UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

itee PhD information technology electrical engineering

DIETI. UNINA

Jessica Illiano

On the Protocol Stack for the Quantum Internet

Tutor: Prof. Angela Sara Cacciapuoti

co-Tutor: Dr. Antonio Manzalini

Cycle: XXXVI

Year: 3rd

itee PhD information technology electrical engineering

Background information

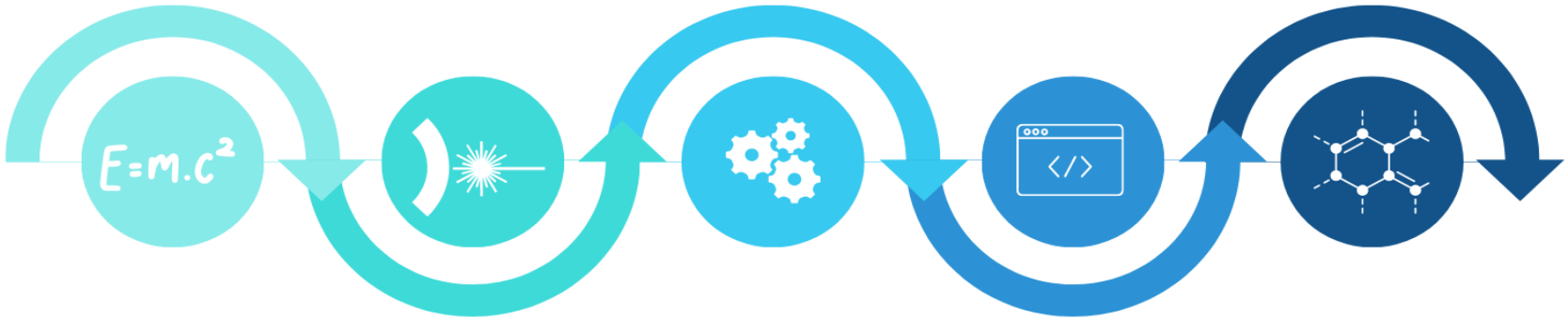
- MSc degree : Telecommunication Engineering
- Research group/laboratory: Quantum Internet Research Group
- PhD start date: 1/11/2020
  end date: 31/10/2023
- Scholarship type: company funded
- Partner company: TIM S.p.A.
- Periods abroad: Nu-Quantum L.t.d., Cambridge (UK)
  Oct 22-Jan 23

Summary of study activities

- Courses:
  - Quantum Information
  - Nanotechnologies for Electrical Engineering
  - Introduction to Quantum Circuits
  - Quantum Photonic Technologies
- Seminars (partial list):
  - Quantum communications with continuous variables of light
  - The Quantum Internet: the quest for a network paradigm shift
  - Cavity magnonics in strong coupling regime – from magnon-polariton hybrid states to perspectives for quantum sensing
- Attended Conferences (partial list) :
  - International conference on Quantum Technologies for High Energy Physics, QTHEP22, 1-4/11/22, CERN Geneva, Svitzerland
  - Conference on Quantum Computing Theory in Practice, QCTiP23, 17-19/04/2023 Jesus College, University of Cambridge, United Kingdom;
  - NATO Quantum Science and Technology Workshop,12-15/06/2023, Turin, Italy

Research areas

- Design of the protocol stack for the Quantum Internet
  - communication network envisioning at its final stage to globally interconnect heterogeneous quantum networks.
- ICT area of quantum technologies domain



Theoretical physics | Experimental physics | Engineering | Computer Science | Application Area Sciences

Research results

- Analysis of the impact of quantum entanglement on the design of an abstract quantum network model;
- Design and analysis of a genuinely quantum protocol for solving the entanglement access functionality:
  - Entanglement Access Control (EAC) protocol;
  - Theoretical model for noisy entanglement distribution;
  - Performance analysis of the EAC protocol;
- Optimized decision for multiple attempt entanglement distribution strategy;
- Conceptualization and analysis of the classical-quantum interface:
  - bi-directional interplay between classical Internet and the Quantum Internet;
  - enhancement of classical Internet network functionalities;
- Application perspective on the impact of entanglement on the Quantum Internet: Distributed Quantum Computing

