

Roteamento em Redes Quânticas

Tópicos Especiais em Redes: Novas Tecnologias para Internet do Futuro

PPGCC UFPA
2023.2

Diego Medeiros de Abreu

Eng. Computação - UFPA
Mestre em Ciência da Computação - UFPA
Doutorando em Ciência da Computação -PPGCC/UFPA



GERCOM UFPA

Research Group on Computer Networks and
Multimedia Communication
UFPA - Brazil

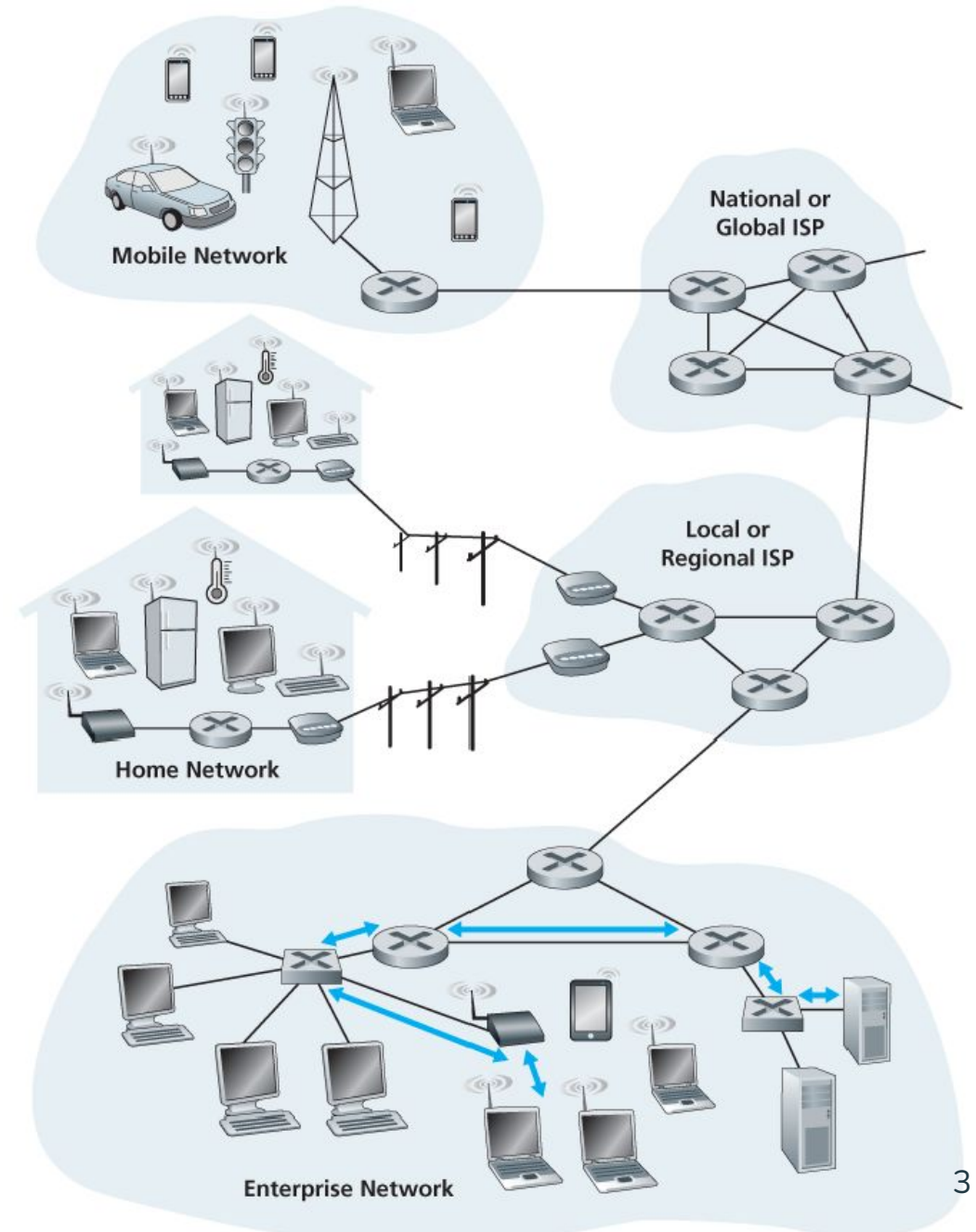


Roteiro

1. Introdução
2. Redes Quânticas
3. Roteamento em Redes Quânticas
4. Redes Quânticas Móveis
5. Roteamento em Redes Quânticas Móveis
6. Estado da Arte e Desafios
7. Conclusão

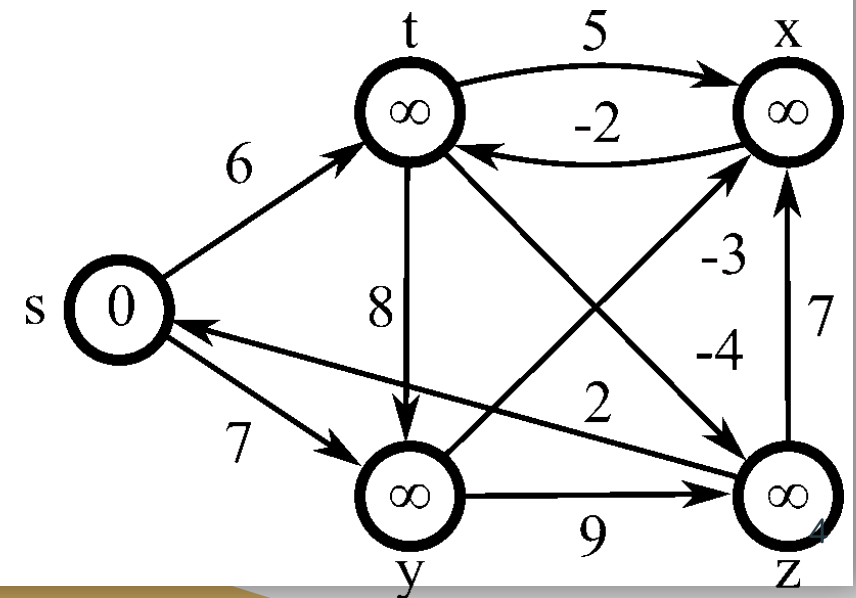
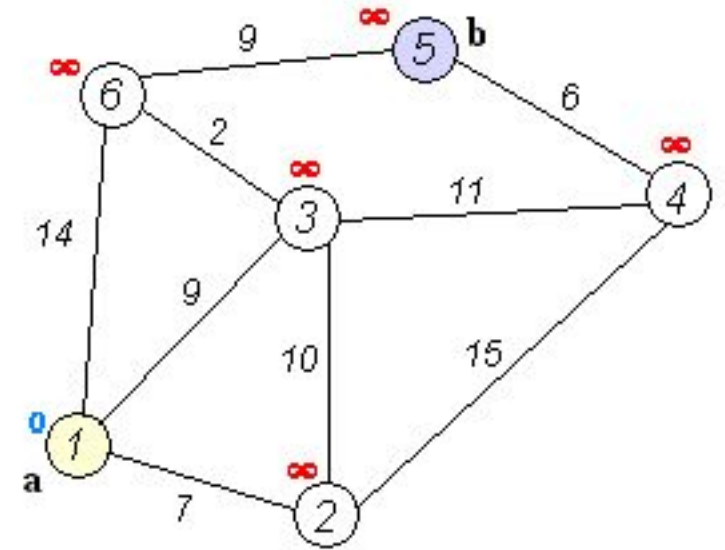
Introdução

- Em redes de computadores complexas, a escolha do caminho é importante.
 - Permite a comunicação eficiente entre dispositivos em diferentes redes.
- Qualidade do Serviço
- Balanceamento de Carga
- Qualidade do Serviço (QoS)
- Controle de Congestionamento
- Adaptar a topologias dinâmicas

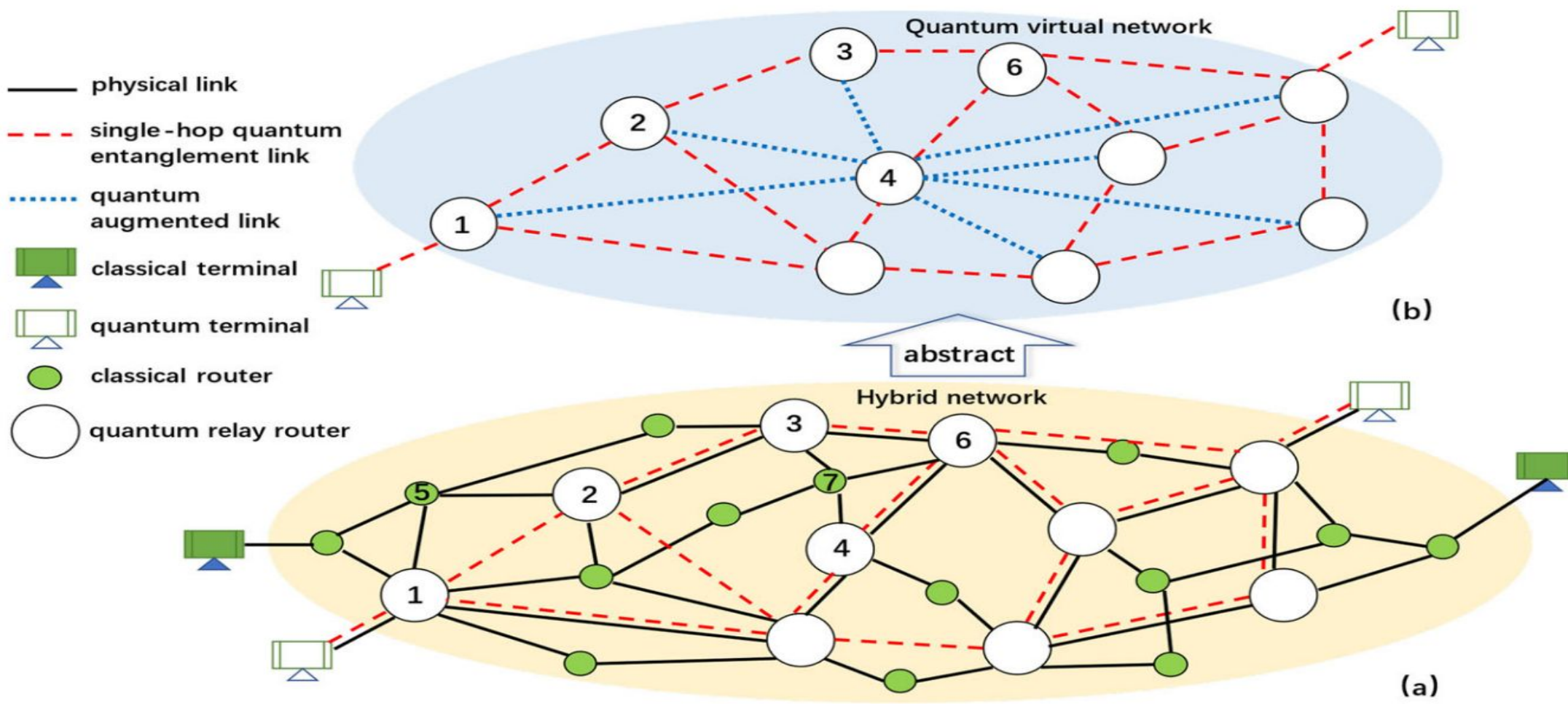
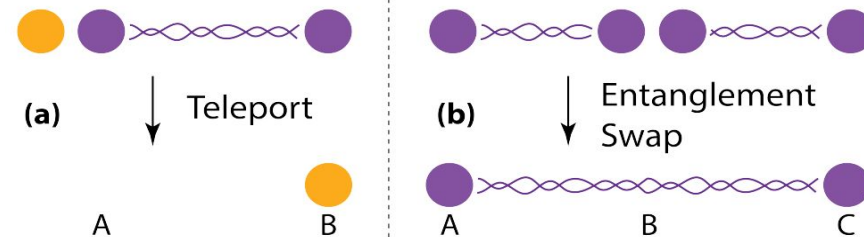


Roteamento Clássico

- Estado de Enlace
 - visão global, link cost info → E.g. Dijkstra
- Vetor de Distância
 - visão local, link costs to neighbors → E.g. Bellman Ford
- Objetivos:
 - Determinar o melhor caminho para encaminhar os dados de origem para destino

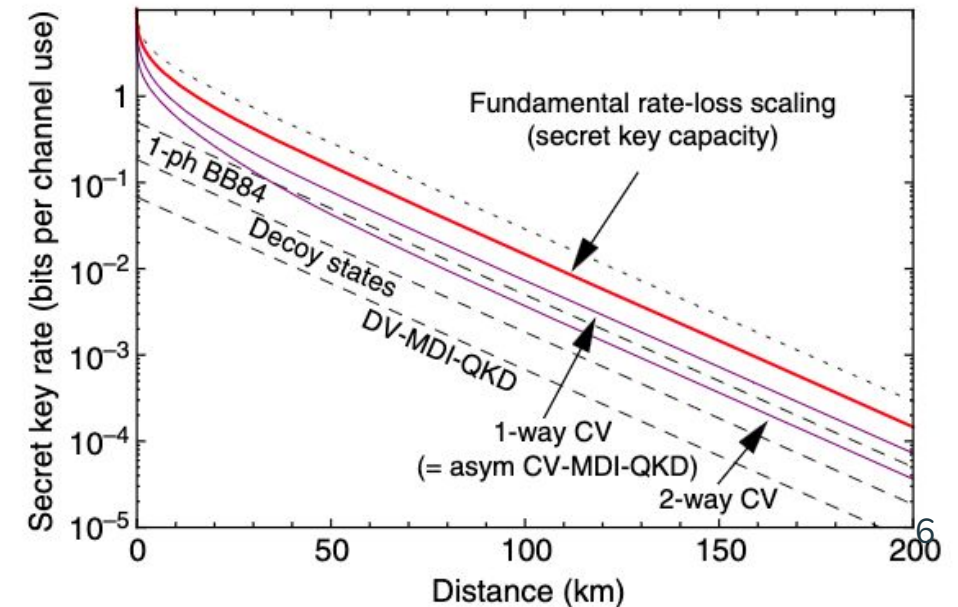
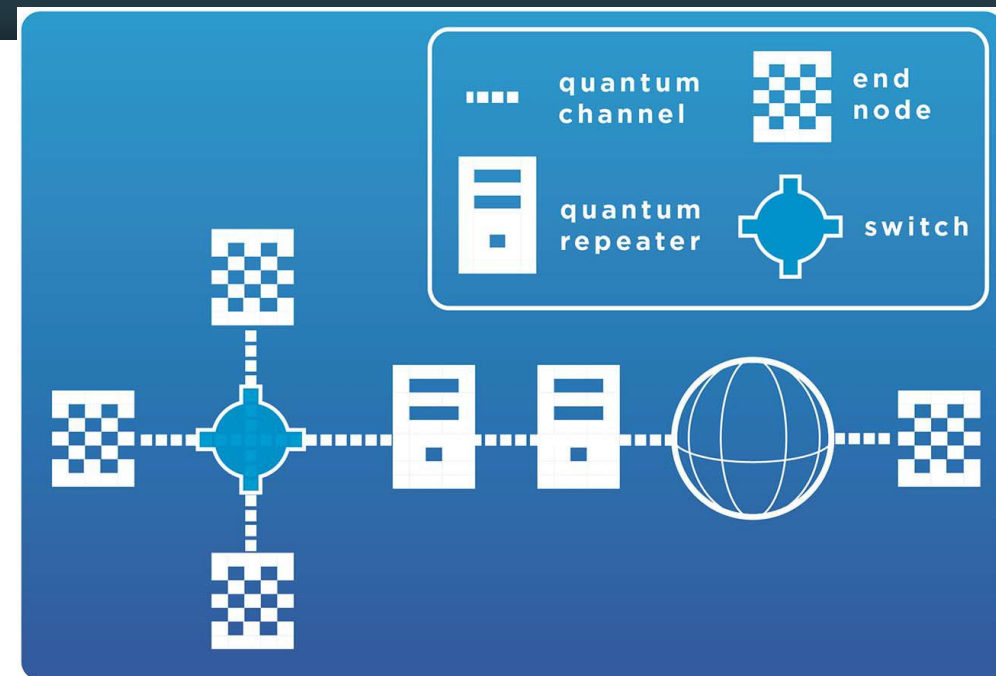


