Routing in Quantum Mobile Networks

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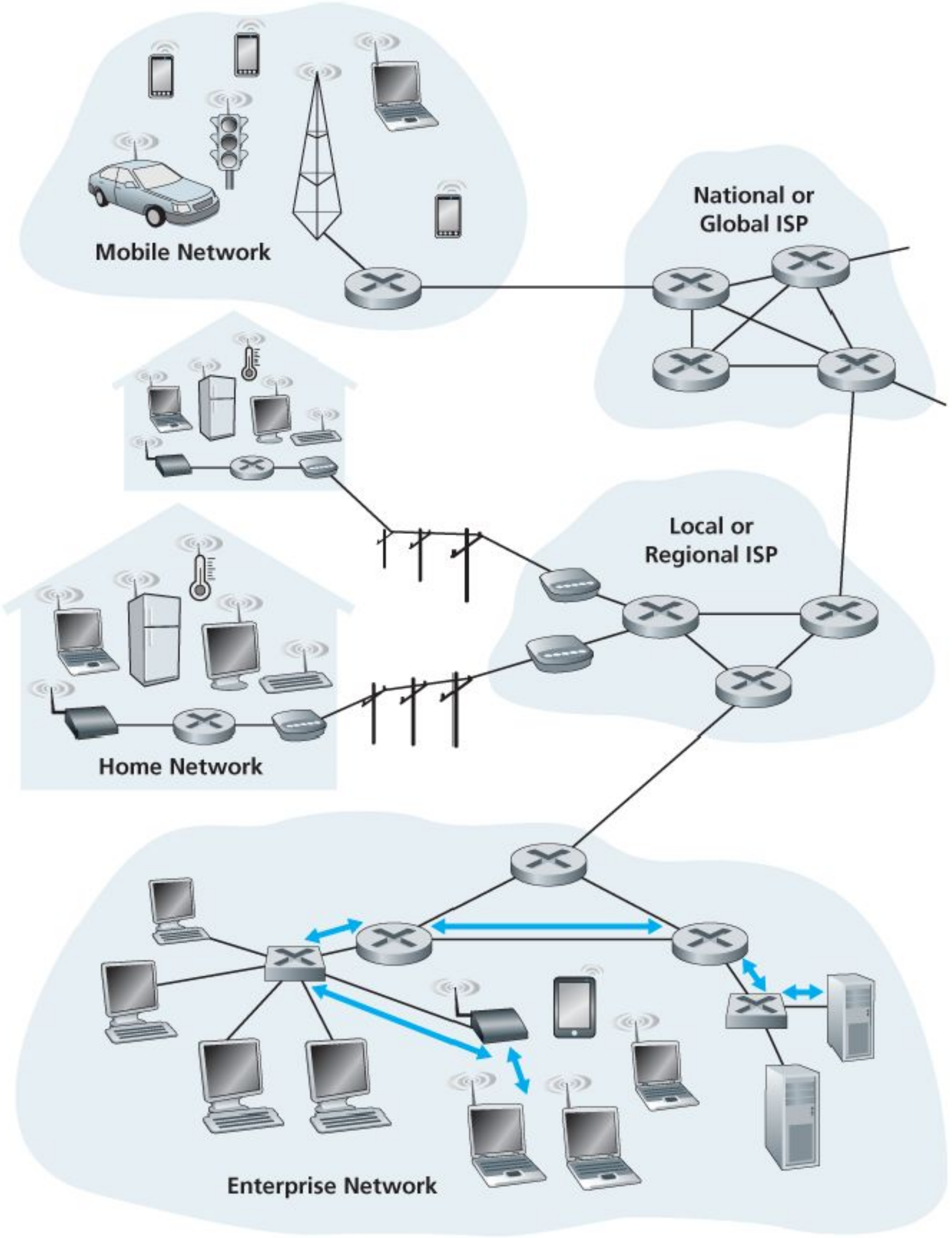
Today’s Presentation

1. Introduction
2. Motivation
3. Quantum Routing
4. Quantum Mobile Routing
    a. MANET
    b. Satellites
5. Summary and Challenges
6. Questions

Introduction

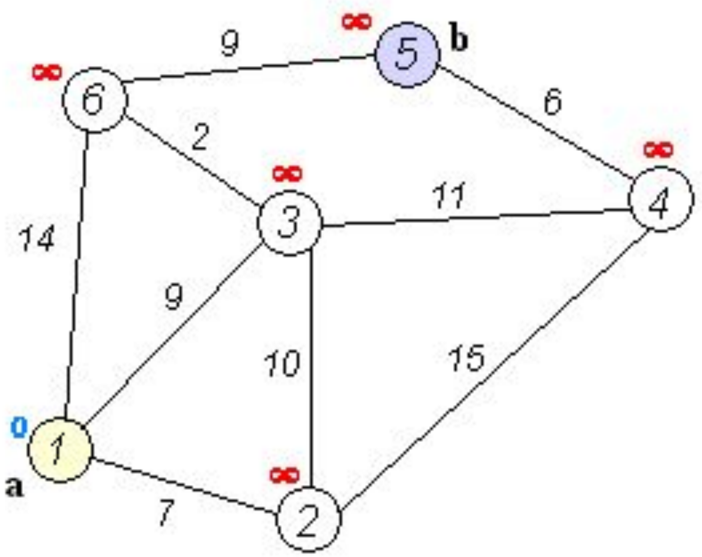
- Networks are complex, path selection is important
- Quality of service
- Fairness/NUM
- Load balancing
- Congestion avoidance
- Adapt to changing topology

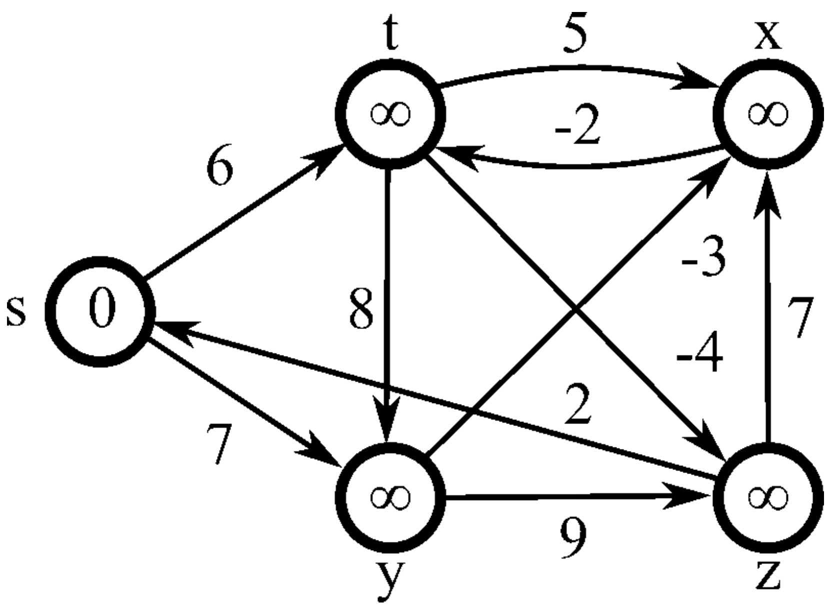


Kurose, James, and Keith Ross. "Computer networks: A top down approach featuring the internet." (2010).

Motivation: Classical Routing

- Link state
  - all routers have complete topology, link cost info
  - E.g. Dijkstra
- Distance Vector
  - router knows physically-connected neighbors, link costs to neighbors
  - iterative process of computation, exchange of info with neighbors
  - E.g. Bellman Ford



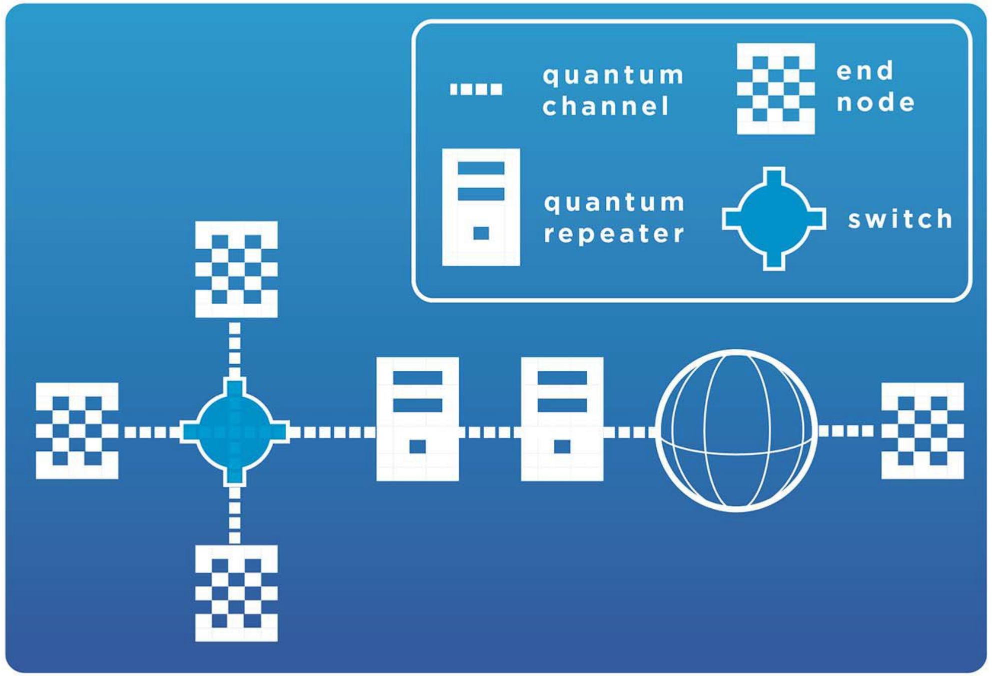


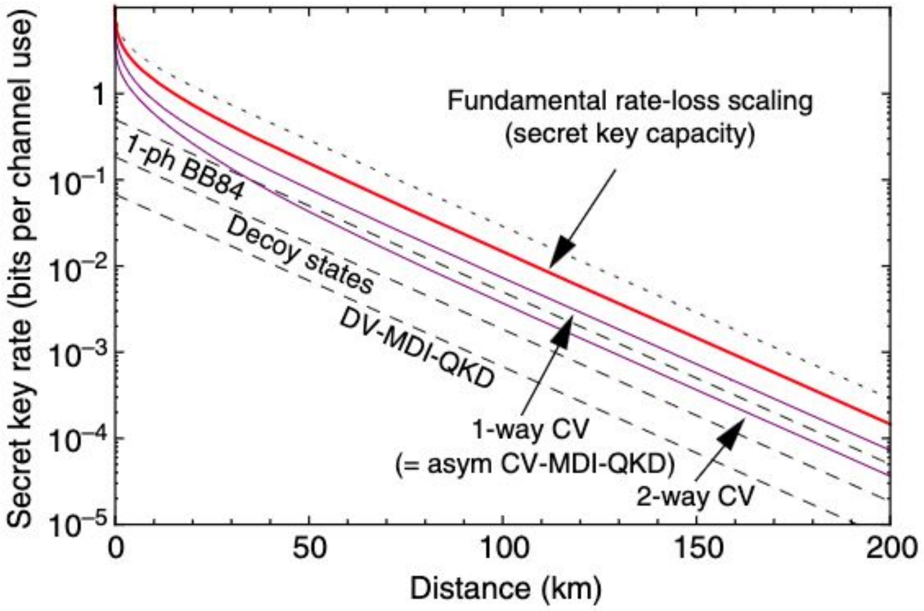
Source: Wikipedia

Motivation

Routing entanglement vs qubits

- Can't copy a qubit - No cloning theorem
- Unlike CC, can't increase rate by increasing transmission power
    - photon loss fundamentally limits the entanglement rate over any single link, which must decay exponentially with the length of optical fiber. Transmission losses > 0.2 dB/km
    - Loss and decoherence in channel; **communication fidelity decreases exponentially**
    - Need repeaters
- Unlike Classical information flow, entanglement flow is directionless





Pirandola, Stefano, et al. "Fundamental limits of repeaterless quantum communications." *Nature communications* 8.1 (2017): 15043.

Motivation: Quantum Routing Algorithms

- Teleportation based
- Entanglement based

Teleportation Based Routing

Use shared entanglement between parties to teleport quantum or classical information

One way vs two way schemes

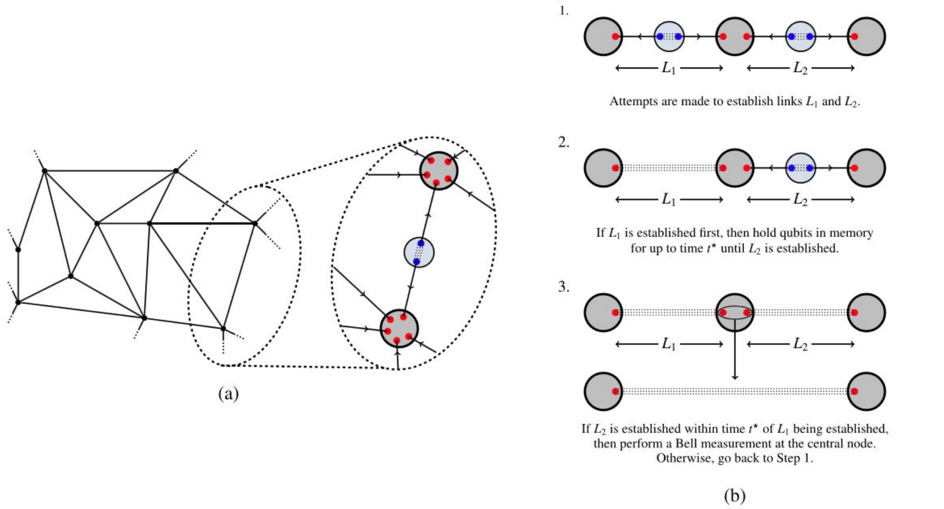
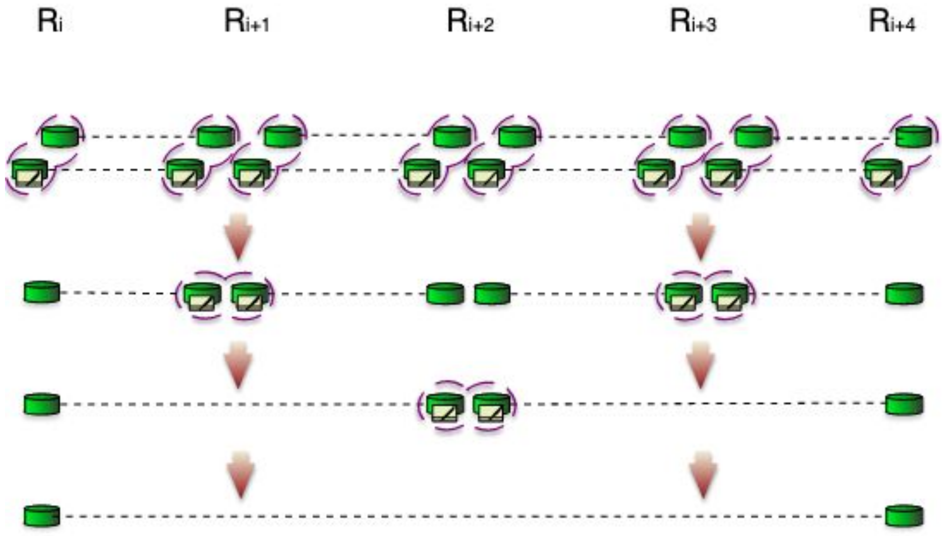


FIG. 1. The network architectures that we consider in this work are based on graphs of arbitrary topology. (a) The vertices of the graph correspond to the nodes in the network, and the edges correspond to the elementary links. At the center of each elementary link is a source of entangled photonic qubits (indicated in blue) that fires entangled photons toward the nodes at the ends of the link, where they are held in quantum memories (indicated in red). (b) An example of the general procedure to create bipartite entanglement between two nonadjacent nodes that are connected to a common node.