Research products – 3rd year

[P1]	A. S. Cacciapuoti, J. Illiano, M. Caleffi, *Quantum Internet Addressing,* to appear on **IEEE Network**, 2023
[P2]	A. S. Cacciapuoti, M. Viscardi, J. Illiano, M. Caleffi, *Entanglement Distribution in the Quantum Internet: Knowing when to Stop!,* under review.
[P3]	J. Illiano, M. Caleffi, M. Viscardi, A. S. Cacciapuoti, *Design and Analysis of Genuine Entanglement Access Control for the Quantum Internet,* under review.
[P4]	M. Caleffi, M. Amoretti, D. Ferrari, D. Cuomo, J. Illiano, A. S. Cacciapuoti, *Distributed Quantum Computing: a Survey,* under review.
[P5]	L. D'Avossa, M. Caleffi, C. Wang, J. Illiano, S. Zorzetti, A.S. Cacciapuoti, *Towards the Quantum Internet: entanglement rate analysis of high-efficiency electro-optic transducer*, To appear in Proc. of **IEEE International Conference on Quantum Computing (QCE23)**, Sep 17–22, 2023
[P6]	M. Viscardi, J. Illiano, A.S. Cacciapuoti, M. Caleffi *Entanglement Distribution in the Quantum Internet: an optimal decision problem formulation*, To appear in Proc. of **IEEE International Conference on Quantum Computing (QCE23)**, Sep 17–22, 2023
[P7]	J. Illiano, A. S. Cacciapuoti, *On the Entanglement Role for the Quantum Internet*, In: M.S. Greco, D. Cassioli, S.L. Ullo, M. J. Lyons, (eds) Women in Telecommunications. Women in Engineering and Science. **Springer, Cham**.

Research products - 1st and 2nd year

[P8]	J. Illiano, M. Caleffi, A. Manzalini, A. S. Cacciapuoti *Quantum Internet Protocol Stack: a Comprehensive Survey,* **Computer Networks**, vol. 213, August 2022, 109092,
[P9]	A. S. Cacciapuoti, J. Iliano, S. Koudia, K. Simonov, M. Caleffi, *The Quantum Internet: enhancing Classical Internet Services one Qubit at a Time,* **IEEE Network**, vol.36, no.5, p 6-12, September/October2022.
[P10]	A. S. Cacciapuoti, J.Illiano, M. Viscardi, M. Caleffi, *Quantum Internet: the Dawn of the Quantum Paths*, Invited Paper, Proc. of **ACM International Conference on Nanoscale Computing and Communication (ACM NANOCOM 22)**, October 5-7, 2022,
[P11]	J. Illiano, M. Viscardi, S. Koudia, M. Caleffi, AS.. Cacciapuoti. *Quantum Internet: from Medium Access Control to Entanglement Access Control,* Proc. of **IEEE Globecom** 2022, pp. 1329- 1334,
[P12]	M. Caleffi, J. Illiano, S. Koudia. A.S. Cacciapuoti, *The Quantum Internet: a Communication Engineering Perspective,* Proc. of **IEEE International Conference on Quantum Computing and Engineering (QCE)**, 2021, pp. 365-365,
[P13]	J. Illiano, A. S. Cacciapuoti, A. Manzalini, M. Caleffi, *The Impact of the Quantum Data Plane Overhead no the Throughput*, Proc. of **ACM International Conference on Nanoscale Computing and Communication (ACM NANOCOM21)**, September 2021, Pages 1-6,

PhD thesis overview

- Problem statement:
  - The Quantum Internet is at its early stage of conceptualization
  - It is not possible to exploit classical strategies
  - Its design requires a network paradigm shift to harness quantum mechanics specificities
- Objective:
  - Design of the Quantum Internet protocol stack
- Methodology:
  - Analysis of the impact of entanglement on the design of the Quantum internet protocol stack
  - Design of protocols for quantum network functionalities (EAC)
  - Classical-quantum Interface

PhD thesis

- Design of the Quantum Internet protocol stack demands for a network paradigm shift [P8, P1]
- Analysis of the impact of entanglement on the design of the Quantum Internet functionalities [P8,P9,P2]
- Design and analysis of Entanglement Access Control protocol [P3]
- Classical-Quantum Interface [P9]