Redes de Comunicação Quântica



Roteamento em Redes Quânticas

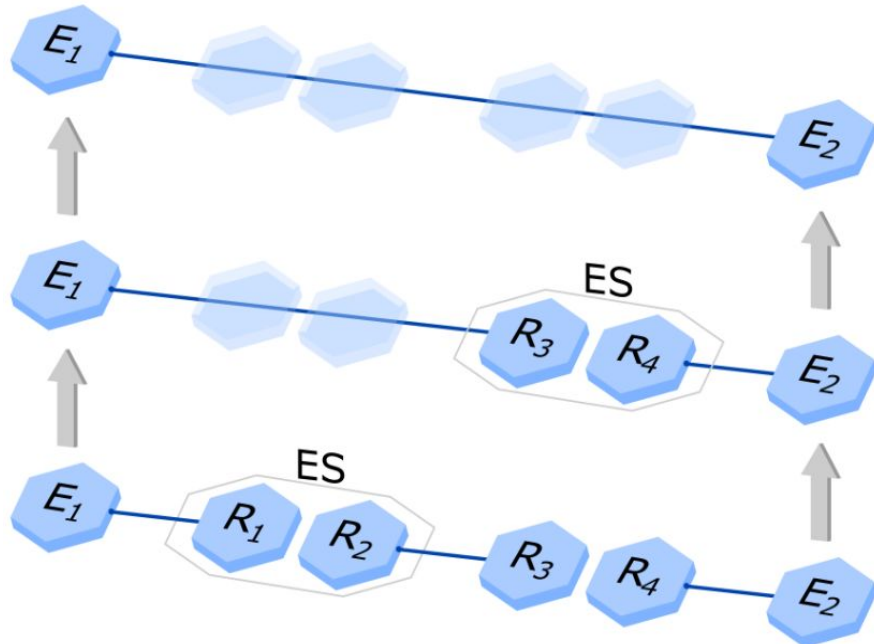
- Desafios
 - Qubit não pode ser copiado (No cloning theorem)
 - Não posso fazer retransmissão ou aumentar a potência.
- Duas formas de roteamento
 - Bi-partido: Baseado em Teletransporte / Estados de Bell / 2 nós
 - EPR = Einstein-Podolsky-Rosen
 - Multi-partido: Baseado em estados GHZ /n nós.
 - GHZ =Greenberger-Horne-Zeilinger



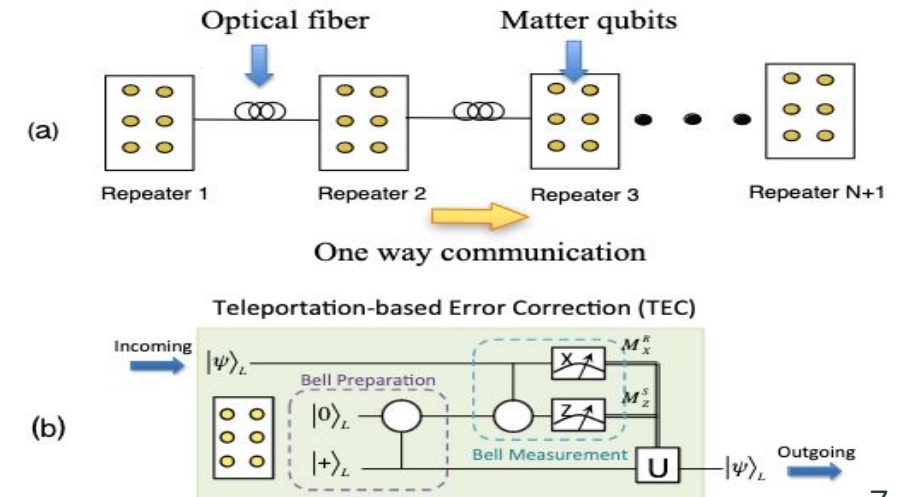
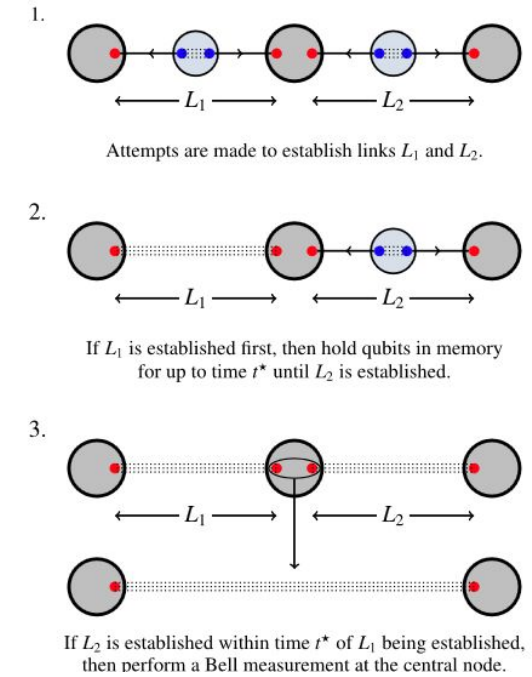
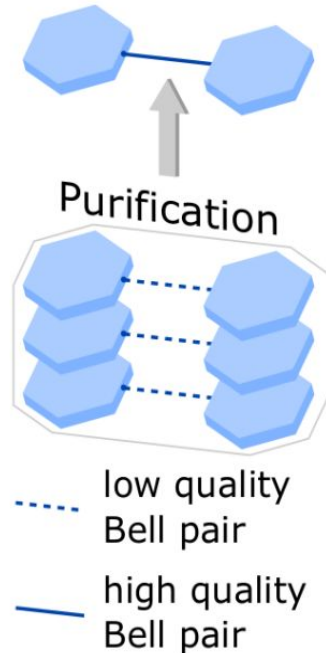
Roteamento Bi-partido

- Utiliza entrelaçamento compartilhado entre 2 nós para realizar o teletransporte quântico
- Two ways (com intermediário) ou One way (sem o intermediário)
- Repetidores geram os pares ERP e fazem o Entanglement Swapping
- **ERP** como **recurso** a ser compartilhado

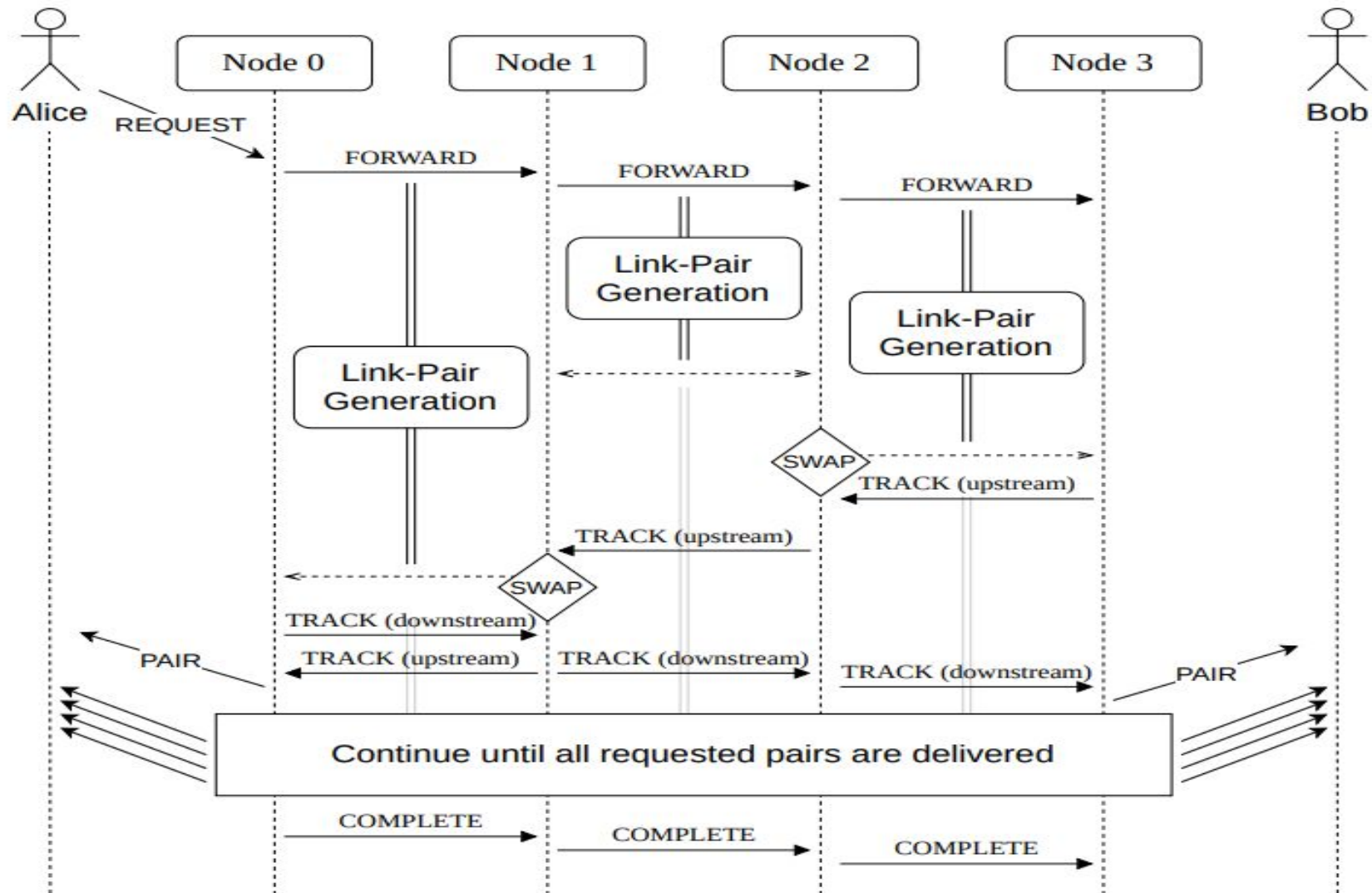
a) End-to-end entanglement



b) Error detection



Redes Quânticas: Exemplo, criação dos ERP



Roteamento Multi-partido

- Utiliza estados GHZ para realizar entrelaçamentos multi-partido entre nós da rede.
- Aplicações distribuídas / broadcast.

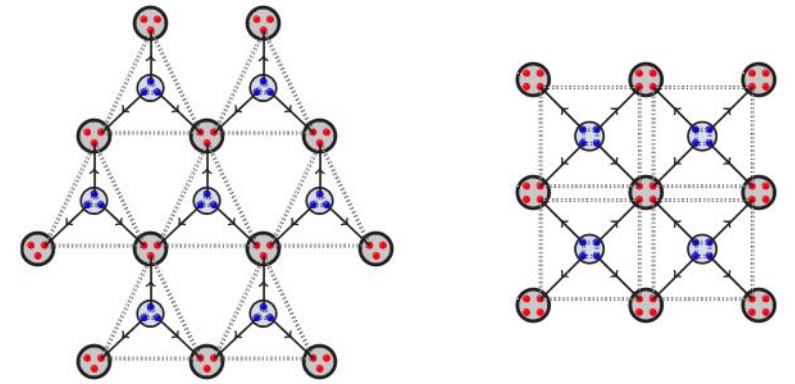
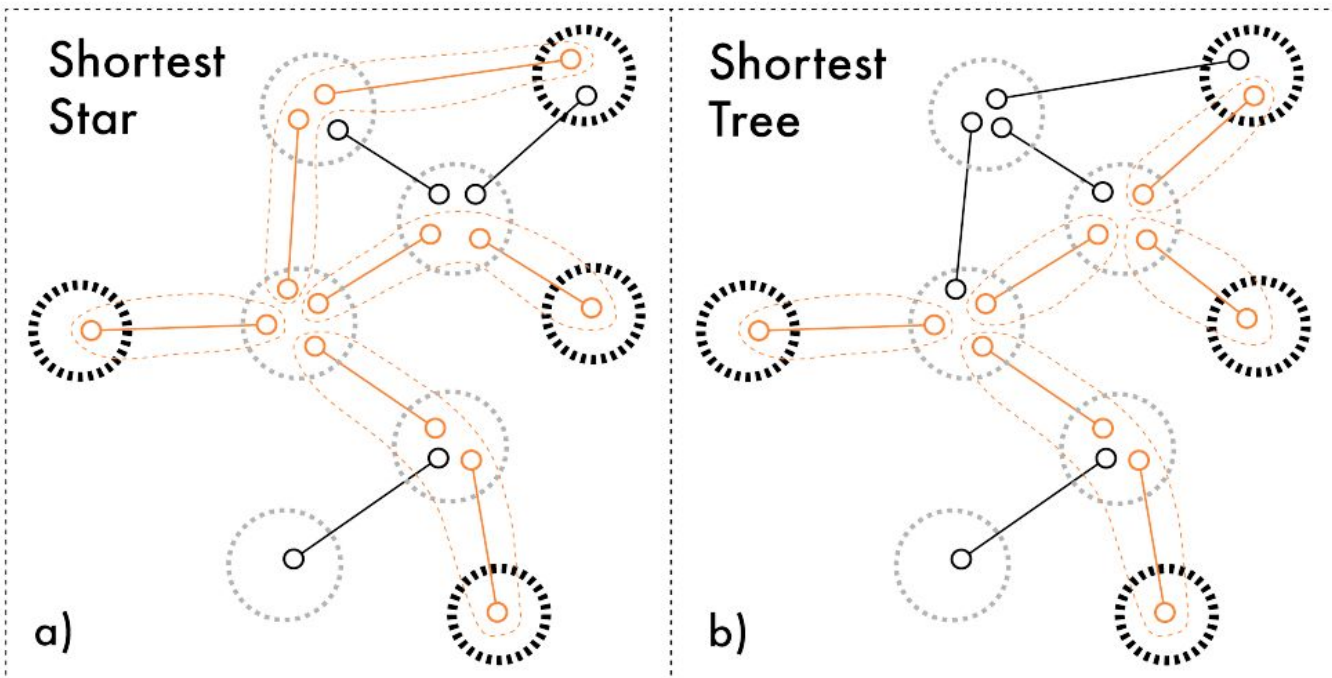
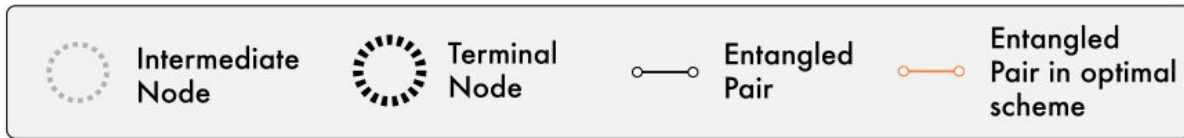
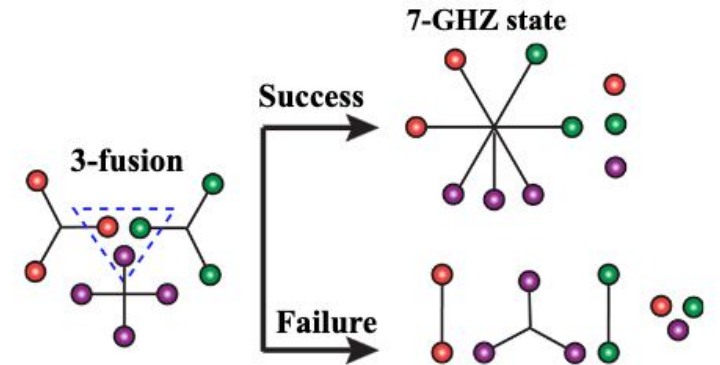
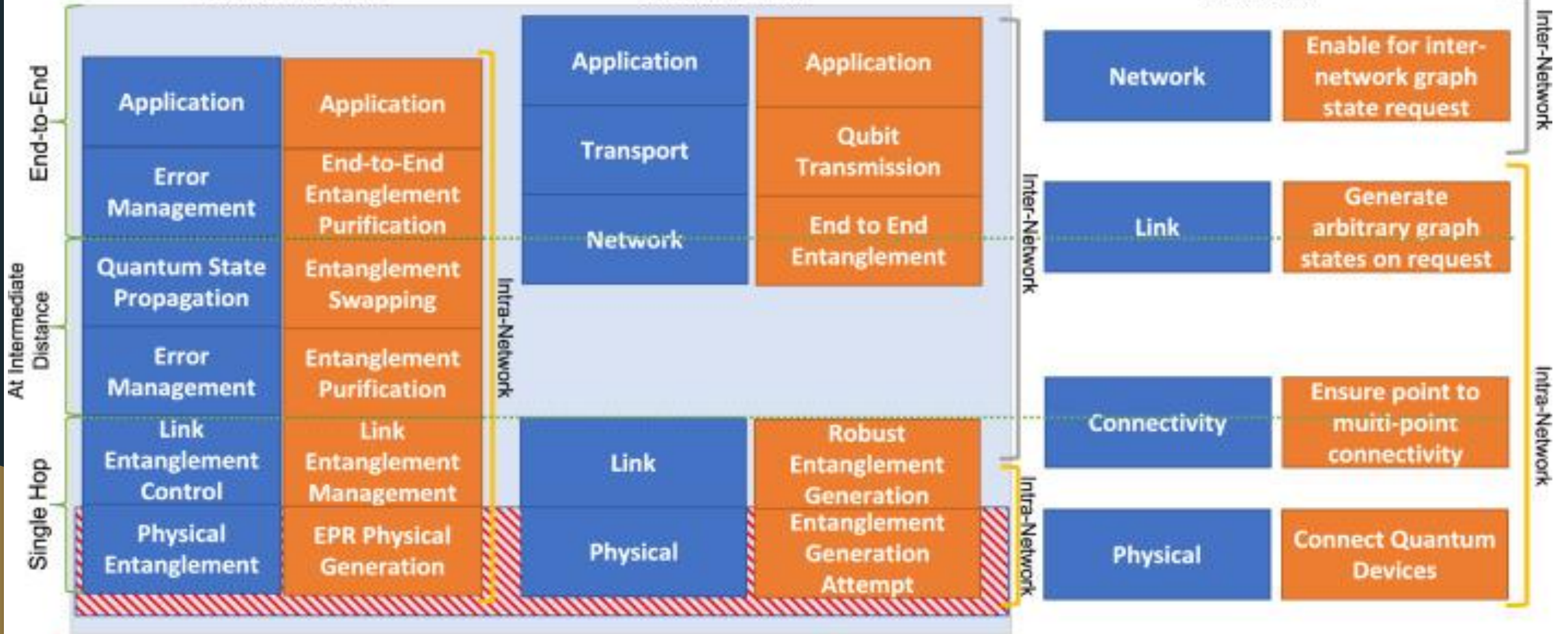


FIG. 2. Instead of bipartite entanglement, as in Fig. 1(a), the elementary links in a quantum network can consist of multipartite entanglement; for example, we can have elementary links of tripartite (left) or four-partite (right) entanglement.