Khatri, Sumeet, et al. "Practical figures of merit and thresholds for entanglement distribution in quantum networks." *Physical Review Research* 1.2 (2019): 023032.

Muralidharan, Sreraman, et al. "Optimal architectures for long distance quantum communication." *Scientific reports* 6.1 (2016): 20463.

Teleportation Based Routing

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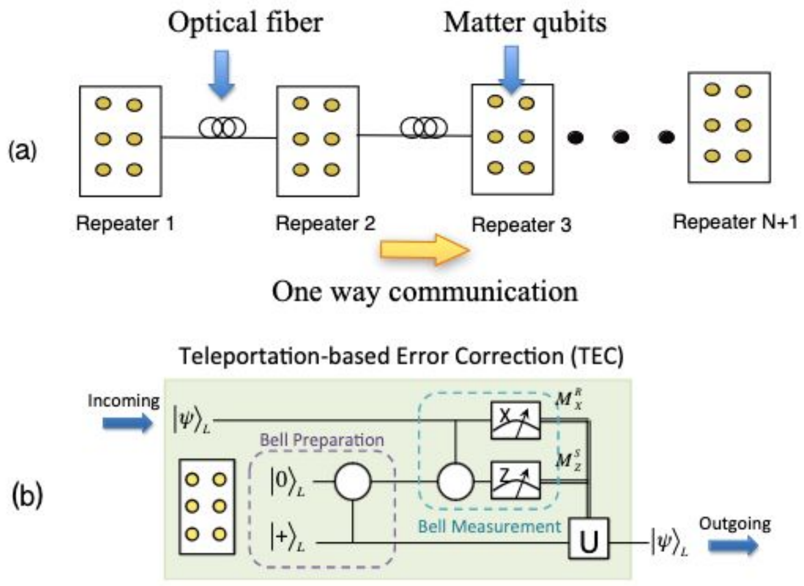
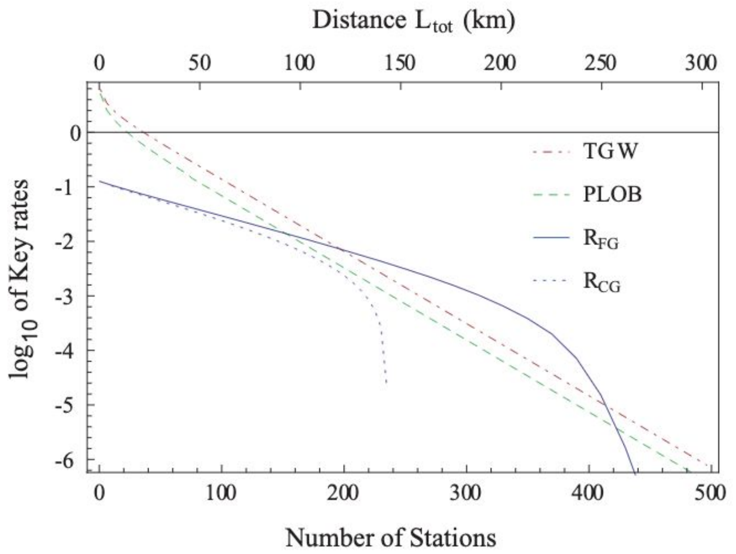




Muralidharan, Sreraman, et al. "Optimal architectures for long distance quantum communication." *Scientific reports* 6.1 (2016): 20463.

Entanglement based routing

- Solves the need for parallel quantum communication
- Can use multi-partite entangled states (Pant et al, Patil et al) or graph states (Hahn et al 2019) to achieve long distance parallel comms

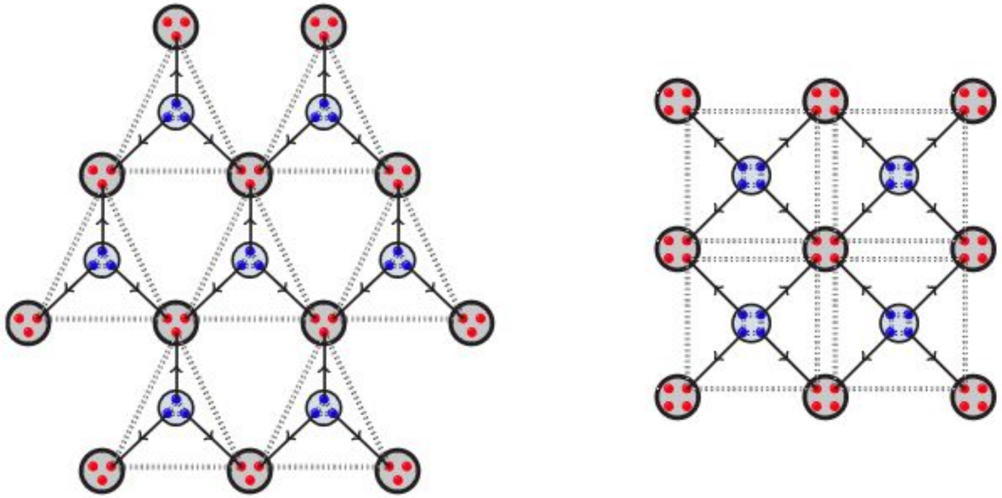
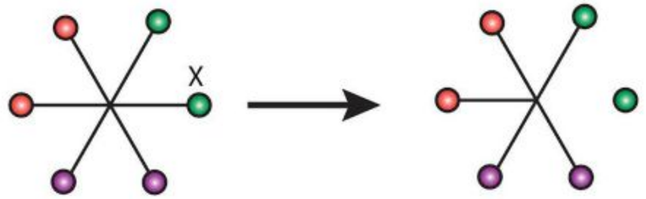


FIG. 2. Instead of bipartite entanglement, as in Fig. 1(a), the elementary links in a quantum network can consist of multipartite entanglement; for example, we can have elementary links of tripartite (left) or four-partite (right) entanglement.

Khatri, Sumeet, et al. "Practical figures of merit and thresholds for entanglement distribution in quantum networks." *Physical Review Research* 1.2 (2019): 023032.



Measuring in X basis removes the qubit from the n-GHZ state

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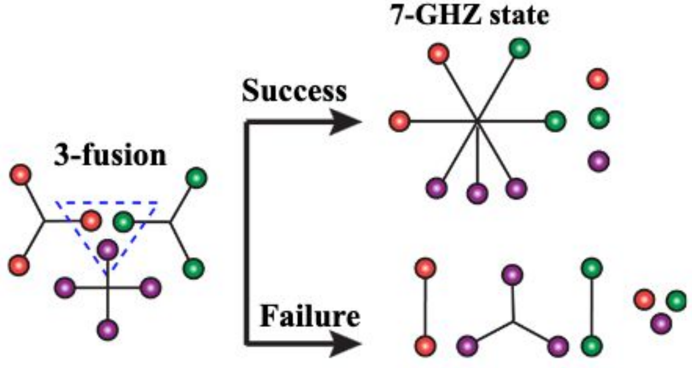
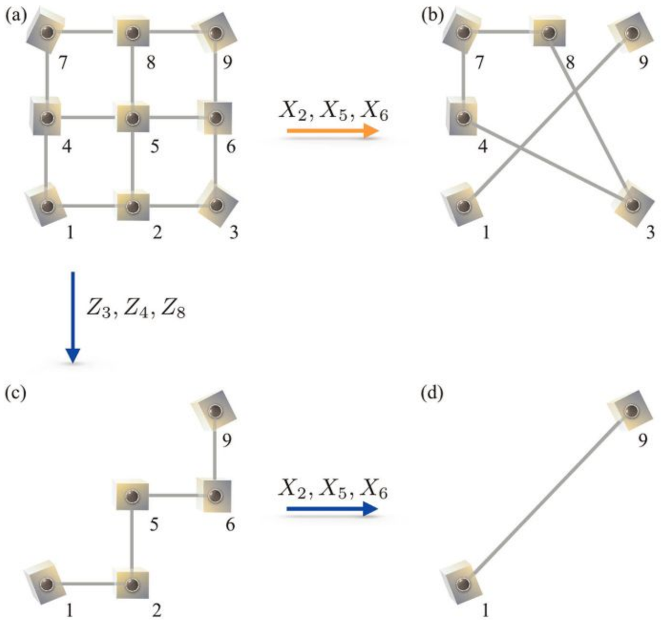
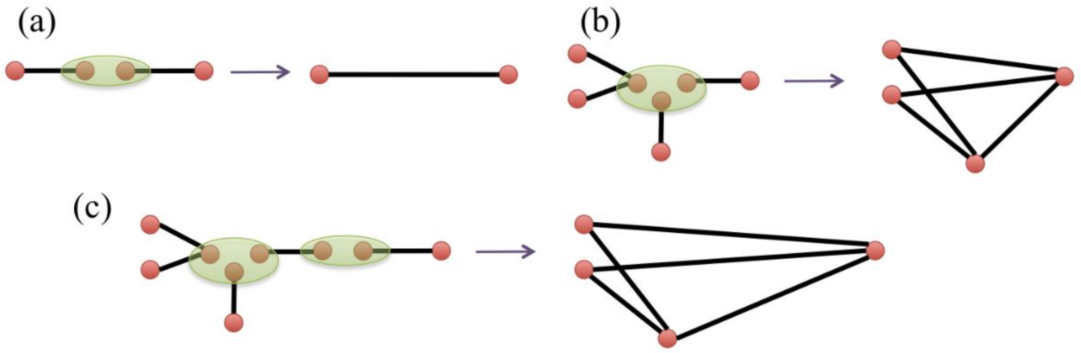
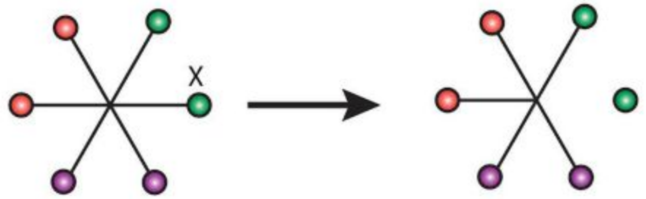




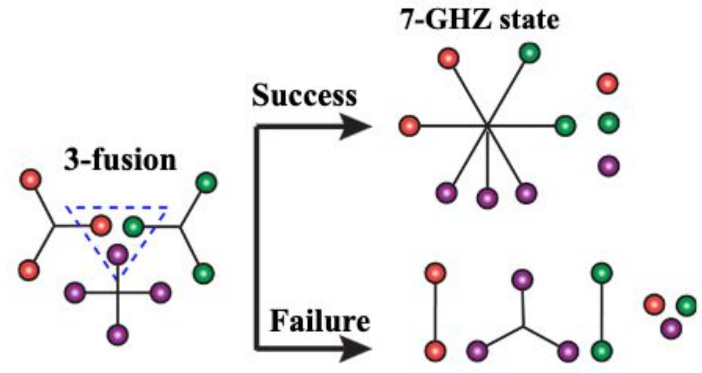


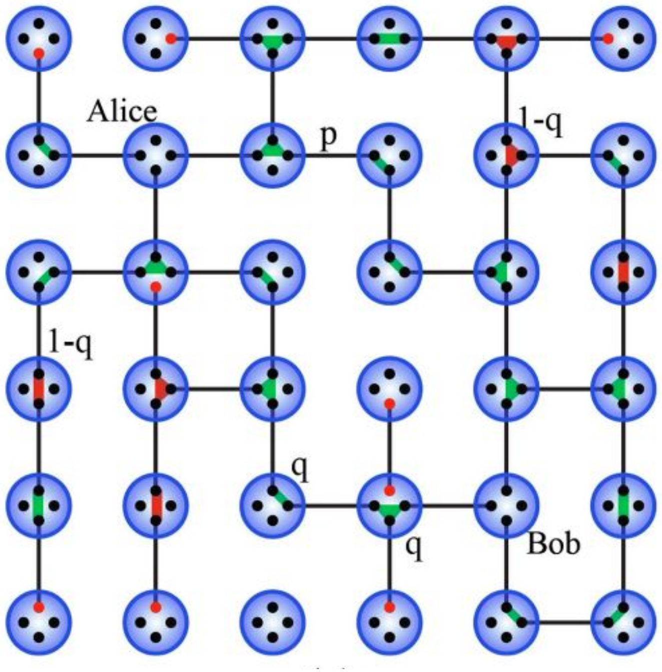
Pant, Mihir, et al. "Routing entanglement in the quantum internet." *npj Quantum Information* 5.1 (2019): 25.
Hahn, Frederik, A. Pappa, and Jens Eisert. "Quantum network routing and local complementation." *npj Quantum Information* 5.1 (2019): 76.
Patil, Ashlesha, et al. "Entanglement generation in a quantum network at distance-independent rate." *npj Quantum Information* 8.1 (2022): 51.