Design of the Quantum Internet protocol stack

- The design of an abstract quantum network model that leads to the definition of a reference standard for the quantum Internet is still an open problem
- The design of the Quantum Internet demands a network paradigm shift:
  - Governed by the laws of quantum mechanics
  - Phenomena with no counterpart in classical networks:
    - no-cloning, quantum measurement, entanglement, decoherence
  - Entanglement revolutionizes the concept of communication network

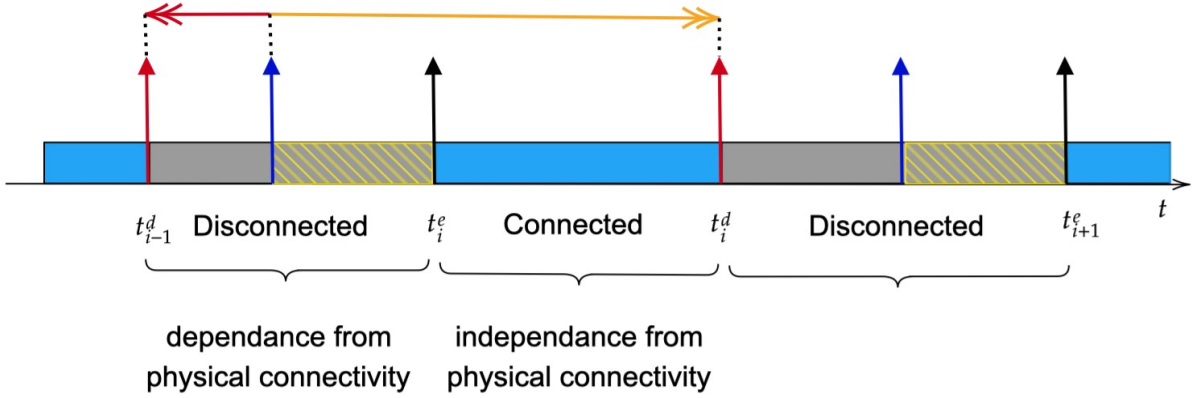
Entanglement Unconventional Features

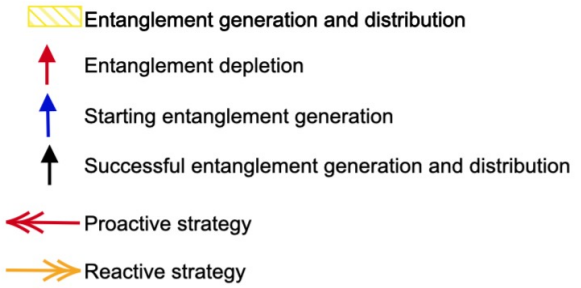
Table 1
A schematic summary of the differences arising with quantum bits and quantum entanglement with the respect to classical bits.

	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

J. Illiano, M. Caleffi, A. Manzalini, A. S. Cacciapuoti, "*Quantum Internet Protocol Stack: a comprehensive survey*", Computer Networks, p. 109092, 2022