EPR based

Multipartite entanglement based



Layer

Main functionality

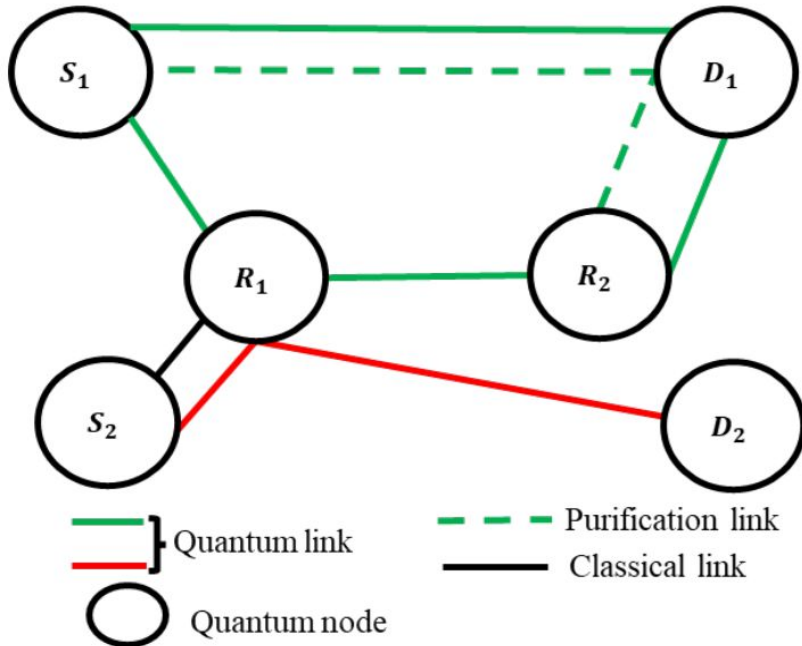


Local Operations and Classical Communications

Quantum Communications

Propostas de Roteamento : Considerando Fidelidade e Purificação

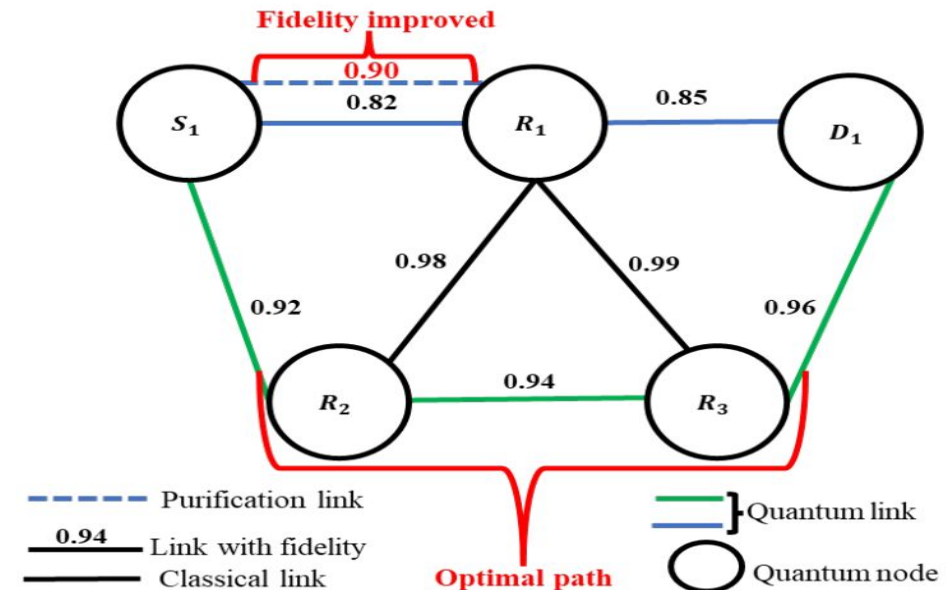
- Fidelidade fim-a-fim
- Purifica o caminho todo
- A purificação pode demorar muito



(a) End-to-end fidelity aware routing—where the dashed green line shows the purified path and the solid green and red lines entangle the path for e2e fidelity.

Y. Zhao, G. Zhao, and C. Qiao, “E2e fidelity aware routing and purification for throughput maximization in quantum networks,” in IEEE **INFOCOM 2022**-IEEE Conference on Computer Communications. IEEE, 2022, pp. 480–489

- Fidelidade a cada “enlace”
- Purifica a cada passo
- Pode acabar purificando caminhos desnecessários



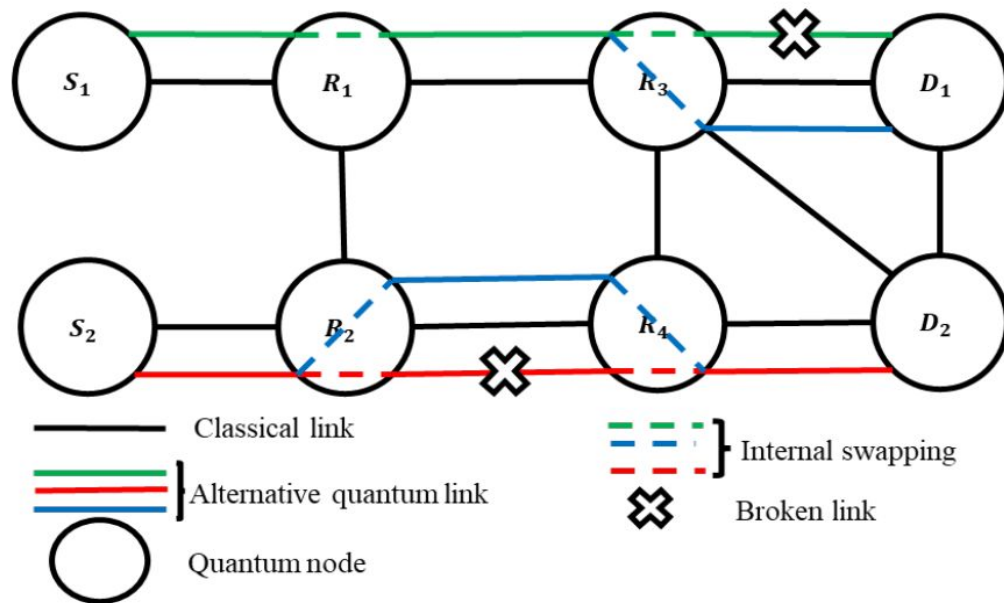
(b) Fidelity-based routing—where the dashed blue line shows the fidelity improvement path. So, $S_1 \rightarrow R_1 \rightarrow D_1$ and $S_1 \rightarrow R_2 \rightarrow R_3 \rightarrow D_1$ optimal path for entanglement.

J. Li, M. Wang, K. Xue, R. Li, N. Yu, Q. Sun, and J. Lu, “Fidelity-guaranteed entanglement routing in quantum networks,” **IEEE Transactions on Communications**, vol. 70, no. 10, pp. 6748–6763, 2022

Propostas de Roteamento : Considerando falha na “rede”

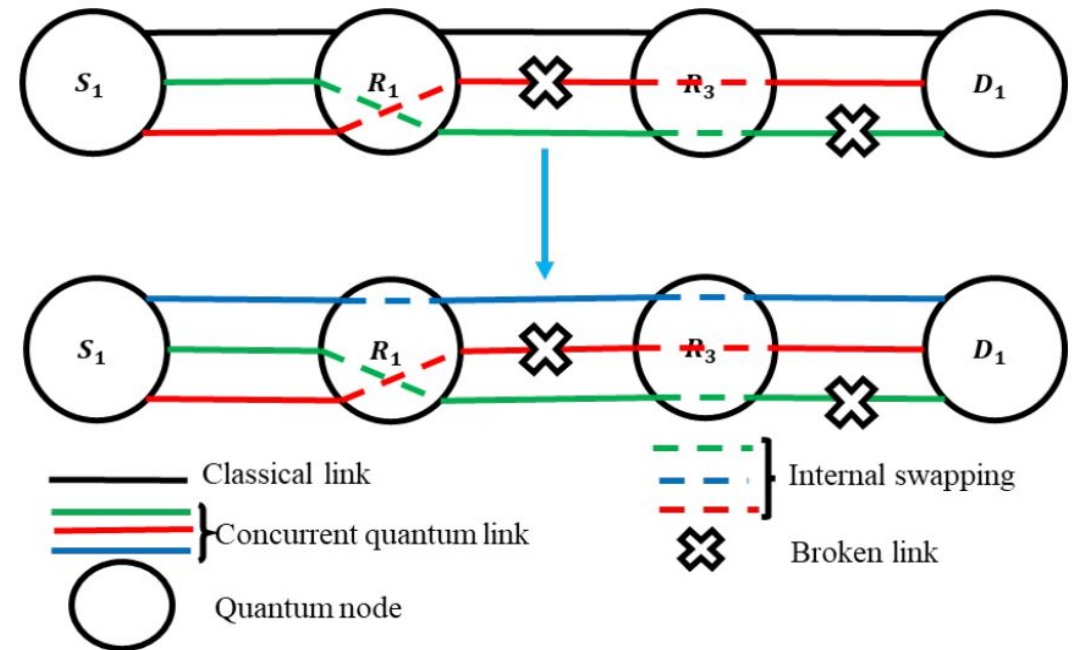
Quando criar o caminho alternativo?

- Link quântico alternativo: no ponto de falha → Como fazer?
- Sempre manter um caminho alternativo → Qual o custo?



(a) Redundant entanglement routing—where solid blue line (R_3, D_1) & (R_2, R_4) are redundant paths.

Y. Zhao and C. Qiao, “Redundant entanglement provisioning and selection for throughput maximization in quantum networks,” in **IEEE INFOCOM 2021**-IEEE Conference on Computer Communications. IEEE, 2021, pp. 1–10.

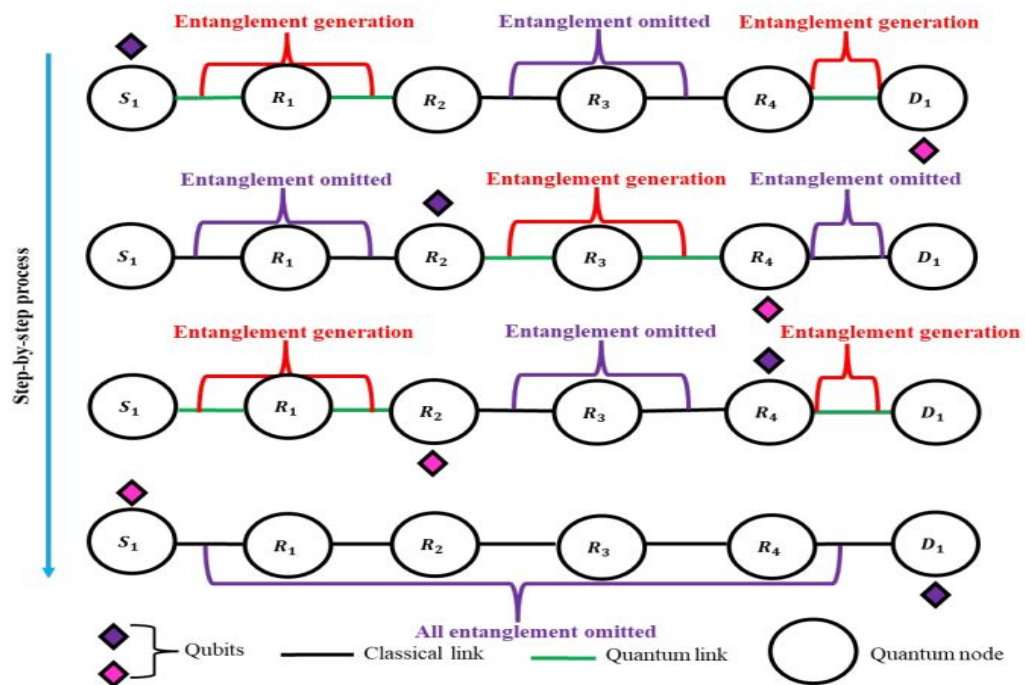


(b) Concurrent routing—where all solid blue, red, and green lines represent concurrent paths in a one-time slot.

S. Shi and C. Qian, “Concurrent entanglement routing for quantum networks: Model and designs,” in Proceedings of the Annual conference of the **ACM** Special Interest Group on Data Communication on the applications, technologies, architectures, and protocols for computer communication, 2020, pp. 62–75.

Propostas de Roteamento : caso oportunístico e multi-usuário

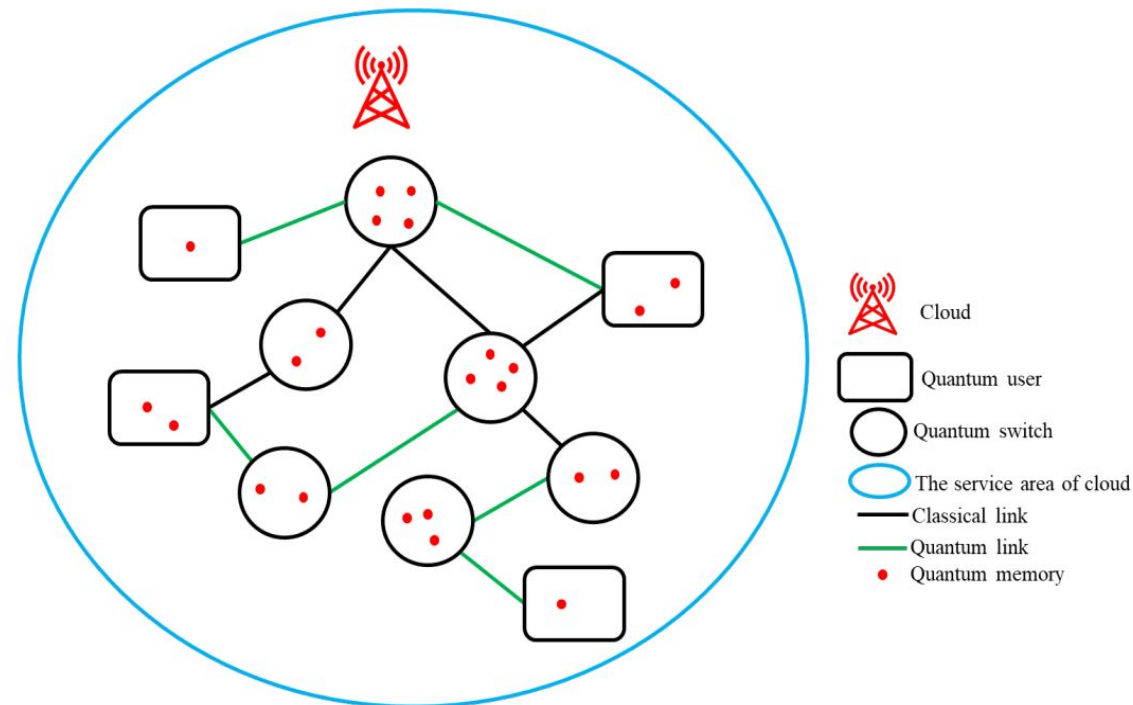
- Faz o teletransporte ponto-a-ponto assim que possível
- Não espera o ERP ficar pronto em todo o caminho.