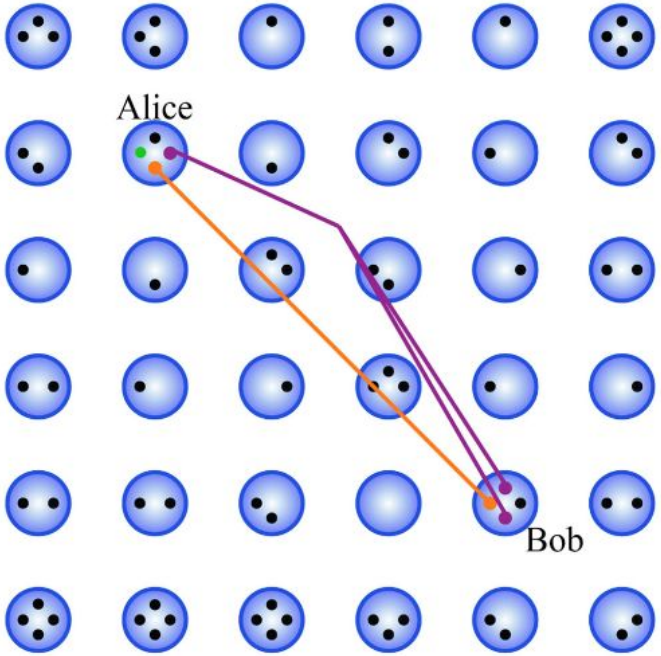
Entanglement based routing



Measuring in X basis removes the qubit from the n-GHZ state



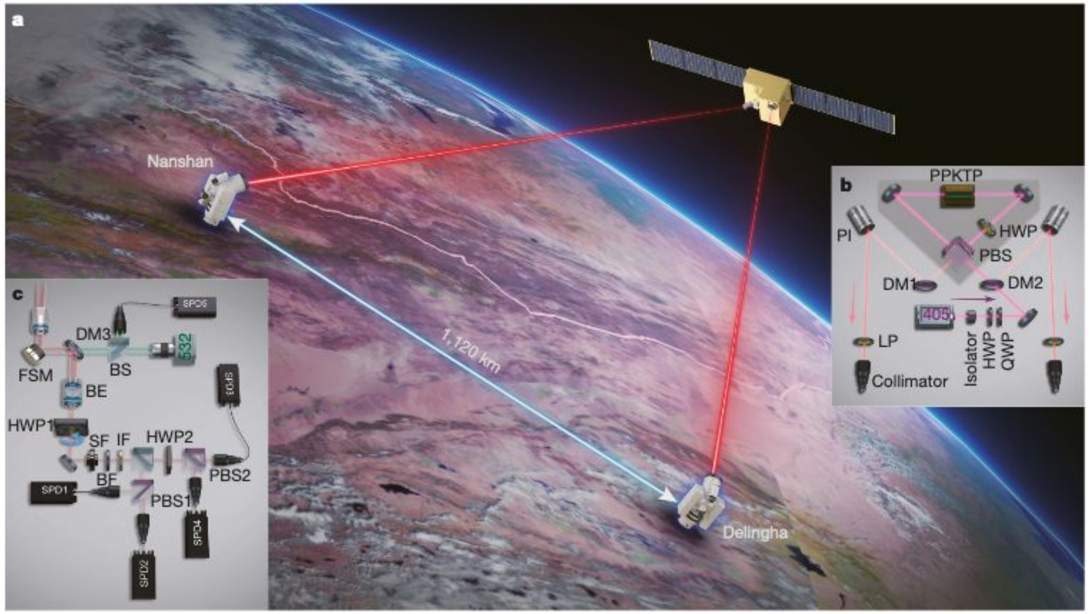




Patil, Ashlesha, et al. "Entanglement generation in a quantum network at distance-independent rate." *npj Quantum Information* 8.1 (2022): 51.

Motivation: Why use Mobile Networks?

- Can’t go far with ground based networks
- Inter-continental fibre based quantum networks are difficult to implement even with repeaters
    - Erasure errors and other channel errors
        - Distance scaling $\propto e^{-\frac{L_0}{L_{att}}}$
- Free space



Demonstration of secure quantum cryptography over 1120 km using satellite (Yin et al 2020)

Yin, Juan, et al. "Entanglement-based secure quantum cryptography over 1,120 kilometres." *Nature* 582.7813 (2020): 501-505.

Motivation: Why use Mobile Networks?

- Integrated Networks

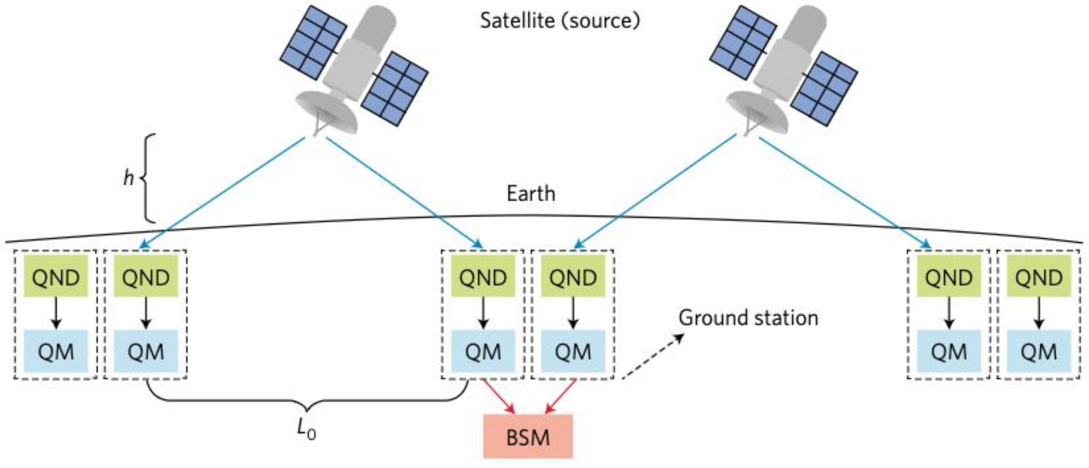


Fig. 1 | Quantum repeater architecture with satellite links. Each individual link (of length L_0) consists of an entangled photon pair source on a low-Earth-orbit satellite (at height h) and two ground stations consisting of quantum non-demolition (QND) measurement devices and quantum memories (QM). The arrival of a photon at each ground station is heralded by the QND devices, which detect the presence of a photon non-destructively and without revealing its quantum state. The entanglement is then stored in the memories until information about successful entanglement creation in a neighbouring link is received. Then the entanglement can be extended by entanglement swapping based on a Bell state measurement (BSM). A small number of such links are sufficient for spanning global distances. Figure adapted from ref. [34], APS.

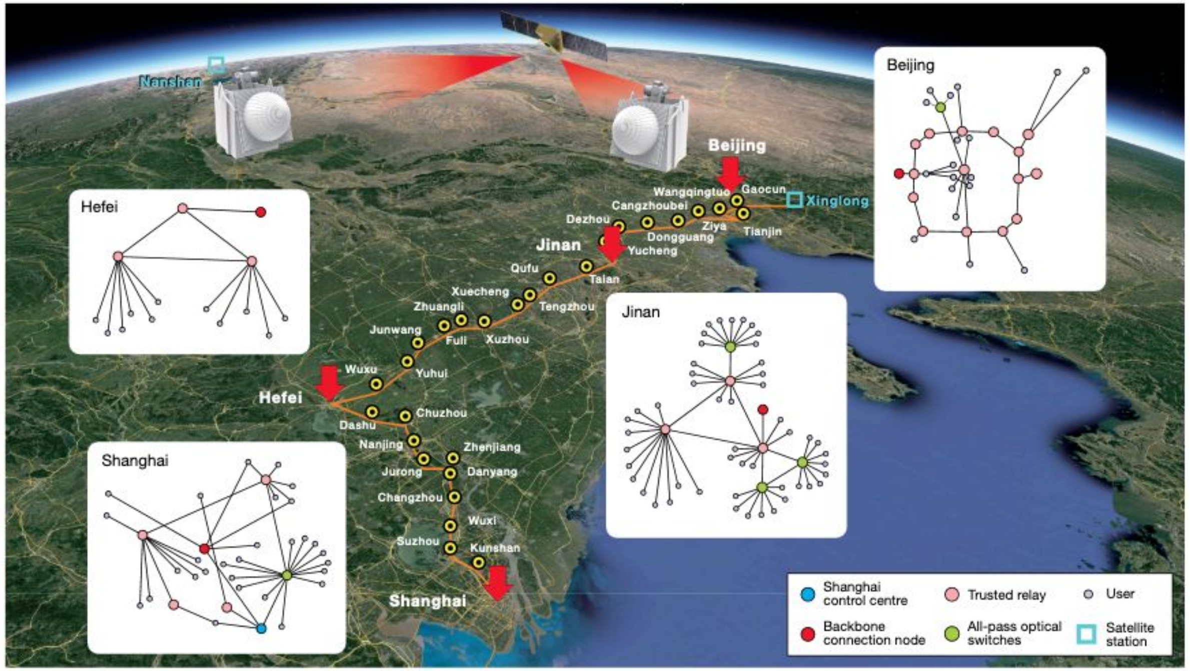


Fig. 1 | Illustration of the integrated space-to-ground quantum network. The network consists of four QMANs (in Beijing, Jinan, Shanghai and Hefei; red arrows), a backbone fibre link over 2,000 km (orange line) and two ground–satellite links that connect Xinglong and Nanshan (blue squares), separated by 2,600 km. There are three types of node in the network: user nodes (purple circles), all-pass optical switches (green circles) and trusted relays (pink circles). Each QMAN consists of all three node types (see insets). The backbone is connected by trusted relays (shown as yellow and black circles in the main image and red circles in the insets). A quantum satellite is connected to the Xinglong and Nanshan ground stations; Xinglong is also connected to the Beijing QMAN via fibre. In Beijing, the Beijing control-centre node is located at the same location as the backbone connection node (indicated by the red circle). Map data: Google, Data SIO, NOAA, US Navy, NGA, GEBCO, Landsat/Copernicus; copyright ZENRIN.

Simon, Christoph. "Towards a global quantum network." *Nature Photonics* 11.11 (2017): 678-680.
Chen, Yu-Ao, et al. "An integrated space-to-ground quantum communication network over 4,600 kilometres." *Nature* 589.7841 (2021): 214-219.

Motivation: Why use Mobile Networks?

- Still need repeaters!

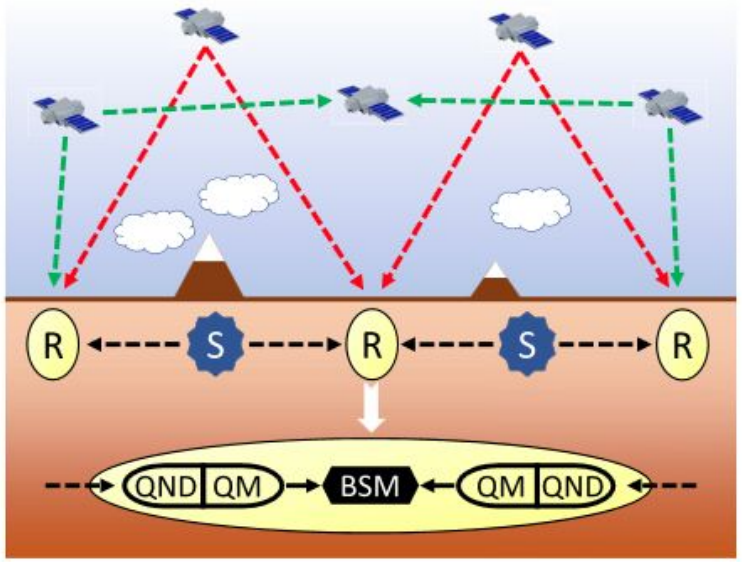
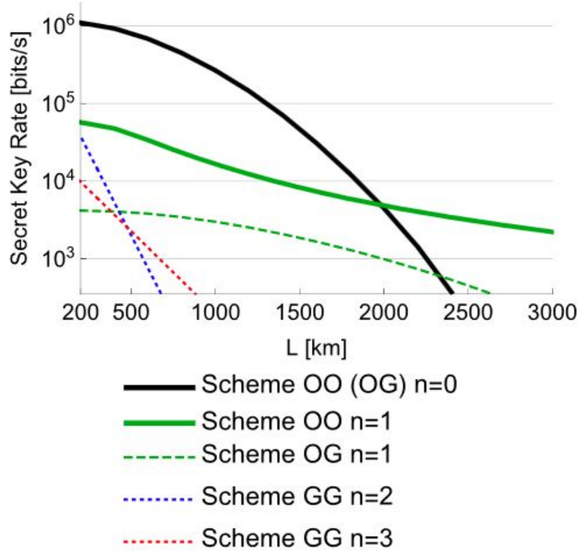
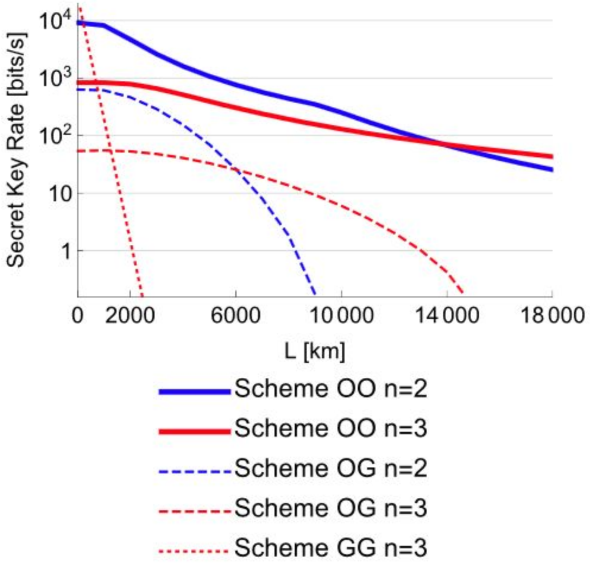


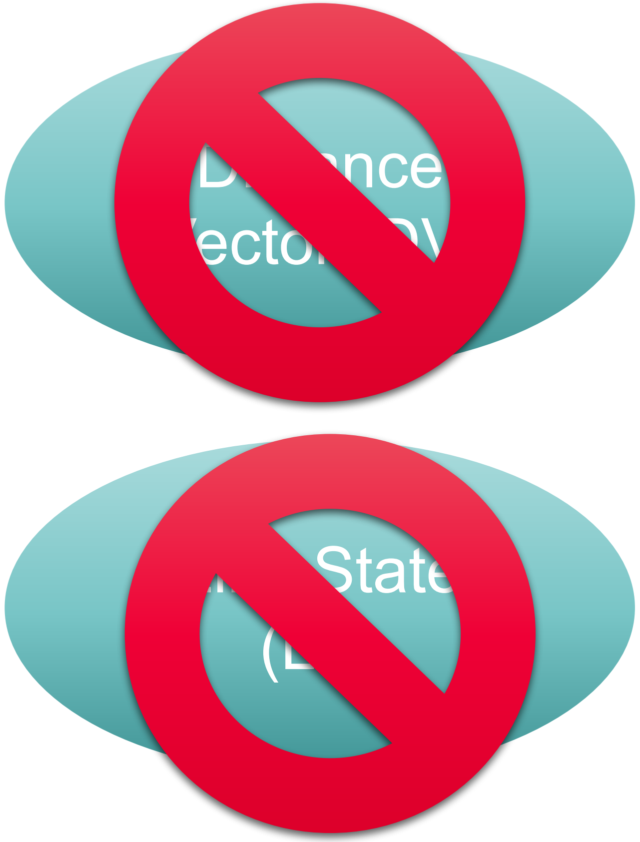
Figure 2. Schematic comparison between the satellite-based scheme OO (green arrows), the standard fibre-based implementation (GG, in black) and the scheme studied in [22] (OG, in red). Here *S* represent entanglement sources and *R* QR stations. The incoming photons are heralded by QND measurement devices and the quantum information is loaded into QMs. Finally, the quantum states are read and a BSM is performed, as part of the ES protocol.





