Scaling Quantum Communication Networks (QCNs)

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Agenda

01 Background and motivation

02 QCN scalability challenges and contributions

03 Scaling limits of QCNs

04 RIS-assisted QCNs

05 Brief overview on quantum federated learning

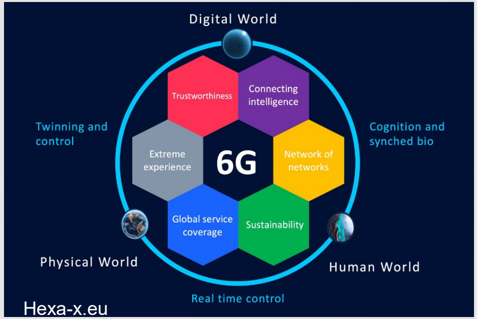
06 Conclusion

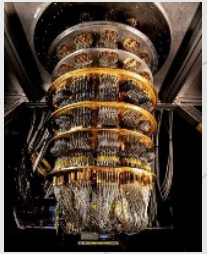
Next-generation communication networks

- Increased connectivity, data-hungry complex applications:
  - Extended reality, digital twins, Metaverse …
- Computational overhead and security challenges
- Today’s electronics relied for over 50 years on *Moore’s law*.
  - Started being violated, cannot ignore quantum impacts

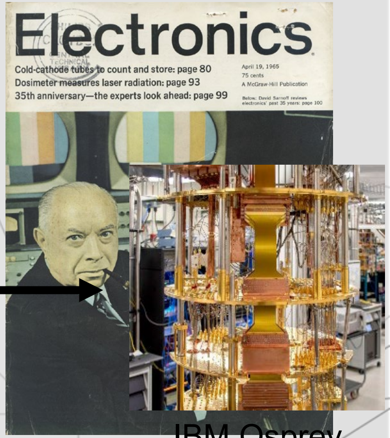
We should go Quantum!

- **Quantum computers** can
  - Provide superior computational speedups
  - Handle exponential growth in data dimensions
- Applications in healthcare, finance, optimization, and AI





Google Sycamore
53 qubits (2018)


Electronics
Cold-cathode tubes to count and store: page 80
Dosimeter measures laser radiation: page 93
35th anniversary—the experts look ahead: page 99
April 19, 1965
75 cents
A McGraw-Hill Publication

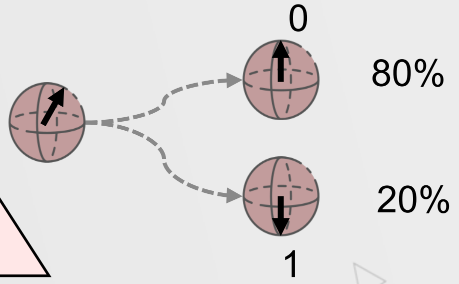
IBM Osprey
433 qubits (2022)

Quantum Communications Preliminaries

Quantum States (Qubits)

Any **superposition** of 0 and 1

- $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$, where $|c_0|^2 + |c_1|^2 = 1$
- Measurements are probabilistic & collapse qubit



Entangled Qubits

Two qubits correlated no matter how far away they are separated, measuring one directly affects the other.

Bell states $|\phi_{\pm}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$,

Decoherence & Fidelity

Losses due to interactions with environment.
Fidelity: Measure of quality of quantum state

Quantum Communication Networks (QCNs)

quantum repeaters

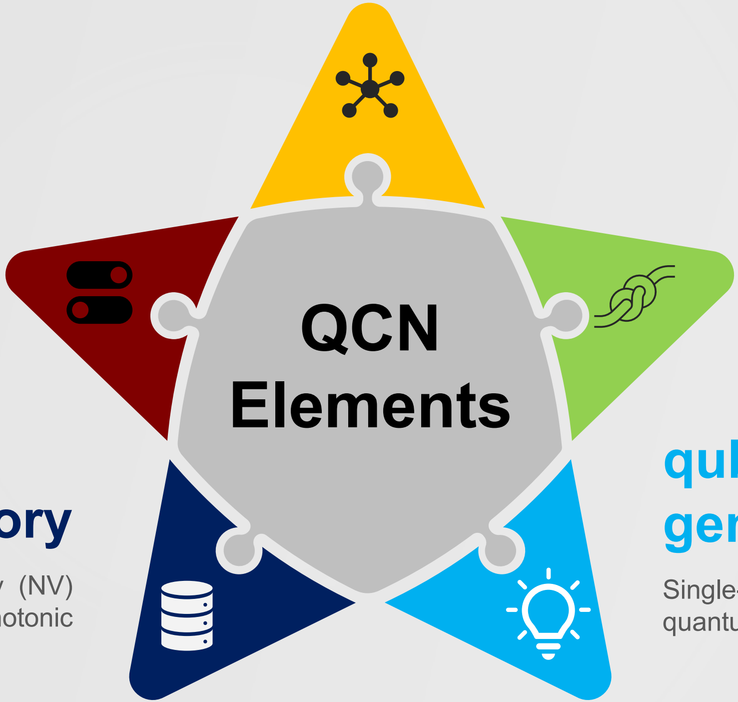
No cloning theorem, cannot copy states, requires entanglement swapping, extends communication distance

quantum switches

Perform routing, path selection, association, and resource allocation

quantum channels

Fiber optics, or free space optical (FSO) channels



quantum memory

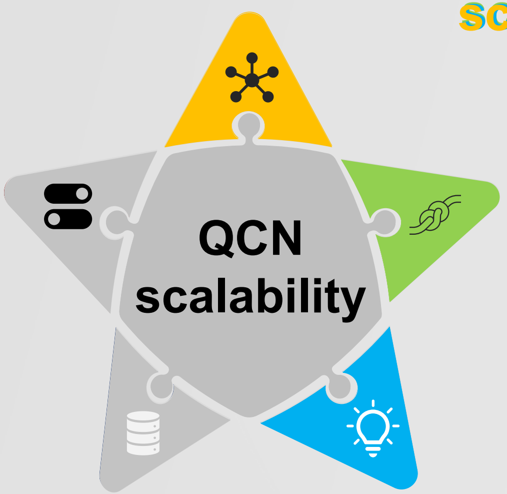
Solid-state memories (e.g., Nitrogen Vacancy (NV) centers in diamonds), atomic ensembels, photonic memories, …

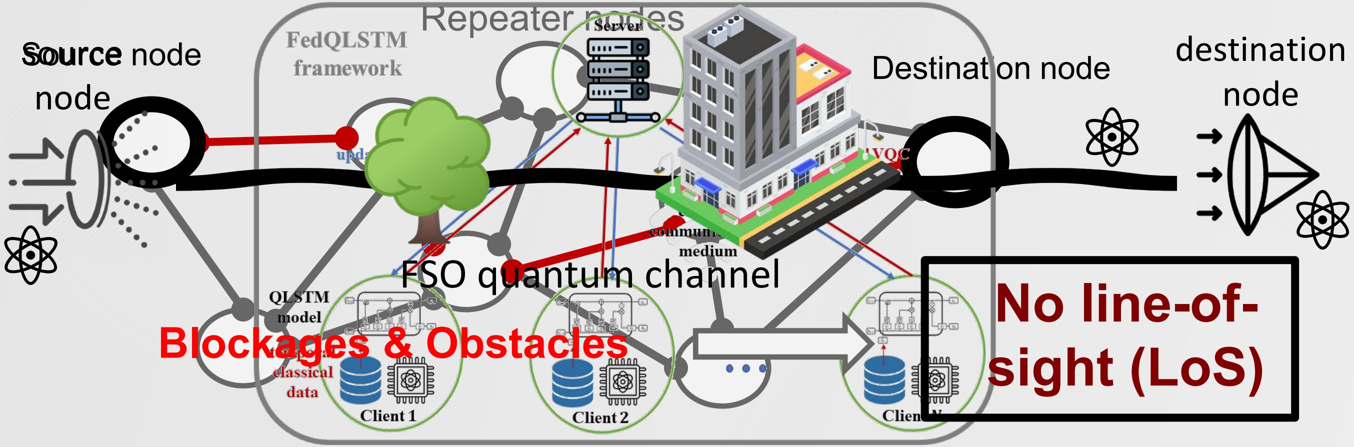
qubits and entanglement generation sources

Single-photon sources like NV centers in diamond, quantum dots, and down-converted laser beams.