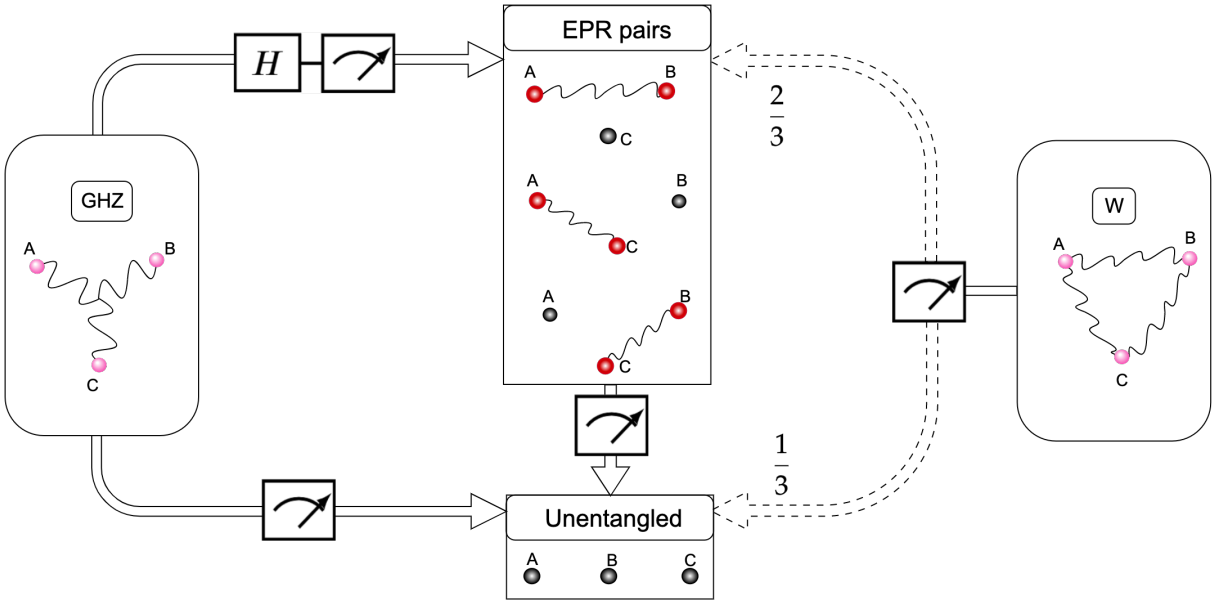
Impact of entanglement





- quantum teleportation: transmission of qubit without any use of a quantum link as long as EPR shared
- qubit transmission regardless of the instantaneous conditions of the underlying physical quantum channel

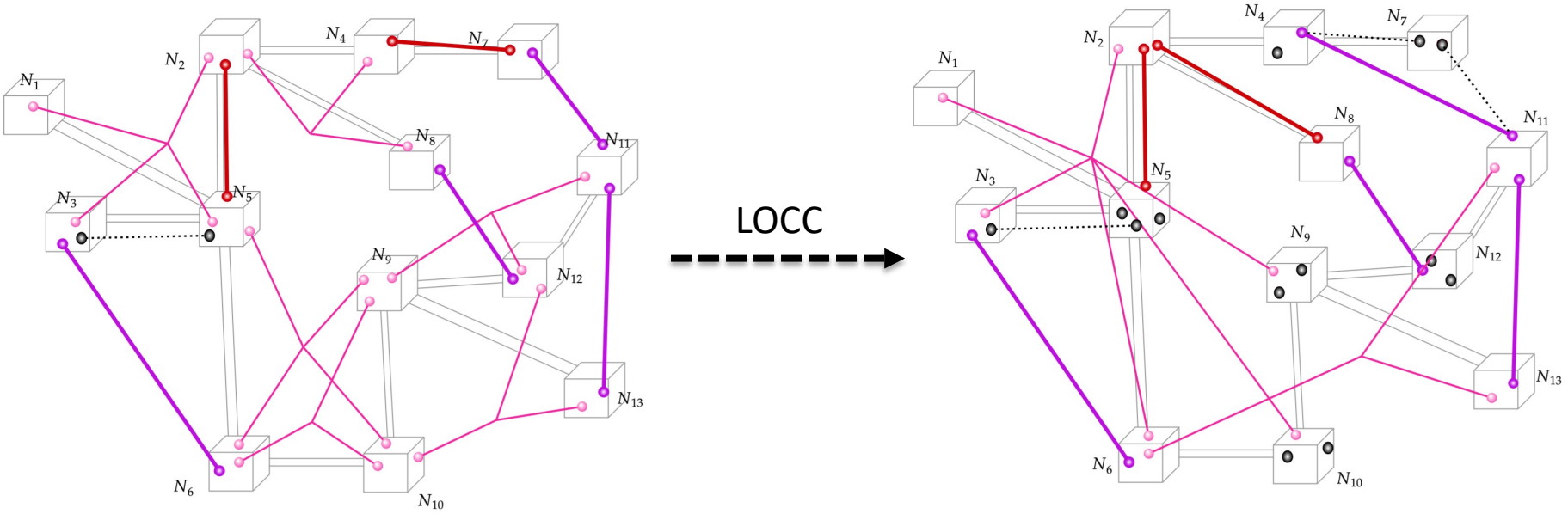
Entanglement- based connectivity



- EPRs resemble of an half-duplex unicast channels
- Multipartite entangled states represent a shared resource and enable multiple unicast channels between disjoint pairs of nodes

J. Illiano, M. Caleffi, A. Manzalini, A. S. Cacciapuoti, "*Quantum Internet Protocol Stack: a comprehensive survey*", Computer Networks, p. 109092, 2022

Entanglement- based connectivity



- The new concept of connectivity affects the entire network stack
- It redefines the concept of neighbor nodes, which is at the base of many communication functionalities in classical network
- Demands for ad-hoc functionalities such as *entanglement access*