Liorni, Carlo, Hermann Kampermann, and Dagmar Bruß. "Quantum repeaters in space." *New Journal of Physics* 23.5 (2021): 053021.

Conventional Routing Protocols



- ‘Count-to-infinity’ problem and slow convergence
- Loop formation during temporary node failures and network partitions

- Protocols that use flooding techniques create excessive traffic and control overhead

<u>NOT designed for higly dynamic, low bandwidth networks</u>

Why is routing in MANETs different?

1) Self-organizing networks

2) Topology changes dynamically

3) Rate of link failure/repair due to node mobility may be very high

4) Network partitions

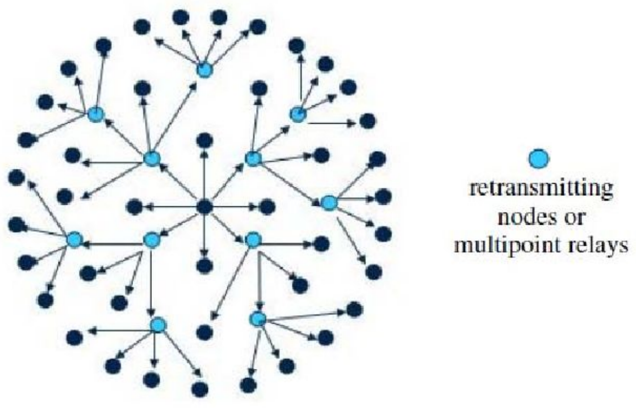
5) Asymmetric links

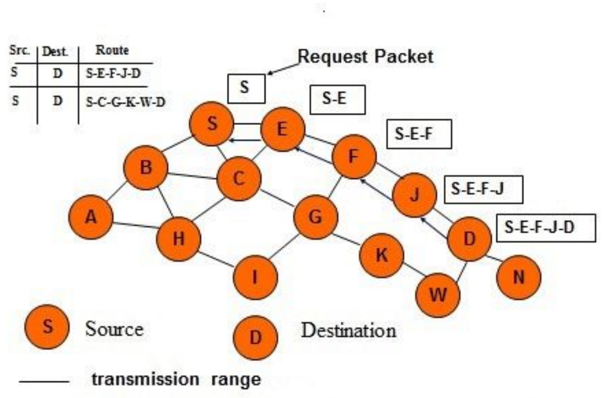
6) Limited bandwidth, reduced even more due to exchange of routing information

7) New performance criteria

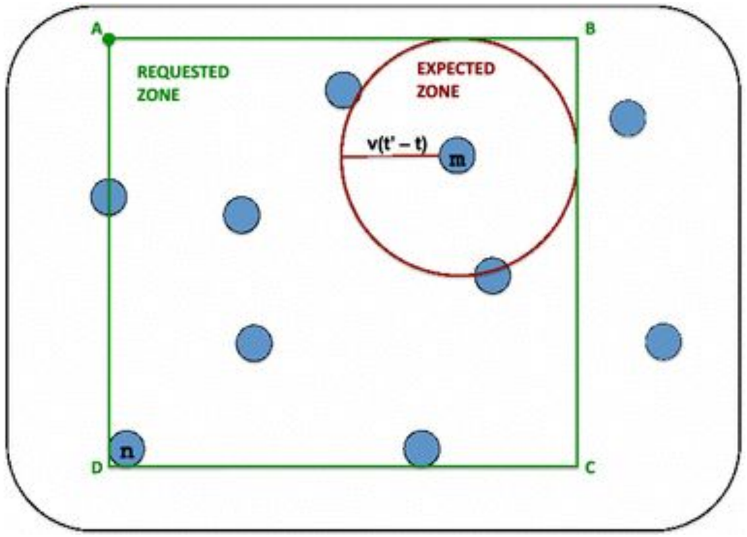
Routing Protocols for MANETs

- **Topology based Routing**
  - Proactive approach
  - Reactive approach
  - Hybrid approach





- **Position based Routing**
  - Location services;
  - Forwarding strategy



Maurya, Ashish Kumar & Singh, Dinesh & Kumar, Ajeet. (2013). Performance Comparison of DSR, OLSR and FSR Routing Protocols in MANET Using Random Waypoint Mobility Model. International Journal of Information and Electronics Engineering. 3. 4. 10.7763/IJIEE.2013.V3.353.
Tarique, Mohammed & Islam, Rumana. (2021). Optimum Neighbors for Resource-Constrained Mobile Ad Hoc Networks. International Journal of Ad hoc Sensor & Ubiquitous Computing. 12. 1-14. 10.5121/ijasuc.2021.12201.
Gallina, Lucia & Marin, Andrea & Rossi, Sabina. (2016). Connectivity and energy-aware preorders for mobile ad-hoc networks. Telecommunication Systems. 63. 10.1007/s11235-015-0122-6.

Routing Protocols for MANETs
The Proactive approach

Determines routes independent of traffic pattern

- Based on distance vector and link-state mechanisms
- Attempts to maintain consistent, up-to-date routing information from each node to every other node in the network

Responds to changes by propagating updates throughout the network

Good for connection-less traffic where you traffic is sent to any node at any time

PRO:
Immediately available paths;
each node has an up-to-date view of the network topology

CONS:
Large routing tables;
Low scalability;
High bandwidth and energy consumption due to periodic updates

Routing Protocols for MANETs
The Reactive approach

Maintains routes only if needed

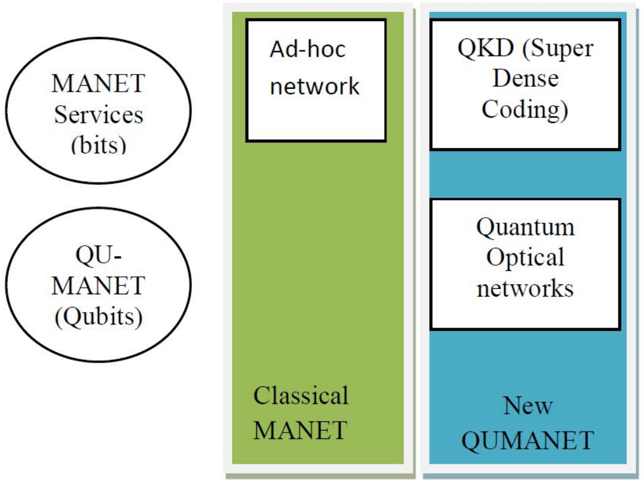
- Routes are only created when desired by the source node
  - Route discovery phase
  - Route maintenance phase

PRO:
Paths are only computed on-demand;
no need for periodic updates;
energy and bandwidth saving; nodes may go in sleep mode.

CONS:
Longer path set-up delays (route discovery);
Path search efficiency depends on the node mobility;
need of memory to keep discovered paths;
Longer packet's header to store path.

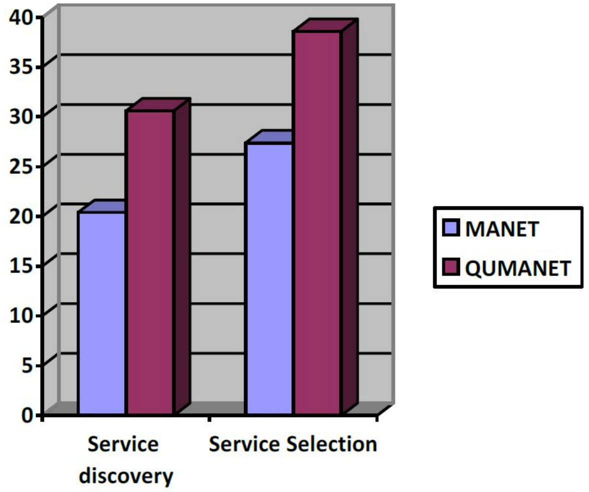
What's new in a QuMANET?

Quantum mechanics — Quantum entanglement — Quantum measurement



Classical MANET Vs QUMANET

NEWS: **quantum key distribution** (QKD) and **superdense coding**



Comparison of MANET and QUMANET: Service discovery and selection with the help of QUMANET will be fast as compared to Classical MANET

QuMANET- changes in Mobile ad-hoc network with quantum bits for reliability, Shruti Mishra, Dr. B. Dhanasekaran

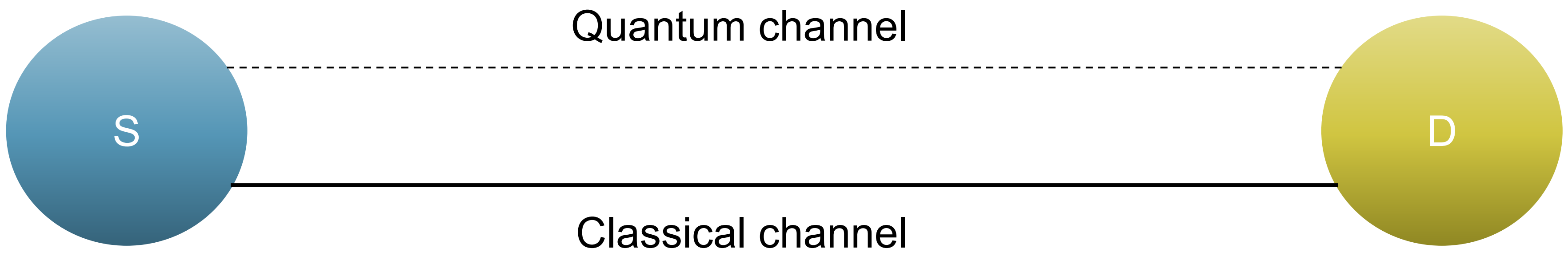
Title	Approach	Reference Protocol	Simulation Results	Analytical Results	Additional Algorithms
New quantum-genetic based OLSR protocol (QG-OLSR) for Mobile Ad hoc Network[1]	Proactive	OLSR	✓ MATLAB	✓	✓
Optimisation of the routing protocol for quantum wireless Ad Hoc network[2]	Reactive	AODV	✗	✓	✗

[1]Zhang, De-gan, Yu-ya Cui, and Ting Zhang. "New quantum-genetic based OLSR protocol (QG-OLSR) for mobile ad hoc network." *Applied Soft Computing* 80 (2019): 285-296.

[2]*Zhang, Ling, and Qin Liu. "Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022): 5-12.*

What's new in a QuMANET?

Quantum teleportation to transmit quantum bits (qubits)



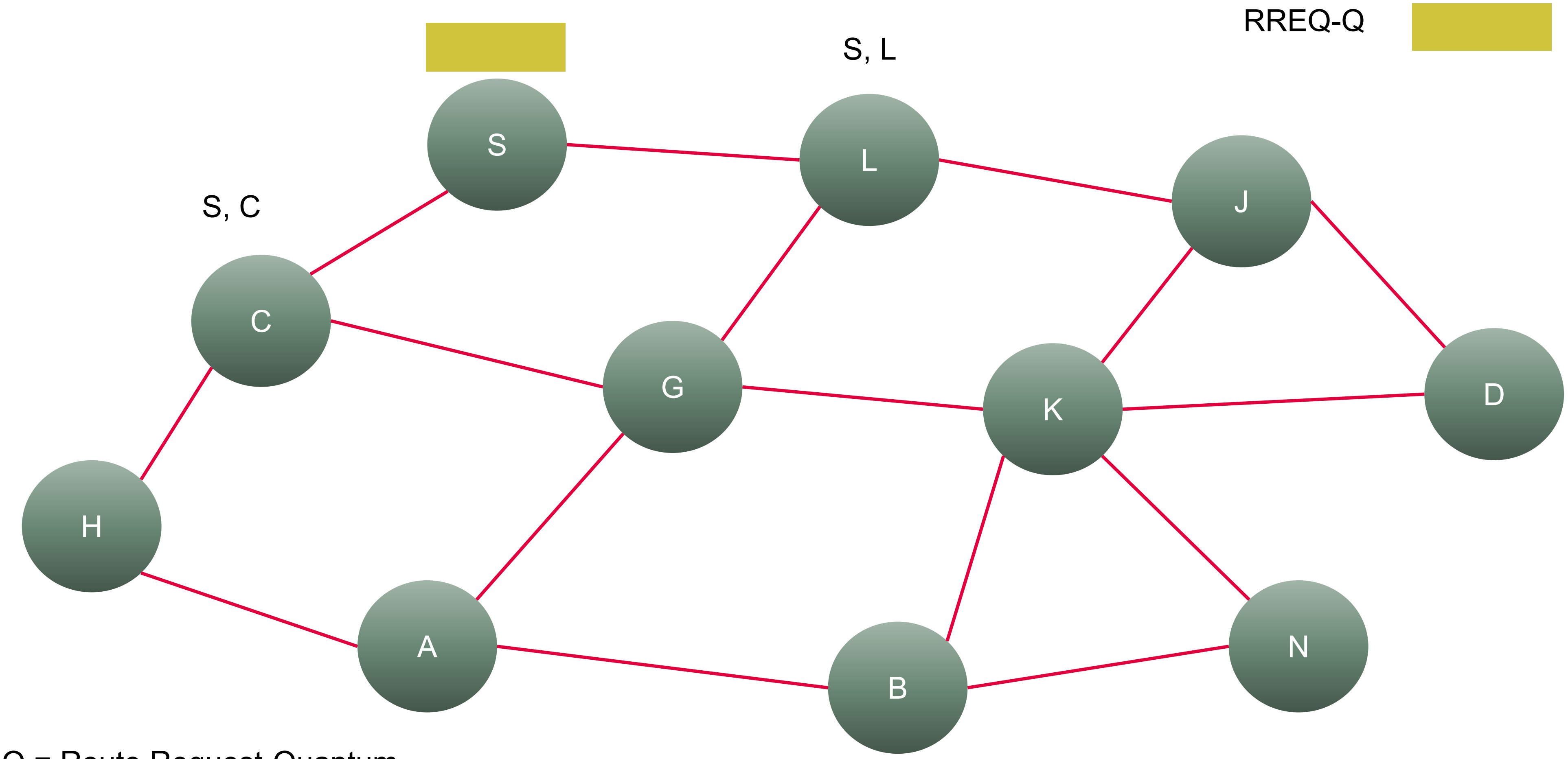
The application of the quantum teleportation technology to wireless Ad Hoc networks can improve:

- Security
- Capacity

The quantum wireless Ad Hoc network adopts the on-demand routing protocol (in this case)!