QCN scalability: Applications and challenges

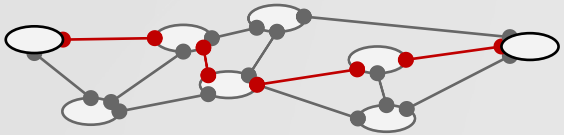
- QCNs at **scale** form the quantum Internet:
  - Applications in quantum key distribution, distributed quantum computing and sensing
- But … what is **scalability**?
  - Extending geographical length (longer distances/coverage/number of nodes)
  - Optimal management of limited resources (memories and entangled qubits)
  - Increasing number of qubits and computing power





Limitations of the state-of-art

Scaling QRNs over fiber



Challenges

- QRN analysis focused on routing, and path-selection
- Scalability factors studied **separately**:
  1) Distillation scheduling without QRN length and repeater placement analysis [Hu, 2021]
  2) Repeater placement without distillation scheduling [da Silva, 2023]
  3) QRN length without distillation or quality-of-service (QoS) constraints [Victora, 2020, Dai, 2020]

Contributions

- **Joint optimization** of (1) QRN length, (2) repeater placement, and (3) distillation operations scheduling, under various QoS constraints.

Scaling QCNs over FSO

Challenges

- FSO channels without blockages
  1) Line-of-sight (LoS) always assumed present [Hassan 2023, Alshaer 2021]
- If no LoS, use a reconfigurable intelligent surface (RIS) [Kundu, 2023], but
  1) A single point-to-point link considered
  2) Only environmental losses are considered, no analysis of quantum noise effects
  3) No entanglement generation rate (EGR) allocation
  4) No QoS constraints

Contributions

- RIS-assisted, (1) **multi-user** FSO QCN with blockages, (2) model environmental effects on **noise and losses**, (3) joint optimization of **RIS placement and EGR allocation**, and (4) **heterogeneous QoS** requirements

Scaling Limits of Quantum Repeater Networks

M. Chehimi, S. Pouryousef, N. K. Panigrahy, D. Towsley, and **W. Saad**

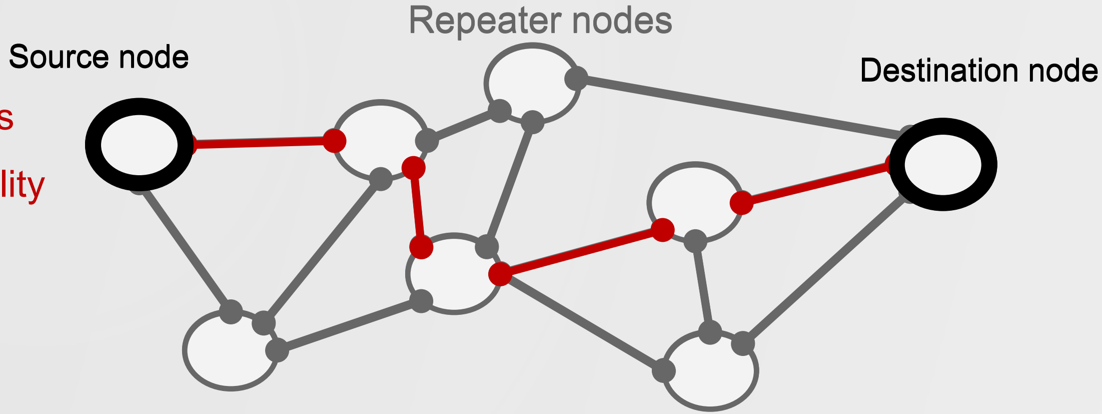
IEEE International Conference on Quantum Computing and Engineering (QCE 2023) and IEEE Quantum Week

Best Paper Award

Quantum Networking Track

Quantum Repeater Networks (QRN)

- Repeaters perform operations (like entanglement swapping and distillation)
    - ➢ Unavoidable noise and imperfections limit scalability
- End-to-end links are linear repeater chains
- **Scalability … How far can we go?**
    - ➢ Number of repeaters
    - ➢ Repeaters' separation
    - ➢ Scheduling of repeaters' operations
    - ➢ QoS requirements on rate and fidelity



Entanglement swapping

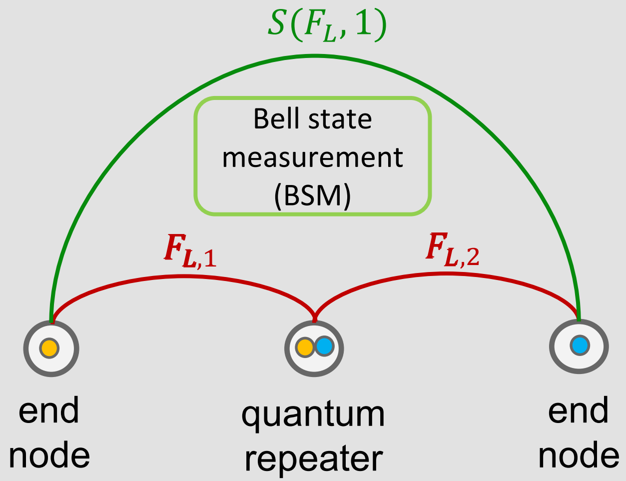
to extend communication distance

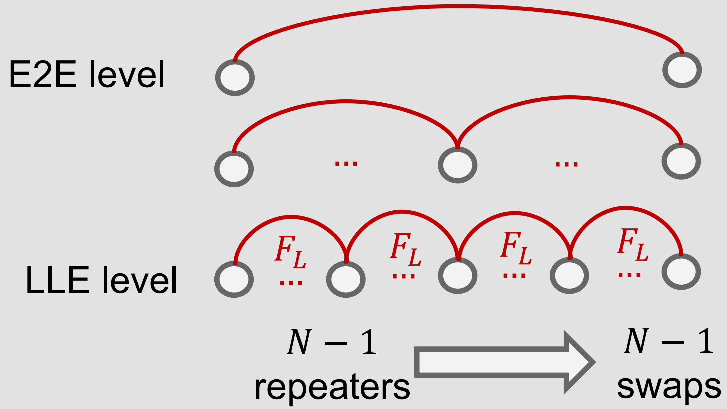
End-to-end (E2E) states

Link-level entangled (LLE) states

All LLE states have same fidelity, i.e.,

$$F_{L,1} = F_{L,2} = \cdots = F_{L,N} = F_L$$





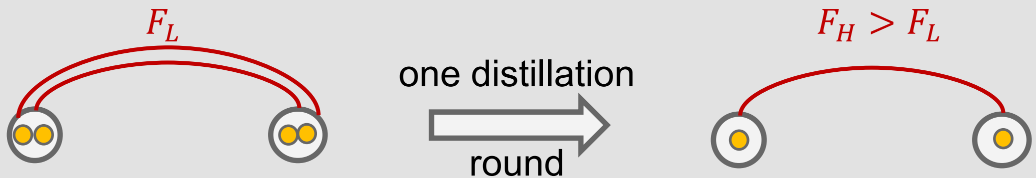
- Fidelity after performing $N-1$ swaps over the N states:

$$S(F_{\mathrm{L}}, N) = \frac{1}{4} + \frac{3}{4}\left(\frac{P_2(4\eta^2-1)}{3}\right)^{N-1}\left(\frac{4F_{\mathrm{L}}-1}{3}\right)^{N}$$

- P_2 is the two-qubit gate fidelity
- η is the measurement fidelity of the entanglement swapping operation

Entanglement distillation

to enhance entanglement quality (fidelity)



