Quantum Internet: Some Research Challenges

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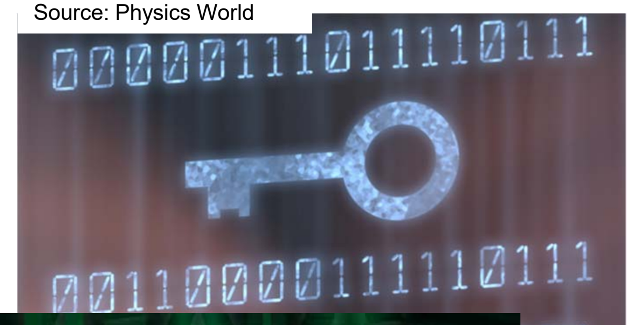
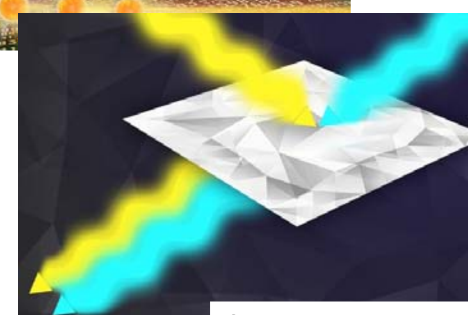
Why Quantum Interet?

- cryptography, security – quantum key distribution (QKD)
- (distributed) quantum computing – Shor's algorithm, …
- high resolution sensing
- high-precision clock synchronization

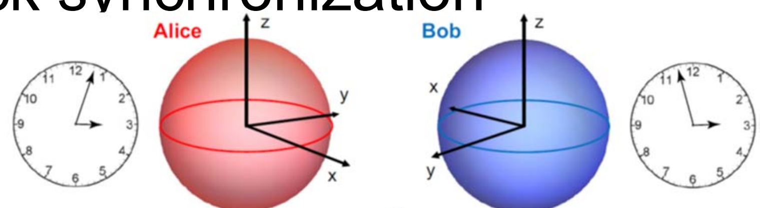
Source: Physics World



Source: IQOQI, H. Ritsch



Source: MIT Technology



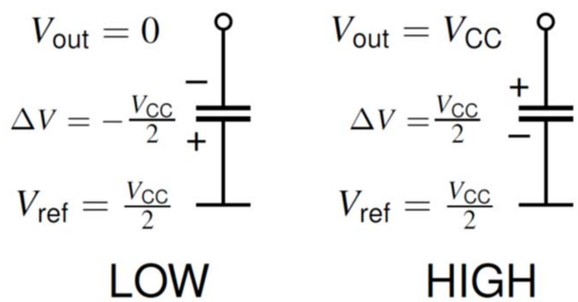
Source: nature.com

Outline

- quantum 101
- challenges
- routing
- quantum swithing

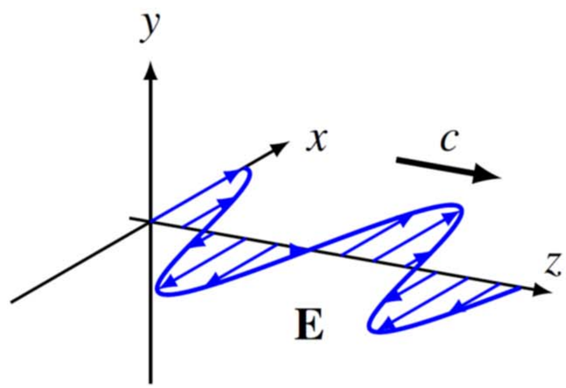
Elementary quantum 101

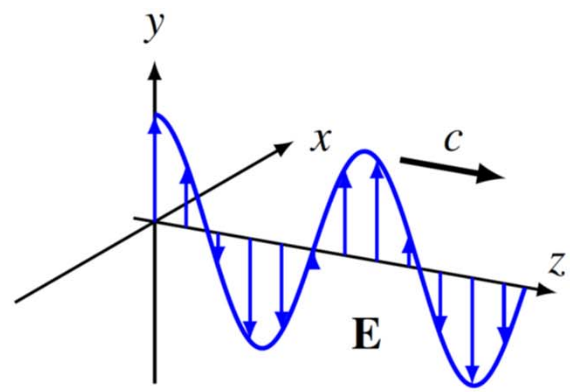
- bit has only two values: 0,1
- physically represented by two state device



Quantum bits

- qubit - two-state quantum-mechanical system
- example: photon polarization





Horizontally polarized

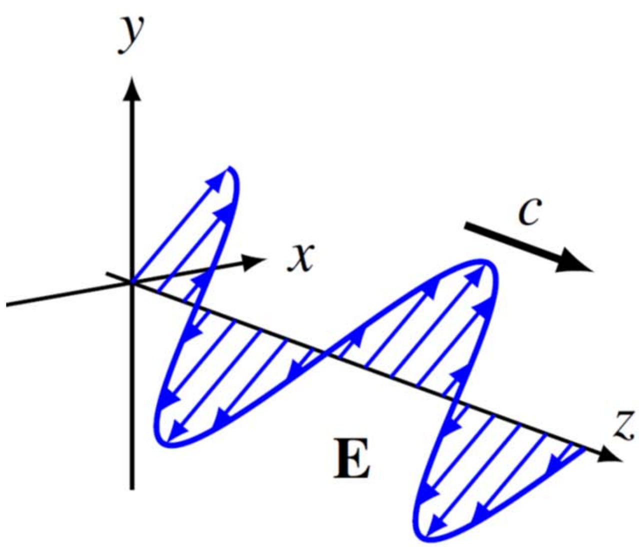
$$|x\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

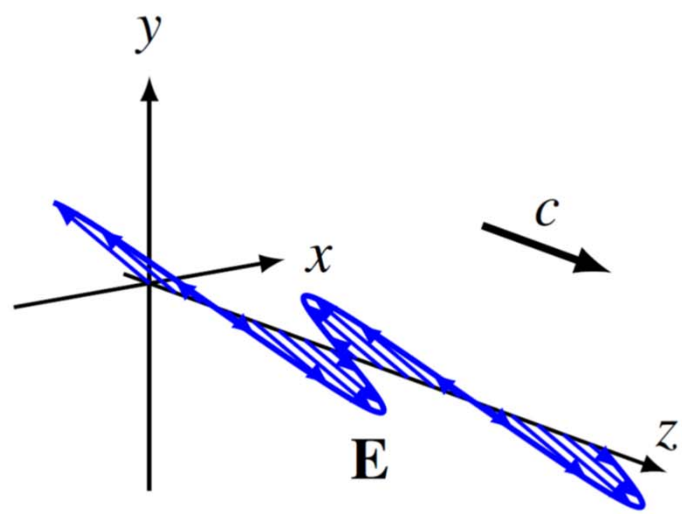
Vertically polarized

$$|y\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Superposition of states

$$|\phi\rangle = \alpha|x\rangle + \beta|y\rangle, \qquad \alpha^2 + \beta^2 = 1$$



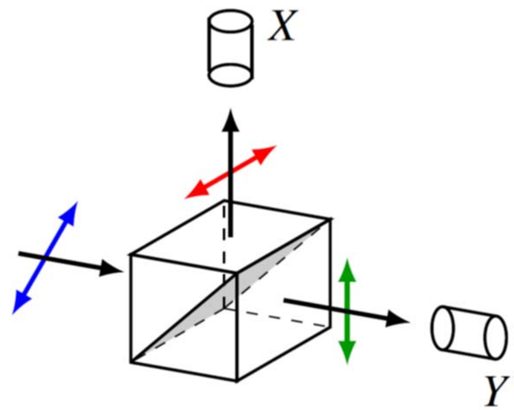


$$|+\rangle = \frac{1}{\sqrt{2}}(|x\rangle + |y\rangle) = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} \qquad |-\rangle = \frac{1}{\sqrt{2}}(|x\rangle - |y\rangle) = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$$

Measurement

- uncountable number of states

$$|\phi\rangle = \alpha\,|x\rangle + \beta\,|y\rangle$$



- single photon: either X or Y goes off, not both
- repeat many times: $P(x) = \alpha^2, \; P(y) = \beta^2$

Two qubits

- four basis states, $|00\rangle, |01\rangle, |10\rangle, |11\rangle$

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle, \qquad \sum \alpha_{ij}^2 = 1$$

- Bell state (Einstein-Podolsky-Rosen(EPR) pair)

$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

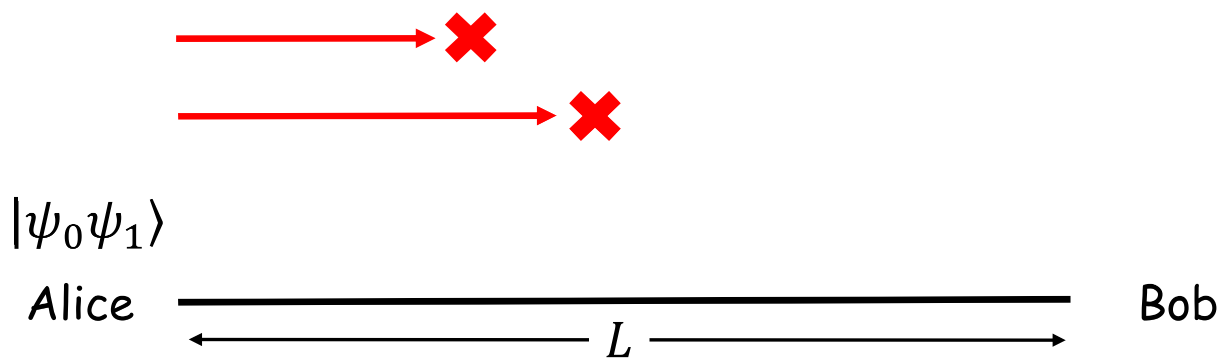
Two qubit states

- Bell state (EPR pair)

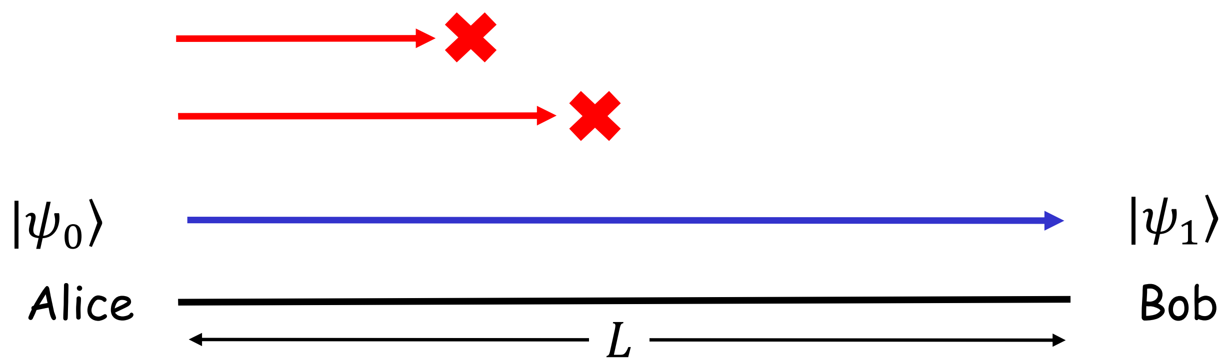
$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