How does an on-demand routing protocol work?

The general method:



RREQ-Q = Route Request-Quantum

Zhang, Ling, and Qin Liu. "Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022): 5-12.

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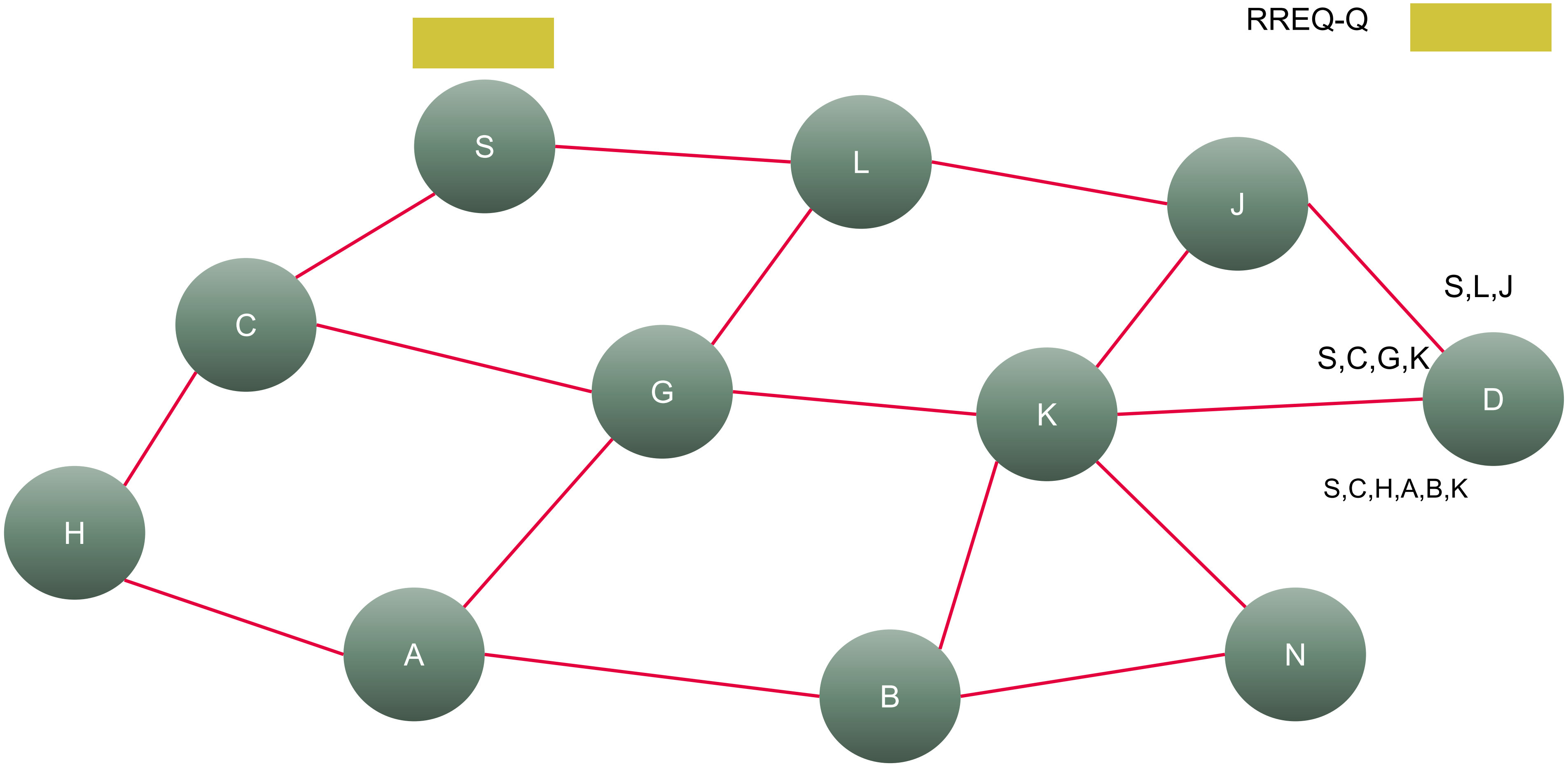

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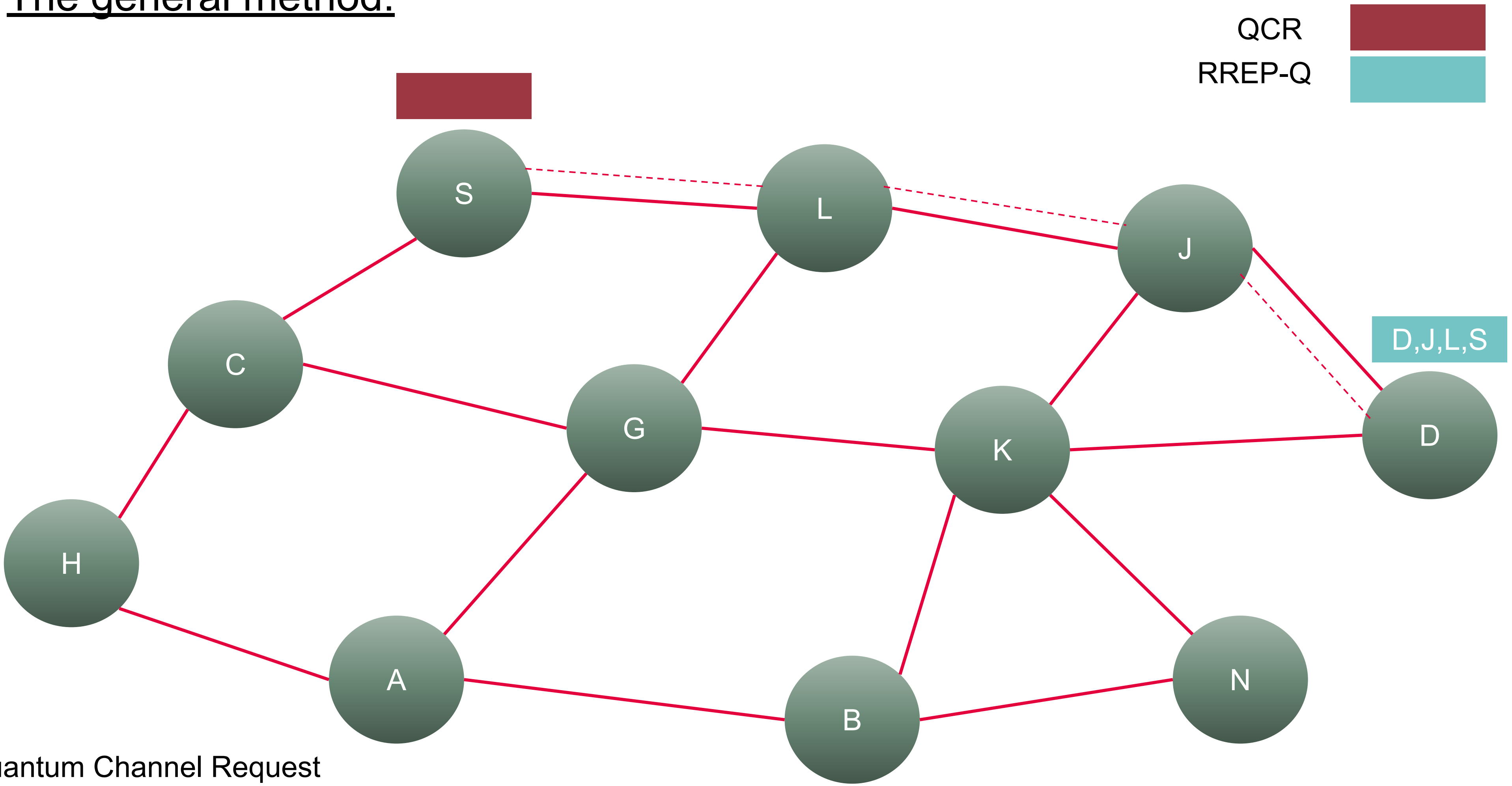
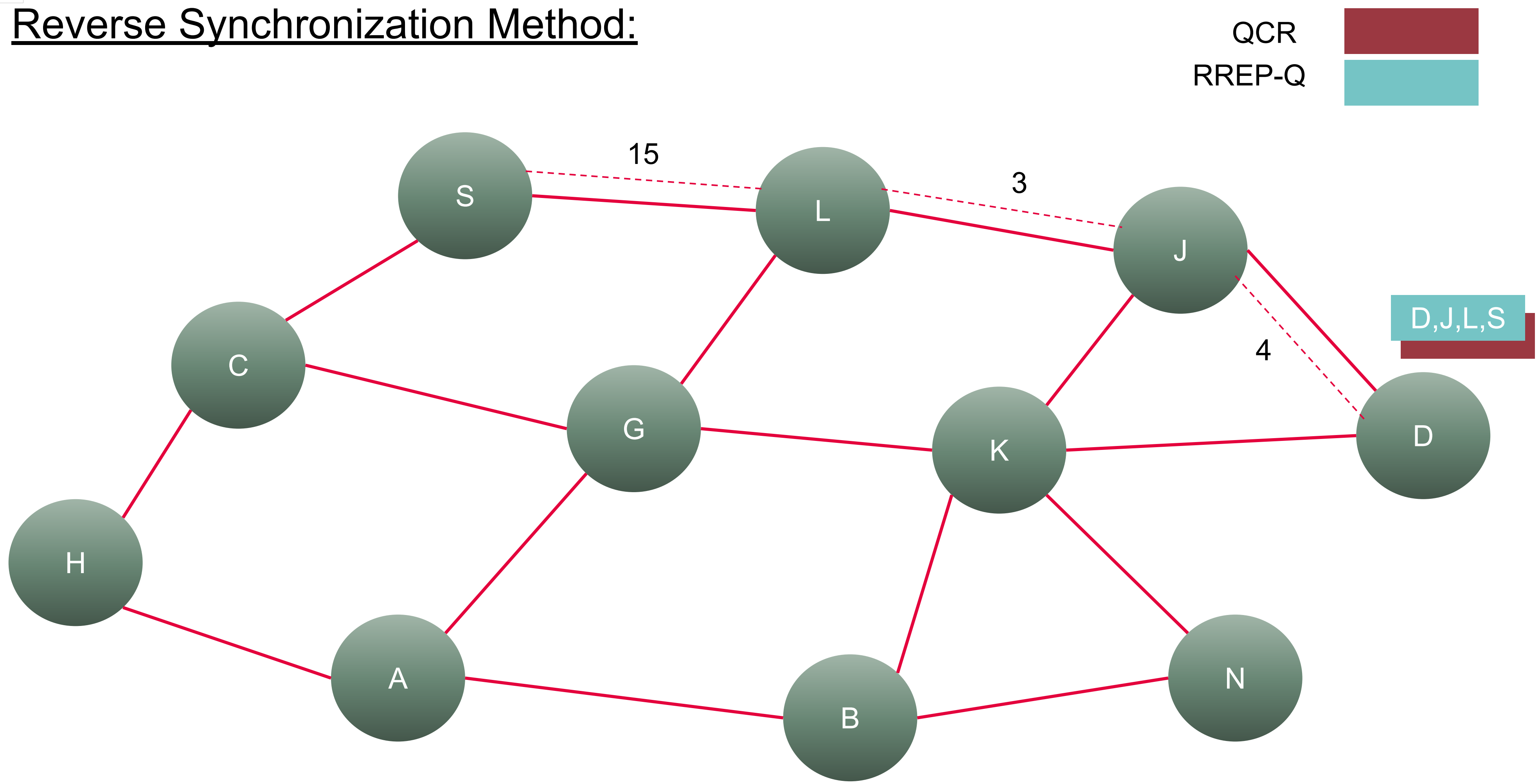


QCR = Quantum Channel Request
RREP-Q = Route Reply-Quantum

Zhang, Ling, and Qin Liu. "Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022): 5-12.

How is this protocol optimised?

<u>Reverse Synchronization Method:</u>



Zhang, Ling, and Qin Liu. "Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022): 5-12.

How is this protocol optimised?

