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Quantum Internet Addressing

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Research topics

Distributed Quantum Computing

- key applications in the panorama of quantum technologies: **bridge to step beyond** the current **NISQ era**
- by inter-connecting spatially distributed quantum processors, we aim at achieving a **computing power** which **scales exponentially** with the computing resources

Quantum Internet Protocol Stack

- designing an **abstract model,** enabling the **standardization** by abstracting from the particulars
- peculiarities of quantum phenomena impose a **major paradigm shift:** no one-to-one mapping between classical Internet and Quantum Internet protocol stack

Entanglement Generation and Distribution

- investigating the intriguing genuinely quantum phenomena of **entanglement** and **quantum coherence** in the phenomena of **superadditivity, superactivation** and **causal activation** of quantum channel capacities
- for **generating entanglement** in quantum networks in a distributed manner.

Quantum Internet testbed

- exploit currently available technology for **distributing entanglement** via metro-scale fiber network **with a communication-engineering perspective**
- leveraging proof-of-concept demonstration as **feedback** for on-going **research activities**

- Images: flaticon.com

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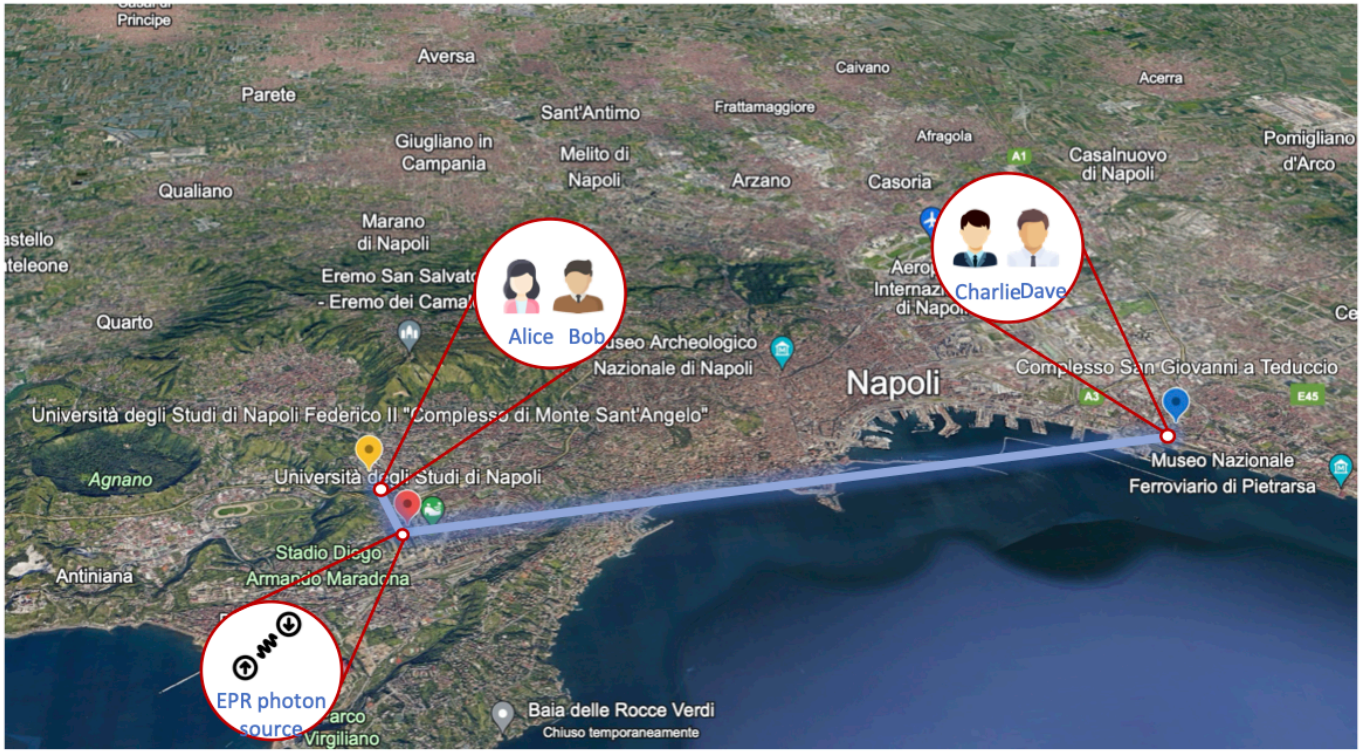
ONGOING TESTBED EFFORTS

