applications

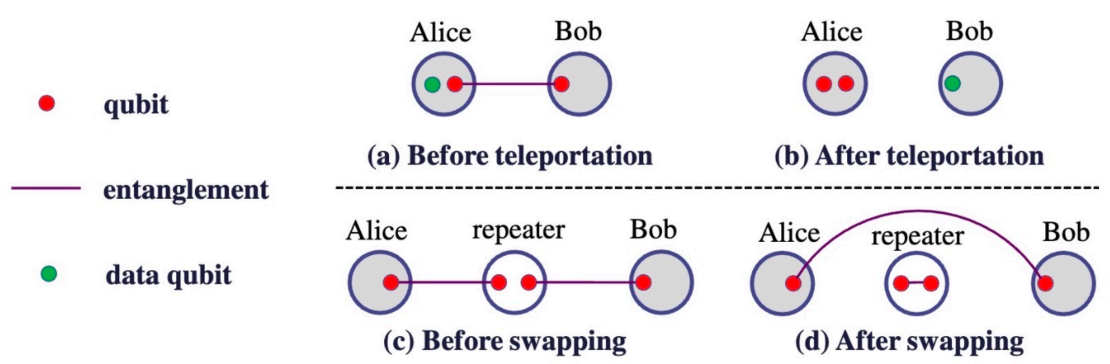
- Leadership elections without communication [DP2008]
- Clock Synchronization [Kómár+2014]
- Quantum Key Distribution (a cryptographic protocol) [BB2014]
- Distributed Quantum Algorithms [DP2008]

BUT, Quantum Network are unreliable

- We want to transmit Quantum Bits over a Quantum Network:
- aka "Qubits"
- $|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$
- Quantum Operations are 'noisy'
- Exponential loss over length of communication channels

How do you even transmit qubit in the first place?

- Option 1: "Tell-n-go" approach:
  - Problematic because of the exponential loss over length
- Option 2: State Teleportation:
  - More "moving parts", so to speak:
    - EPR Pairs
    - Swap operation
    - End-to-end EPR pairs (E2E pairs)
  - Application will use them to teleport the data qubit
  - Some applications use them directly

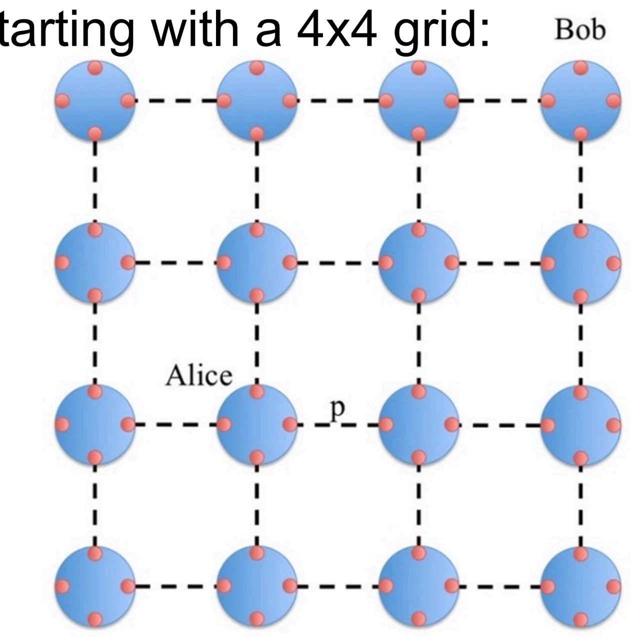


Example showing teleportation. Reproduced from [SQ2020]