TABLE 1 Route Request-Quantum (RREQ-Q) packet message format

Command frame identifier	Quantum route request ID	Source address	Destination address	Last hop address	Quantum routing metric	Quantum routing record (QRR)

TABLE 2 Quantum Route Reply (RREP-Q) packet message format

Command frame identifier	Quantum route request ID	Source address	Destination address	Quantum routing metric	Flagged Quantum routing record (QRR-F)	Quantum Channel Request (QCR)

Route Maintenance:

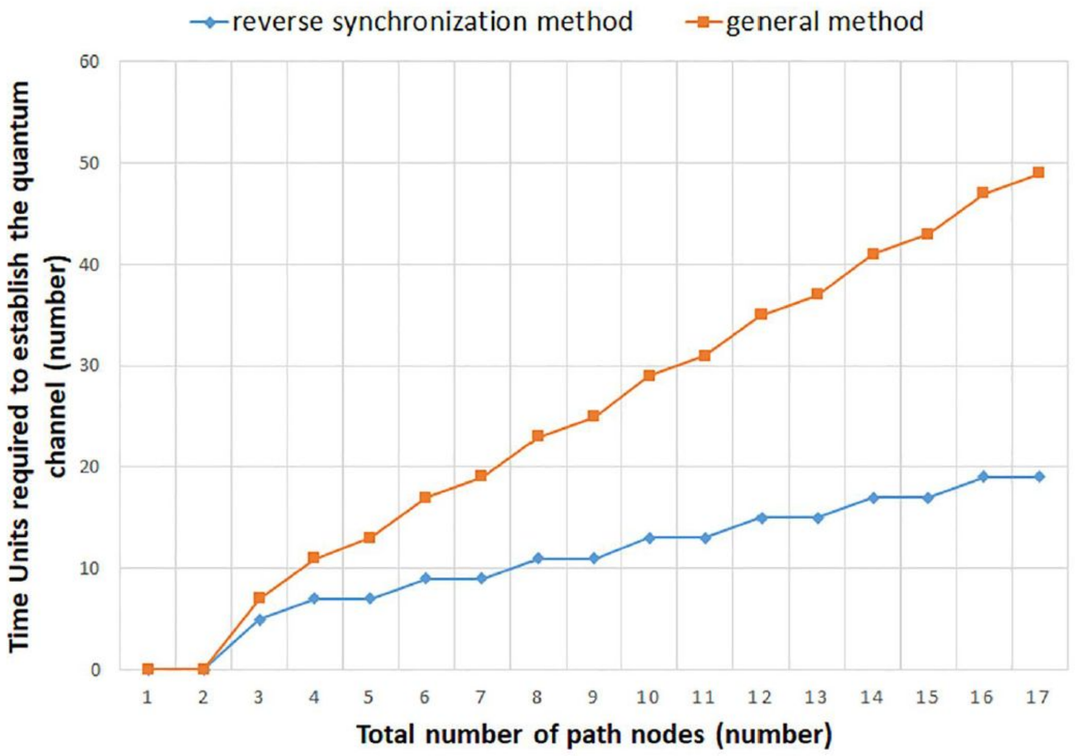
- Node movement and EPR pairs' consumption may lead to changes in the network topology

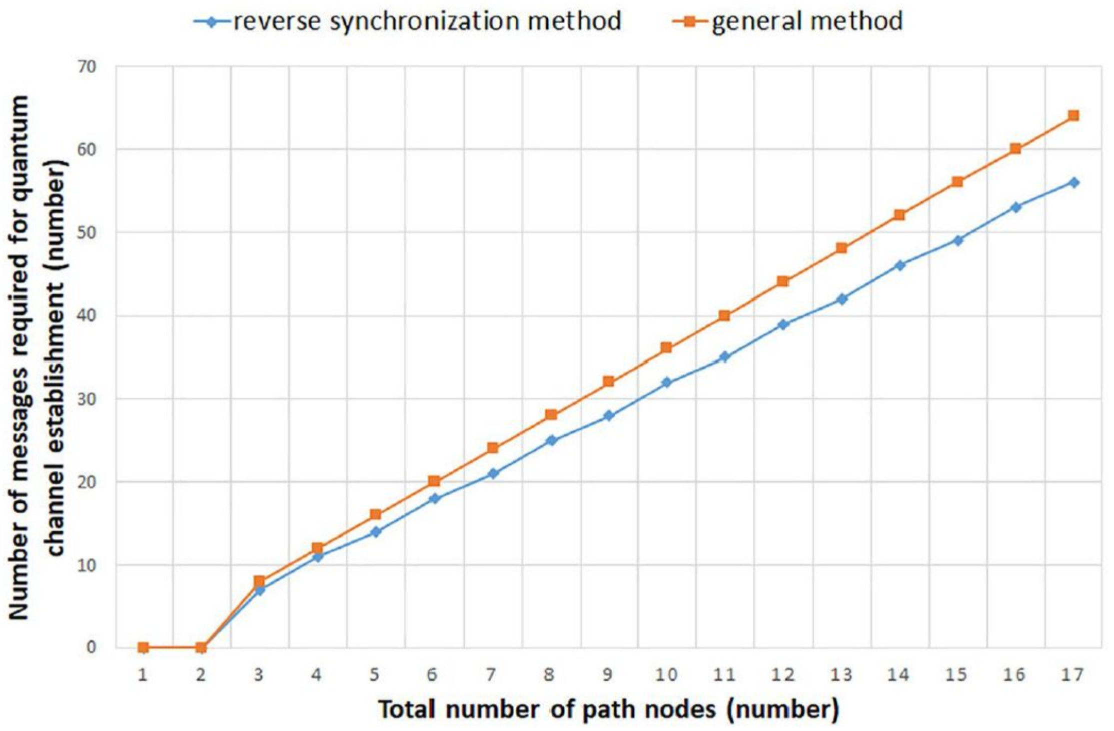
- The unknown quantum state cannot be copied and retransmitted due to the principle of quantum non-cloning

Before the source node starts to transmit the quantum state, it need to determine whether the nodes on the current path are still valid for this transmission (PATH VERIFICATION REQUEST).

Zhang, Ling, and Qin Liu. "Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022): 5-12.

Results





This method reduces the quantum channel establishment time and the number of messages, so it improves the efficiency. But routing in quantum networks is more complicated. The next step is to model these protocols and evaluate their effectiveness by simulation.

Zhang, Ling, and Qin Liu. "Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022): 5-12.

Quantum Mobile Routing - Satellites

Quantum Mobile - Satellites

1.Mobility: The Nodes are not fixed!
-Physical Implementation Challenges
-Each node has it tragetory
2.The Link expires:
-The LEO Satellites have limited coverage
Quantum Satellites Papers'

1. EntangleNetSat: A Satellite-Based Entanglement Resupply Network
2. Quantum Key Distribution Over Double-Layer Quantum Satellite Networks
3. Quantum Key Distribution Over Double-Layer Quantum Satellite Networks

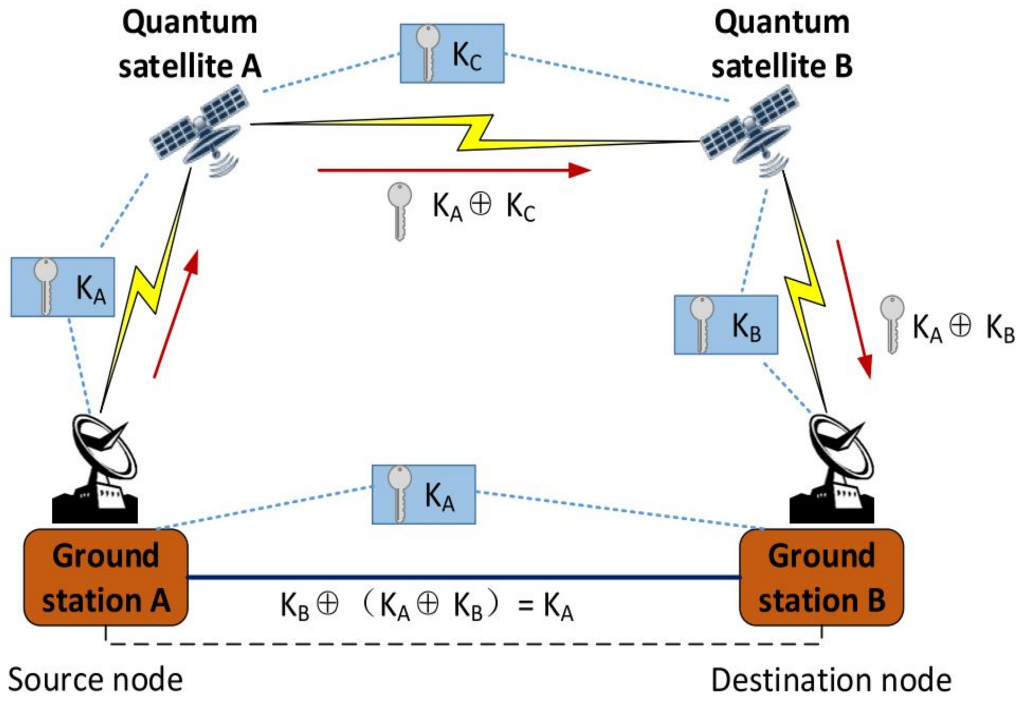
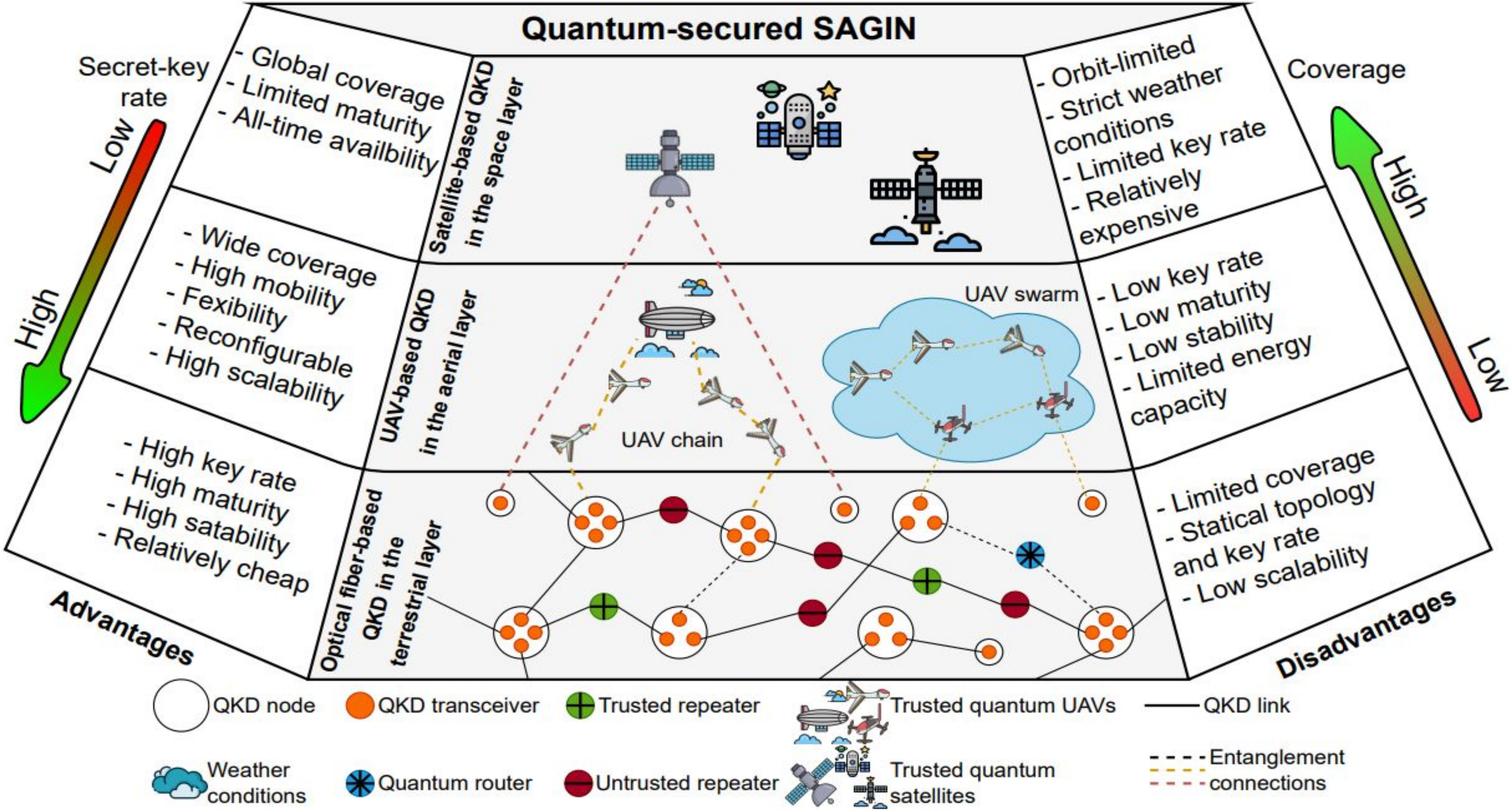


FIGURE 1. Principle of trusted-repeater-based satellite QKD.

Huang, Donghai, et al. "Quantum key distribution over double-layer quantum satellite networks." *IEEE Access* 8 (2020): 16087-16098.



Xu, Minrui, et al. "Quantum-secured space-air-ground integrated networks: Concept, framework, and case study." *IEEE Wireless Communications* (2022).

EntangleNetSat: A Satellite-Based Entanglement Resupply Network

- Provide global coverage to Quantum Networks
- Ground stations → Multiples Satellites
- Trade off : efficiency vs accuracy
- Present a routing schema using a hybrid ground and satellite network
- Two Steps Routing Protocol
  - Local knowledge
  - Bellman-Ford approach

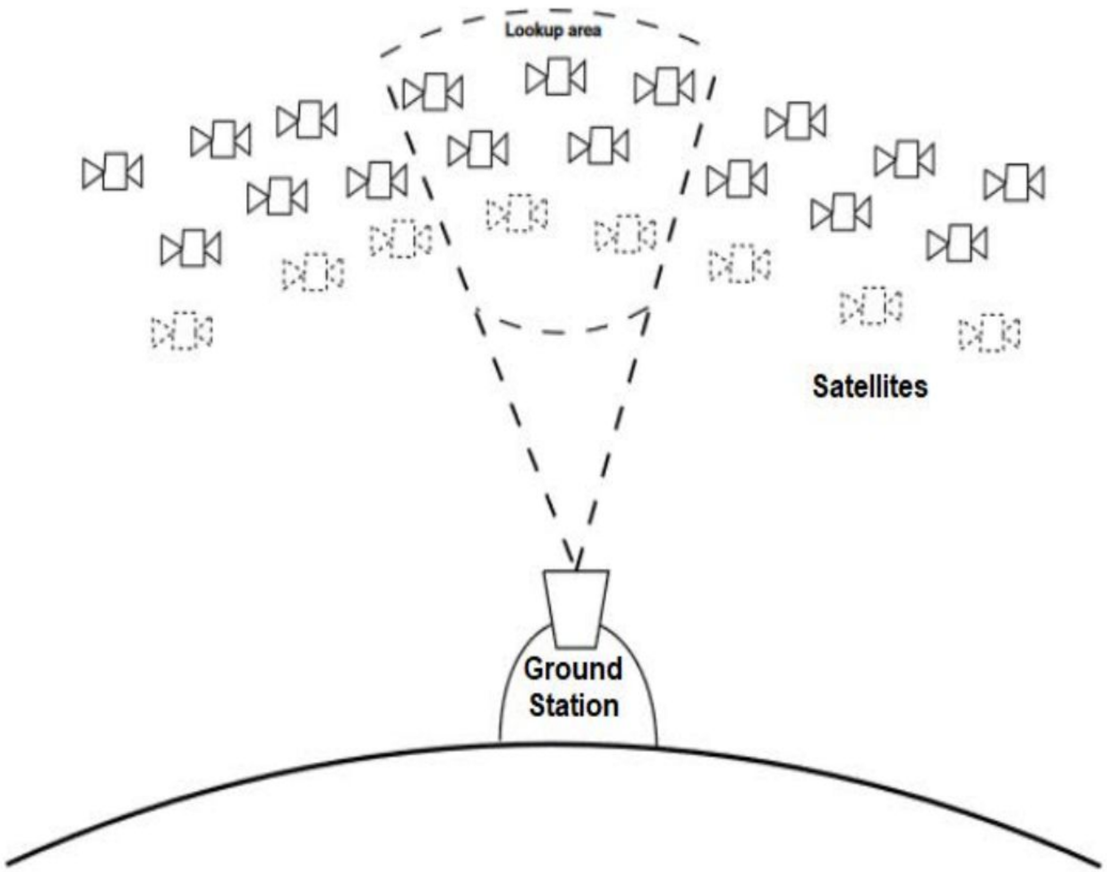


FIGURE 4. The trade-off we suggest, in terms of accuracy and computational efficiency, is a precomputed lookup table for satellites.