- measuring first qubit yields 0,1
  - if 1, measuring second qubit yields 1
  - if 0, measuring second qubit yields 0
  - can generate shared randomness across distances
- other powerful entanglements
- basis of quantum computing, quantum key distribution

Long distance entanglement



Long distance entanglement

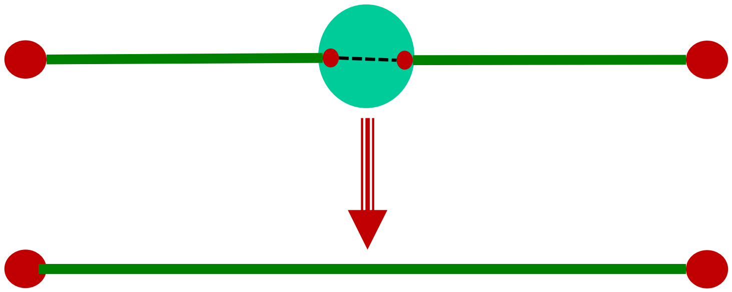


$P_{succ} = e^{-\alpha L}$ in fiber

P_{succ} decays exponentially fast in distance

Quantum Repeater

- quantum memories to store qubits
- generate link Bell states (entanglements)
- propagate entanglements
  - destructive Bell state measurement
  - note: repeater does not know superposition state



Transmitting Quantum Information

Suppose Alice wants to send qubit to Bob

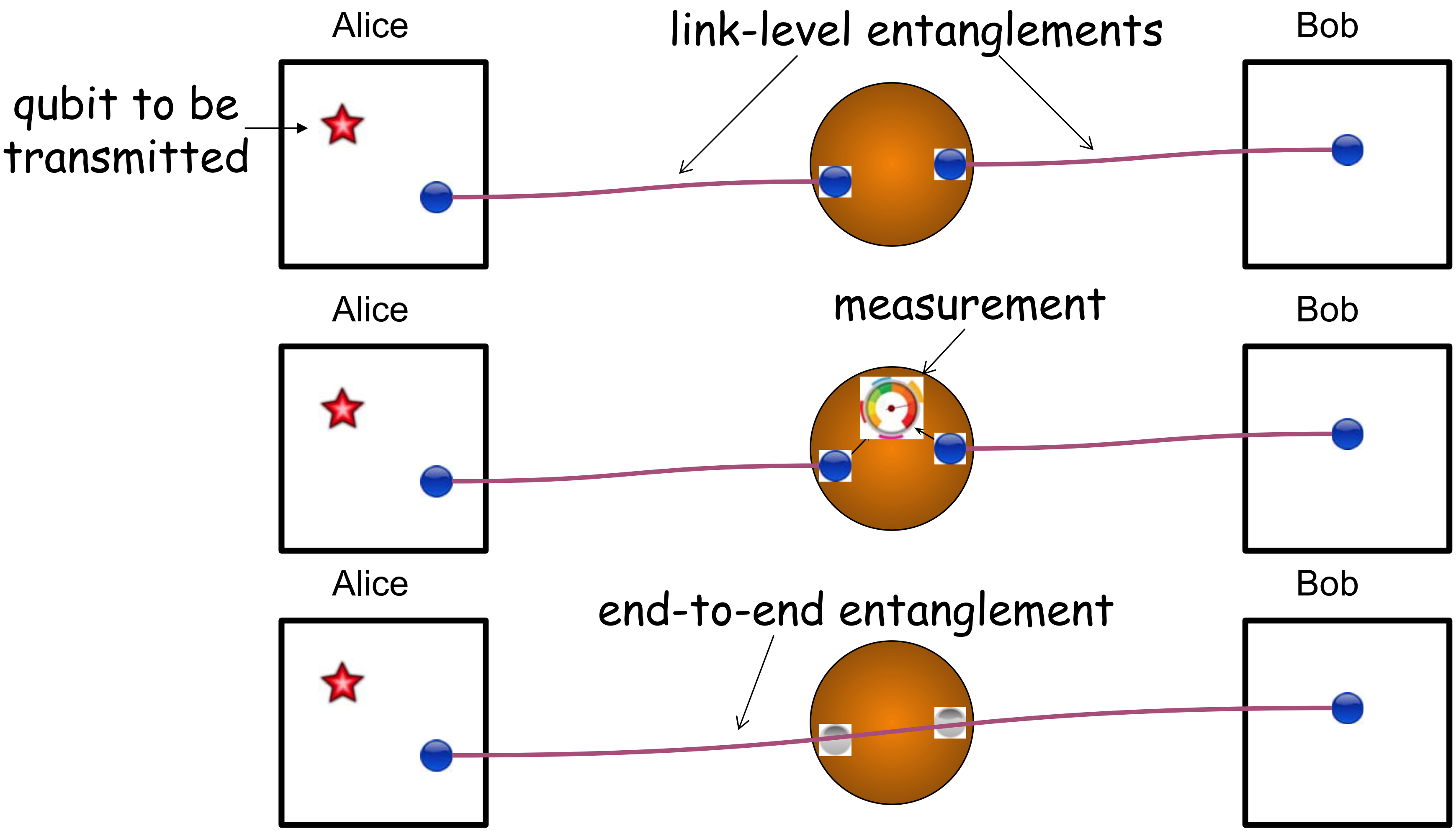
End-to-end entanglements

+

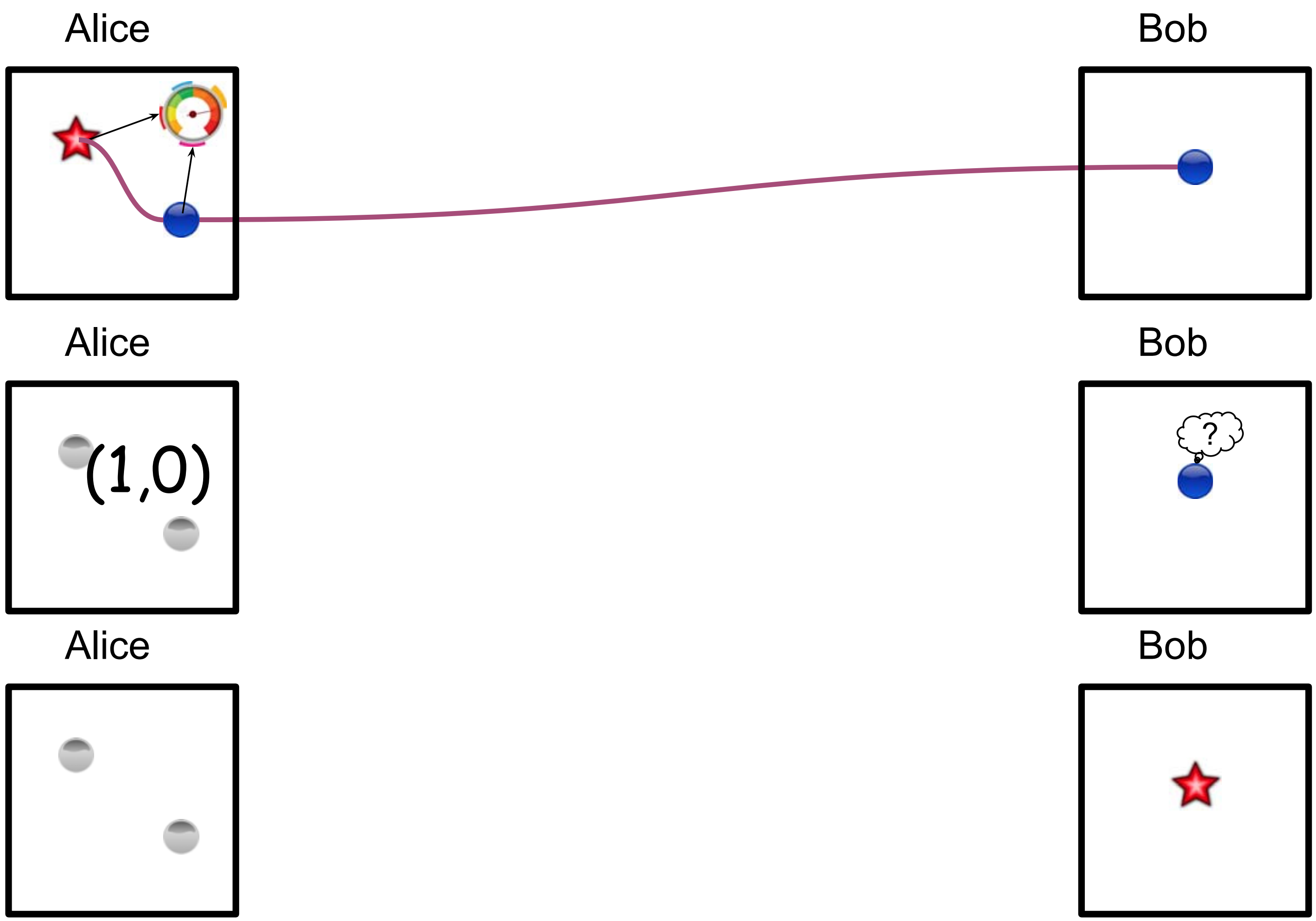
Teleportation*

*Quantum teleportation consumes a resource: an **entanglement**.