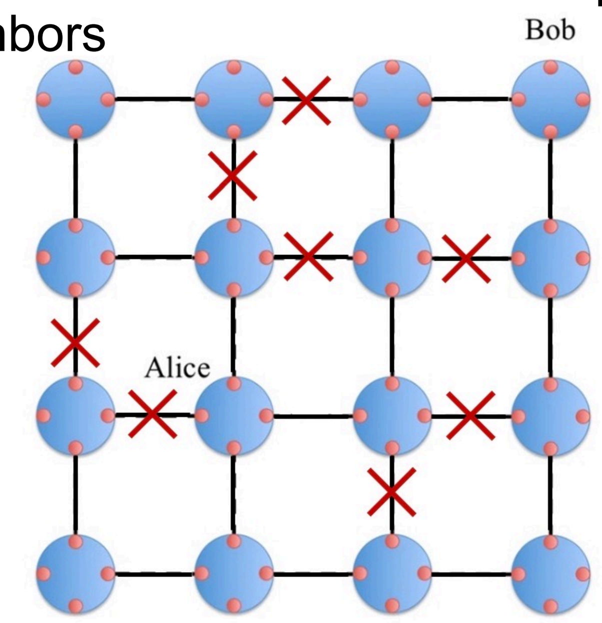
Example of how the 'State Teleportation' approach works

Figures are adapted from [Pant+2019]

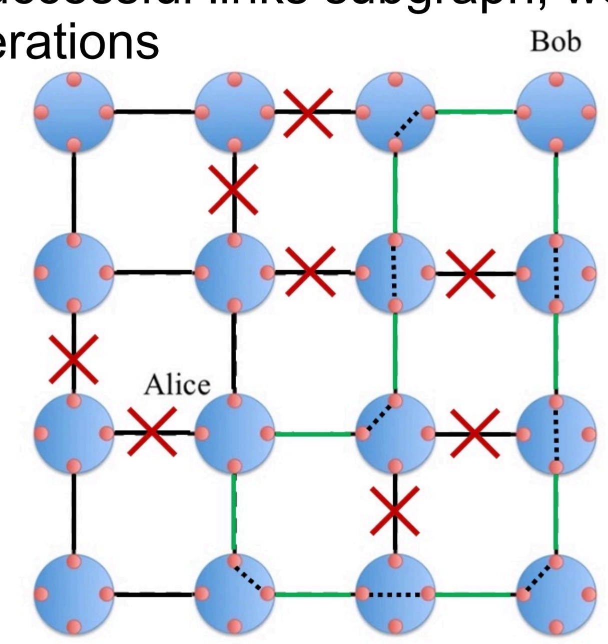
We are starting with a 4x4 grid:



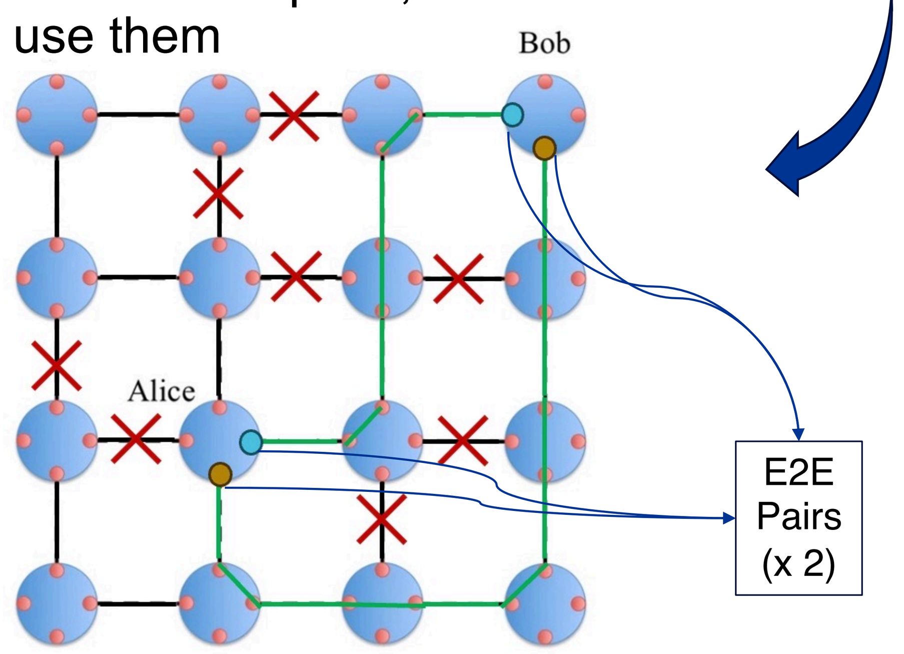
Not all nodes are able to share EPR pairs with their neighbors