- Output fidelity after distilling 2 qubits with identical fidelity F_{in} (minimum value of 0.5) is:

$$f(F_{\text{in}}) = \frac{A(F_{\text{in}}) \times B(\eta) + C(F_{\text{in}}) \times D(\eta) + E(P_2)}{H(F_{\text{in}}) \times B(\eta) + C(F_{\text{in}}) \times 4D(\eta) + 4E(P_2)}$$

Initial fidelity

Measurment fidelity

Two-qubit gates fidelity

- Distillation *probability of success* P_s due to imperfections, is:

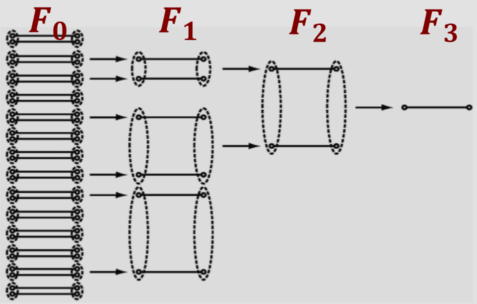
$$P_S(F_{\text{in}}) = {P_2}^2 \times \left[H(F_{\text{in}})B(\eta) + C(F_{\text{in}})4D(\eta) + 4E(P_2)\right]$$

- Distillation repeated n times **Fidelity: $F_3 > F_2 > F_1 > F_0$**

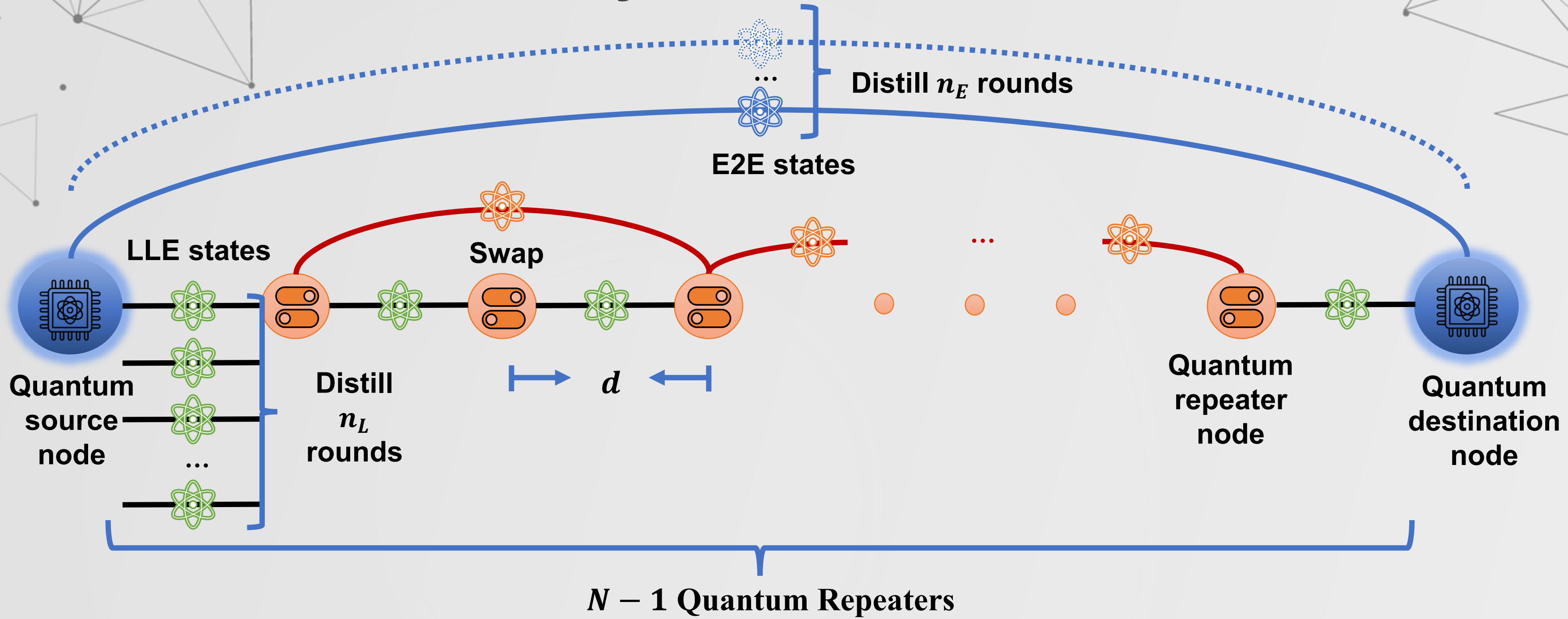
recursive function g:

$$g(n, F_0) = \begin{cases} F_0 & \text{if } n = 0 \\ g(n-1, f(F_0)) & \text{otherwise} \end{cases}$$

$$F_i = g(i, F_0) = g(i-1, f(F_0)) = f(F_{i-1})$$



System Model



- Linear chain QRN, N quantum links, and $N-1$ quantum repeater nodes, same imperfections, d uniform separation distance
- Entanglement swaps are deterministic, distillation only at link-level and end-to-end level
- **Scalability:** overall maximum length of QRN chain, $(N \times d)$ for a given QoS requirements

End-to-end fidelity and rate

- LLE states are homogeneous **Werner states**, with same initial fidelity $\boldsymbol{F_0}$, and initial entanglement generation rate $\boldsymbol{R_0}$
- Neighboring nodes perform $\boldsymbol{n_L}$ homogeneous LLE entanglement distillation, followed by $\boldsymbol{N}$ deterministic swaps, then $\boldsymbol{n_E}$ homogeneous end-to-end entanglement distillation rounds
- End-to-end fidelity: $F_{\mathrm{E},n_{\mathrm{E}}+1}(n_{\mathrm{E}}, n_{\mathrm{L}}, F_0, N)) = g(n_{\mathrm{E}}, F_{\mathrm{E},1}(n_{\mathrm{L}}, F_0, N))$
- End-to-end rate: $R_{\mathrm{E}}(n_E, n_L, N, d, R_0, F_0) = \dfrac{R_{\mathrm{L}}(R_0, n_{\mathrm{L}}, d, F_0)}{\prod_{j=1}^{n_{\mathrm{E}}} \frac{2}{P_{\mathrm{S}}(F_{\mathrm{E},j})}}$

Repeater separation distance

Prob. of success of distillation

Fidelity of each E2E distillation round

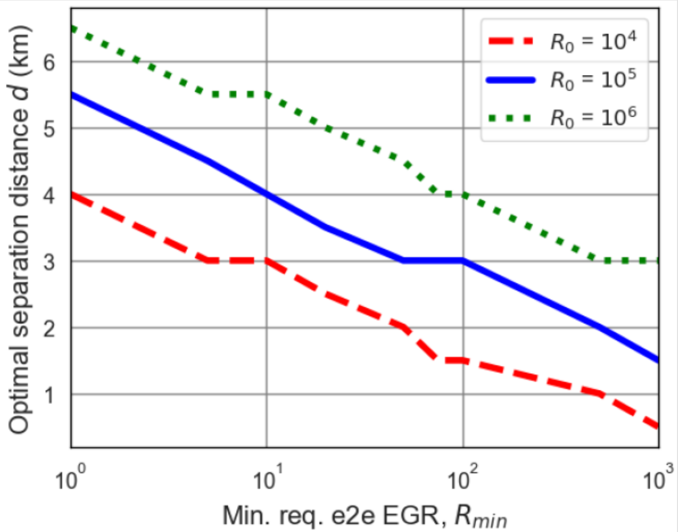
QRN scalability optimization problem formulation