Entanglement Access Control

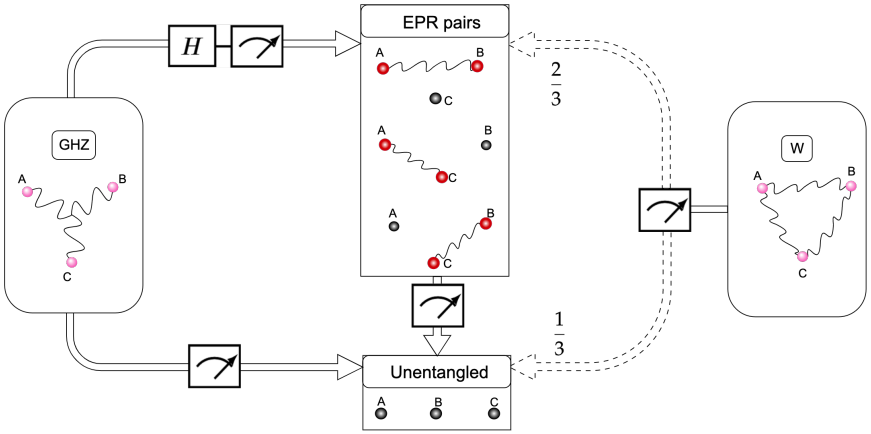


Table 1
A schematic summary of the differences arising with quantum bits and quantum entanglement with the respect to classical bits.

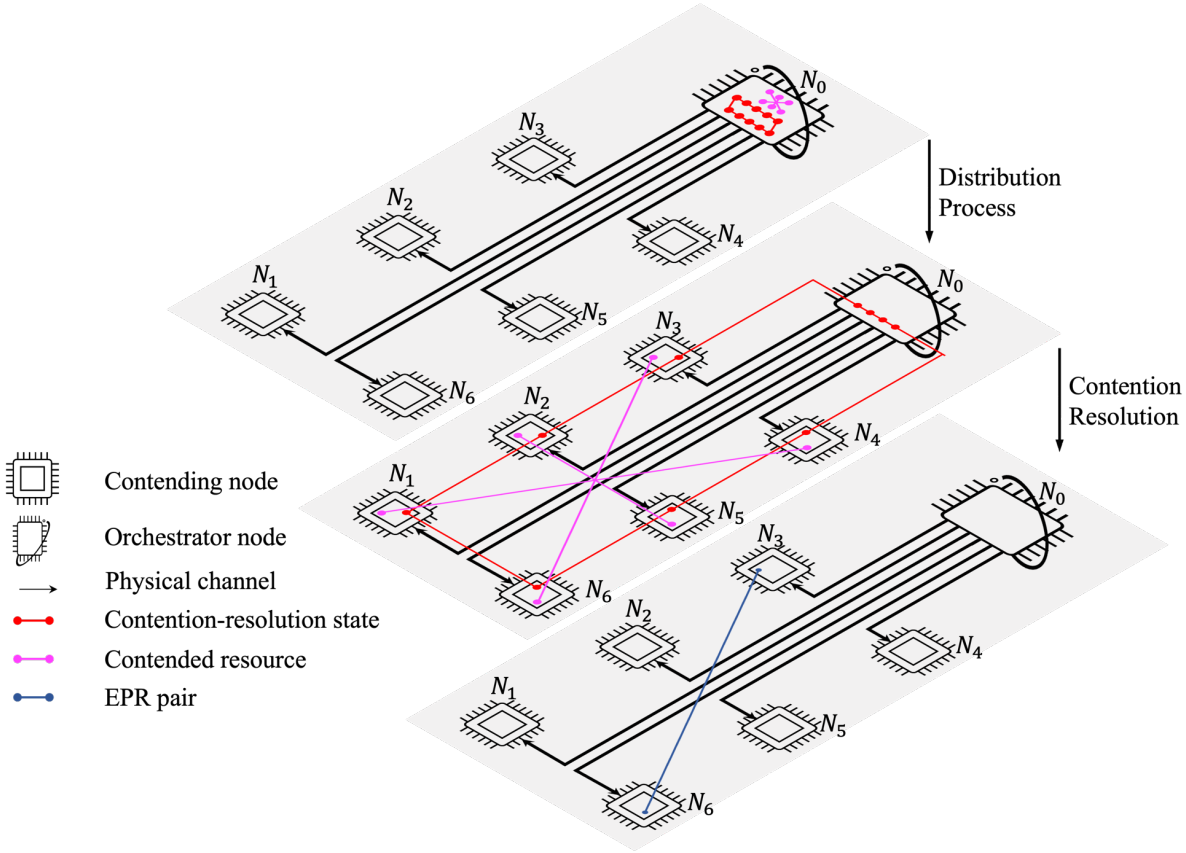
	Bit	Qubit	Entanglement
Temporal constraints	**No**: can be stored indefinitely	**Yes**: irreversibly degrades over time as a consequence of the decoherence process	
Duplication constraints	**No**	**Yes**: due to the no-cloning theorem	**No**: entangled states exploited in the network are in a known state, 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