(d) Opportunistic routing—where diamonds shape blue qubit transfer from the left to right and pink qubit transfer from right to left.

A. Farahbakhsh and C. Feng, “Opportunistic routing in quantum networks,” in **IEEE INFOCOM 2022**-IEEE Conference on Computer Communications. IEEE, 2022, pp. 490–499

- Mantém links “inativos” para evitar conflito entre multiusuários
- Cloud = determina as rotas e “liga” os switches. → Rede híbrida.

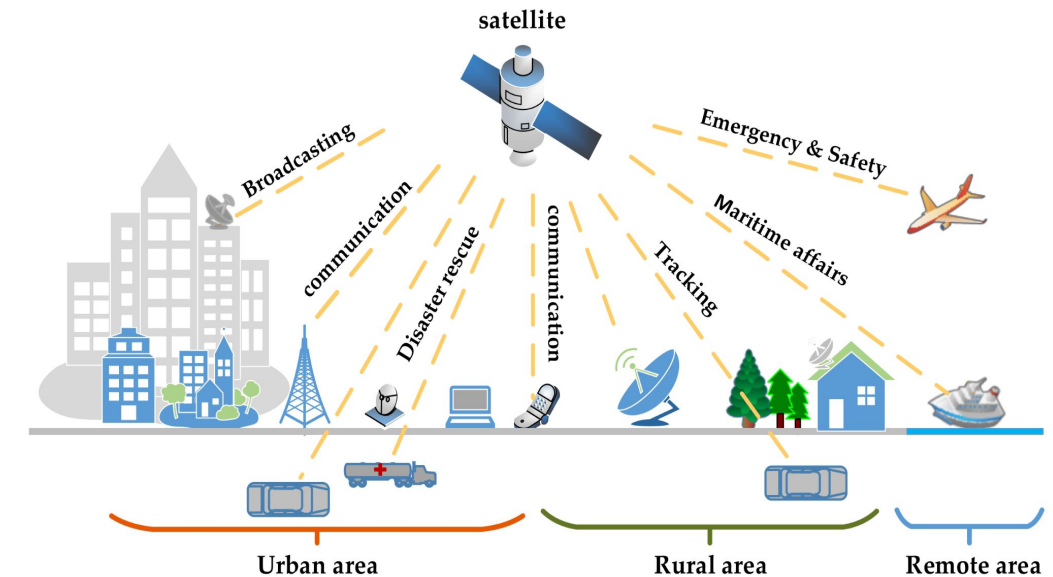
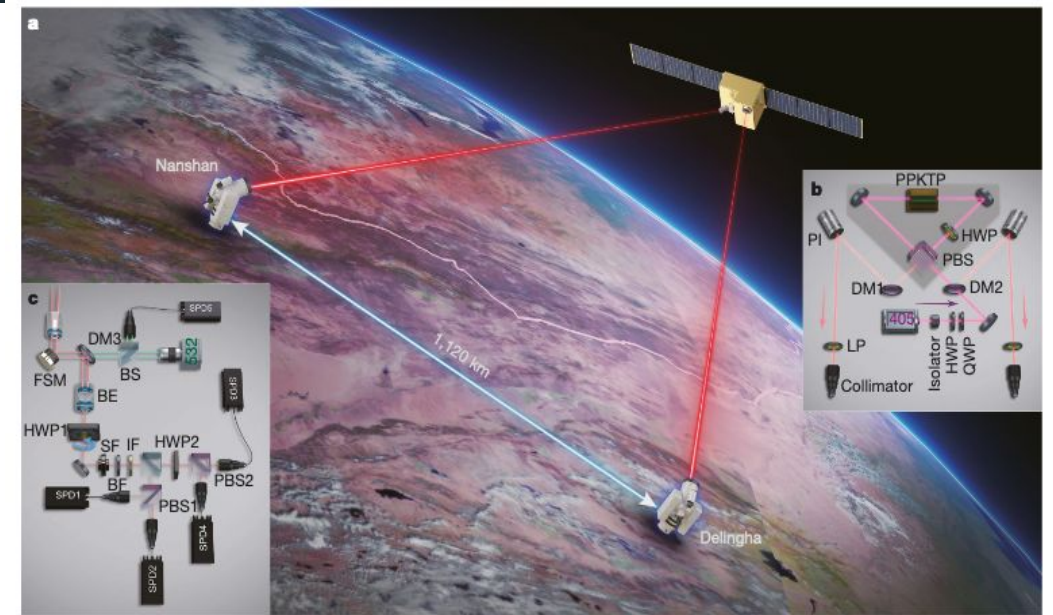


(c) Multi-user routing—where all quantum users communicate with quantum switch without overlapping with each other.

Y. Zeng, J. Zhang, J. Liu, Z. Liu, and Y. Yang, “Multi-entanglement routing design over quantum networks,” in **IEEE INFOCOM 2022**-IEEE Conference on Computer Communications. IEEE, 2022, pp. 510–519

Redes Quânticas Móveis

- Limitações da rede quântica “terrestre”
 - Baseada em uma cadeia de repetidores
 - Difícil de implementar em longas distâncias
 - Dificuldade de escala
- Vantagens de redes quânticas móveis
 - A perda de fidelidade do canal quântico é muito menor
 - Maior cobertura: redes de longas distâncias
 - Transmissão de photons via satélite
 - Entrelaçamento entre estações base e satélites



Redes Quânticas Móveis: Integração com rede cabeada

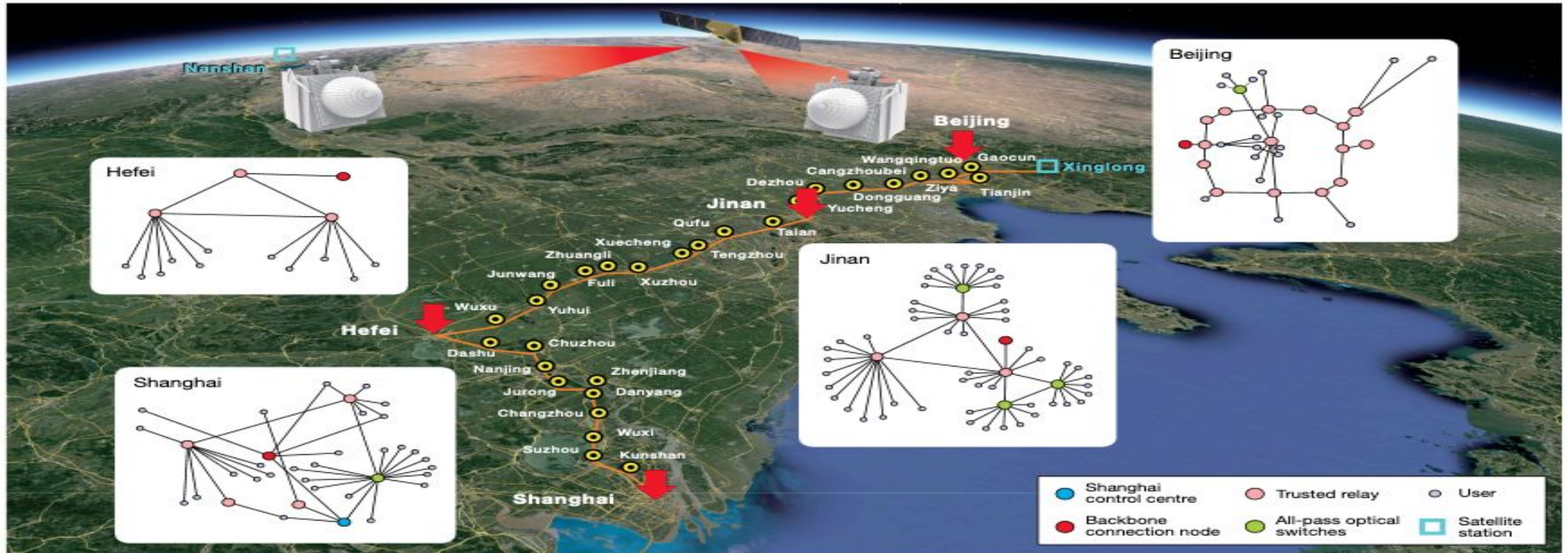
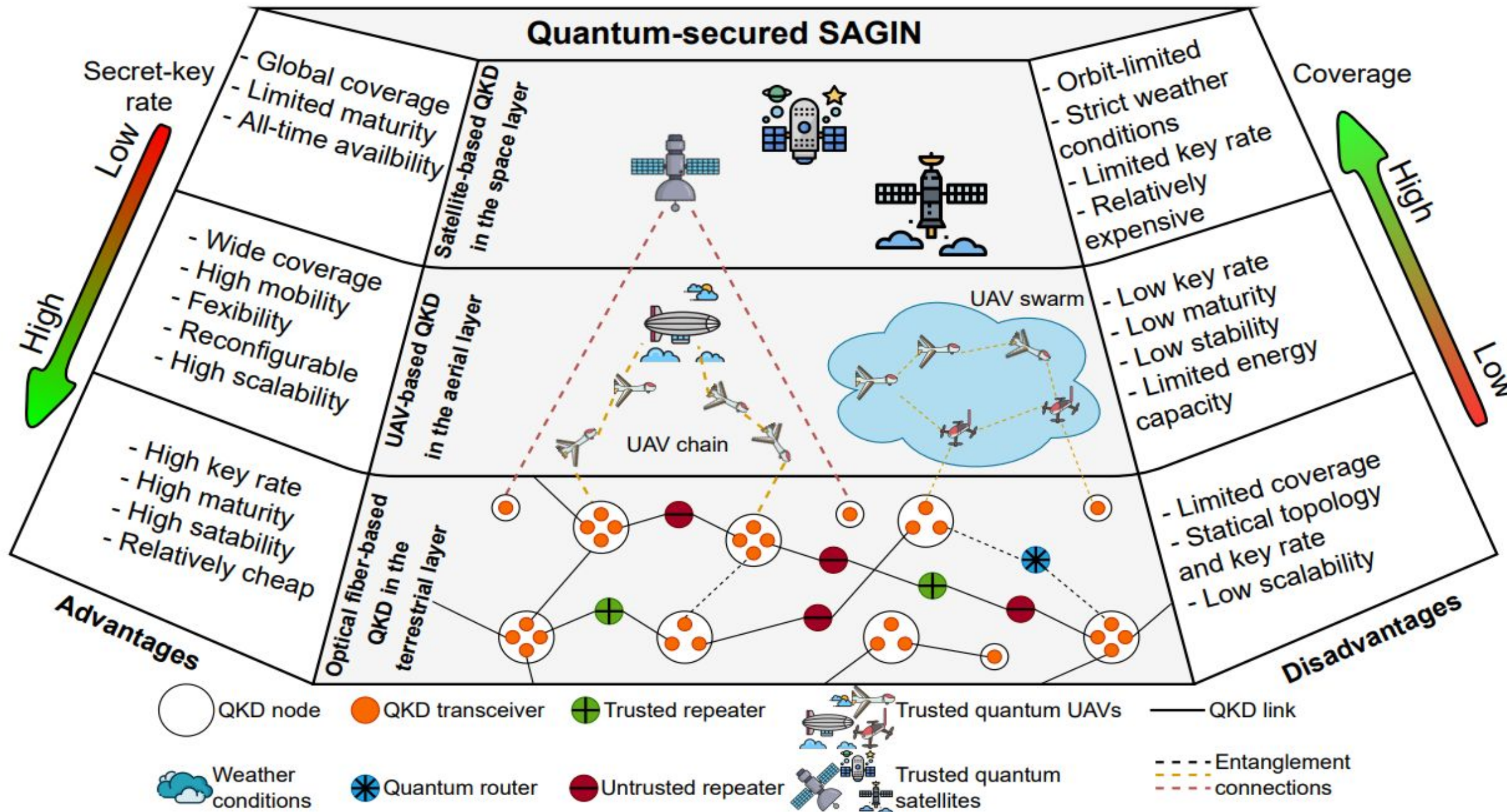


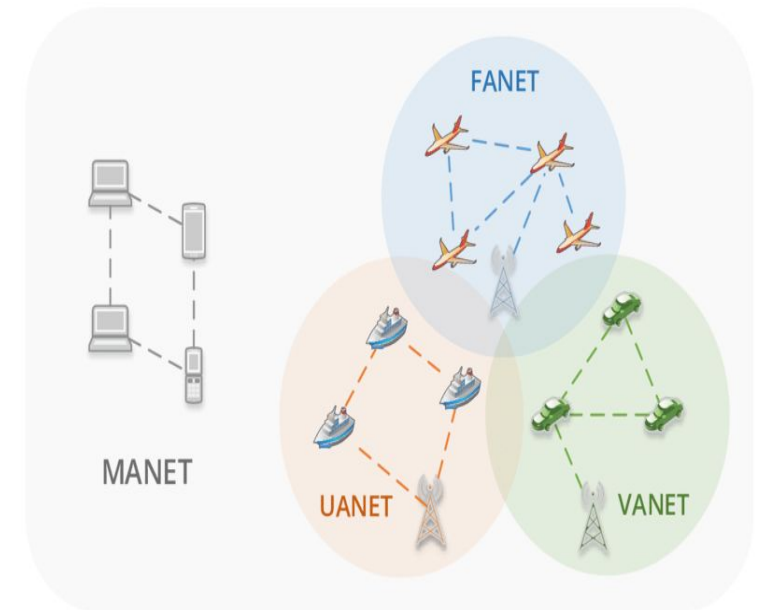
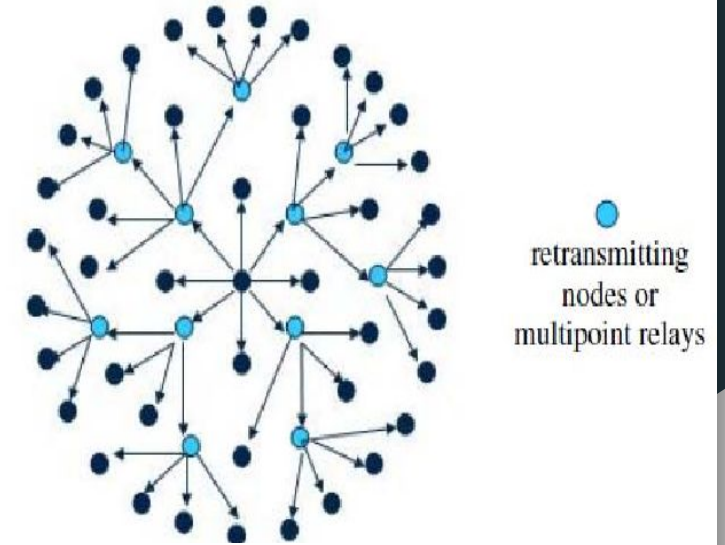
Fig. 1 | Illustration of the integrated space-to-ground quantum network. The network consists of four QMANs (in Beijing, Jinan, Shanghai and Hefei; red arrows), a backbone fibre link over 2,000 km (orange line) and two ground-satellite links that connect Xinglong and Nanshan (blue squares), separated 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.



MANET: Mobile Ad-hoc Networks

- **Principais características**
 - Topologia dinâmica
 - Redes auto-organizáveis
 - Links assimétricos
 - Mobilidade
 - A taxa de falha/reparo do link devido à mobilidade do nó pode ser muito alta
- Largura de banda limitada, reduzida ainda mais devido à troca de roteamento.