Ciobanu, Bogdan-Cãlin, Voichiţa Iancu, and Pantelimon George Popescu. "EntangleNetSat: A Satellite-Based Entanglement Resupply Network." *IEEE Access* 10 (2022): 69963-69971.

EntangleNetSat: A Satellite-Based Entanglement Resupply Network

STEP 1: TERMINAL SATELLITE SELECTION

- Choose the satellite that keep maximum transmission fidelity (possible)
  - as close to the zenith of the requesting stations
- Offline: Precomputed Mapping.
- Online: Mapping-on-demand
- Hybrid: Trade-off between the low computational cost of offline and accuracy of online

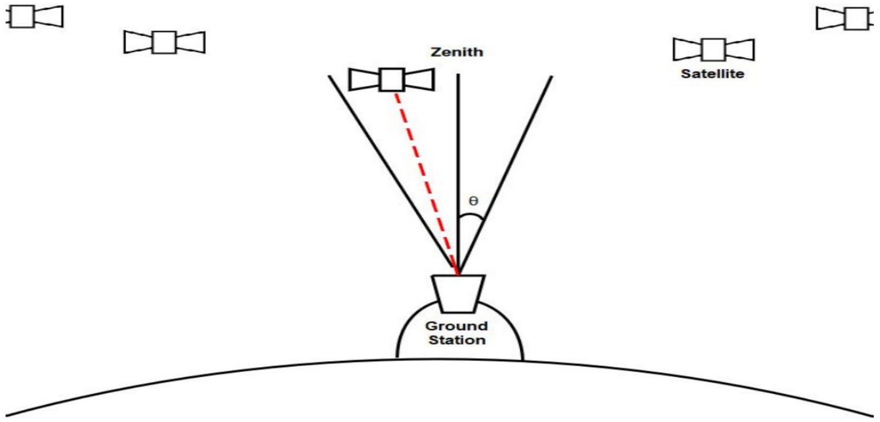


FIGURE 2. Transmittance of the photon beam depends on the deviation from the Zenith direction of the receiver. Ideally, the satellite closest to the zenith position (terminal satellite) should perform the down-link transmission.

STEP 2: ROUTE SATELLITE SELECTION

$$\tau_u = \tau_c + QR_d + \tau_t$$

Tc= commutation time:

Tu= Time that a satellite is allocated to be part of the transmission

QRd= d is the delay introduced by a quantum repeater

Tt= photon transmission time

$$\tau_r = QR_d \times \max\{n_{qr}(Source \longrightarrow S_A), \times n_{qr}(Source \longrightarrow S_B)\}$$

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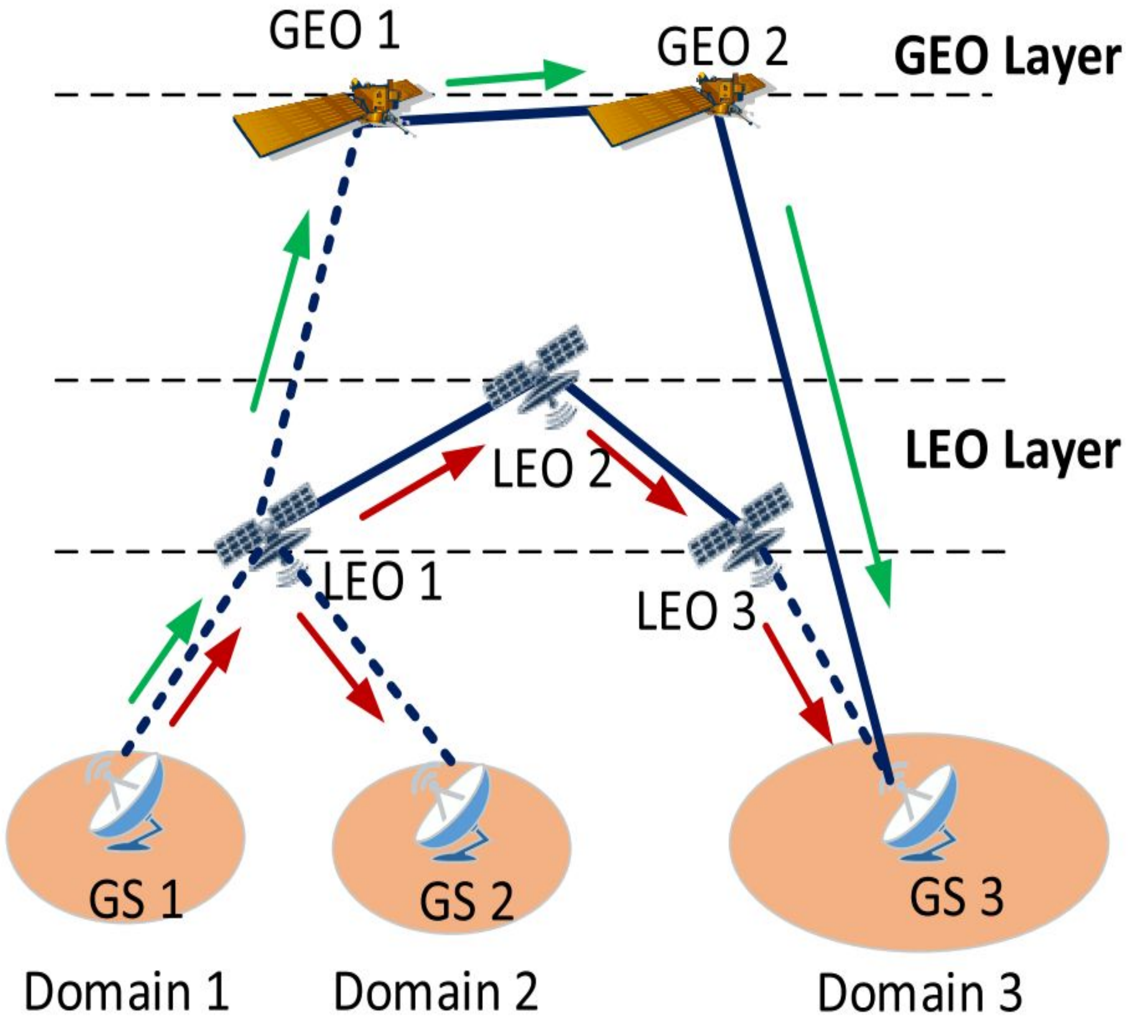
Quantum Key Distribution Over Double-Layer Quantum Satellite Networks

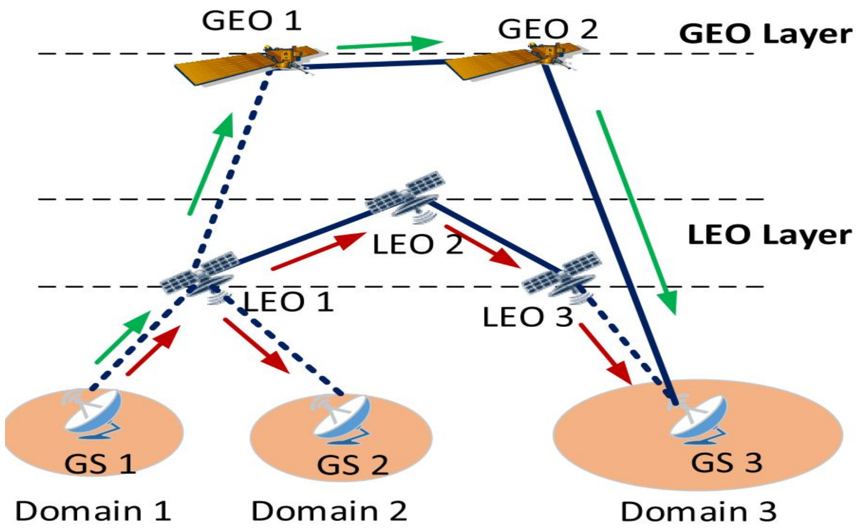
- Satellite Coverage
  - A single satellite cannot perform QKD for ground stations for the whole day
- LEO vs GEO
  - LEO:limited time of the day
  - GEO: continuously, all day; can suffer from high channel loss and limited key generation. igh channel losses of geostationary earth orbit (GEO) satellite
- Double layer = LEO ←→ GEO Links
  - helps improve routing!
- Dijkstra is used in both cases to find the shortest path (global knowledge)



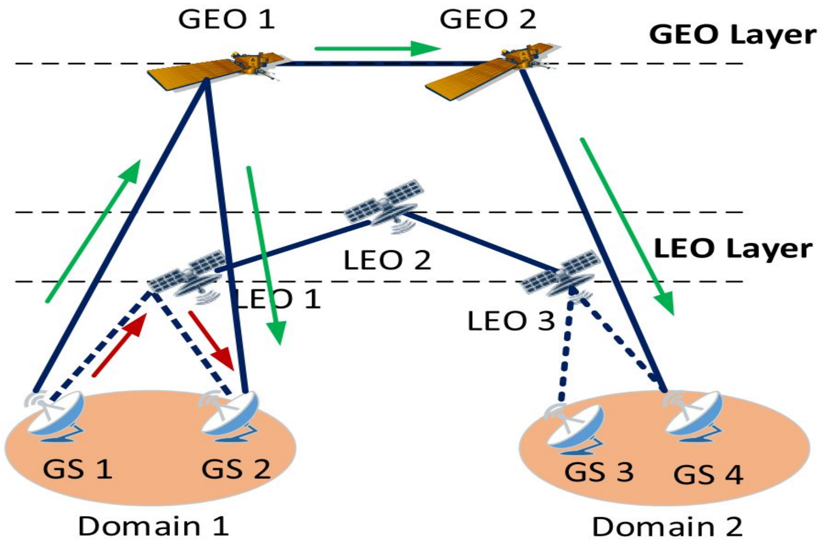
Huang, Donghai, et al. "Quantum key distribution over double-layer quantum satellite networks." *IEEE Access* 8 (2020): 16087-16098.

Quantum Key Distribution Over Double-Layer Quantum Satellite Networks

- Double Layer With GEO-LEO links :
  - terrestrial node searches for available LEOs as access satellite and chooses the best one which satisfies wavelength and key requirements
  - If there is no available LEO, it turns to select GEO as access satellite



- Double Layer **Without** GEO-LEO links
  - the terrestrial node searches available LEOs as priority selection.
  - If there is no available LEO, the source and destination nodes both turn to search GEO as access node because there are no GEO-LEO links



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Quantum Key Distribution Over Double-Layer Quantum Satellite Networks

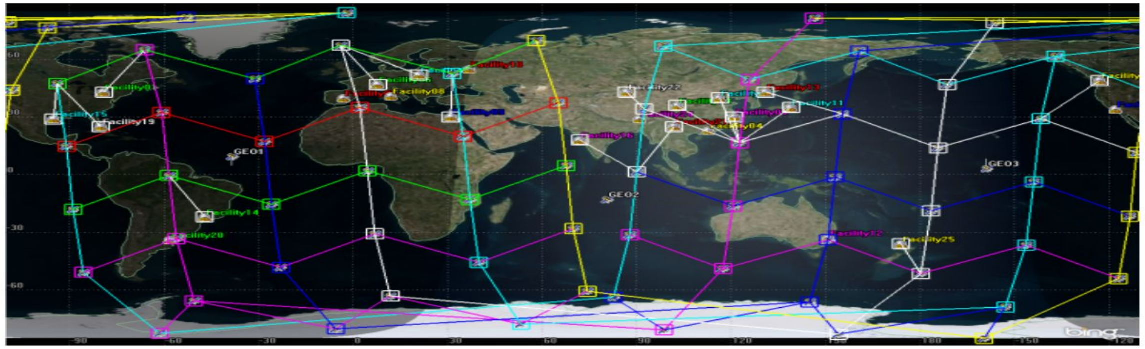
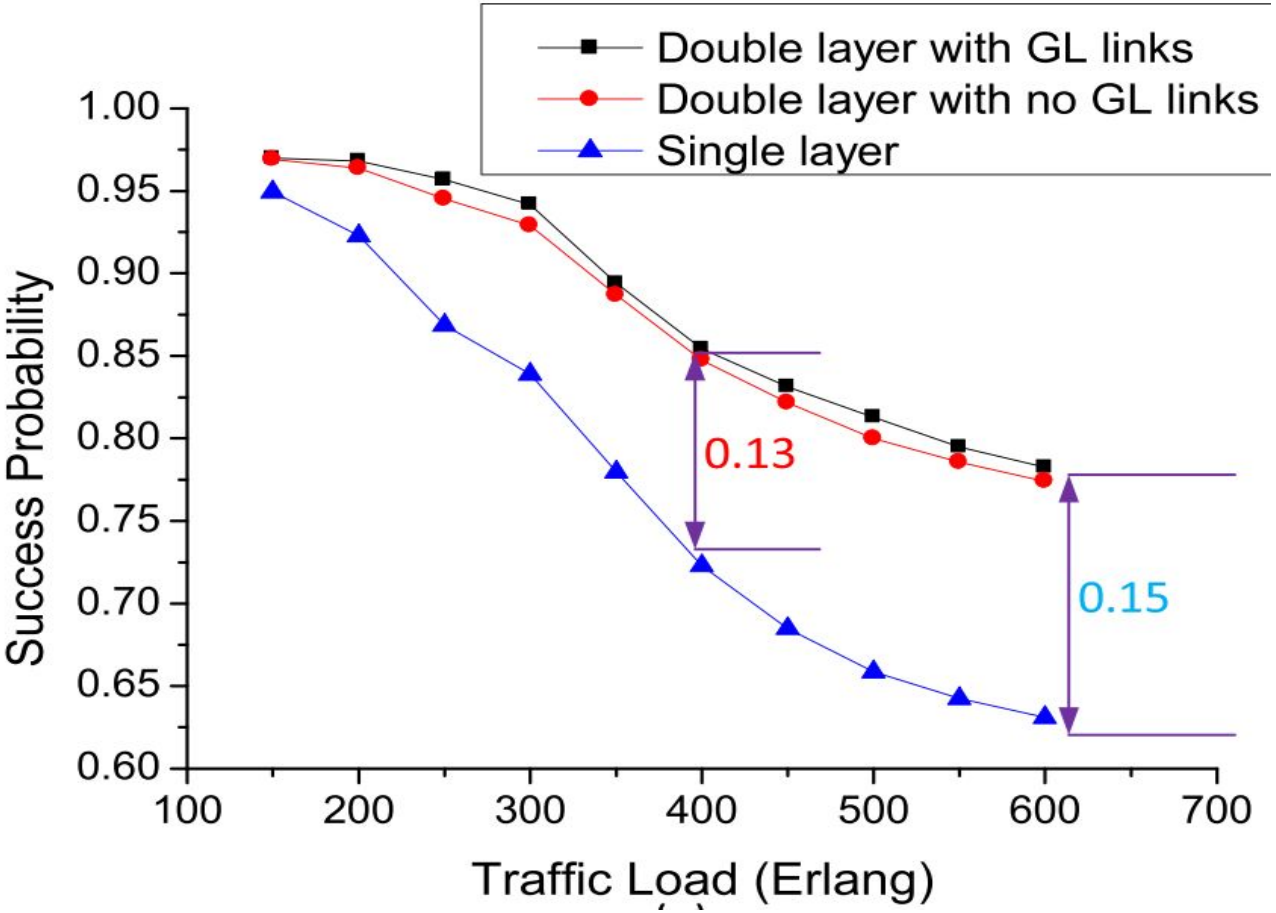


FIGURE 6. Satellite network topology used in simulation. (Picture from STK.) Considered ISL are drawn in the picture.