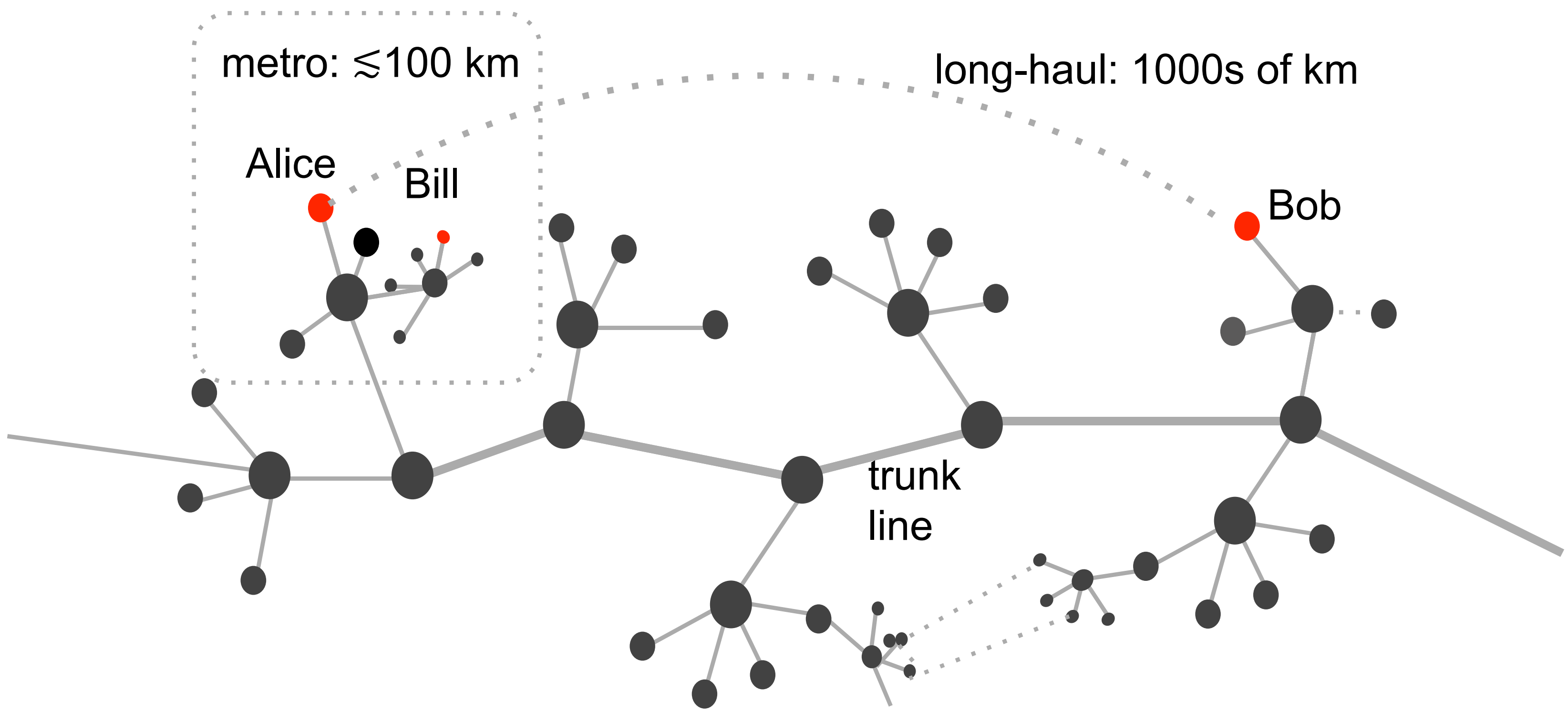
Entanglement Creation



Teleportation



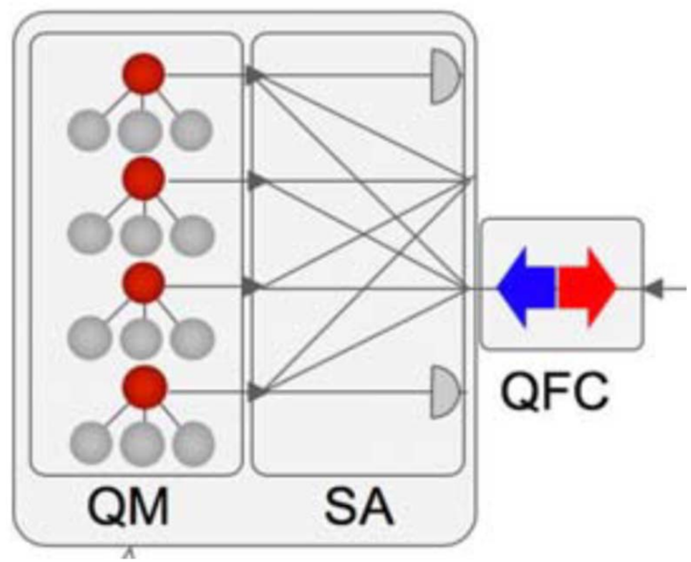
Quantum Networks



Many Challenges

- devices
  - memories
    - decoherence
  - photon detectors
  - transducers
- quantum switch
  - putting pieces together
- quantum network

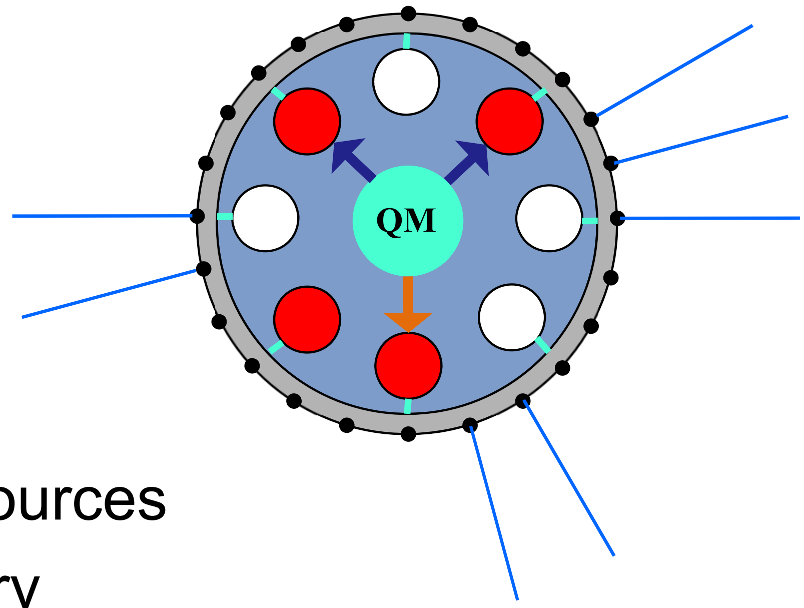
Quantum switch



Networking Challenges

- evaluating capacity region
- resource allocation
- stateless vs stateful control
- static routing vs opportunistic routing

A quantum switch



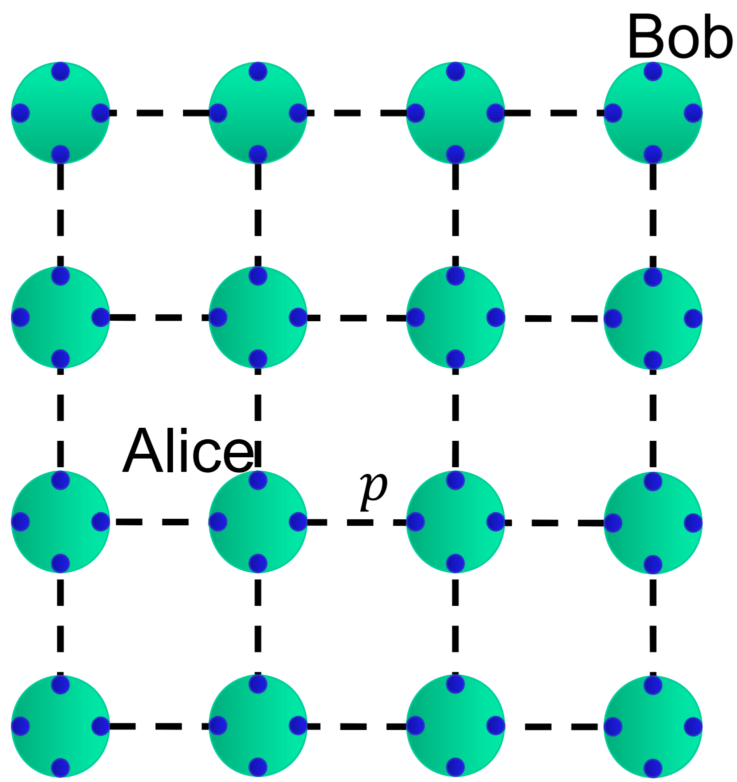
- entanglement sources
- quantum memory
- fault-tolerant quantum logic, e.g., quantum measurements (QMs), …
- classical computing and communications

State information, path diversity

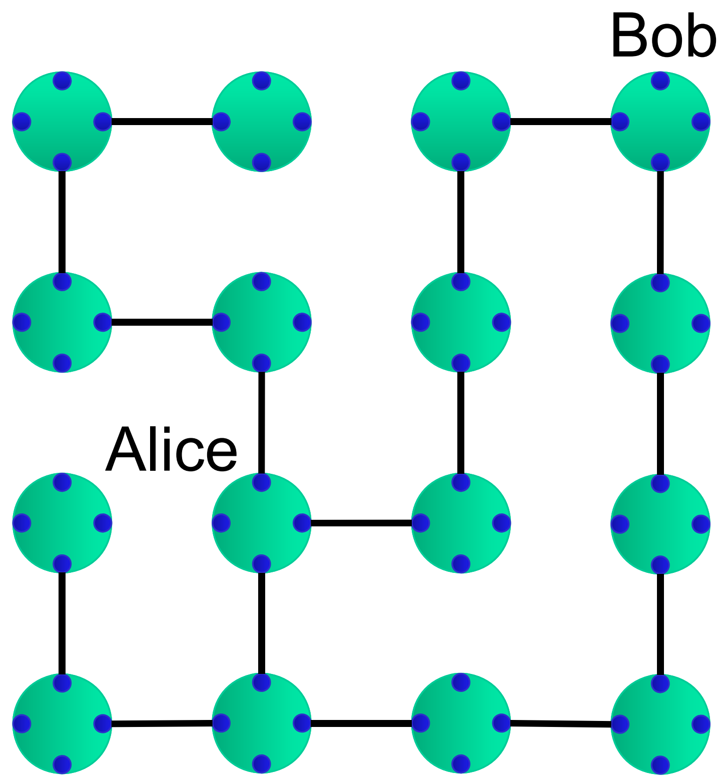
- grid network
- single mode per link
- one memory per repeater per link per mode
- one pair of end-to-end communicating nodes

Pant, etal. NPJ Quantum Information (2019)