- EPRs resemble of an half-duplex unicast channels
- Multipartite states enable the extraction of an EPR pair among any disjoint couple of nodes sharing it

- Non-local scope
- Global value
- Stateful resource
- Heterogeneous resource

The principles of quantum mechanics forbid to use classical strategies

Entanglement Access Control protocol



- Contended resource

$$|GHZ_n\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle^{\otimes n} + |1\rangle^{\otimes n}\right)$$

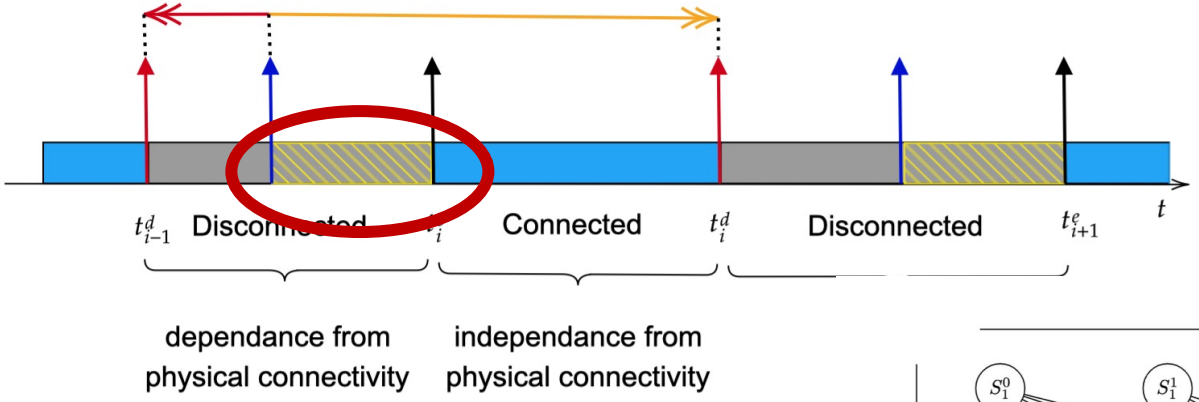
- Contention resolution state

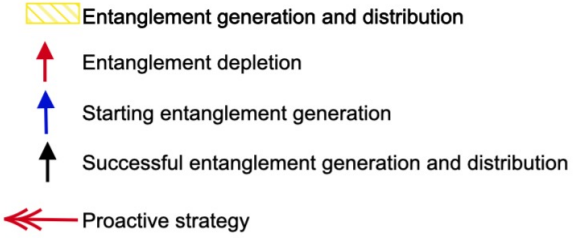
$$|D_n^k\rangle = \left[\binom{n}{k}\right]^{-\frac{1}{2}} \sum_{i\in\{0,1\}^n : d_H(i)=k} |i\rangle$$