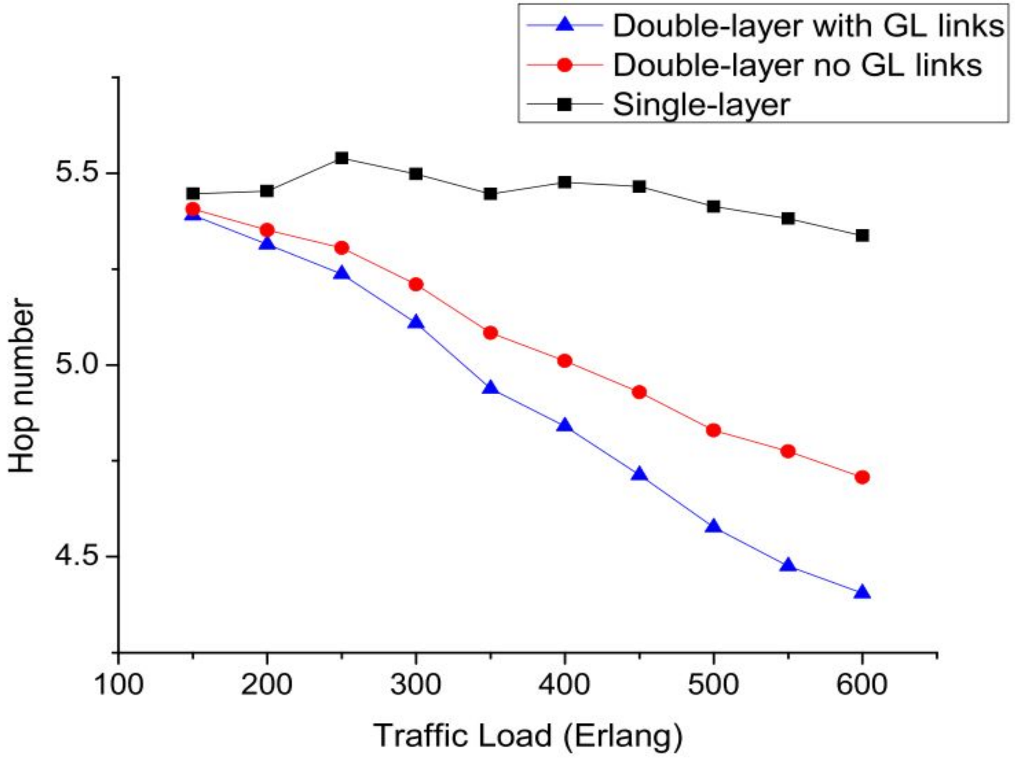


FIGURE 13. Average hop number of route path for key-relay service under different topologies. ($LN = 10$, $N_G = 2000$, $N_S = 20000$, $N = 20$).

Picchi, Roberto, et al. "Towards quantum satellite internetworking: A software-defined networking perspective." *IEEE Access* 8 (2020): 210370-210381.

Towards Quantum Satellite Internetworking
A Software-Defined Networking Perspective

- SDN based Routing
- Control Plane → Classical Channel
  - Routing
  - Signaling operation
  - SDN controller → Centralize and Global
- Data Plane → Quantum Channel
  - Create the Bell pairs
  - Photon transmission
- Aim to min number of hops for E2E connection and maximizing network capacity
- Evaluates three diferentes strategies
  - Centralized using Dijkstra algorithm
  - Two Distributed:
    - ACO: Ant Colony Optimization
    - MRW: Modified Random Walk

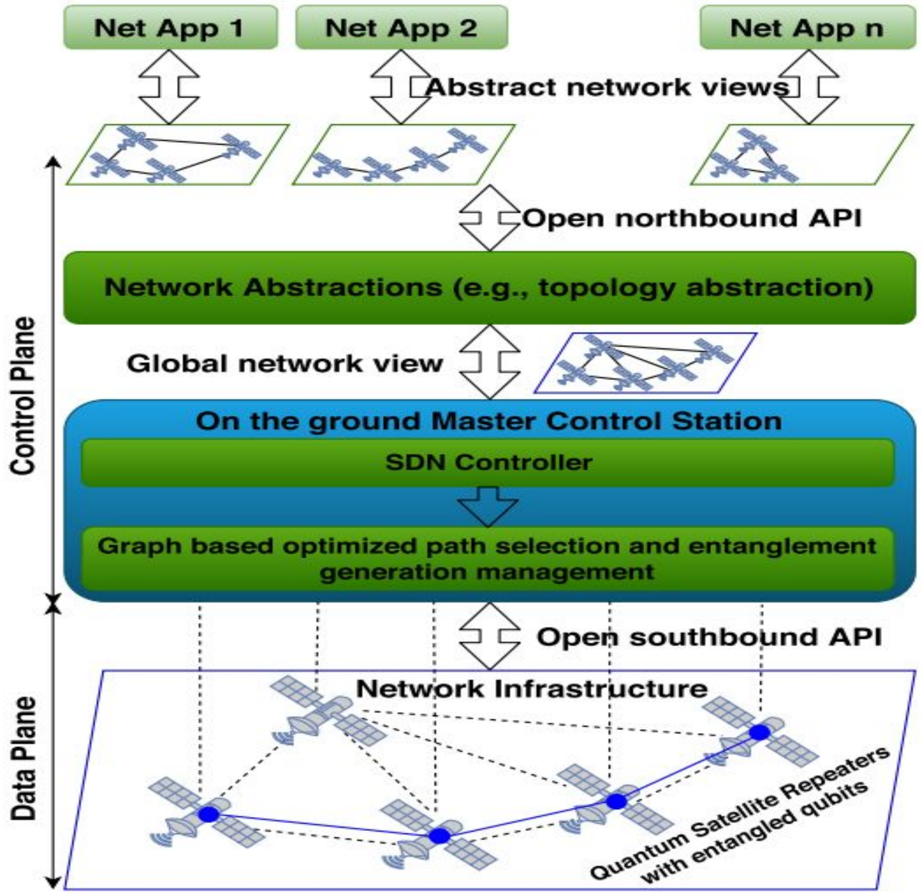


FIGURE 2. **Quantum Software-Defined Internetworking architecture.**

Picchi, Roberto, et al. "Towards quantum satellite internetworking: A software-defined networking perspective." *IEEE Access* 8 (2020): 210370-210381.

Towards Quantum Satellite Internetworking
A Software-Defined Networking Perspective

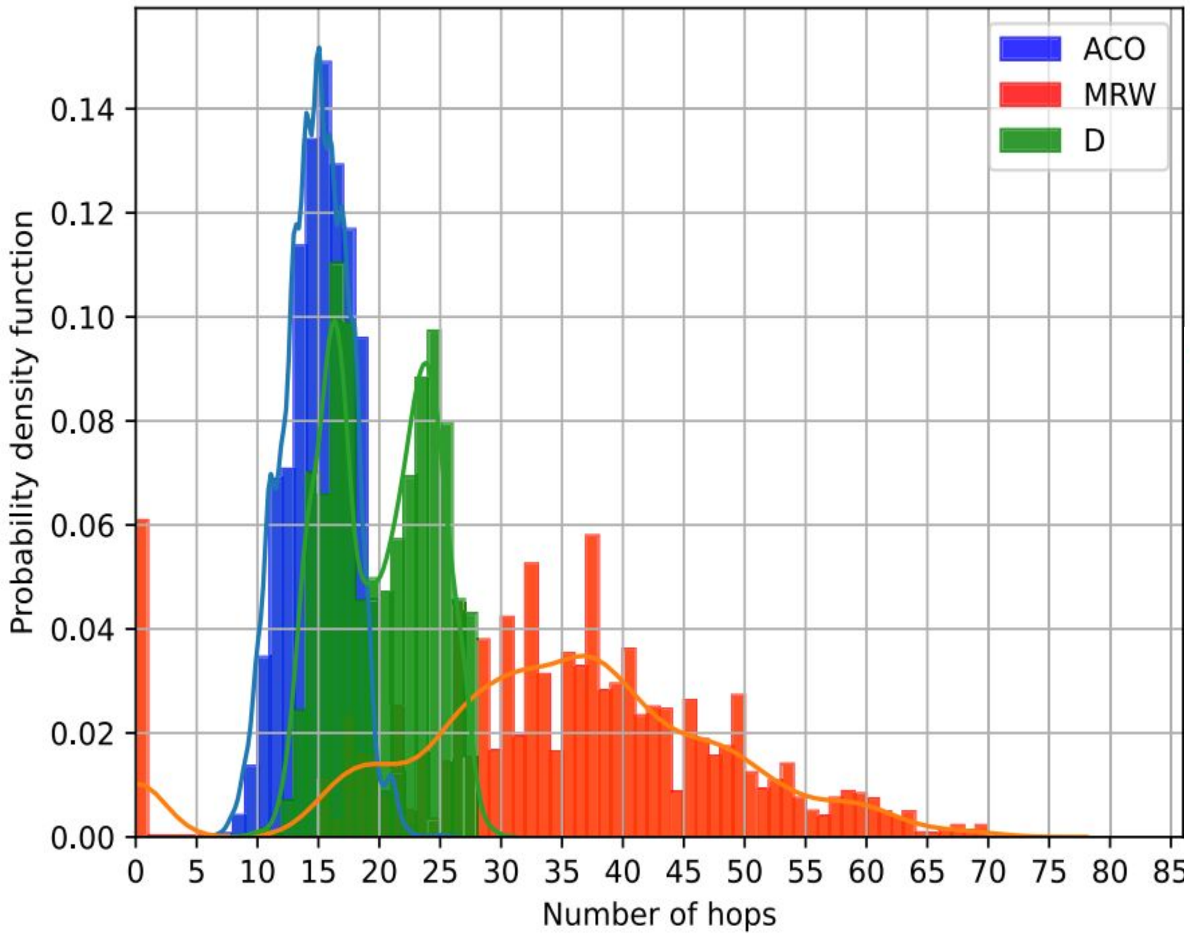


FIGURE 8. Number of hops Probability Density Functions for the considered MRW, ACO and Dijkstra protocols.

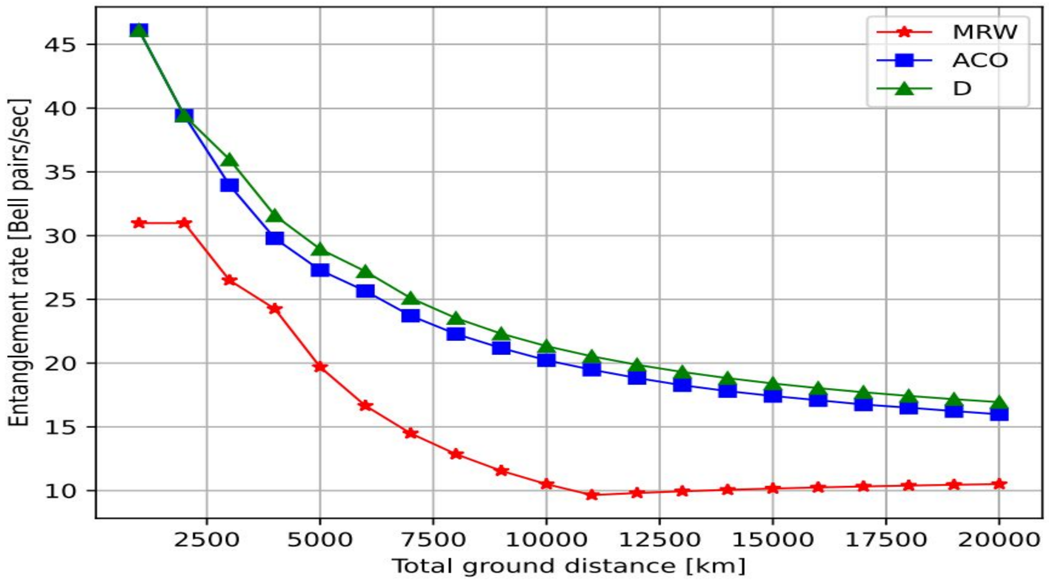


FIGURE 10. Entanglement rate as the distance between ground stations varies for the considered MRW, ACO and Dijkstra protocols.

TABLE 2. Average and standard deviation of the evaluated parameters for the considered MRW, ACO and Dijkstra protocols.

Algorithm	MRW		ACO		D	
Average and Standard deviation	μ	σ	μ	σ	μ	σ
End-to-end path length [km]	75610	34774	31897	2755	38965	6598
Maximum single link length [km]	4218	751	4229	564	3745	195
Number of hops	35	14	15	3	19	4
Entanglement rate [Bell pairs / s]	11.196	3.224	11.786	1.194	13.175	0.724

Picchi, Roberto, et al. "Towards quantum satellite internetworking: A software-defined networking perspective." *IEEE Access* 8 (2020): 210370-210381.

Summary and Challenges

- Routing in Quantum Networks is different from classical networks
- Mobility, Topology
- Open Challenges:
  - Physical-Aware metrics to consider
  - Entanglement-Based Routing in Mobily networks.

Questions

1. What are the advantages and disadvantages of quantum mobile in Satellites?
2. Describe how the reverse synchronization method works
3. Given three 3-qubit GHZ states, what are resultant states of a successful 3-fusion measurement? What are the resultant states in case of a failure event?