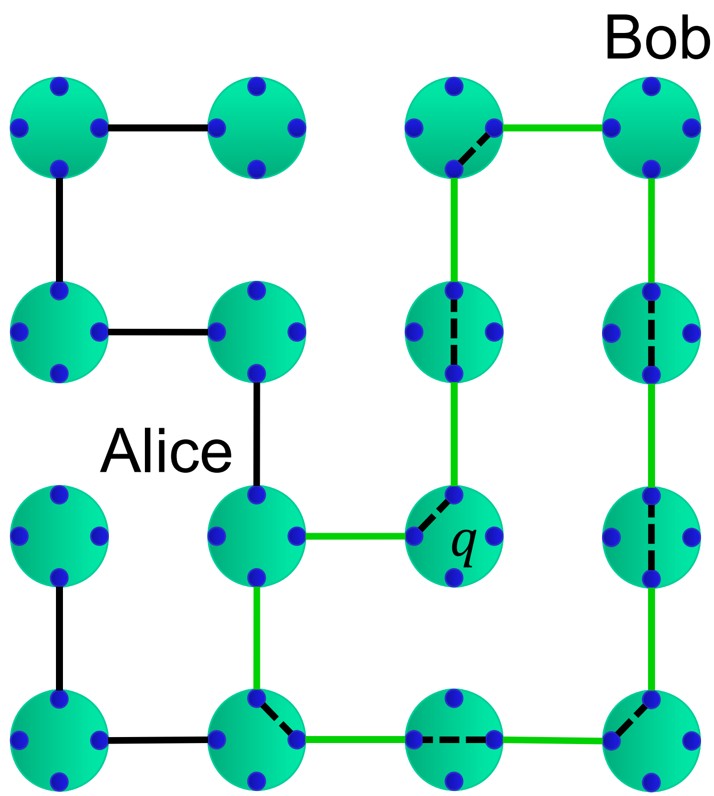
Grid network



Grid network - phase 1



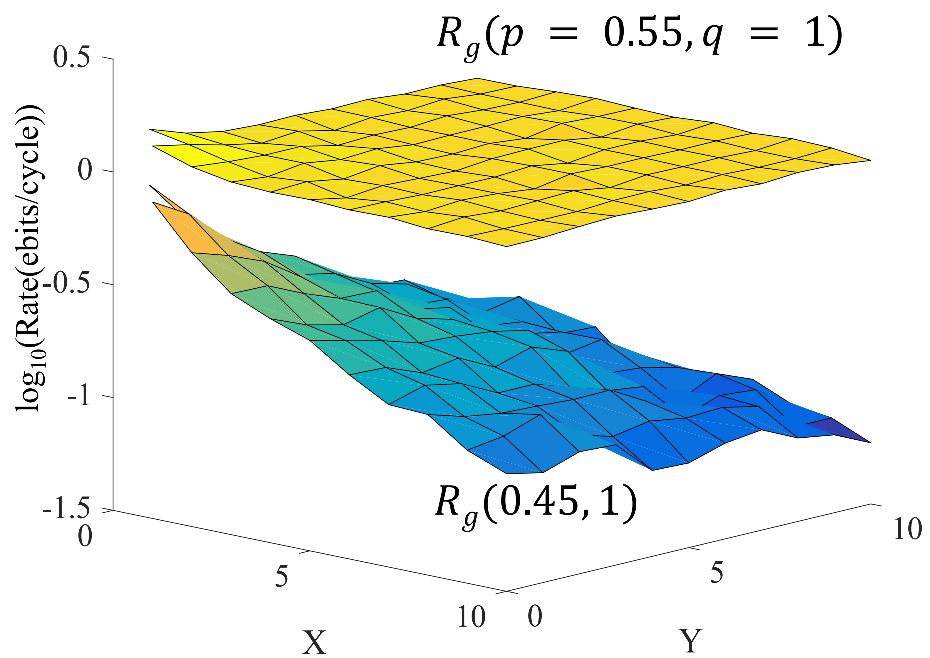
Grid network - phase 2



Rate dependence on p

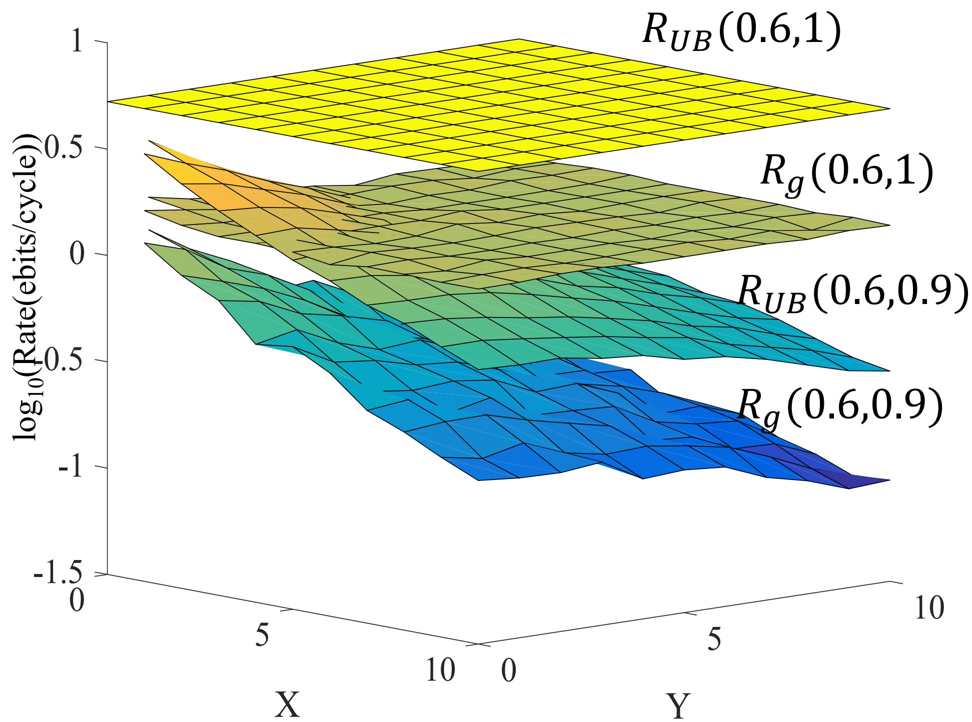
- greedy shortest path algorithm
  - find shortest path
  - next shortest path
  - …
- requires global information
- $R_g(p,q)$ – entanglement rate

Note: when $q = 1$, 2-D grid percolates at $p > 0.5$

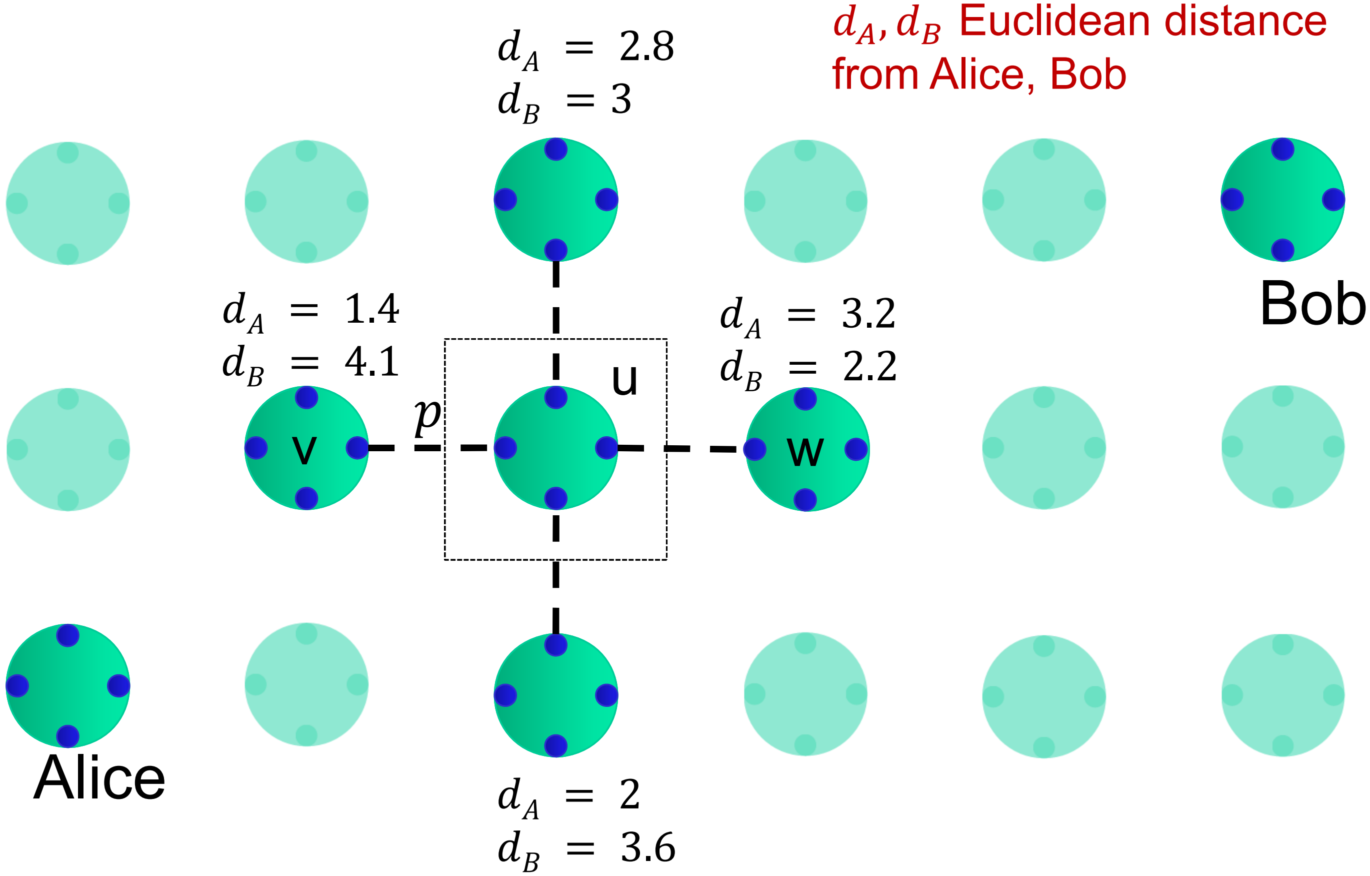


Value of global state information

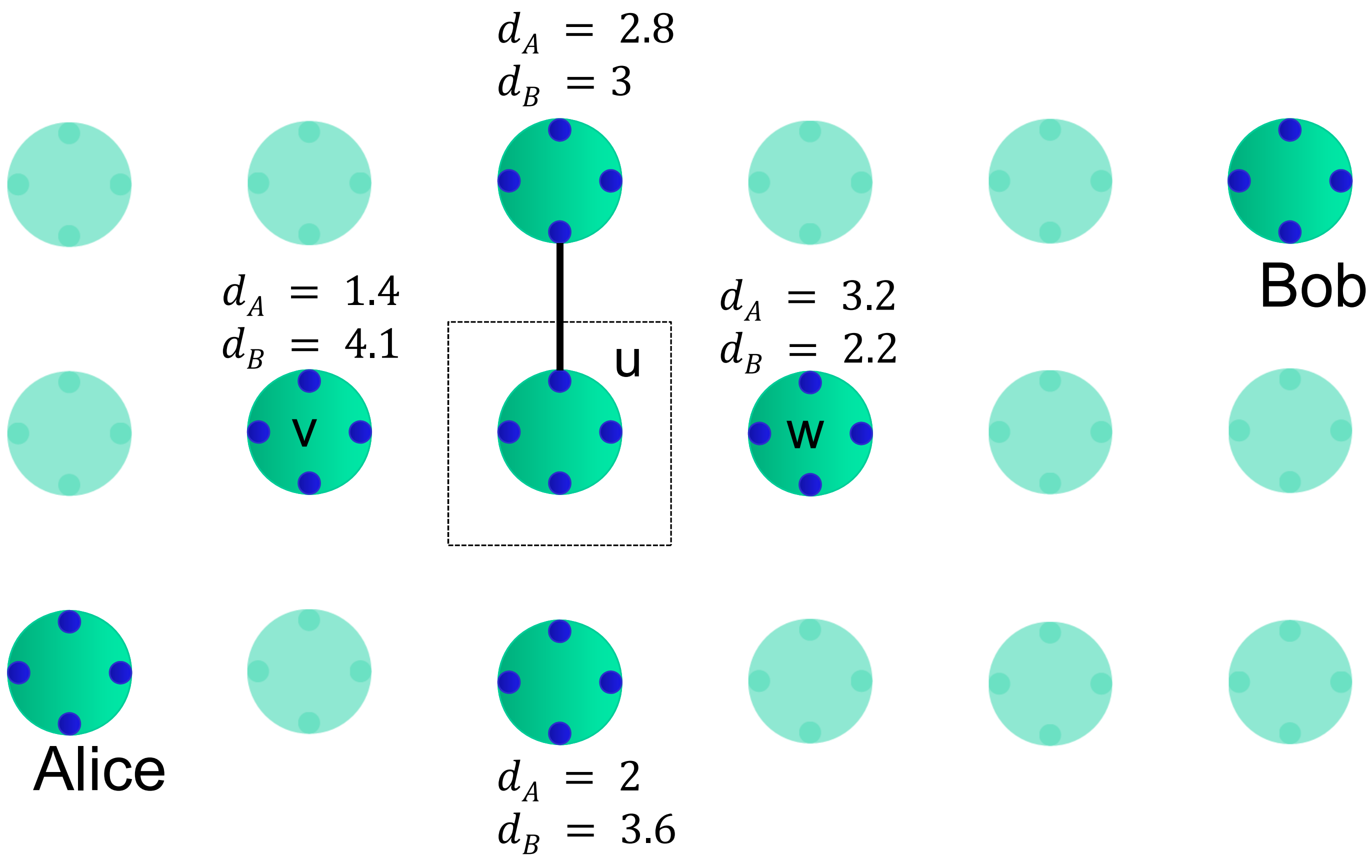
- $R_{UB}(p,q)$ – upperbound
- $q = 1$, max flow
  - achievable with global information
- $q < 1$, $4 \times R_g$