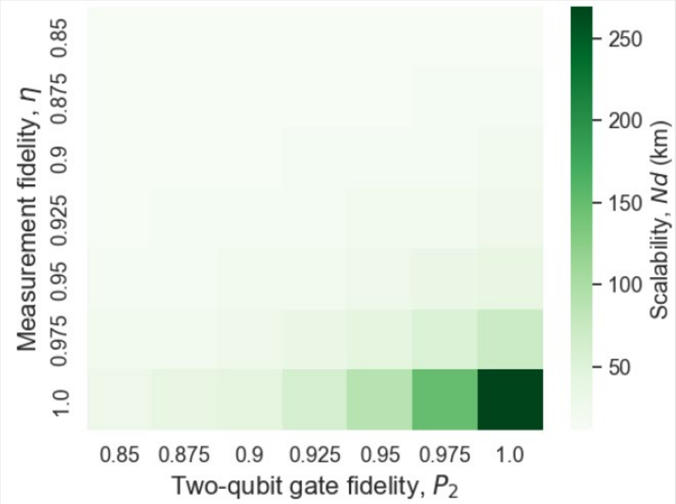
- Maximize length of linear QRN while satisfying QoS requirements
- Control variables:
  - n_L: # link-level entanglement distillation
  - n_E: # end-to-end entanglement distillation
  - N: # intermediate entangled states (N-1 is # of quantum repeaters)
  - d: separation distance between neighboring nodes
- Challenging mixed-integer non-linear programming problem with complex derivatives
- Used derivative-free metaheuristic solution (genetic algorithm)

QoS constraints

$$
\begin{aligned}
\mathcal{P}1: \quad \max_{N,d,n_{\mathrm{L}},n_{\mathrm{E}}} \quad & N \times d \\
\text{s.t.} \quad & R_{\mathrm{E}}(n_{\mathrm{E}}, n_{\mathrm{L}}, N, d) \geq R_{\min}, \\
& F_{\mathrm{E},n_{\mathrm{E}}+1}(n_{\mathrm{E}}, n_{\mathrm{L}}, N) \geq F_{\min}, \\
& n_{\mathrm{L}} \geq 0, \\
& n_{\mathrm{E}} \geq 0, \\
& N \geq 1, \\
& d \geq 0,
\end{aligned}
$$

Simulation results





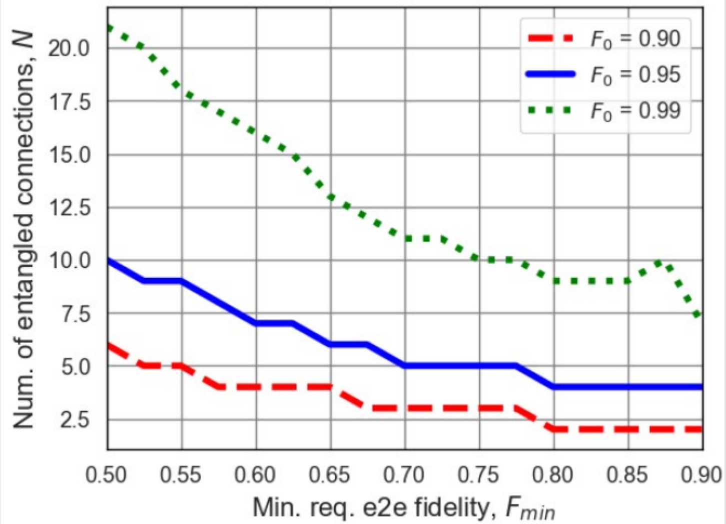
Impact of varying QoS requirements on separation distance

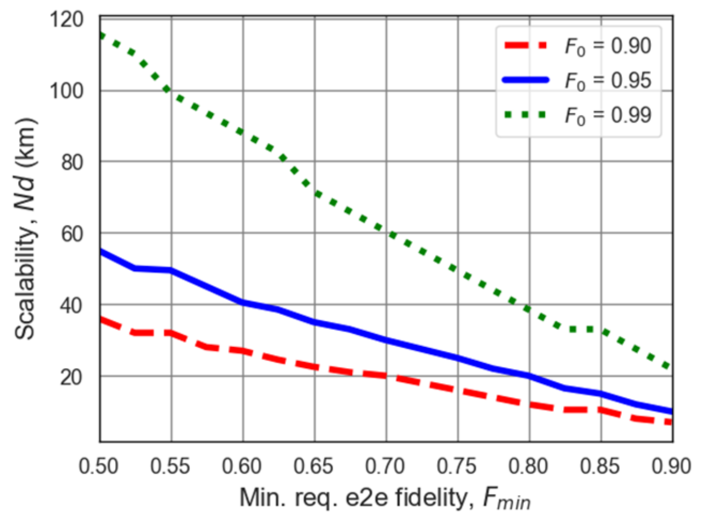
- d reduced since larger separation increases travelled distance
- Optimal d values are not infinitely large

Impact of Varying Imperfections on scalability

- Measurement imperfections (η) have greater impact on scalability, compared to two-qubit gate noise P_2.
- In the absence of device imperfections, QRN scalability reaches ≈ 267 km (can use multiplexing)

Simulation results





Impact of having no link-level distillation ($n_L = 0$)

- Significantly reduced scalability
  - ➢ Link-level distillation maximizes LLE state fidelity before swaps
- Number of swaps and N is reduced
  - ➢ N drops by 50% when F_0 reduced by 4% for $F_{min} = 0.5$

Impact of having no E2E distillation ($n_E = 0$)

- Extremely difficult to achieve high e2e fidelity in this scenario
  - ➢ End-to-end distillation captures noise during swaps
  - ➢ Scalability is compromised, and number of repeaters is reduced

Reconfigurable Intelligent Surfaces (RISs) for Free-Space Quantum Communication Networks

M. Chehimi, M. El Hattab, **W. Saad**, G. Vardoyan, N. Panigrahy, D. Towsley, & C. Assi

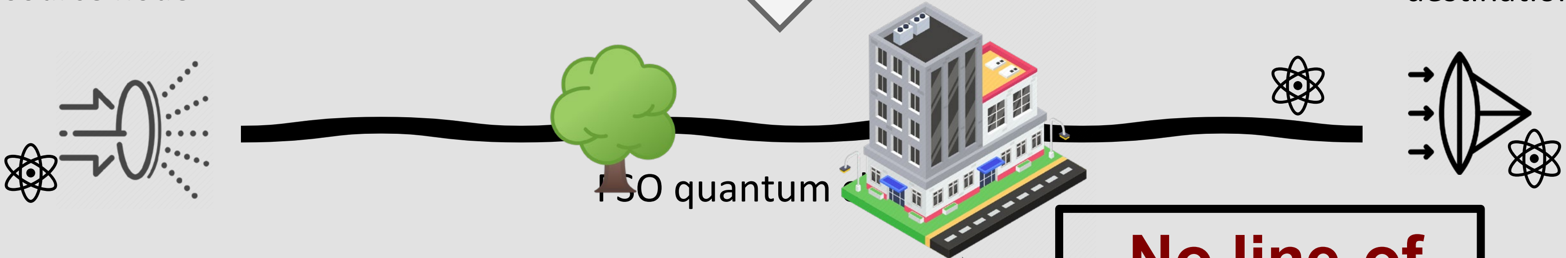
Submitted to IEEE Transactions on Wireless Communications