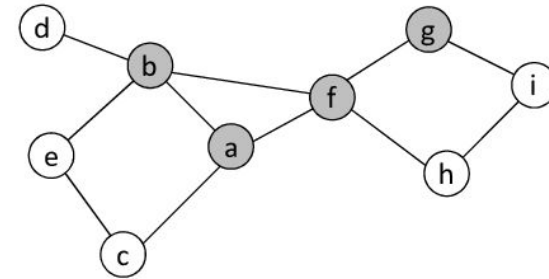


Roteamento em Manet:

- Protocolos de redes estruturadas não foram pensados para redes dinâmicas e com baixa largura de banda.
- Vetor de Distância
 - ‘Count-to-infinity’ problem and convergencia demorada
 - Formação de loops durante falhas ou partições na rede
- Estado de Enlace
 - Pode gerar um flooding da rede e criar tráfego excessivo e overhead de dados de controle
- Protocolos de Manets
 - Protocolos Reativos (on-demand)
 - Protocolos Proativos

Protocolos Proativos : Ex. OLSR

- Criam as tabelas de rotas para todos os nós.
- Tenta manter informações de roteamento consistentes e atualizadas de cada nó para todos os outros nós da rede.
- Responde a mudanças propagando atualizações por toda a rede
- Bom para tráfego sem conexão, onde o tráfego é enviado para qualquer nó a qualquer momento
- **PRO:**
Caminhos imediatamente disponíveis; cada nó tem uma visão atualizada da topologia da rede
- **CONS:**
Grandes tabelas de roteamento; Baixa escalabilidade; Alta largura de banda e consumo de energia devido a atualizações periódicas



MPRs	Selector Set
a	b, c, f
b	a, e, f, d
f	a, b, h, g
g	f, i

Protocolos Reativos: Ex. AODV

Mantém rotas somente se necessário

- As rotas são criadas apenas quando desejadas pelo nó de origem
 - Fase de descoberta de rota
 - Fase de manutenção da rota
 - **PRO:**
 - Os caminhos são calculados somente sob demanda;
 - sem necessidade de atualizações periódicas;
 - Economia de energia e largura de banda: os nós podem entrar no modo de hibernação.
 - **CONS:**
 - Atrasos de configuração de caminho mais longos (descoberta de rota);
 - A eficiência da busca de caminhos depende da mobilidade do nó;
 - necessidade de memória para manter os caminhos descobertos;
 - Cabeçalho de pacote mais longo para armazenar o caminho.

Optimisation of the routing protocol for quantum wireless Ad Hoc network." IET Quantum Communication 3.1 (2022)

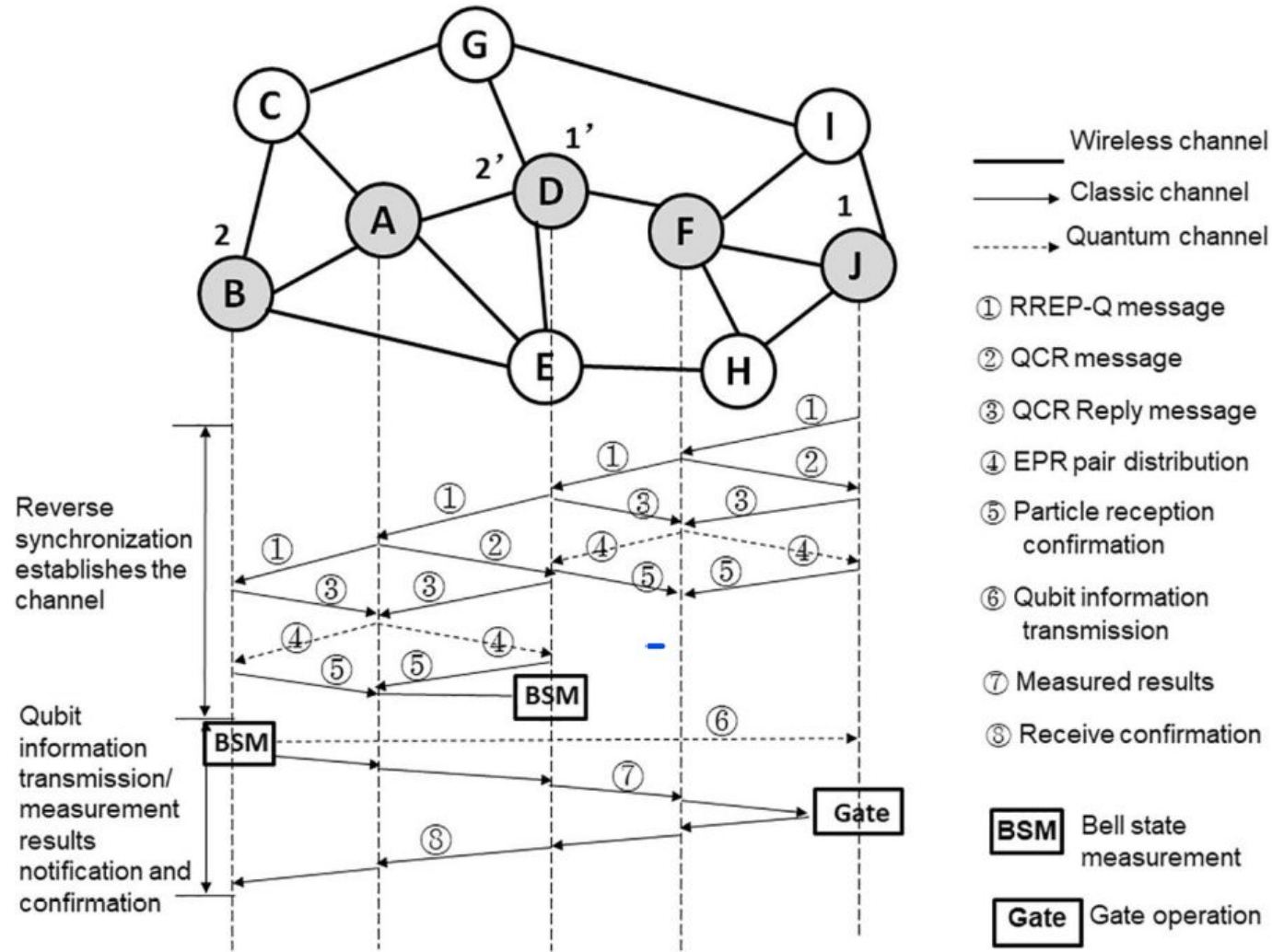
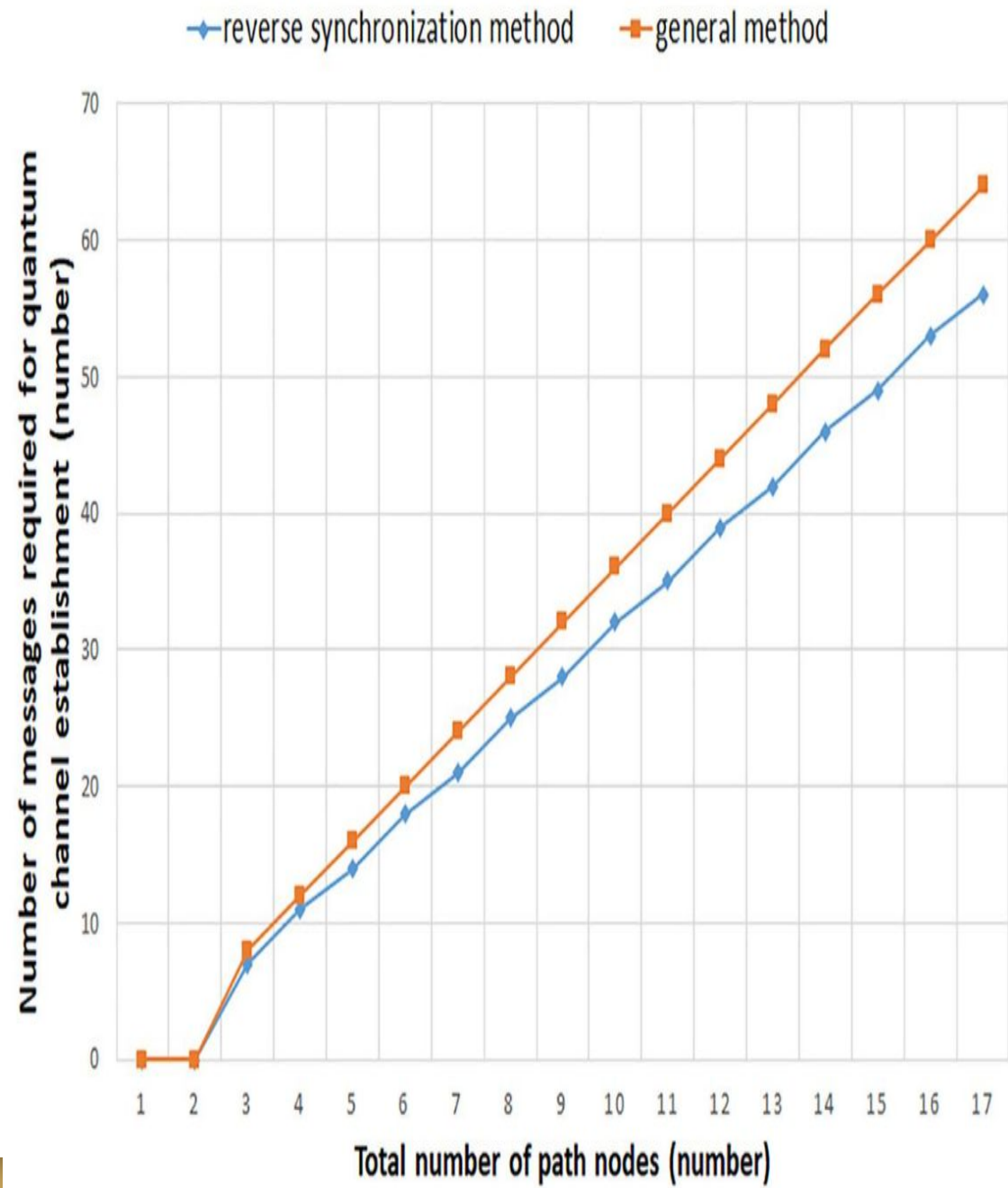
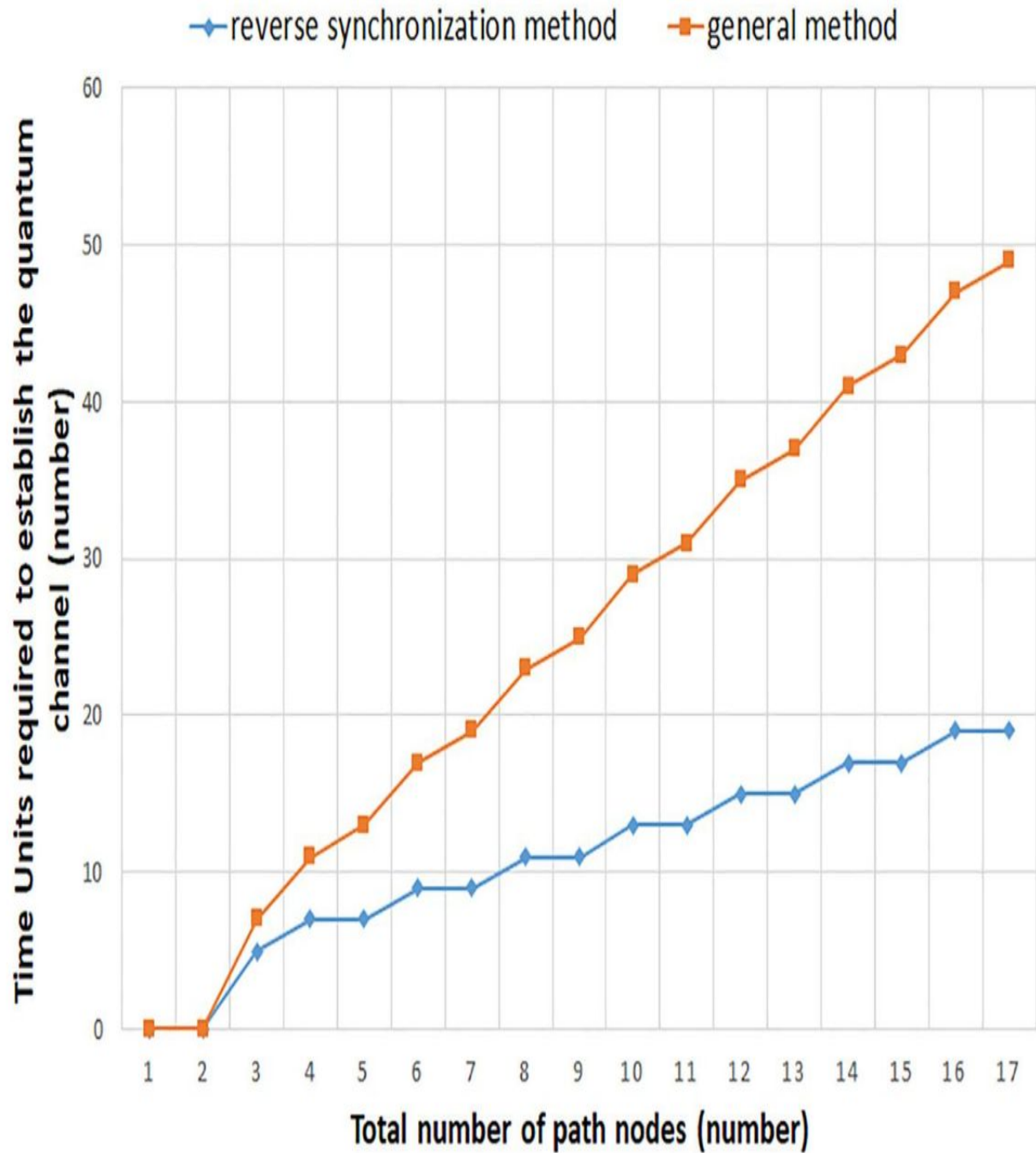


FIGURE 2 Schematic diagram of the quantum channel establishment and transmission analysis in the quantum wireless Ad Hoc network



Redes Quânticas Móveis: Rede de Satélites

1. Mobility: Os nós da rede não são fixos!

- Desafios de implementação física
- Cada nó tem sua própria trajetória

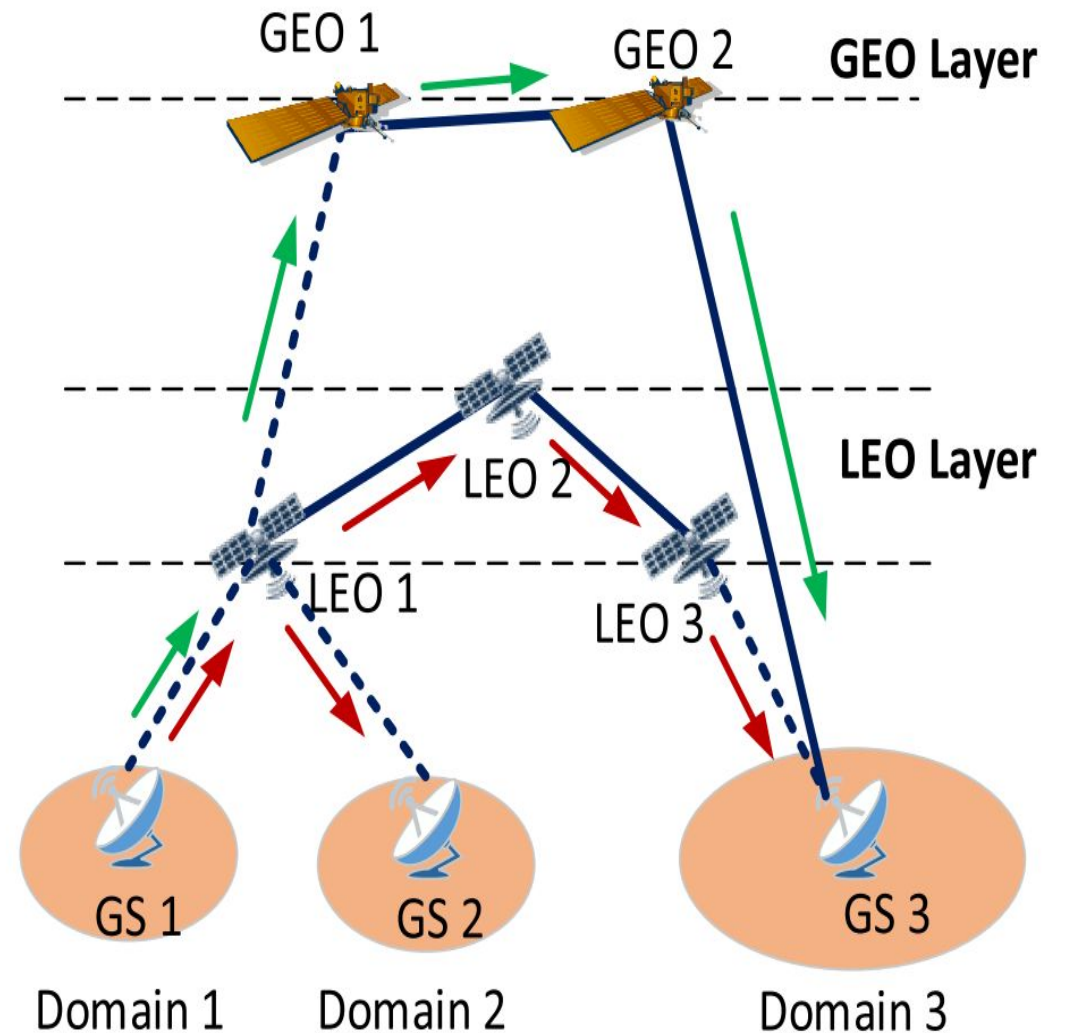
2. O link expira

-Os Satélites LEO têm cobertura limitada (5 to 20 minutes per orbit)

- Artigos de Quantum Satellites
 - Quantum Key Distribution Over Double-Layer Quantum Satellite Networks.
 - Towards Quantum Satellite Internetworking A Software-Defined Networking Perspective.