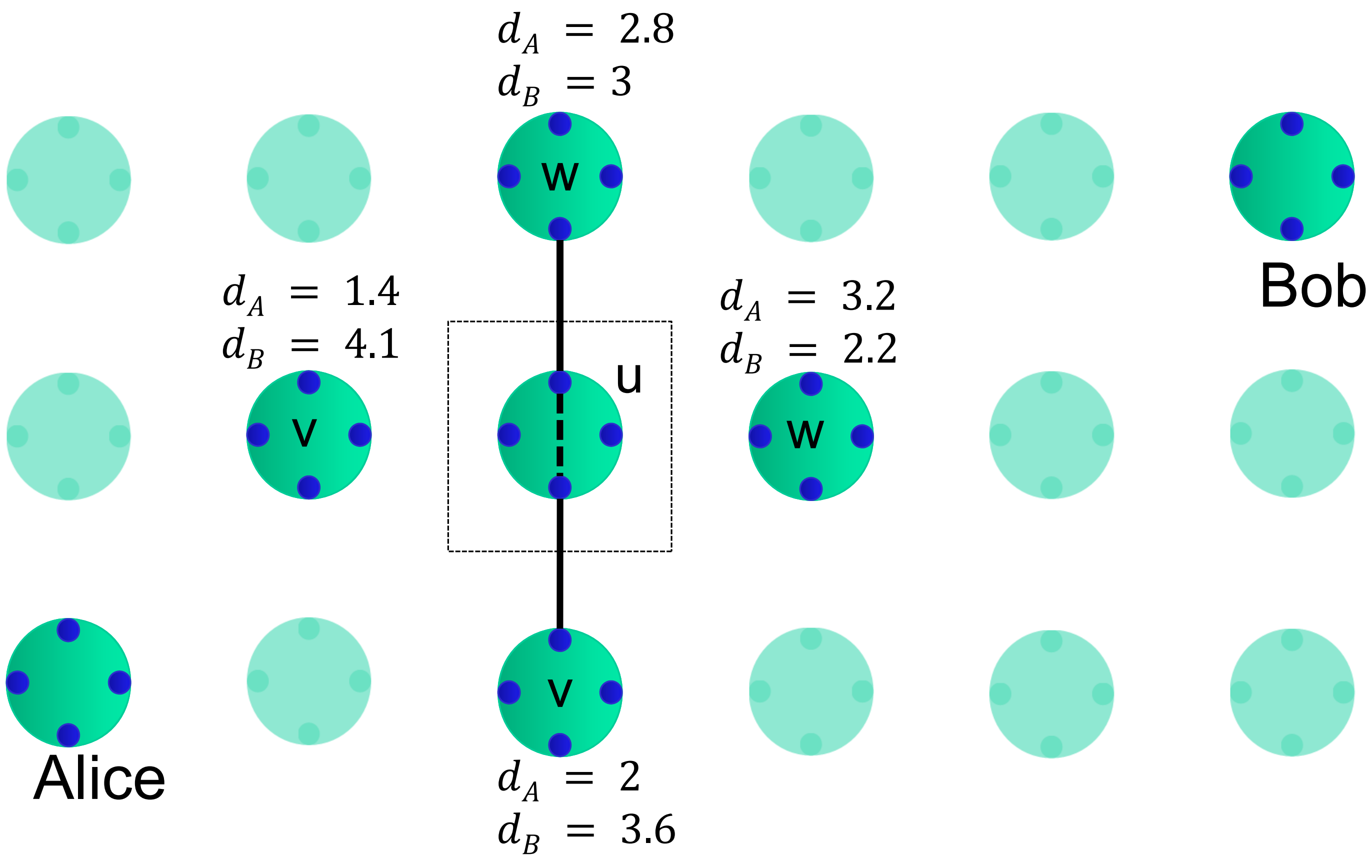
Routing entanglement flows with local state information



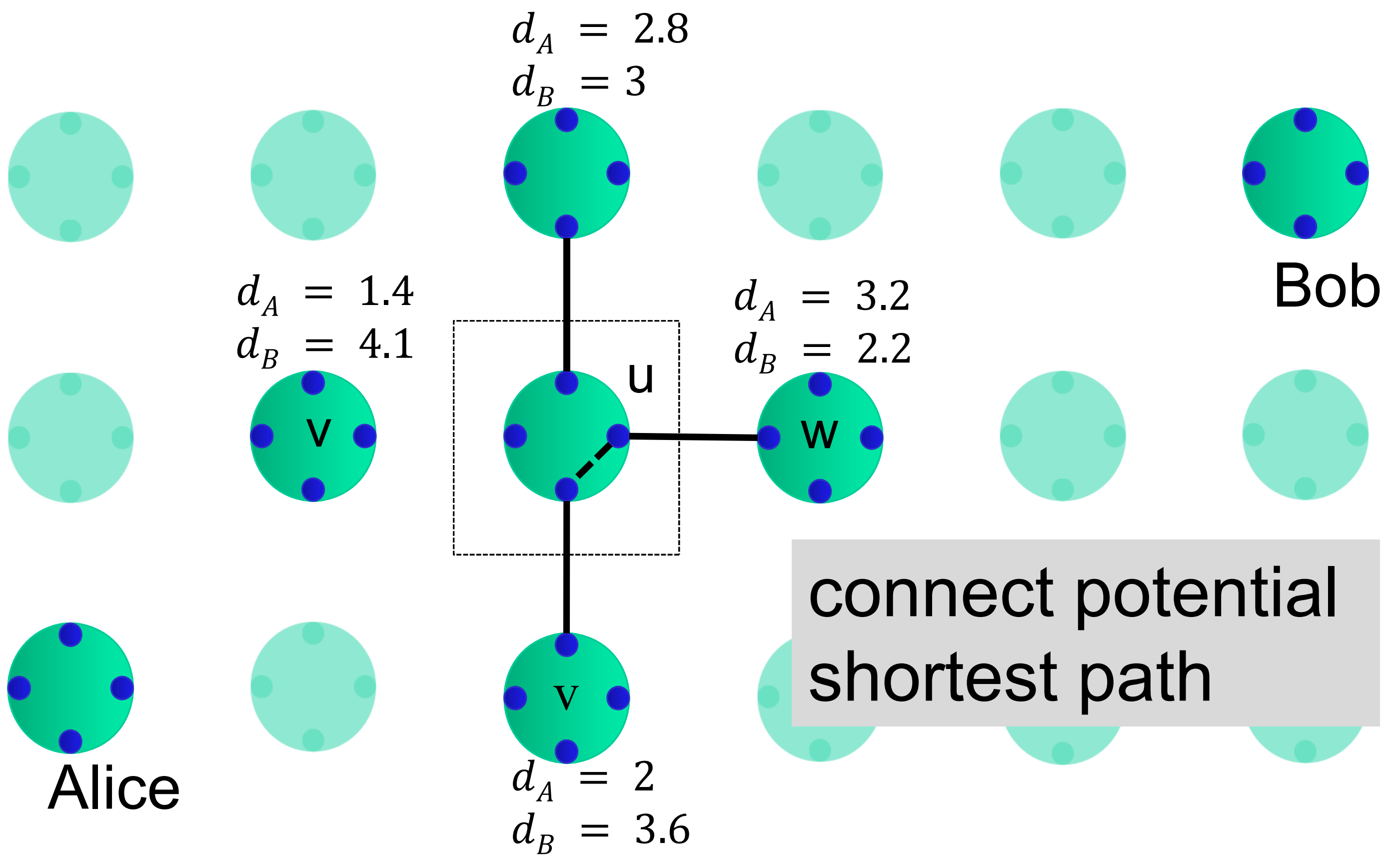
Routing entanglement flows with local state information



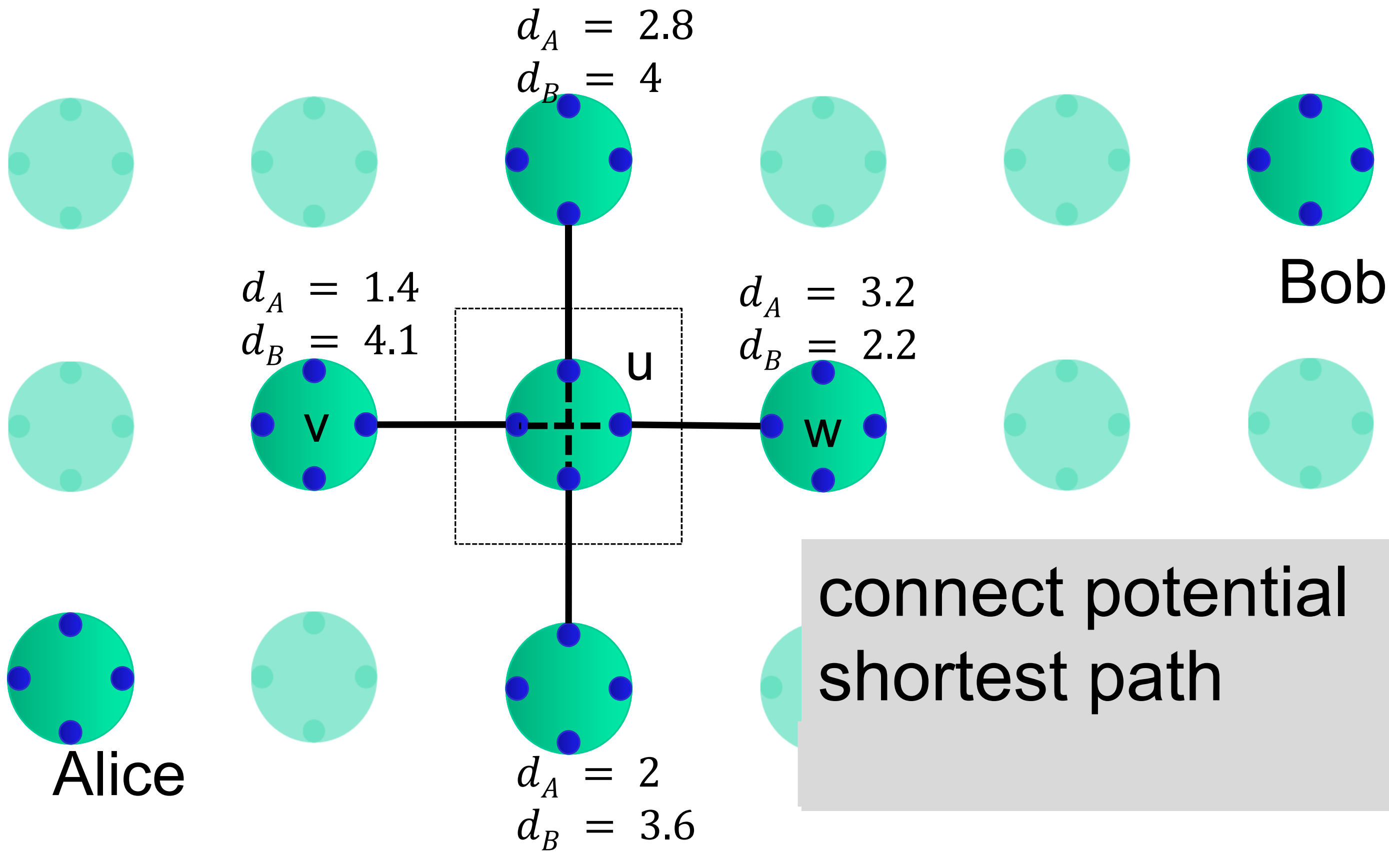
Routing entanglement flows with local state information