…happy to share experiences from other groups offline…



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Some recent results

Distributed Quantum Computing

- "*Towards a Distributed Quantum Computing Ecosystem*", Invited Paper, IET Quantum Communication, 2020.
- "*Compiler Design for Distributed Quantum Computing*", IEEE Transactions on Quantum Engineering, 2021.
- "Optimized compiler for Distributed Quantum Computing", ACM Transactions on Quantum Computing, 2023.
- "*Distributed Quantum Computing: A survey*", arXiv:2212.10609, 2022.

Quantum Internet Protocol Stack

- "*Quantum Internet: Networking Challenges in Distributed Quantum Computing*", IEEE Network, 2020.
- "*When Entanglement meets Classical Communications: Quantum Teleportation for the Quantum Internet*", Invited Paper, IEEE Tr. on Com., 2020.
- "*Quantum Internet Protocol Stack: A Comprehensive Survey*", Computer Networks, 2022.
- "The Quantum Internet: Enhancing Classical Internet Services one Qubit at a Time", IEEE Network, 2022.
- **"Quantum Internet Addressing", IEEE Network, 2023.**
- "*Architectural principles for a quantum internet*", IETF: Internet Engineering Task Force, RFC 9340, March 2023.

Entanglement Generation and Distribution

- "*Quantum Switch for the Quantum Internet: Noiseless Communications through Noisy Channels*", IEEE Journal. on Sel. Areas in Comm., 2020.
- "*How Deep the Theory of Quantum Communications Goes: Superadditivity, Superactivation and Causal Activation*", IEEE Com. Sur. and Tut., 2022.
- "(Causal)-Activation of Complex Entanglement Structures in Quantum Networks", arXiv:2112.00543, December 2021.
- "*Beyond Shannon Limits: Quantum Communications through Quantum Paths*", IEEE Journal. on Sel. Areas in Comm., 2023.

- Recommended reading
- **This presentation is based on**

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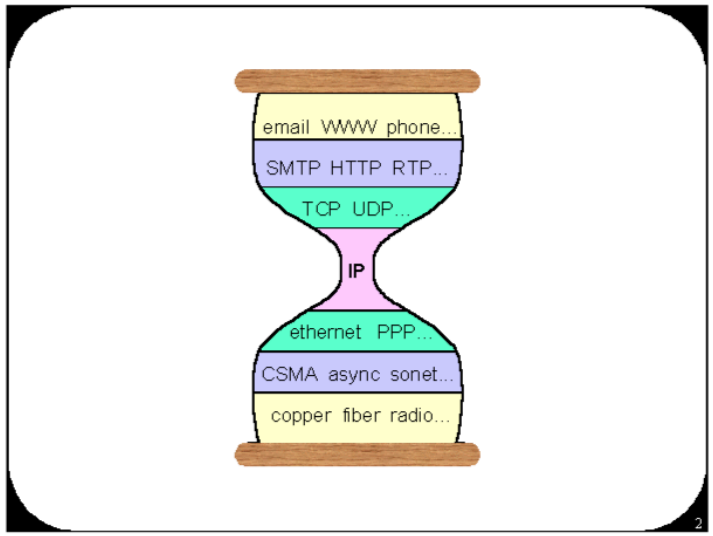
Preliminaries

Classical Internet

- hourglass-shaped architecture
  - protocols @ hourglass waist
    - winners of the (Internet) evolution race