Collision-free genuinely quantum EAC protocol

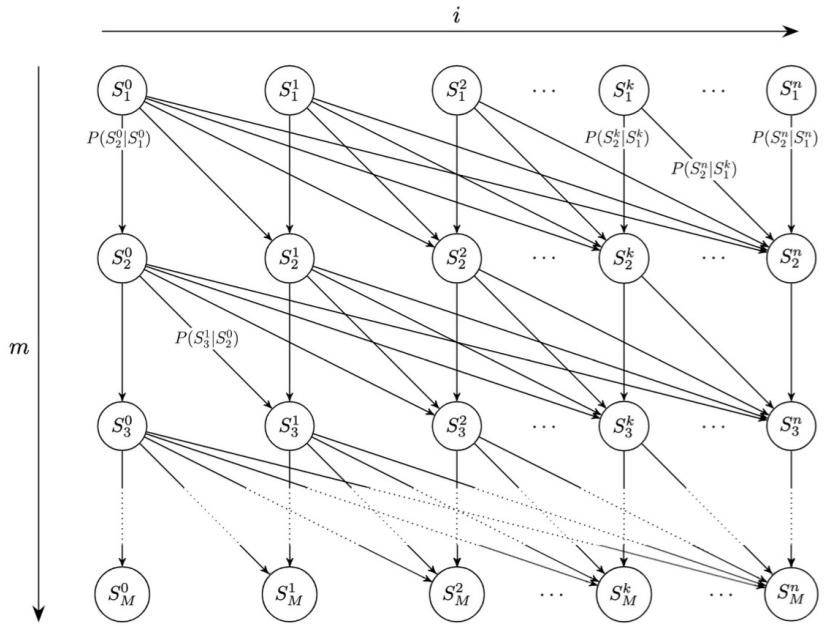
J. Illiano, M. Caleffi, M. Viscardi, A. S. Cacciapuoti, "*Design and Analysis of Genuine Entanglement Access Contol for the Quantum Internet*", arXiv:2305.01276, May 2023