Routing entanglement flows with local state information

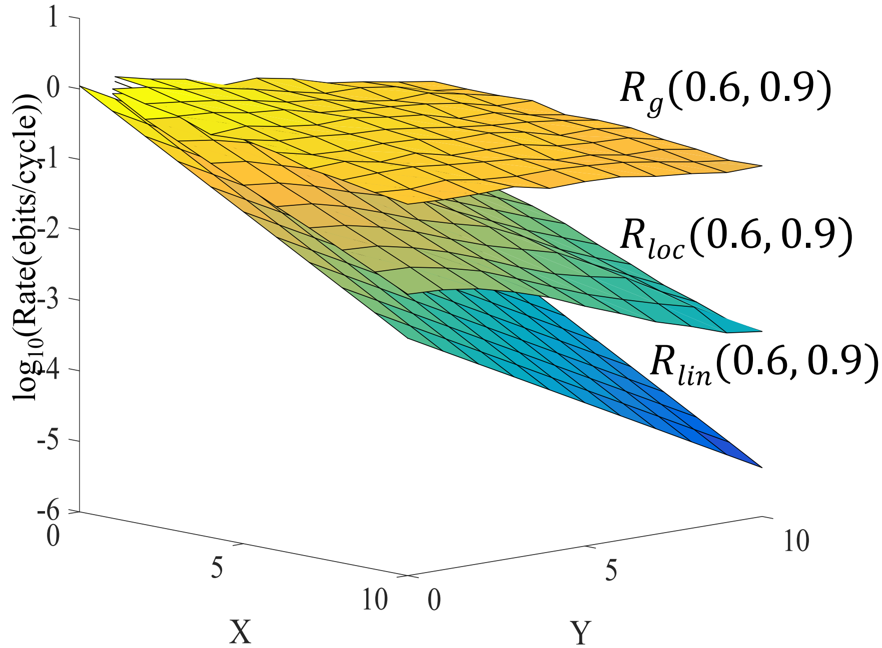


Routing entanglement flows with local state information

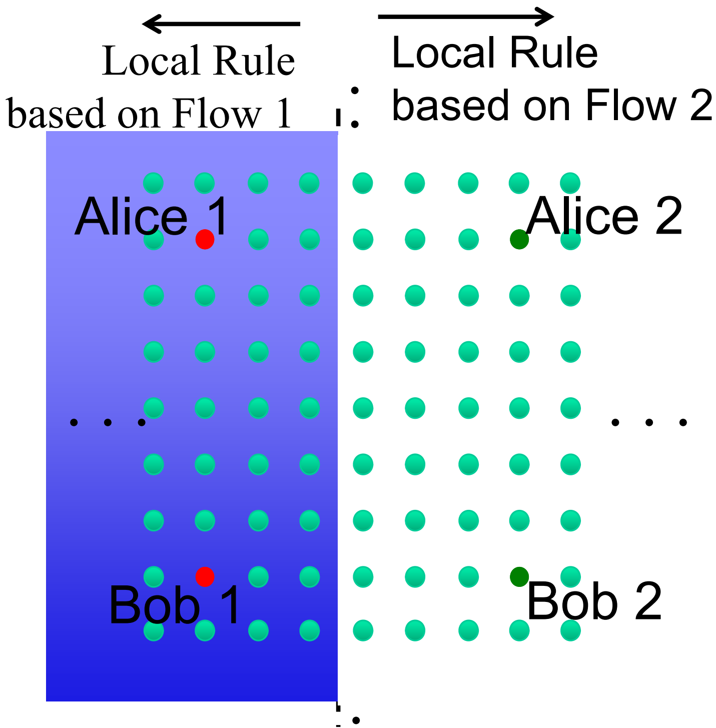


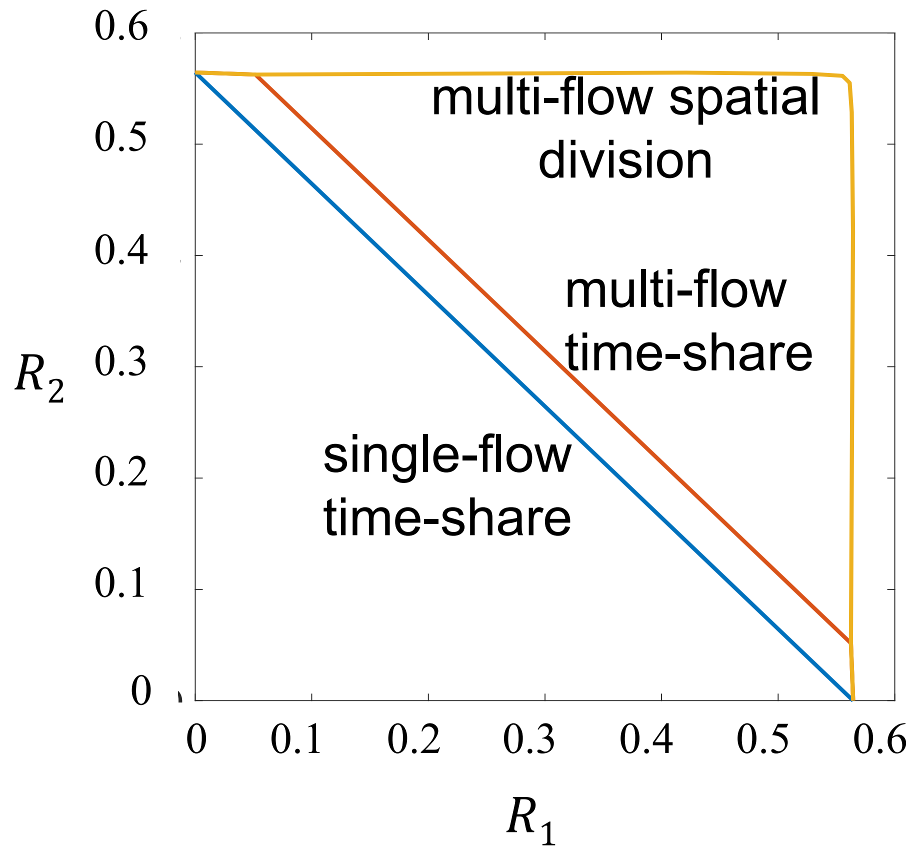
Local information and diversity

- $R_{loc}(p,q)$ – rate using local rule to set up most likely paths
- $R_{lin}(p,q)$ - rate over single path between end points
  - no diversity