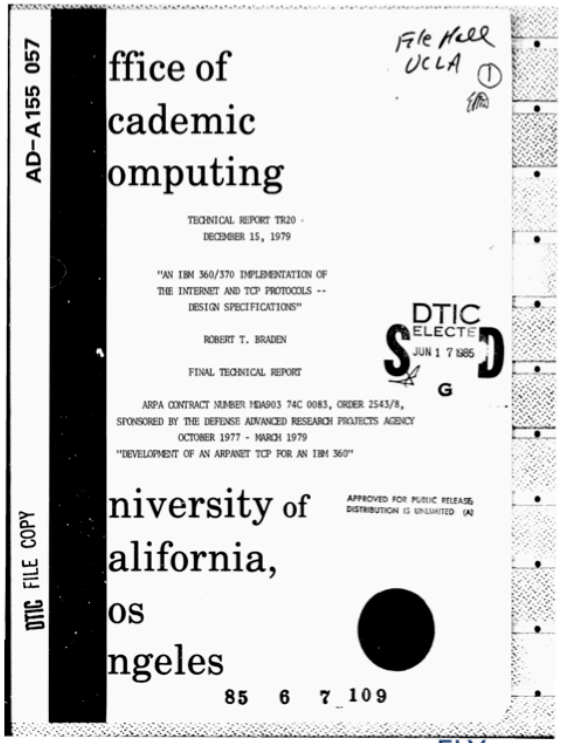
- Image: Steve Deering's plenary talk "Watching the Waist of the Protocol Hourglass" @ IETF 51, Aug 2001

Preliminaries

Classical Internet

- hourglass-shaped architecture
  - protocols @ hourglass waist
    - winners of the (Internet) evolution race
    - issues:
      - ossified protocols
        - haven't been replaced
        - or significantly evolved
      - for almost 40 years

- Image: Bob Braden' report about IBM 360/370 TCP/IP implementation, Dec. 1979



Preliminaries

IP: Internet Protocol

- "..The internet protocol implements two basic functions.."
  - addressing
    - "..internet protocol deals primarily with addresses.."
  - fragmentation

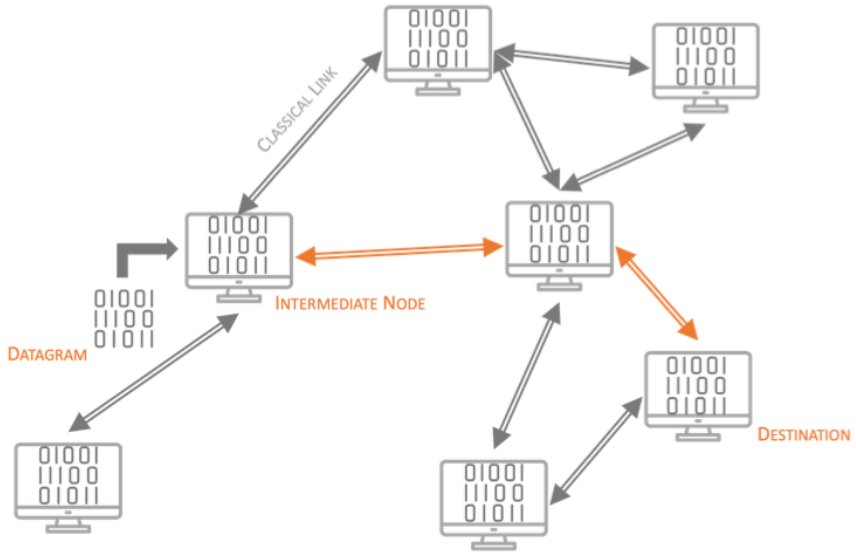
IP addresses: "..a distinction is made.."

- a name
  - indicates what we seek
- an address
  - indicates where it is
- a route
  - indicates how to get there

- Quotations from J. Postel, "Internet Protocol", STD 5, RFC 791, DOI 10.17487/RFC0791, Sept. 1981.

Preliminaries

IP: Internet Protocol



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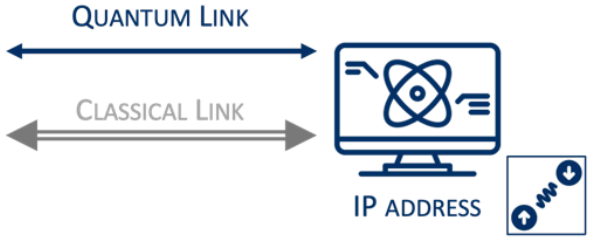
Quantum Internet Addressing

Existing proposals

- quantumness
  - limited to messages
    - namely, qubits or entanglement
  - exchanged between nodes
    - addressed via classical address
      - (underlying assumption)
- routing in a nutshell
  - find a classical path
    - sequence of IP addresses
  - for distributing entanglement
    - between source and destination