Quantum Key Distribution Over Double-Layer Quantum Satellite Networks

- Satellite Coverage
 - Um único satélite não pode executar QKD para estações terrestres durante todo o dia
- LEO vs GEO
 - LEO: tempo limitado do dia
 - GEO: continuamente, o dia todo; pode sofrer de alta perda de canal e geração limitada de chaves. altas perdas de canais do satélite geostacionário da órbita terrestre (GEO)
- Double layer = LEO \longleftrightarrow GEO Links
 - ajuda a melhorar o roteamento!
- Dijkstra é usado em ambos os casos para encontrar o caminho mais curto (global knowledge)

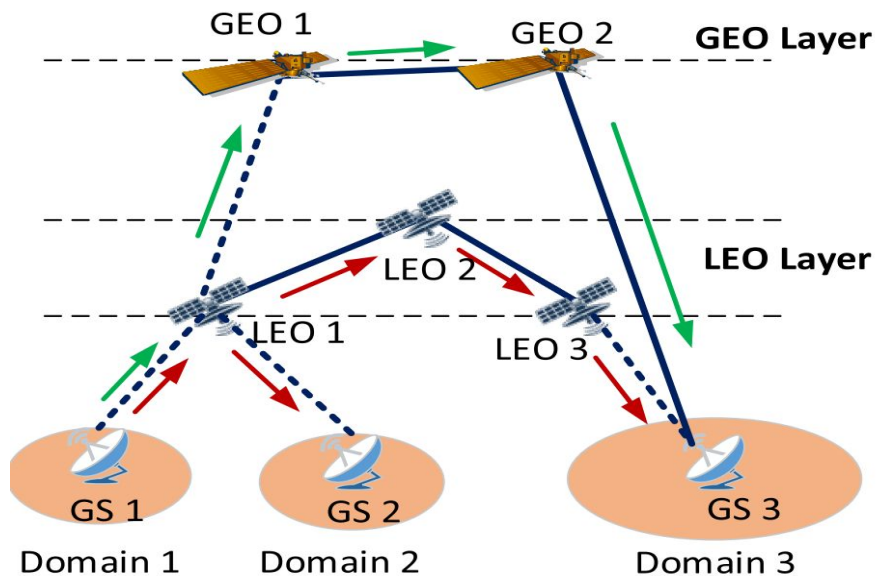


Quantum Key Distribution Over Double-Layer Quantum Satellite Networks

Double Layer With GEO-LEO links :

O nó terrestre procura por LEOs disponíveis como satélite de acesso e escolhe o melhor que satisfaça o comprimento de onda e os principais requisitos

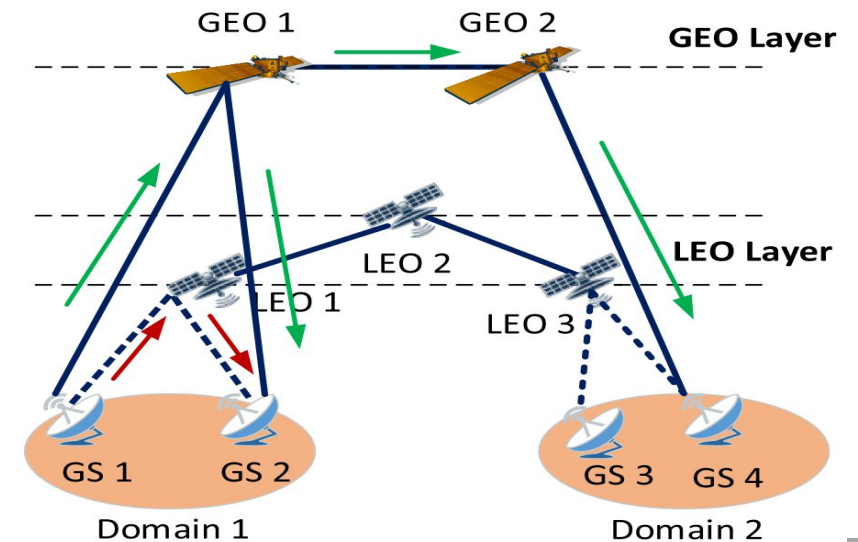
Se não houver LEO disponível, gira-se para seleccionar GEO como satélite de acesso



Double Layer Without GEO-LEO links

O nó terrestre procura LEOs disponíveis como seleção de prioridade.

Se não houver LEO disponível, os nós de origem e destino se voltam para procurar GEO como nó de acesso porque não há links GEO-LEO



Resultados

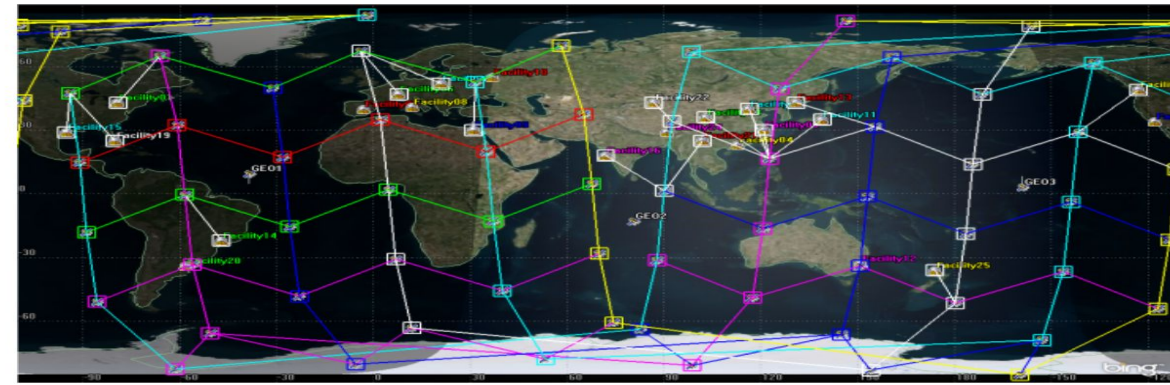


FIGURE 6. Satellite network topology used in simulation. (Picture from STK.) Considered ISL are drawn in the picture.

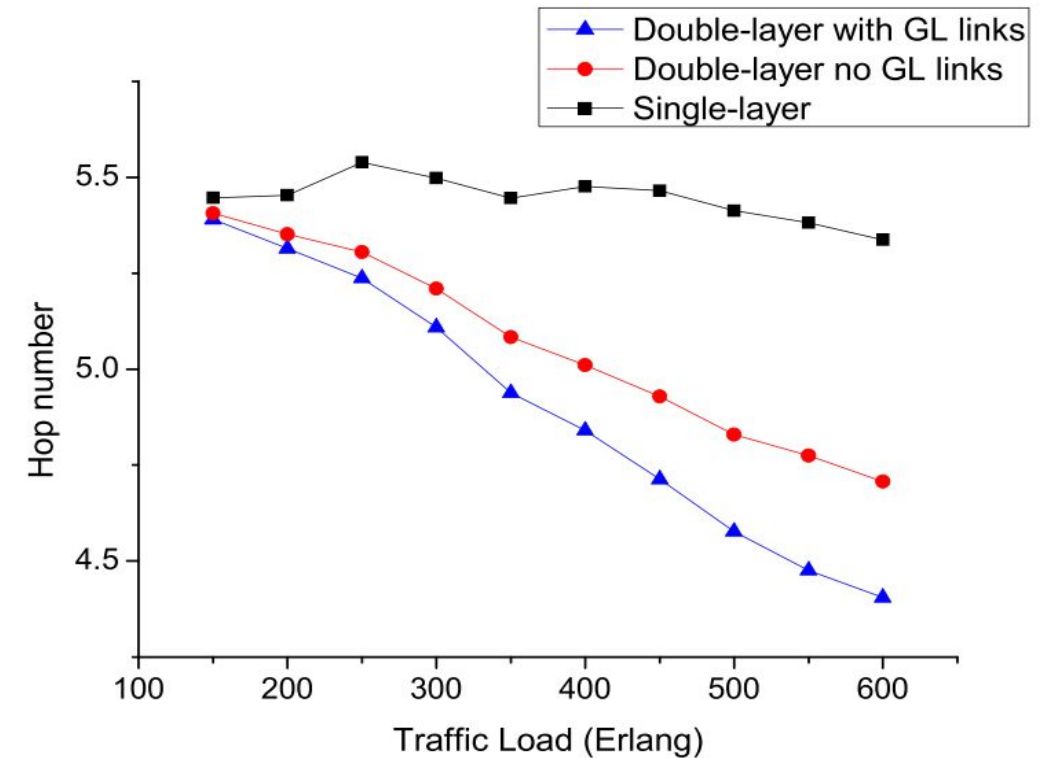
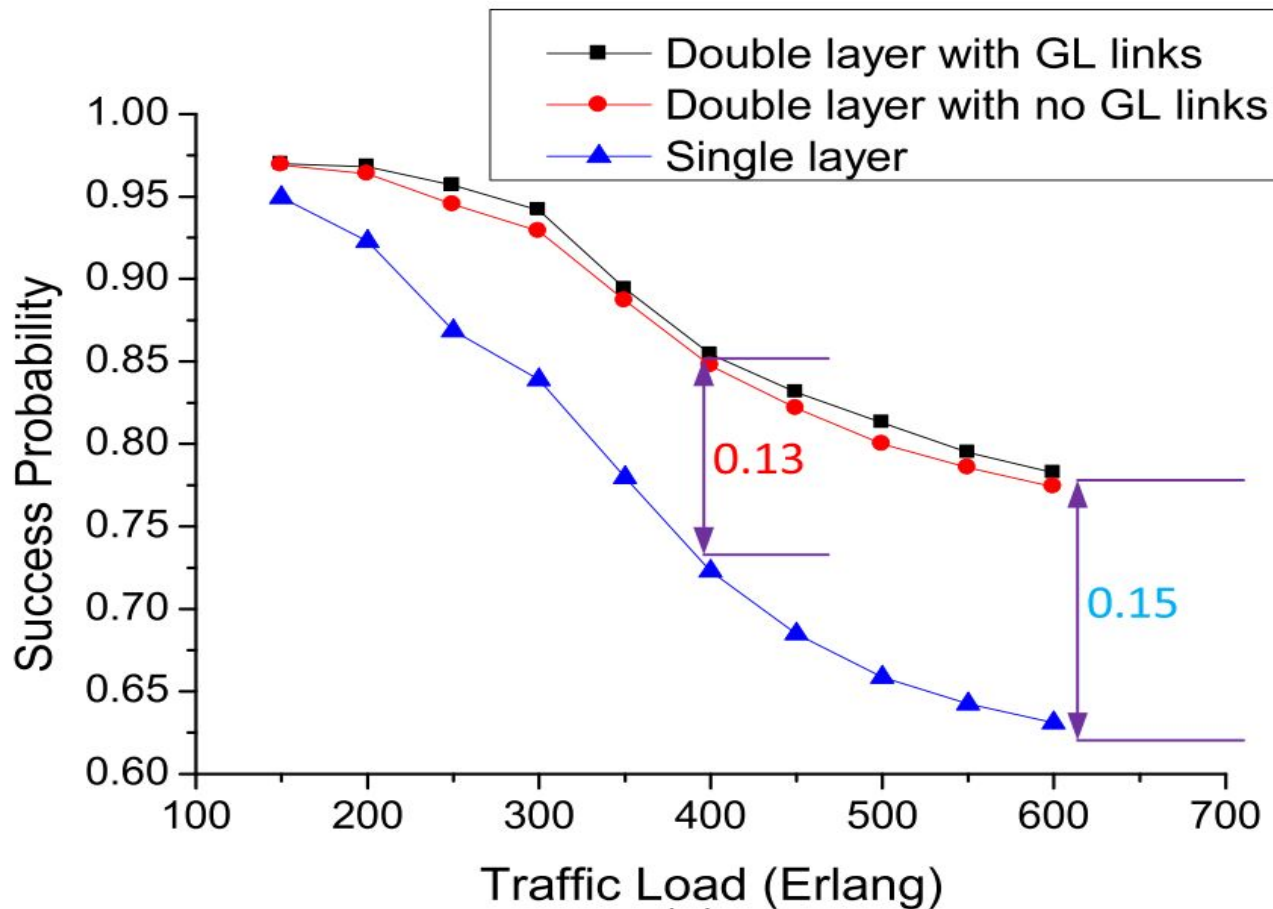


FIGURE 13. Average hop number of route path for key-relay service under different topologies. ($LN = 10$, $N_G = 2000$, $N_S = 20000$, $N = 20$).

Towards Quantum Satellite Internetworking A Software-Defined Networking Perspective

- Plano de Controle → Canal Clássico
 - Roteamento
 - operação de sinalização
 - Controlador SDN → Visão Global
- Plano de Dados → Canal Quântico
 - Criar os pares Bell
 - transmissão de fótons
- Objetivo é reduzir o número de saltos para conexão E2E e maximizar a capacidade da rede
- Avalia três estratégias diferentes
 - Centralizado: Dijkstra
 - Dois Distribuídos:
 - ACO: Ant Colony Optimization
 - MRW: Modified Random Walk

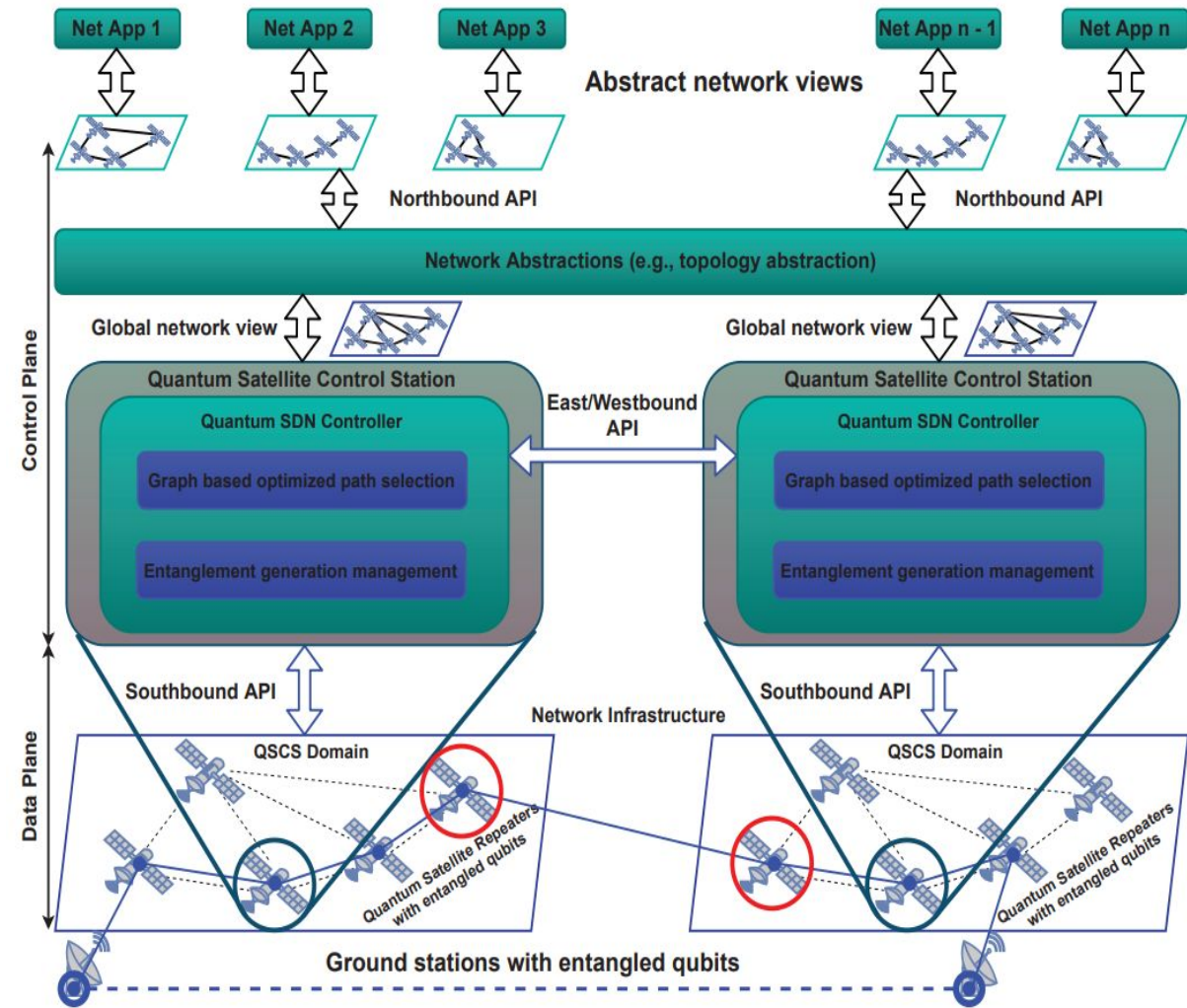


FIGURE 1. Quantum SDN backbone architecture. A Bell pair is generated between GSs through operations driven by the controllers embedded in the LEO constellation.