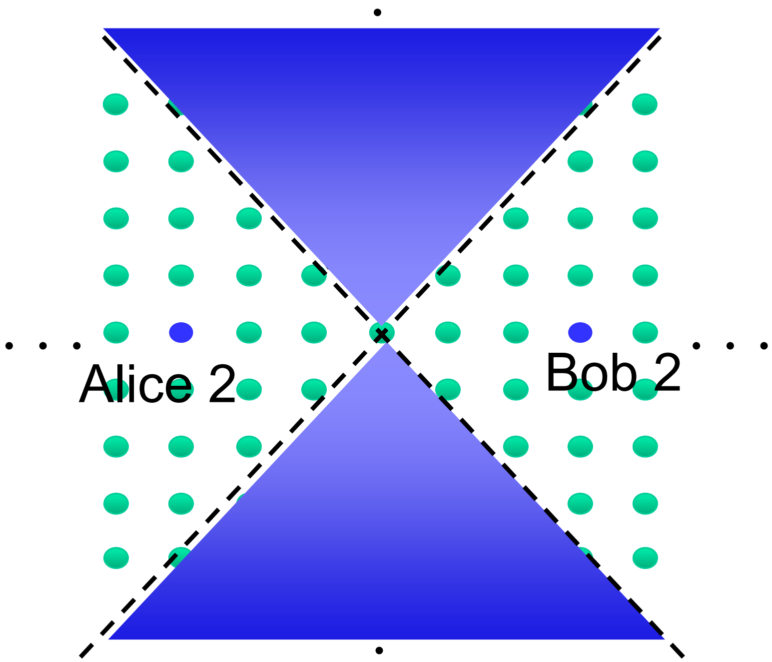


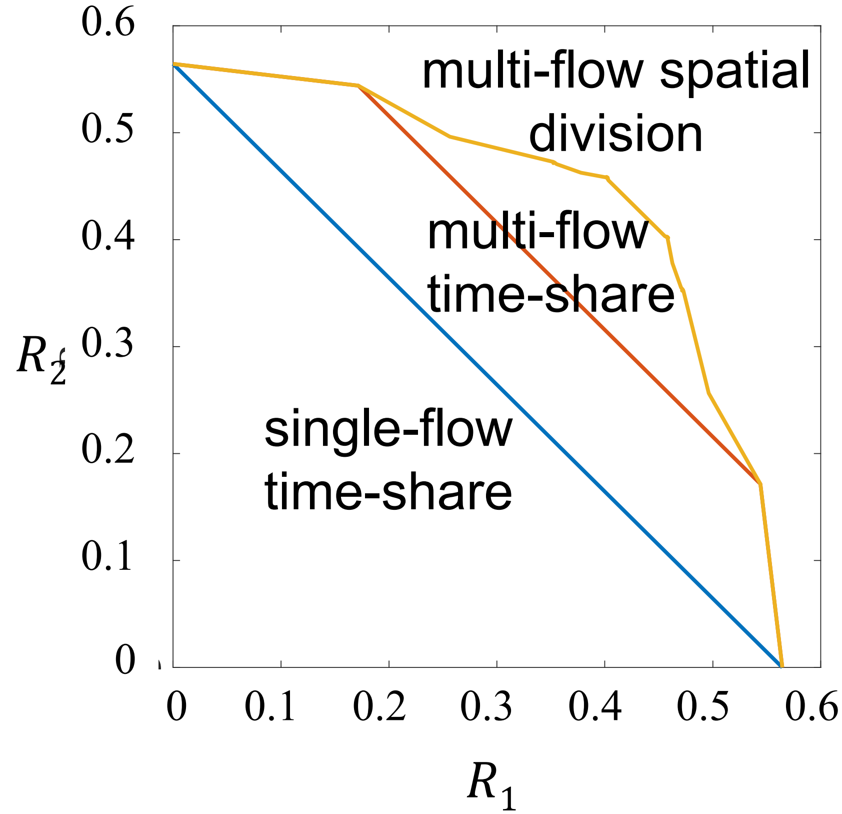
Multi-flow routing





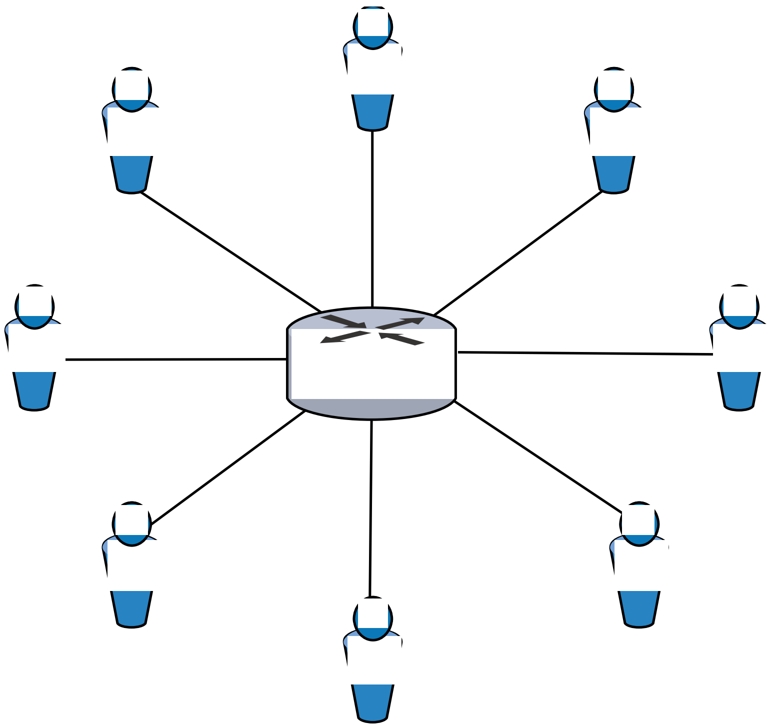
Multi-flow routing





What if switches have “many” good quality quantum memories?

Quantum switch

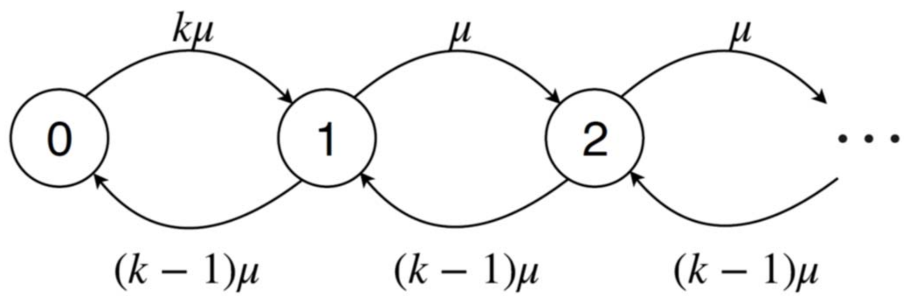


- any two users want to share an entanglement
- link Bell states generated according to Poisson process, μ_i, link I
- switch can store B qubits
- Bell state measurement success probability q
- switch follows *Oldest Link Entanglement First (OLEF)* rule

Vardoyan, etal. arXiv:1903.04420 (2019)