On the successful links subgraph, we perform swap operations



Once we have the E2E pairs, we can let the application use them



Choices made in the teleportation example

We have to make certain choices when setting up the network for the state teleportation:

- On which edges do we attempt to establish EPR pairs?
- If we have more than one source-destination pair, then once we have the edges with successfully shared pairs, for which source-destination pair do we use these for?
- In what order do we attempt the swapping operations

Quantum Routing Algorithms

Quantum Routing Algorithms are concerned with such decisions. At the moment, there are quite a few of such algorithms in the literature, but they may or may not be more suited to particular network topologies, or applications.

It is hard to determine this as we lack a common platform to evaluate different routing algorithms due to lack of a high-level simulator.

Our approach

Compare routing algorithms at a higher level of abstraction on a common platform:

```
def node_algorithm():
    # phase 1:
    establish_links(self.neighbours)
    # phase 2:
    generate_routes(self.nw_subgraph)
    # phase 3:
    if self.role == 'repeater':
        do_swaps()
    else self.role == 'source':
        wait_for_e2e()
        teleport(self.dest_node, self.e2e_routes, self.data_qubit)
    else self.role == 'destination':
        wait_for_e2e()
        receive_data_qubit(self.src_node, self.e2e_routes)
```

Using NetSquid [Coopmans+2021] – a lower-level quantum network simulator – as the base:

```
def handler_node_receives(edge):
    quantum_memory_slot = map[edge.id]
    quantum_memory.put(edge.buffer)
    quantum_memory.apply_noise_model(some_noise_model, quantum_memory_slot)
    ...

def handler_edge_received(node, qubit):
    apply_noise_model(some_noise, qubit)
    if do_i_drop() == 'no':
        ...
    else:
        return
```

Our Goal

Using the tool, understand how different routing algorithms work on realistic quantum networks:

- Realistic network topologies
- Realistic hardware modelling (e.g. quantum memories, channels)

Get insights into tradeoffs between routing algorithms

- How do different design choices affect our performance (by various metrics: E2E pair generation rate, some cost metric, fidelity, etc)

Basically,

- Help us really understand, through experimentation, how they work
- Help us better design and evaluate these algorithms

REFERENCES

- [BB2014] Charles H. Bennett and Gilles Brassard. "Quantum cryptography: Public key distribution and coin tossing". In: Theoretical Computer Science 560 (2014). Theoretical Aspects of Quantum Cryptography – celebrating 30 years of BB84, pp. 7–11
- [Coopmans+2021] Tim Coopmans et al. "NetSquid, a NETwork Simulator for QUantum Information using Discrete events". In: Communications Physics 4.1 (July 2021), p. 164. ISSN: 2399-3650. DOI: 10.1038/s42005-021-00647-8.
- [DP2008] Vasil S. Denchev and Gopal Pandurangan. "Distributed quantum computing: a new frontier in distributed systems or science fiction?" In: SIGACT News 39.3 (Sept. 2008), pp. 77–95.
- [Kómár+2014] P. Kómár, E. M. Kessler, M. Bishof, L. Jiang, A. S. Sørensen, J. Ye and M. D. Lukin "A quantum network of clocks". In: Nature Physics 10.8 (Aug. 2014), pp. 582–587
- [Pant+2019] Pant, M., Krovi, H., Towsley, D., Tassiulas, L., Jiang, L., Basu, P., Englund, D., & Guha, S. (2019). Routing entanglement in the quantum internet. Npj Quantum Information, 5(1). https://doi.org/10.1038/s41534-019-0139-x
- [SQ2020] Shi, S., & Qian, C. (2020). Concurrent Entanglement Routing for Quantum Networks. SIGCOMM '20. https://doi.org/10.1145/3387514.3405853