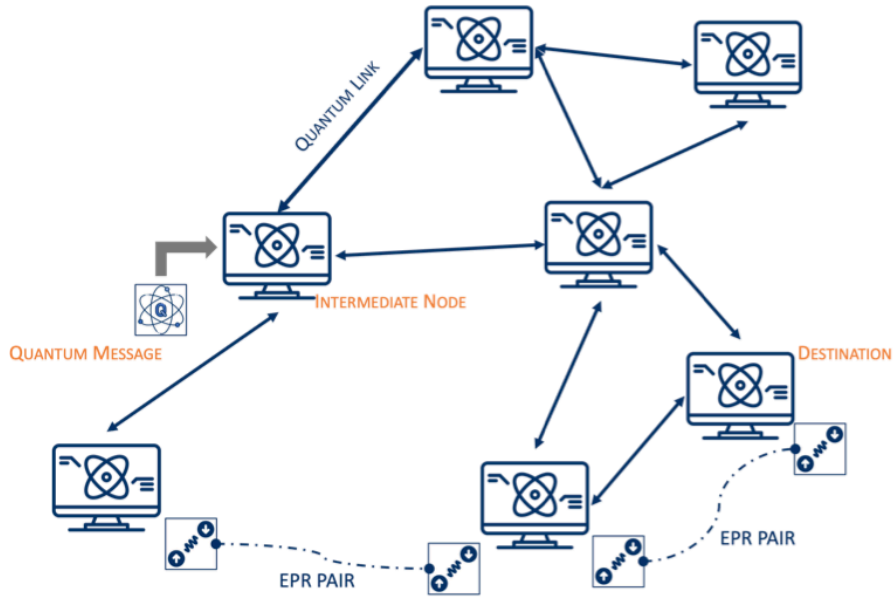
IP addresses…

…from a Quantum Internet perspective

Quantum Internet key questions

- quantum name
  - what is that we seek?
- quantum address
  - where is what we seek?
- quantum route
  - how can we get there?

Bipartite Entanglement



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…from a Quantum Internet perspective

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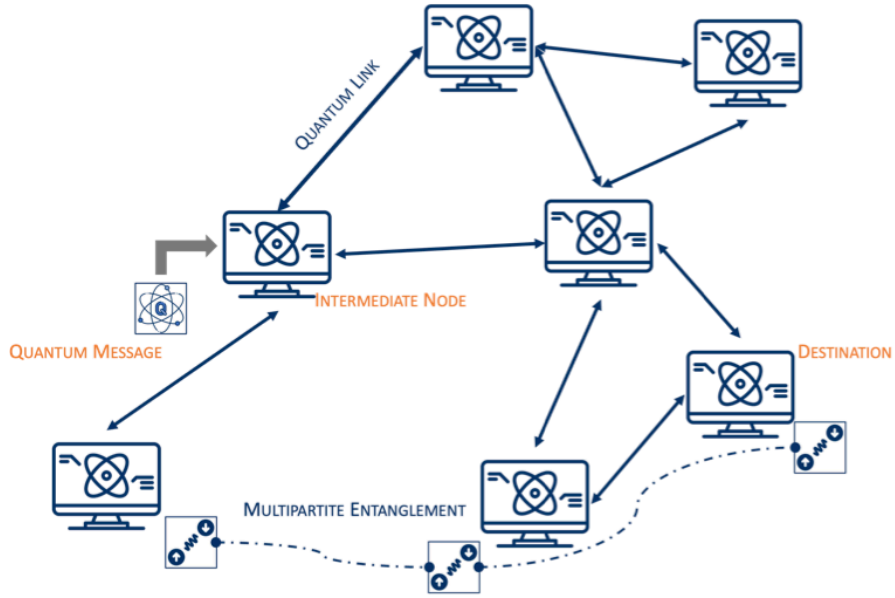
Multipartite Entanglement



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Addressing Quantum Internet nodes

Entanglement

- intrinsic dissimilarities
  - between
    - classical information
    - and entanglement
- far beyond
  - the design of some network functionalities
    - they affect the whole protocol stack

Table 1
A schematic summary of the differences arising with quantum bits and quantum entanglement with the respect to classical bits.