Model

- simple birth-death process, $\mu_i = \mu$



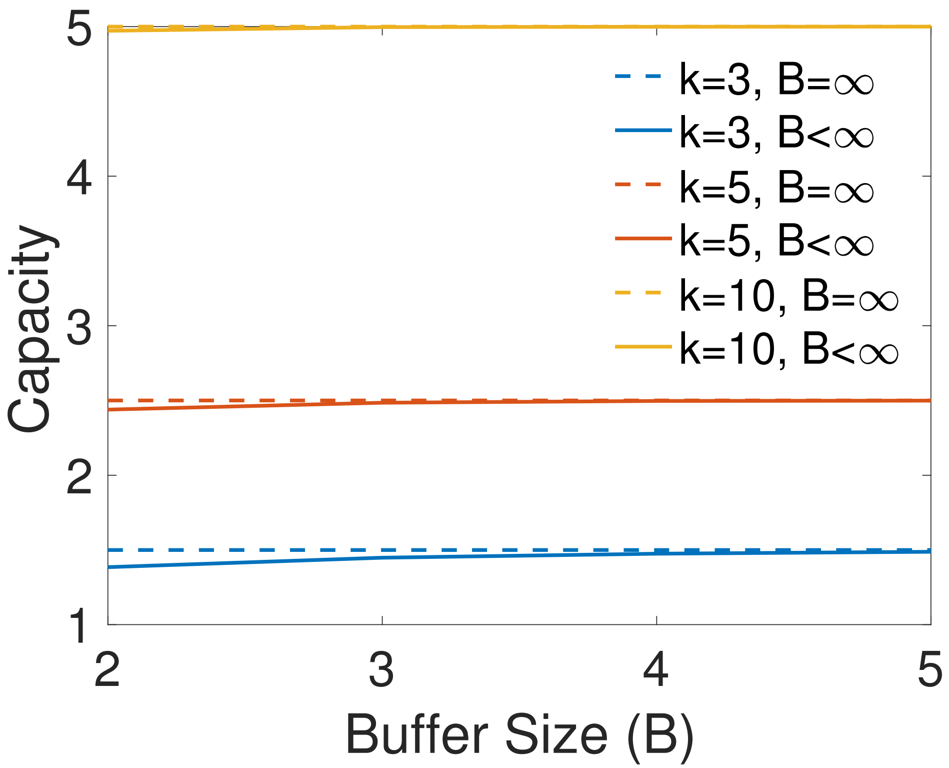
- switch capacity, $B = \infty$

$$R = \frac{q\mu k}{2}$$

- expected number stored qubits

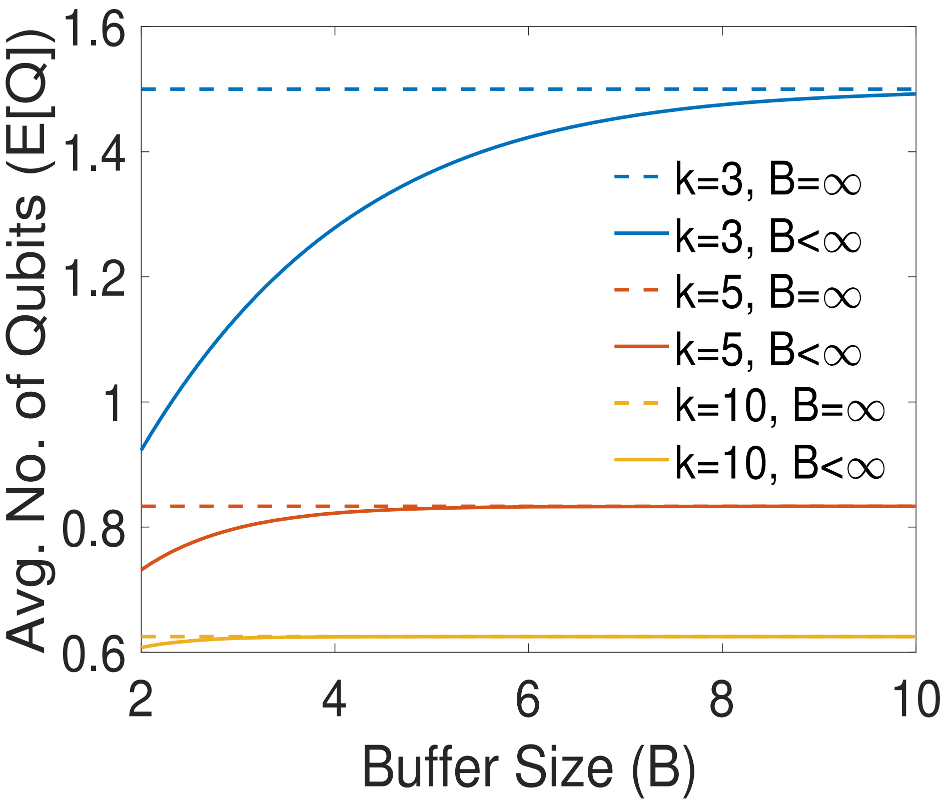
$$E[Q] = \frac{k}{2(k-2)}$$

Buffer size, capacity



- impact of buffer size on entanglement capacity
- small memory requirement

Buffer size and $E[Q]$

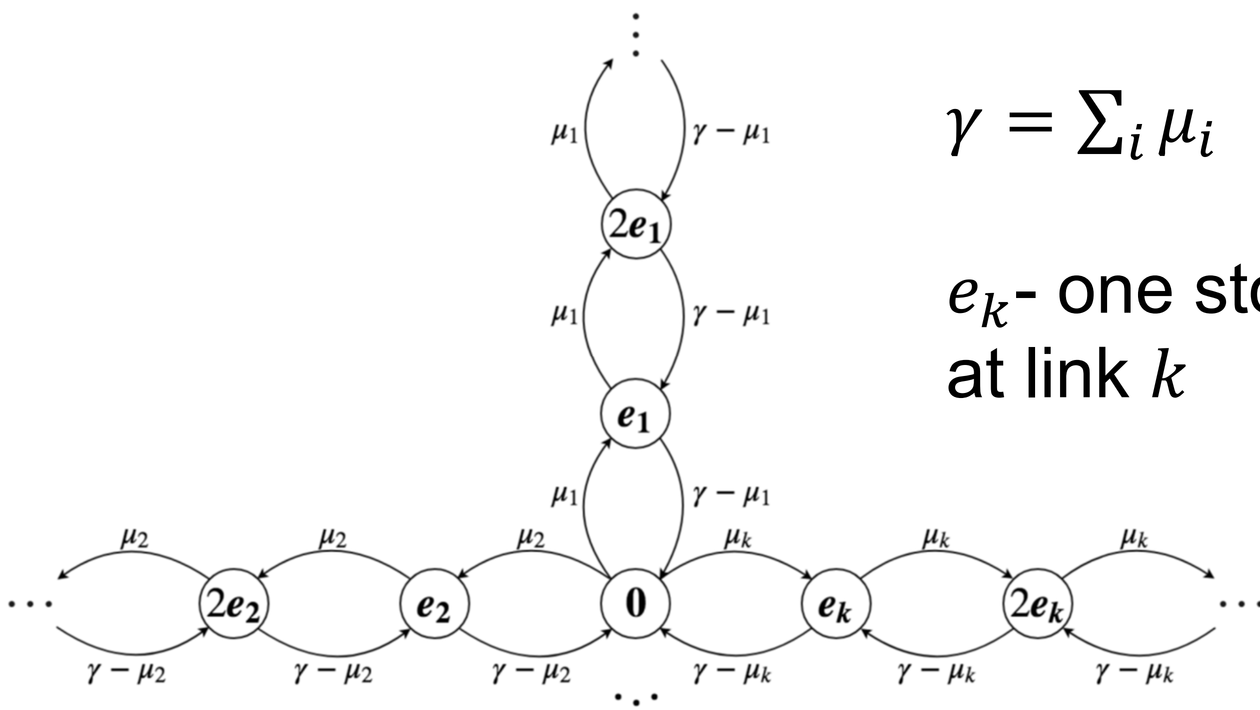


Buffer usage low

- $E[Q] < 1$ for practical configurations

Link heterogeneity

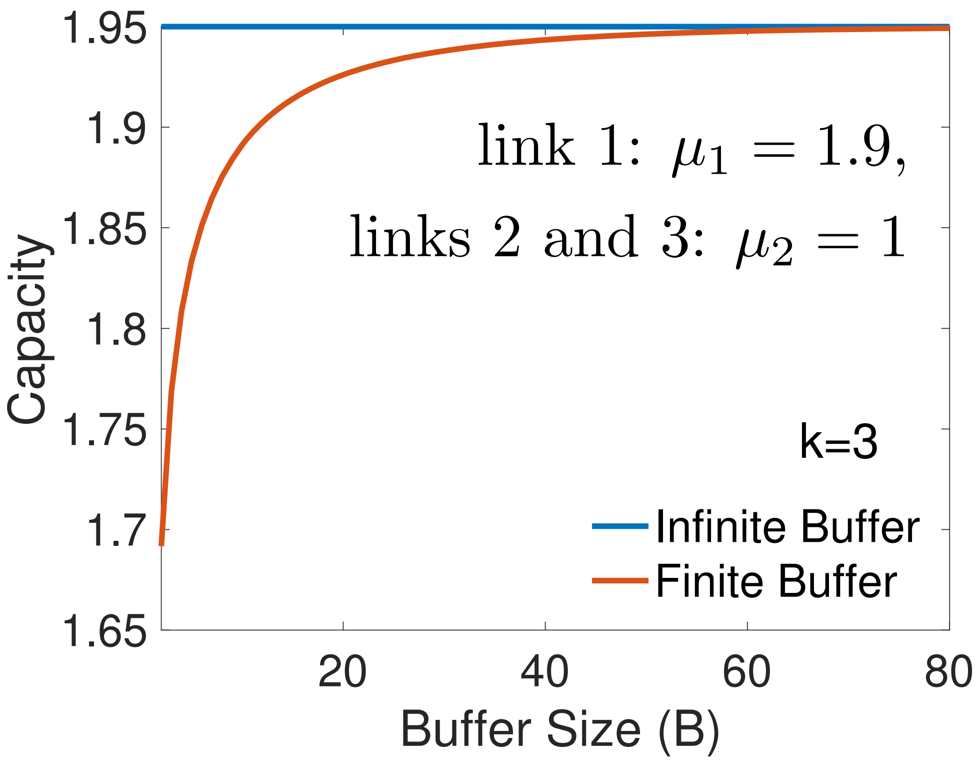
- continuous time Markov chain can be used to obtain stability conditions, expressions for $R, E[Q]$



$\gamma = \sum_i \mu_i$

e_k- one stored qubit at link k

Example, $k = 3$: capacity



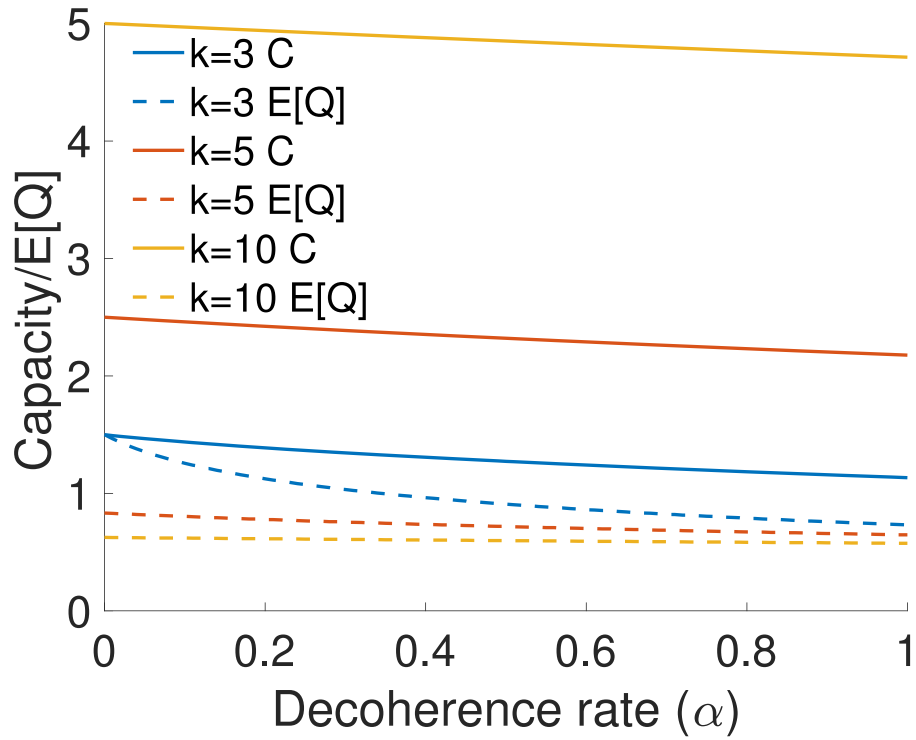
- one link nearly twice as fast as other two links
- mismatch causes storage of entanglements for that link

Decoherence:

Decoherence model:

- qubit good or bad
- α - rate qubit goes from good to bad

- decoherence has little effect when $1/\mu \ll 1/\alpha$



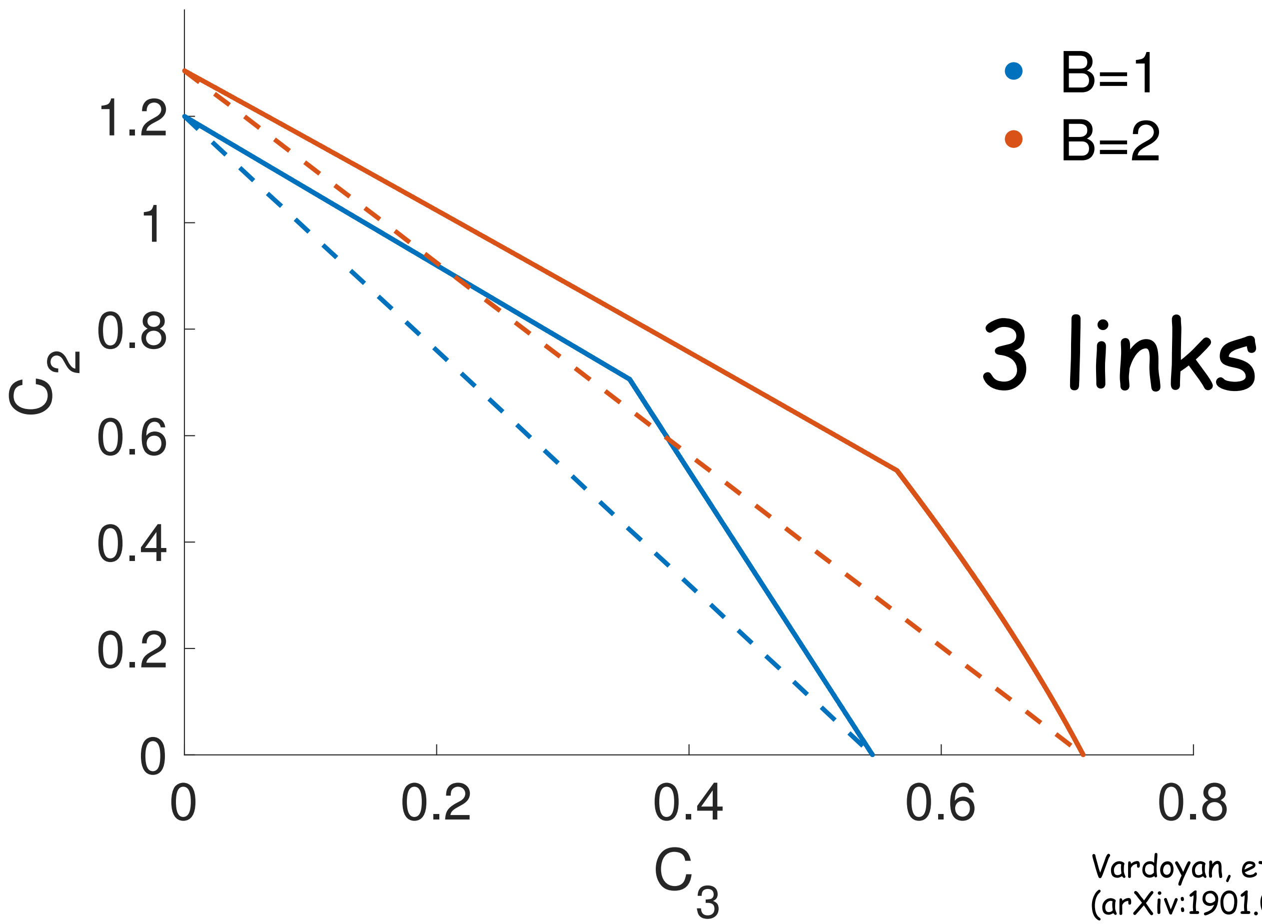
Other extensions

- tripartite entanglement switching $$C = \frac{q\mu k}{3}$$

- can switch serving both bi- and tripartite entanglements do better than TDM?

Yes, but advantage diminishes as number of links grows

Bi- and Tripartite Switching: Comparison



Vardoyan, etal. Qcrypt 2019
(arXiv:1901.06786)

Research questions

- maximum network capacity?
- routing algorithms?
  - static vs. dynamic vs. opportunistic
  - value of state vs. cost of state
- scheduling algorithms?
- dealing with noise?
- accurate (de)coherence models?
- two way (entanglement producing) vs. one way (qubit pushing)

Other Quantum Networking Challenges

- data, control plane design
  - combination classical/quantum – same/separate networks?
  - SDN?
- Q-TCP
- measurement, management

Quantum initiatives

China:

- China’s Quantum Experiments at Space Scale (Micius)
- National Laboratory for Quantum Information Science (Hefei)
  - 76 billion Yuan

Europe:

- Quantum Technology Flagship
  - one billion euros
  - 2017-2027

USA: National Quantum Initiative Act

  - 1.25 billion dolllars
  - 2019-2029

Thanks!