FSO-based QCNs

optical fiber not always easy to install

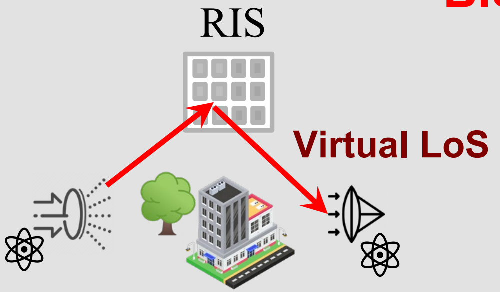
Ground quantum source node

Ground quantum destination node



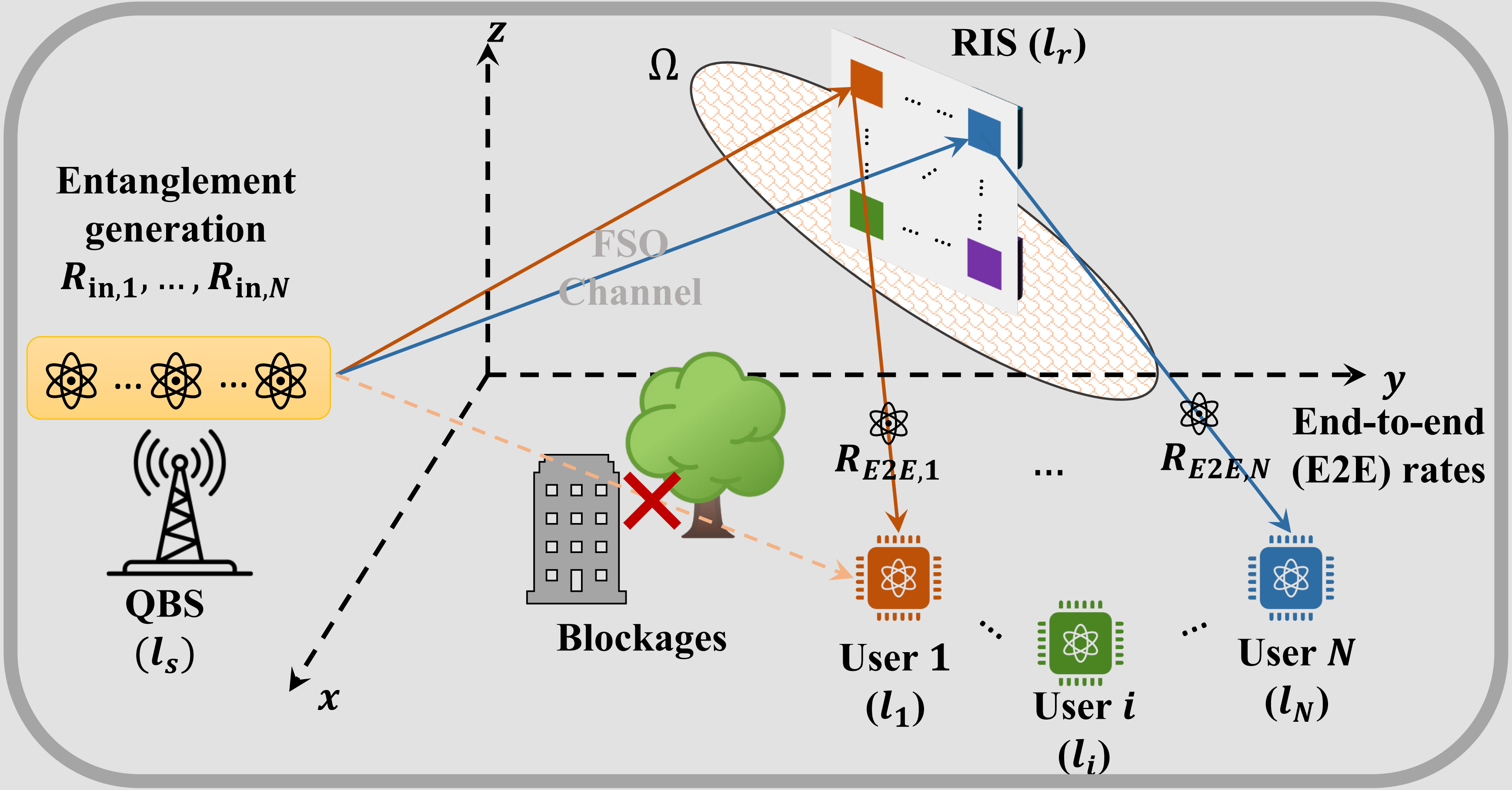
Blockages & Obstacles

No line-of-sight (LoS)



Reconfigurable intelligent surface (RIS)

System model



FSO environmental effects: Losses

Atmospheric loss (h_p)

- Absorption and scattering of light by atmospheric constituents
- Weather-dependent
- Scales exponentially with distance

Turbulence (h_a)

- Temperature fluctuations
- Variations in air refractive index C_n^2
- Distorts phase (Rytov variance σ_R) and intensity of received signal

Pointing Error (h_g)

- Signal misalignment due to beam divergence, angles ϕ and θ
- Mechanical vibrations due to instability in the mounting structure

End-to-end channel gain between QBS and user $i \in \aleph$

$$h_i(\boldsymbol{l}_r) = \zeta \eta h_{p,i}(\boldsymbol{l}_r) h_{a,i}(\boldsymbol{l}_r) h_{g,i}(\boldsymbol{l}_r)$$

RIS location

RIS reflection efficiency

Receiver responsivity

End-to-end entanglement generation rate

For each user $i \in \aleph$: $R_{E2E,i} = R_{in,i} \times P_{succ,i}(\boldsymbol{l}_r)$

Initial entanglement generation rate (controlled variable)

Probability of successfully storing an entangled photon via FSO channel

Theorem: Probability of success

The probability of successfully transmitting an entangled photon over an FSO channel considering atmospheric loss, turbulence, and pointing error is a function of the Meijer G-function, Gamma function, and system parameters:

$$P_{\text{succ},i}(\boldsymbol{l}_r) = 1 - \left(\frac{\vartheta_i(\boldsymbol{l}_r)}{\Gamma(\alpha_i(\boldsymbol{l}_r))\Gamma(\beta_i(\boldsymbol{l}_r))} \times G_{2,4}^{3,1}\left[\frac{\alpha_i(\boldsymbol{l}_r)\beta_i(\boldsymbol{l}_r)\chi_{\text{th}}}{A_{0,i}(\boldsymbol{l}_r)h_{p,i}(\boldsymbol{l}_r)} \middle| \begin{matrix} & 1, & \vartheta_i(\boldsymbol{l}_r)+1 \\ \vartheta_i(\boldsymbol{l}_r), & \alpha_i(\boldsymbol{l}_r), & \beta_i(\boldsymbol{l}_r), \quad 0 \end{matrix} \right] \right)$$

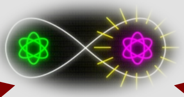
turbulence parameters

atmospheric losses

pointing error

FSO environmental effects: Noise

Entangled pair of qubits



Matter qubit
(stored in quantum memory)

Flying qubit
(transferred over FSO channel)

Quantum depolarizing noise channel

$$\Lambda_{1,i}((\boldsymbol{l}_r)) = (1 - 4p_{1,i}(\boldsymbol{l}_r))\rho + 4p_{1,i}(\boldsymbol{l}_r)\frac{I}{2}$$

$$p_{1,i}(\boldsymbol{l}_r) = \frac{1}{4}(1 - e^{-\frac{t_i(\boldsymbol{l}_r)}{T}})$$

storage time

memory coherence time

$$t_i(\boldsymbol{l}_r) = \frac{d_{\text{E2E},i}(\boldsymbol{l}_r)}{c} + T_{\text{proc}}$$

E2E distance

speed of light

processing time

Phase damping quantum noise

$$\Lambda_{2,i}(\boldsymbol{l}_r) = (1 - p_{2,i}(\boldsymbol{l}_r))\rho + p_{2,i}(\boldsymbol{l}_r)\sigma_Z\rho\sigma_Z$$

$$p_{2,i}(\boldsymbol{l}_r) = \mathit{erf}(\sigma^2_{R,i}(\boldsymbol{l}_r))$$

error function

Rytov variance
(turbulence)

End-to-end entangled state

Proposition: For each user $i \in \aleph$:

For an initial entangled state (represented as a Bell-diagonal state):

$$\rho_{\mathrm{BD},i} = \sum_{j,k\in\{0,1\}} \lambda_{jk,i}\Phi_{\mathrm{jk}}$$

(1) The matter qubit stored in quantum memory for t_i duration (depolarizing noise)

(2) The flying qubit travels in FSO channel with atmospheric losses, pointing error, and turbulence (σ_R) (phase damping noise)

Then, the resulting E2E entangled state is:

$$\rho'_i(l_r) = \sum_{j,k\in\{0,1\}} \lambda'_{jk,i}(l_r)\Phi_{\mathrm{jk}}$$

where

$$\lambda'_{jk,i}(l_r) = (1 - p_{2,i}(l_r))F_{jk} + p_{2,i}(l_r)F_{j(k\oplus 1)}$$

and

$$F_{jk}(l_r) = \left(\frac{1}{4} + \left(\lambda_{jk,i} - \frac{1}{4}\right)e^{-\frac{t_i(l_r)}{T}}\right)$$