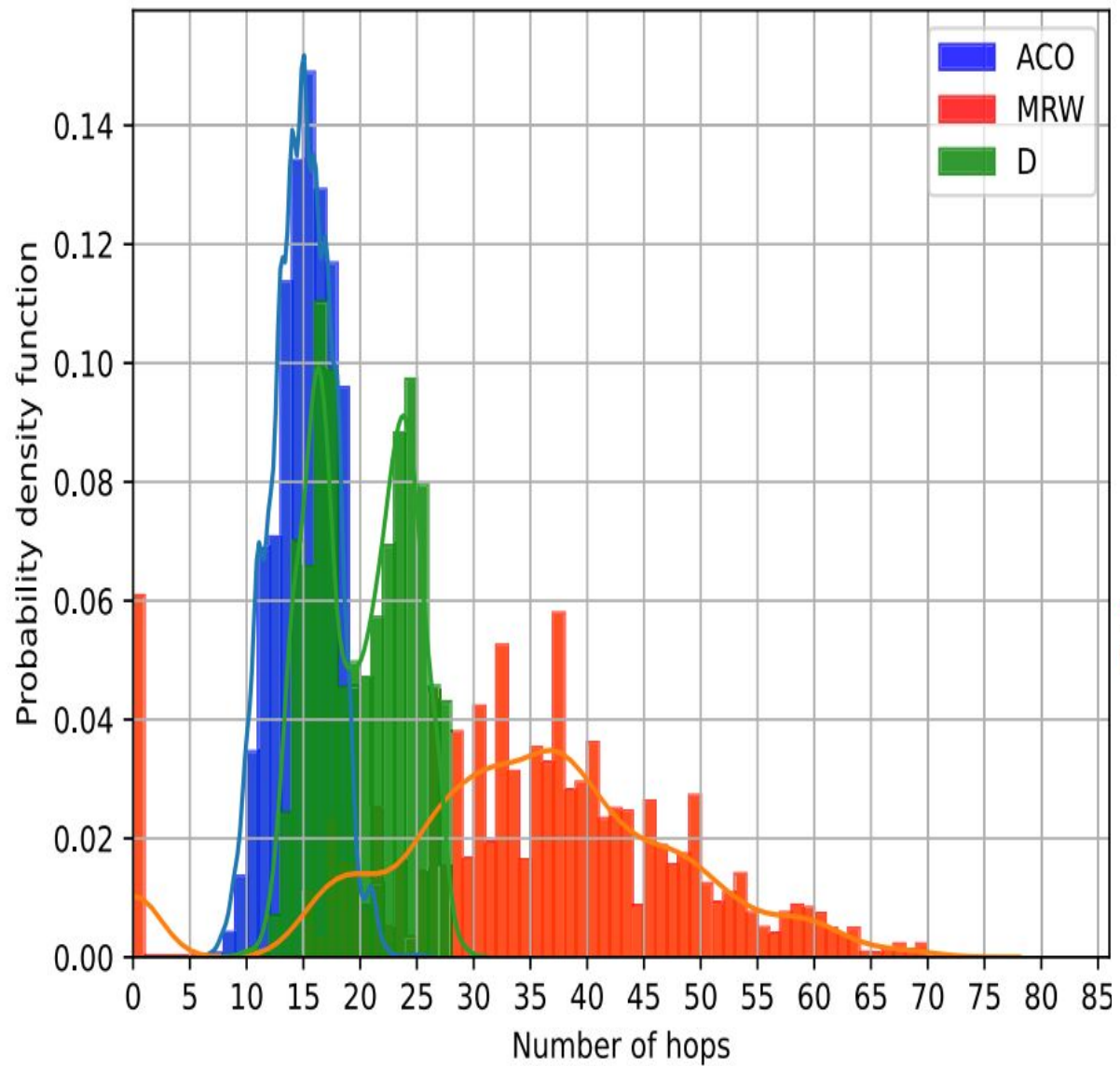


FIGURE 8. Number of hops Probability Density Functions for the considered MRW, ACO and Dijkstra protocols.

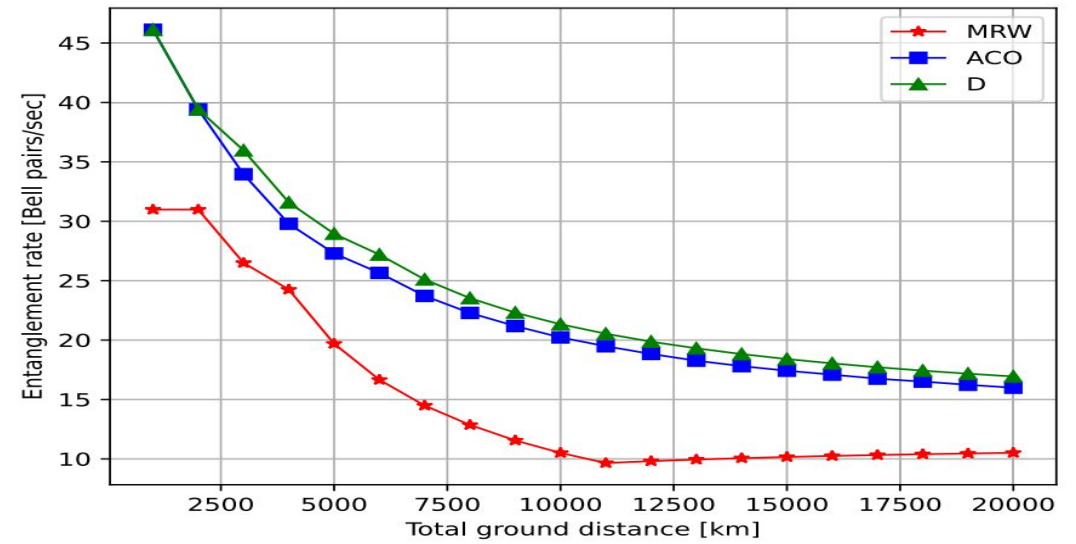


FIGURE 10. Entanglement rate as the distance between ground stations varies for the considered MRW, ACO and Dijkstra protocols.

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

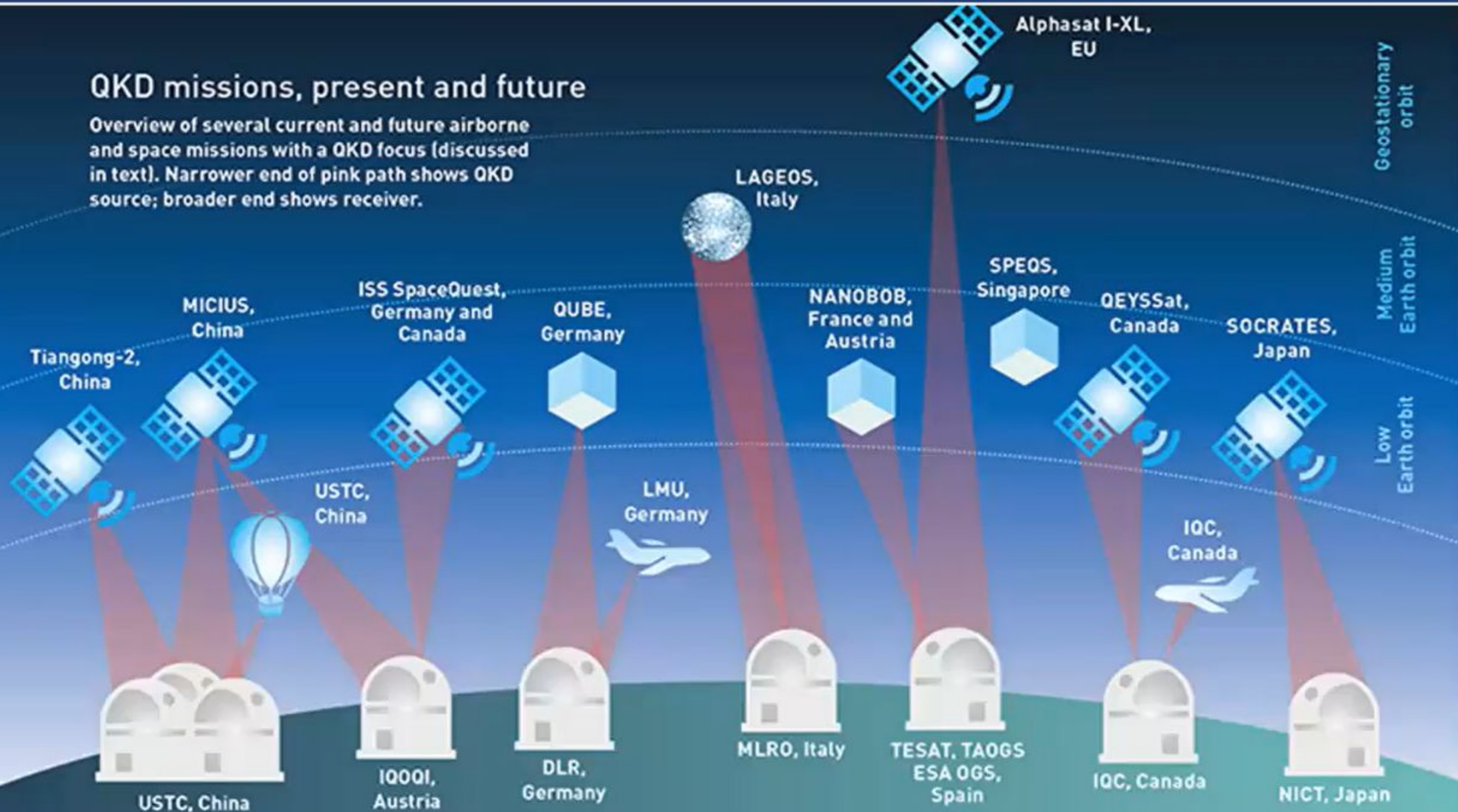
Algorithm	MRW		ACO		D	
	μ	σ	μ	σ	μ	σ
End-to-end path length [km]	75610	34774	31897	2755	38965	6598
Maximum single link length [km]	4218	751	4229	564	3745	195
Number of hops	35	14	15	3	19	4
Entanglement rate [Bell pairs / s]	11.196	3.224	11.786	1.194	13.175	0.724

Desafios atuais e Oportunidade de Pesquisa

- O roteamento em redes quânticas é diferente das redes clássicas
- Redes Quânticas Móveis ajudam no desenvolvimento de uma rede quântica global
- Desafios de Roteamento em Redes Quânticas Móveis
 - Adaptação de Protocolos de MANET clássicos para o contexto quântico
 - Métricas que considerem as particularidades e capacidade real da rede
 - Roteamento bi-partido ainda não foi testado

QKD missions, present and future

Overview of several current and future airborne and space missions with a QKD focus (discussed in text). Narrower end of pink path shows QKD source; broader end shows receiver.



Virtual Exchange Seminars in

QUANTUM MOBILE NETWORKS

Organized by the *University of Bern, Switzerland*
Dr. Antonio Di Maio (antonio.dimaio@unibe.ch)

These seminars explore topics at the interface between
quantum communications and mobile networking.

Place:
Online, Zoom

Time:
Weekly, Feb 2023 - Apr 2023

ECTS:
Ask your professor

You will exchange ideas with students from
around the world while learning about:

- Routing in QMNs
- Performance of QMNs: Capacity, Delay, Buffering
- Gossip Protocols in QMNs
- Media Access Control in QMNs
- Effects of Mobility Patterns on QMN Performance
- Age of Information in QMNs
- Physical Implementations of Quantum Channels in QMNs
- Simulation Tools for QMNs
- and more...



Hes-so



Partner Universities:

HES-SO Valais - Switzerland

University of Massachusetts, Amherst - USA

Nanyang Technological University - Singapore

University of Reggio Calabria - Italy

Technical University of Dresden - Germany

Federal University of Parà - Brazil

University of Luxembourg

Contact your professor or the seminar organizer for more information.

Conclusão

- Foi apresentado o roteamento em redes quânticas, com o enfoque em redes quânticas móveis.
- Os desafios atuais apontam para a necessidade de pesquisa e desenvolvimento na área
- No futuro próximo é esperado um grande crescimento tecnológico de comunicações quânticas
- É necessário uma integração de diversas áreas do conhecimento (computação, física, engenharia).