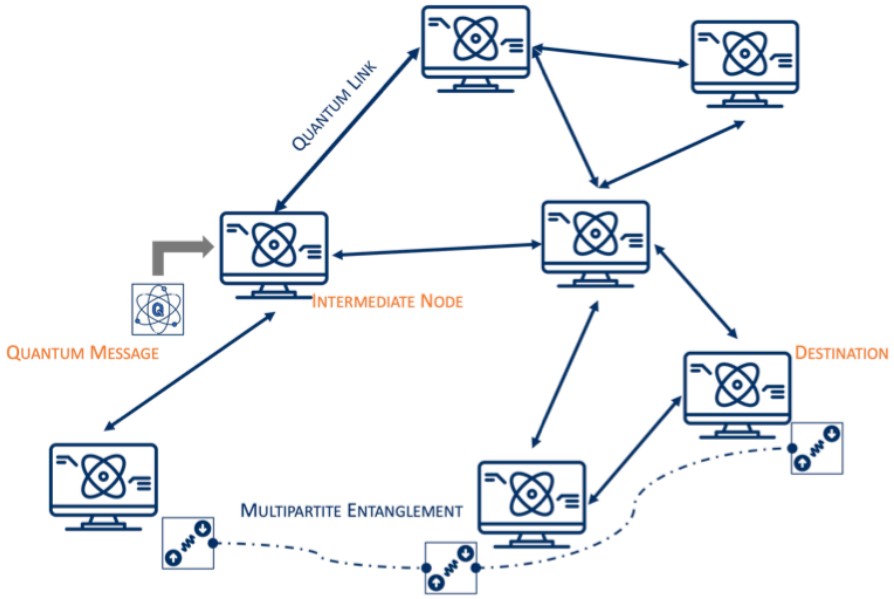
	Bit	Qubit	Entanglement
Temporal constraints	**No**: can be stored indefinitely	**Yes**: irreversibly degrades over time as a consequence of the decoherence process	
Duplication constraints	**No**	**Yes**: due to the no-cloning theorem	**No**: entangled states exploited in the network are in a known state, so they can be prepared repeatedly
Singleton	**Yes**: self-contained entities		**No**: a single entangled qubit is useless in the network without the awareness of the remaining entangled qubits
Scope	**Local**: any processing affects only the information available locally at the node		**Non-local**: any processing of a single entangled qubit has an instantaneous effect on the remaining entangled qubits
State	**Nearly stateless**: the node storing the bit does not need to retain any additional information	**Stateful**: the node storing the qubit needs to retain at least temporal information	**Profoundly stateful**: the node storing the entangled qubit needs to retain temporal information and the identities of the entangled nodes
Value	**Local** and **pre-determined**: the encoded information is valuable only for the destination and not for the intermediate nodes		**Global** and **dynamic**: the entangled state represents a valuable resource for any set of nodes sharing it
Order of operations & Flow direction	**Yes**, with a strict ordering: source, intermediate nodes, destination	**Flexible** the order: among the communication channels traversed by a quantum information carrier, can be indefinite	**Flexible**: the swapping operation can happen simultaneously or without any particular order
Classes	**No**: there exist no classes of bits or qubits		**Yes**: with a complex classification

- Table from "*Quantum Internet Protocol Stack: a Comprehensive Survey*", Computer Networks, 2022.

Addressing Quantum Internet nodes

Entanglement-Enabled Connectivity

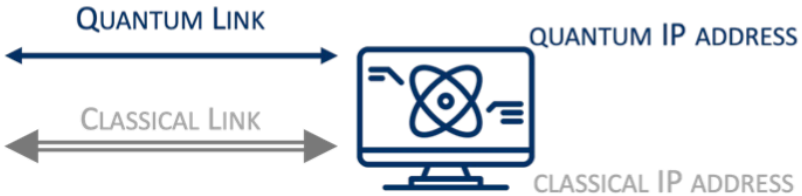
- richer form of connectivity
  - with respect to classical counterpart
  - e.g.,
    - weaker dependency
      - from instantaneous conditions of the underlying quantum channel
    - unconventional temporal dynamics
      - due to entanglement depletion
  - redefines the very same concept of topological neighborhood
    - which may change at run time
      - e.g., due to swapping or local operations for multipartite



Quantum Internet Addressing

What if…

- … we start designing
  - new addressing schemes
    - for the Quantum Internet
  - by properly capturing and tracking
    - the unconventional nature of entanglement-enabled connectivity?
  - … and …
    - even better
  - …we start exploiting quantumness
    - within the address?



Questions? Comments? Feedbacks? Advices?