$\lambda'_{00,i}(l_r)$ is considered to represent fidelity i.e., Φ_{00} is the desired state

Joint RIS placement and EGR allocation optimization problem formulation

$$
\begin{aligned}
\mathcal{P}1: \quad & \max_{\boldsymbol{R}_{\text{in}}, \boldsymbol{l}_r} \sum_{i \in \mathcal{N}} w_i R_{\text{E2E},i} \\
s.t. \quad & \sum_{i \in \mathcal{N}} R_{\text{in},i} \leq C_{\max} \quad, \forall i \in \mathcal{N}, \\
& R_{\text{E2E},i} \geq R_{\min,i} \quad, \forall i \in \mathcal{N}, \\
& U_{\text{WFI}}(\boldsymbol{l}_r, \boldsymbol{R}_{\text{in}}) \geq \delta_{\text{th}} \quad, \forall i \in \mathcal{N}, \\
& \lambda''_{00,i}(\boldsymbol{l}_r) \geq f_{\min,i} \quad, \forall i \in \mathcal{N}, \\
& x_{\min} \leq x_r \leq x_{\max}, \\
& y_{\min} \leq y_r \leq y_{\max}, \\
& H_{\min} \leq H_r \leq H_{\max},
\end{aligned}
$$

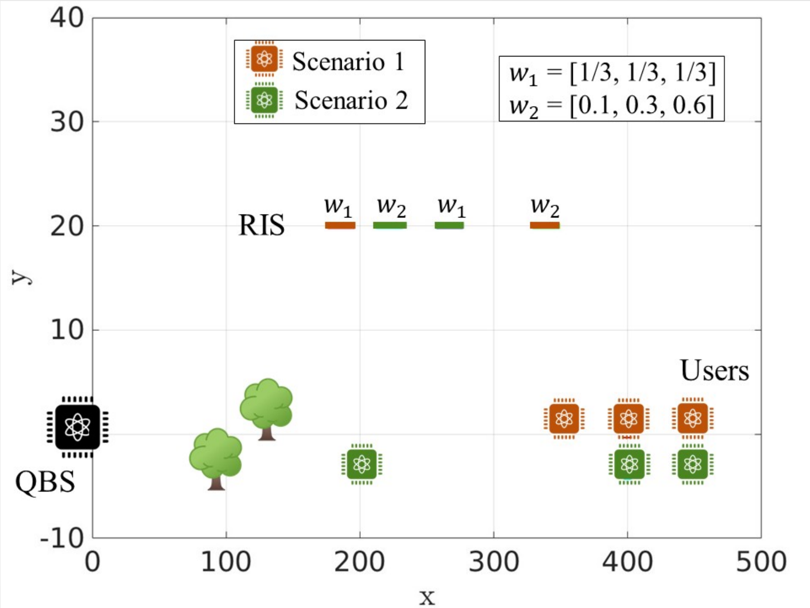
QBS quantum memory capacity constraint

Minimum end-to-end entanglement rate constraint

Minimum fairness level constraint (Proportional Jain's Fairness Index)

Minimum end-to-end fidelity constraint

Simulation results



- Simulated annealing algorithm achieved near-optimal performance (within 6% of optimal solution) and saved 65% of runtime

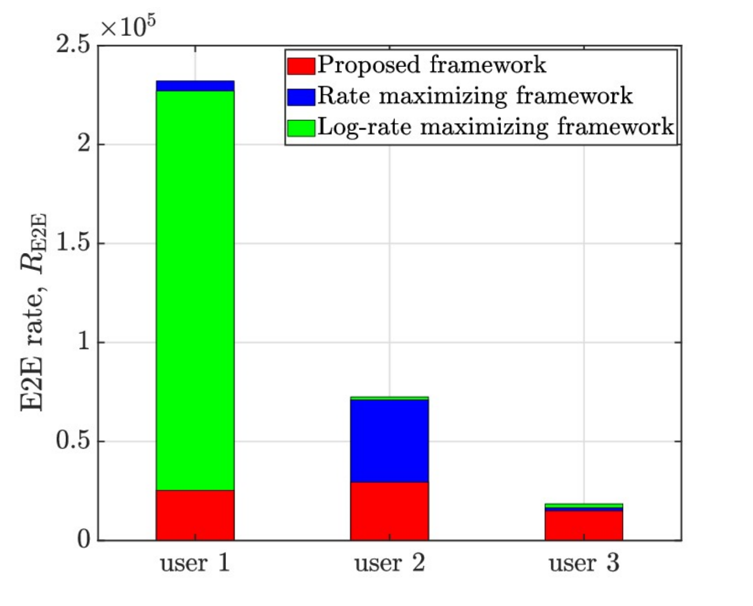
Simulation results

Proposed framework: 95%

fairness threshold

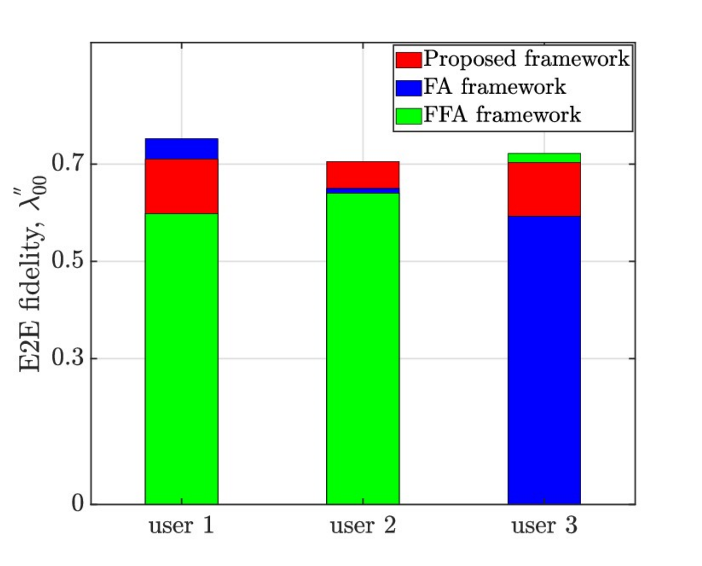
Rate maximizing framework:

no minimum fairness constraint

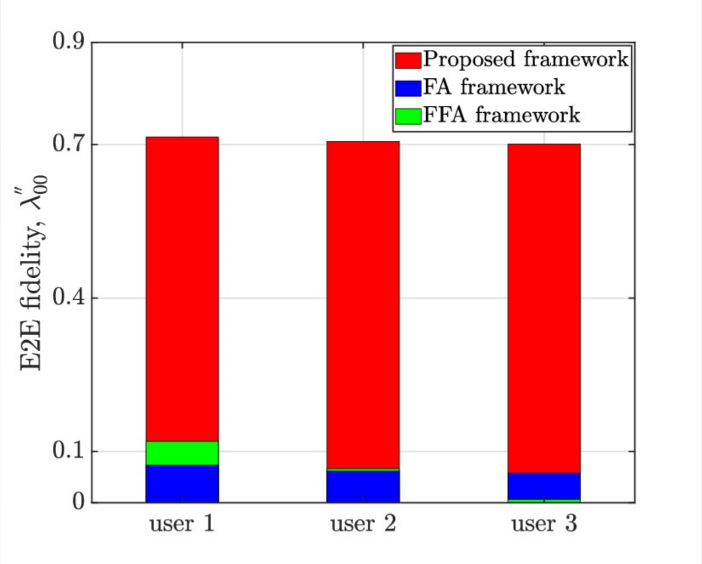


- Around 64% enhancement in fairness level among users

Simulation results



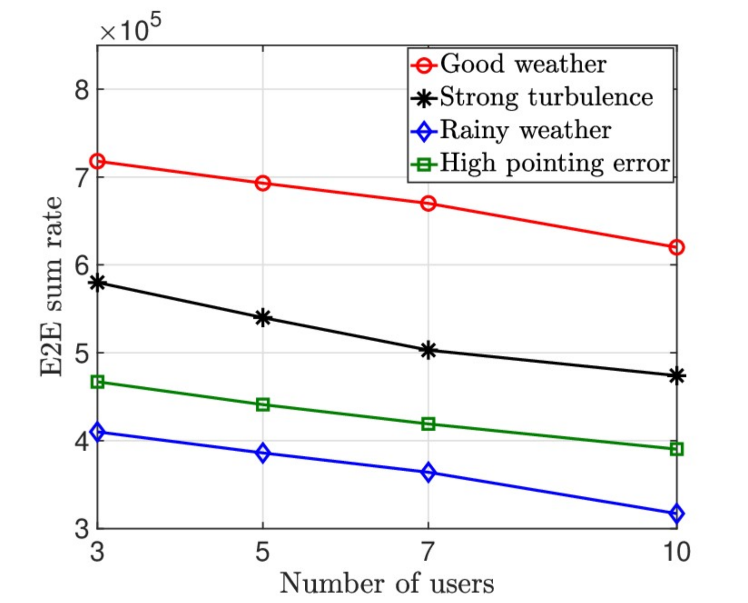
(moderate turbulence)