Slides Extras



University of Waterloo

IQC Institute for Quantum Computing

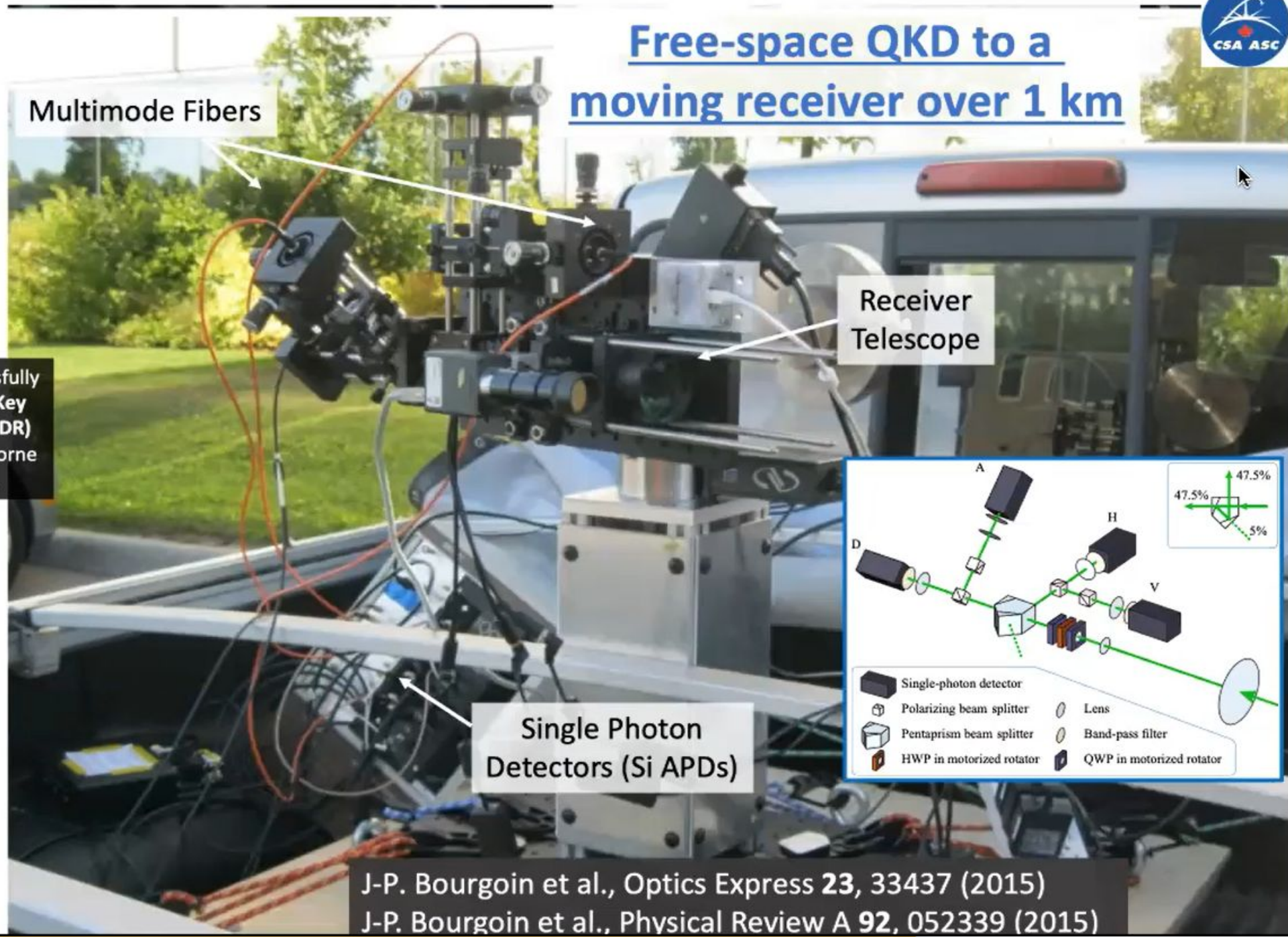
Ontario
H91-82C

Canada Foundation for Innovation
Fondation canadienne pour l'innovation

Free-space QKD to a moving receiver over 1 km



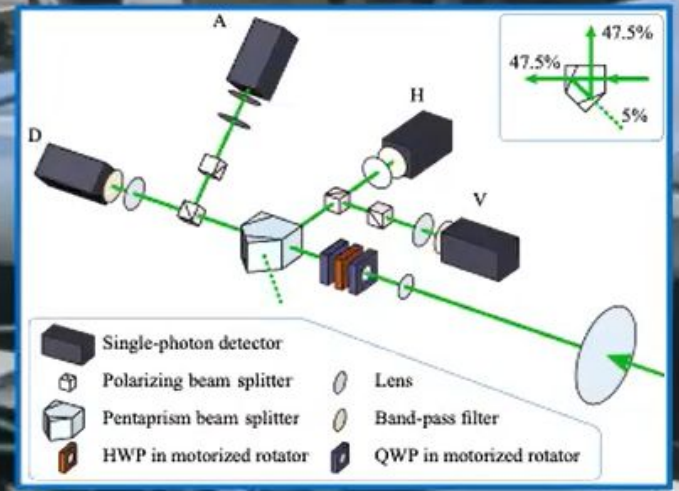
01/2015: IQC team successfully demonstrates Quantum Key Distribution Receiver (QKDR) prototype suitable for airborne and satellite missions.



Multimode Fibers

Receiver Telescope

Single Photon Detectors (Si APDs)

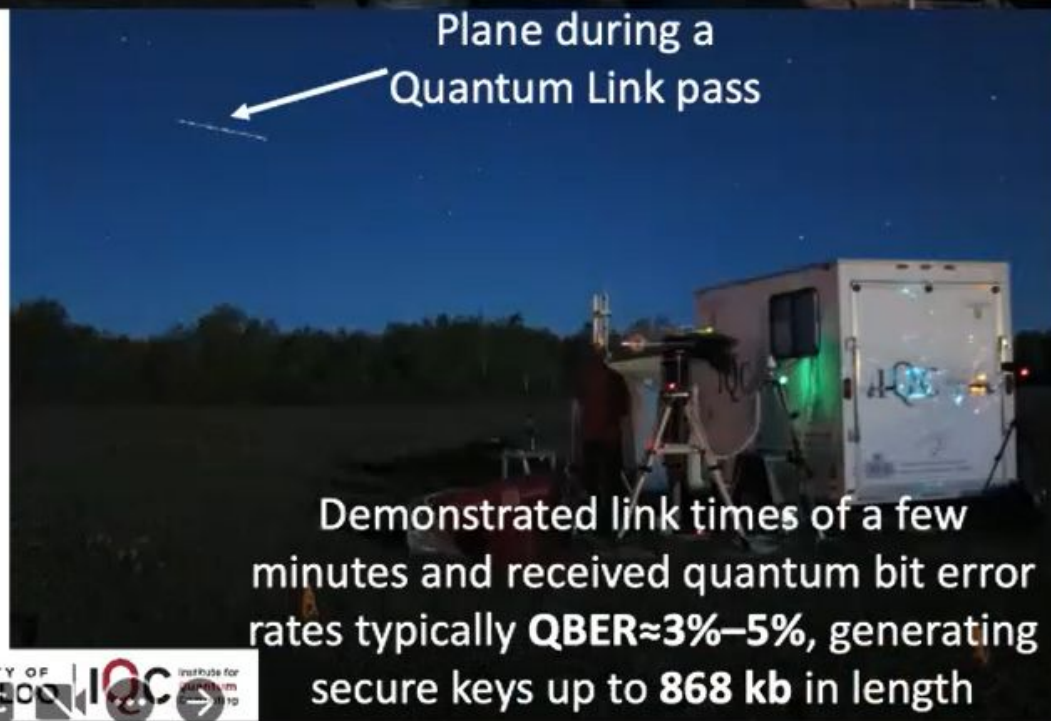


J-P. Bourgoïn et al., Optics Express **23**, 33437 (2015)
 J-P. Bourgoïn et al., Physical Review A **92**, 052339 (2015)

On the ground a source prepared photons in different polarized states.



QKD from a *PLANE!*



Plane during a Quantum Link pass

Demonstrated link times of a few minutes and received quantum bit error rates typically $QBER \approx 3\% - 5\%$, generating secure keys up to **868 kb** in length

09/2016: IQC team demonstrates QKD free-space link between ground station transmitter (Smiths Falls, ON) & Receiver Payload in flight on NRC Twin Otter Airborne Research Aircraft. Demonstrated the viability of QEYSSat mission concept.

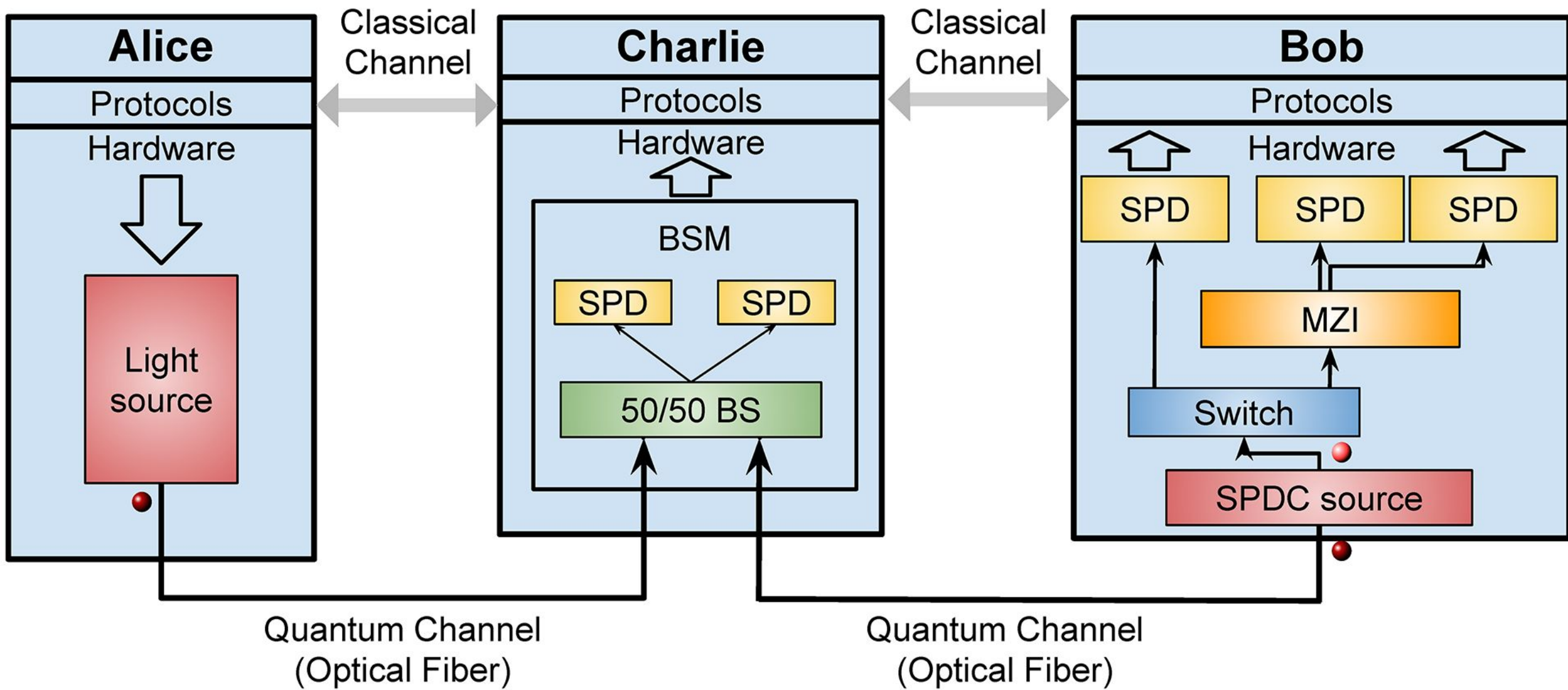


Table 4.2 A comparison of routing protocols for UWSNs

Parameters	DSDV	DSR	AODV	LAR	TORA	ZRP	ABR	OLSR	WRP	FSR
Protocol type	Table driven	On-demand	On-demand	On-demand	Link-reversal	Hybrid, DV and LS	On-demand	Proactive	Table Driven	Proactive
Loop Free	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes, but not instantaneous	Yes
Multiple Route	No	Yes	No	Yes	No	No	No	No	Yes	Yes
Routing Over head	Medium	Low	High	Low	High	Medium	Low	Medium	High	High
Hop count	Medium	Very high	Normal	High	Medium	Medium	Less	Less	Medium	Less
Error Message	More	Less	More	Less		Medium			Less	
Security	No	No	No	No	No	No	No	No	No	No
Periodic broadcast	Yes	No	Possible	Possible	Possible	No	NA	Yes	NA	NA
Congestion	High	Low	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium
Multicast Capability	No	No	Yes	Yes	No	Partly	No	Yes	No	No
Routes maintains in	Route table	Route cache	Route table	Routing table	Route table	Intrazone and Interzone tables	Route table	Route table	Route cache	Route Table
QoS support	No	No	No	No	No	No	No	Yes	No	Yes
Use sequence number	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes
Routing metric	Shortest distance	Shortest path	Shortest path	Shortest path	Shortest path	Local Shortest path	Associativity and Shortest Path	Shortest distance	Shortest path	Shortest path

EntangleNetSat: A Satellite-Based Entanglement Resupply Network

- Fornecer cobertura global para a Quantum Networks
- Estação base → Múltiplos Satellites
- Trade off : eficiência vs acurácia
- Apresentar um esquema de roteamento usando uma rede híbrida de solo e satélite
- Protocolo de Roteamento em Duas Etapas
- Local / Bellman-Ford

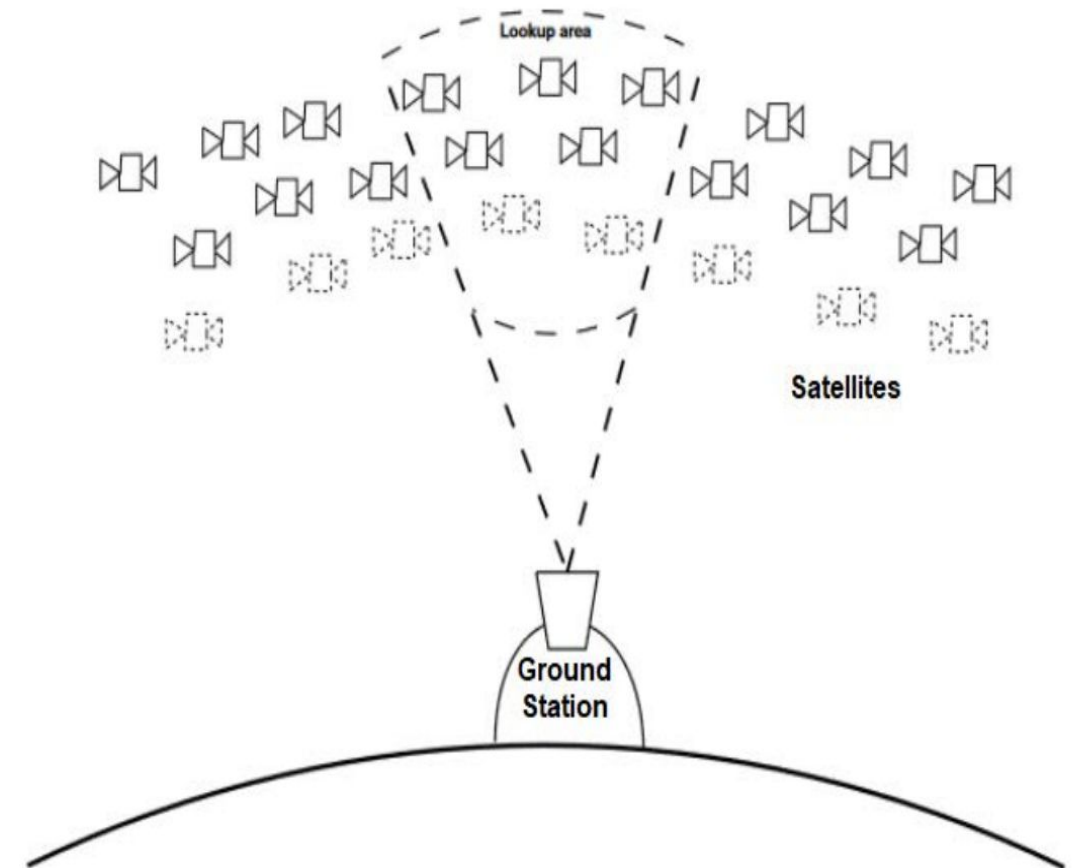


FIGURE 4. The trade-off we suggest, in terms of accuracy and computational efficiency, is a precomputed lookup table for satellites.

EntangleNetSat: A Satellite-Based Entanglement Resupply Network

STEP 1: TERMINAL SATELLITE SELECTION

- Escolha o satélite que mantenha a máxima fidelidade de transmissão (possível)
 - o mais próximo possível do zênite das estações solicitantes
- Offline: Mapeamento pré-computado.
- Online: Mapeamento sob demanda
- Hybrid: Trade-off entre o baixo custo computacional do offline e a precisão do online

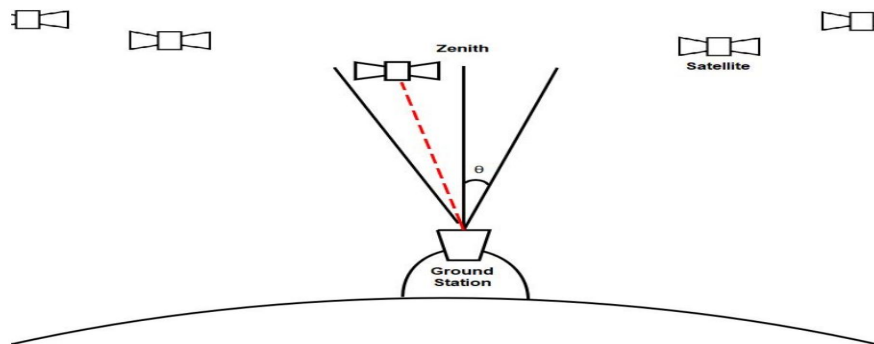


FIGURE 2. Transmittance of the photon beam depends on the deviation from the Zenith direction of the receiver. Ideally, the satellite closest to the zenith position (terminal satellite) should perform the down-link transmission.

STEP 2: ROUTE SATELLITE SELECTION

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

τ_c = commutation time:

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

QR_d = d is the delay introduced by a quantum repeater

τ_t = photon transmission time

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