(strong turbulence)

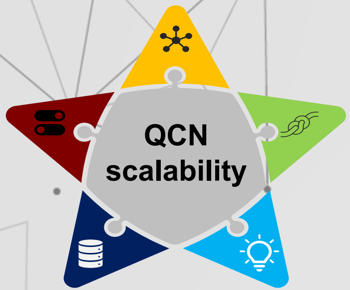
- Benchmarks 1) fidelity-agnostic (FA), and 2) fidelity- and fairness-agnostic (FFA) frameworks
- Proposed framework is only one capable of satisfying minimum fidelity constraint of 0.7
- Under strong turbulence, FA and FFA achieve at least 83% below the minimum required fidelity

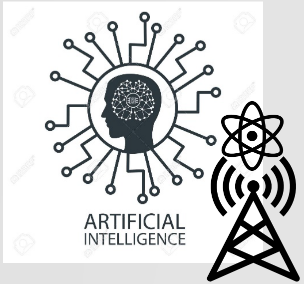
Simulation results



- Weather conditions (e.g., rain) have the most significant effects

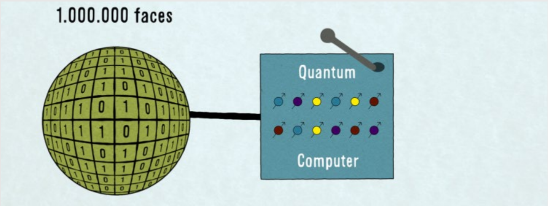
Ongoing and future research directions

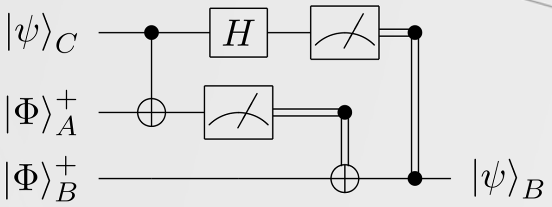




- Scaling quantum switches
  - ➢ Swap-distillation scheduling in multi-switch QCNs
  - ➢ Matching game for request-quantum switch association

- Scaling quantum memories in QCNs
  - ➢ Controlling nuclear spin selection process for storage in NV centers in diamond
  - ➢ Resource allocation in QCNs with quantum distillation protocols





- Delay-aware scalable QRNs
  - ➢ Incorporating operations' delay in scheduling repeater operations under QoS constraints
  - ➢ Integrating scalability analysis with traffic QCN management

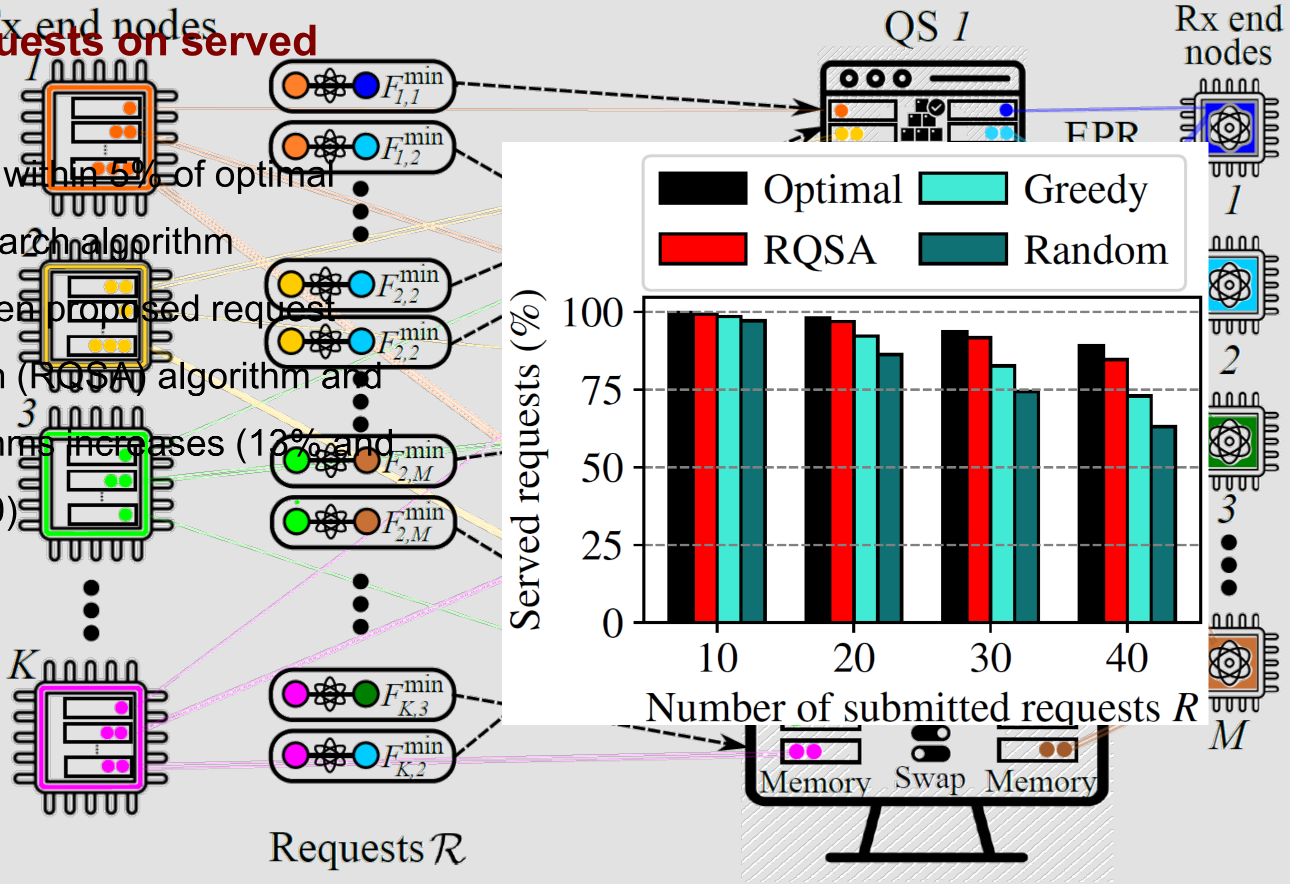
Matching Game for Optimized Association in QCNs

Impact of number of requests on served requests

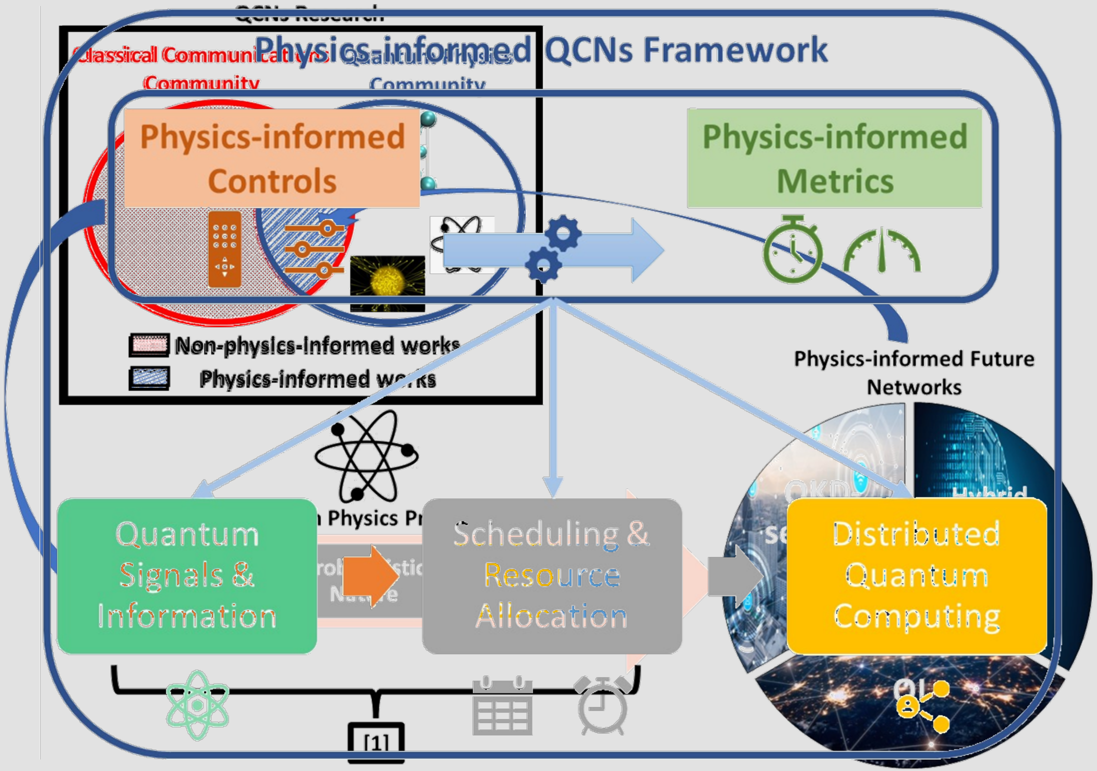
- Near-optimal performance, within 5% of optimal results using exhaustive search algorithm
- As R increases, gap between proposed request-quantum switch association (RQSA) algorithm and greedy and random algorithms increases (13% and 22%, respectively at R = 40)

Contributions:

- ❑ Introduced Quantum data center setup of multi-quantum switch QCNs
- ❑ Novel matching game formulation for request-QS association problem
- ❑ Limited resources and heterogeneous fidelity constraints



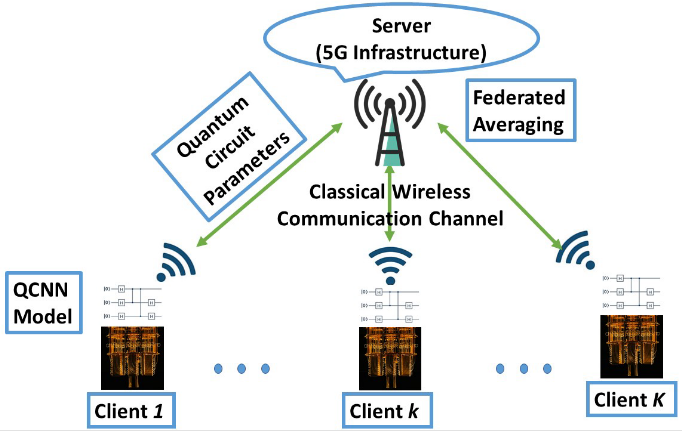
Physics-informed QCNs: A Vision Towards the Quantum Internet



Quantum Federated Learning (QFL) with Quantum Data

Contributions:

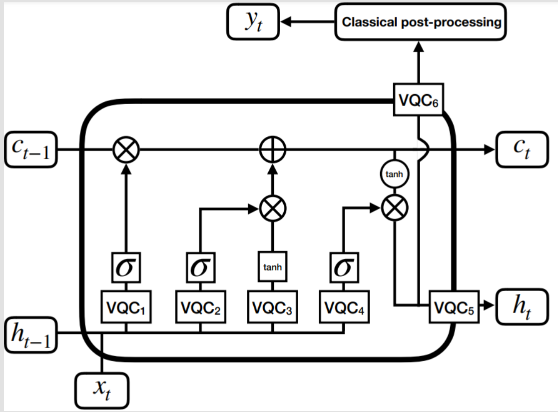
- ❑ Introduced first QFL framework with quantum data
- ❑ Developed first public quantum federated dataset
- ❑ Integrated TensorFlow Federated and TensorFlow Quantum with Google's Cirq in a novel implementation



Federated Quantum Long Short -term Memory (FedQLSTM)

Contributions:

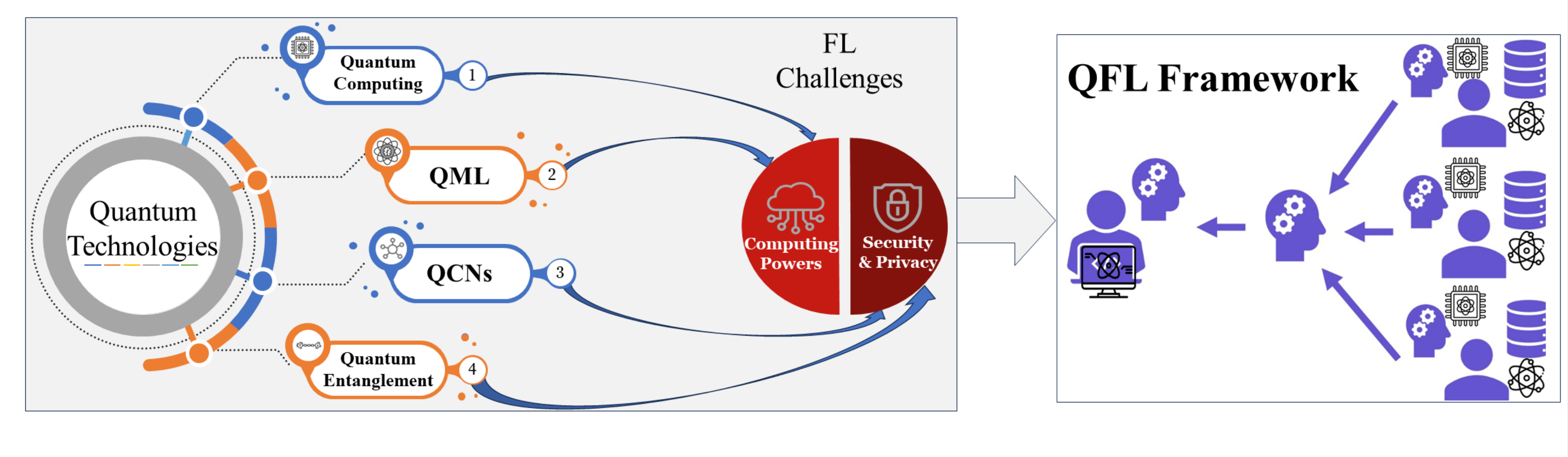
- ❑ Proposed first QFL framework with QLSTM
- ❑ Developed a novel use-case of FedQLSTM for distributed quantum sensing networks



Foundations of QFL Over Classical and Quantum Networks

Contributions:

- ❑ First comprehensive analysis of challenges, opportunities, and open research directions in QFL over both classical and quantum networks.



Conclusions

- Scaling QCNs is a challenging and fundamental problem that cuts across multiple use cases and scenarios
  - ➢ Necessity for fundamental analysis of delay associated with operations like swapping and distillation, and the impact of waiting time on decoherence and fidelity
- QCNs can have different communication backbones (optical vs. FSO), and thus there is a need to capture such heterogeneity
  - ➢ The use of RIS is useful for the FSO use case
- Next-generation QCNs must explicitly account for the underlying physics
  - ➢ Ongoing work – important area
- Quantum computing also has scaling challenges with communication considerations
  - ➢ QFL and its derivatives

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Thank you
Q&A