Noisy Entanglement Distribution

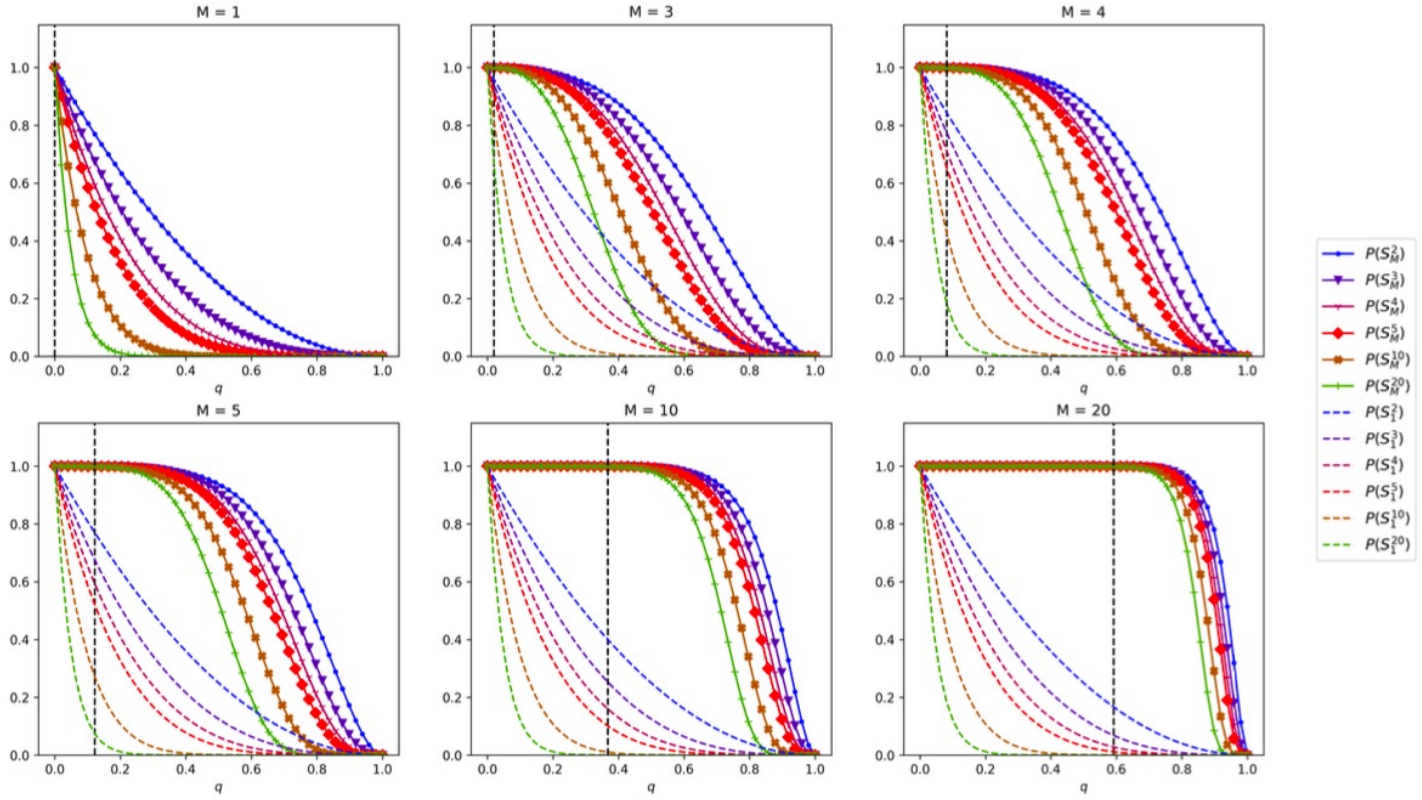




- Quantum absorbing channel (worst case scenario)
- dicrete Markov chain model for multiple attempt entanglement distribution strategy
- Closed form expression for transition probabilities

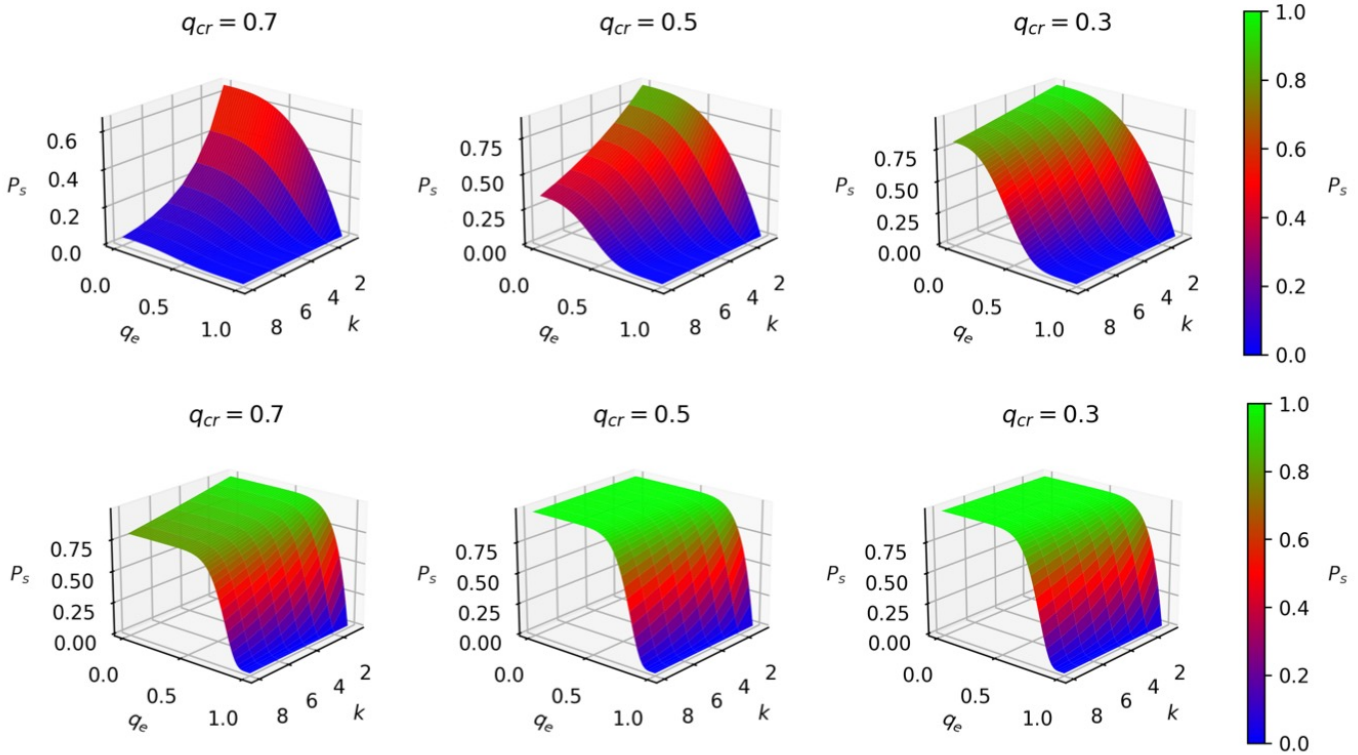


EAC performance evaluation



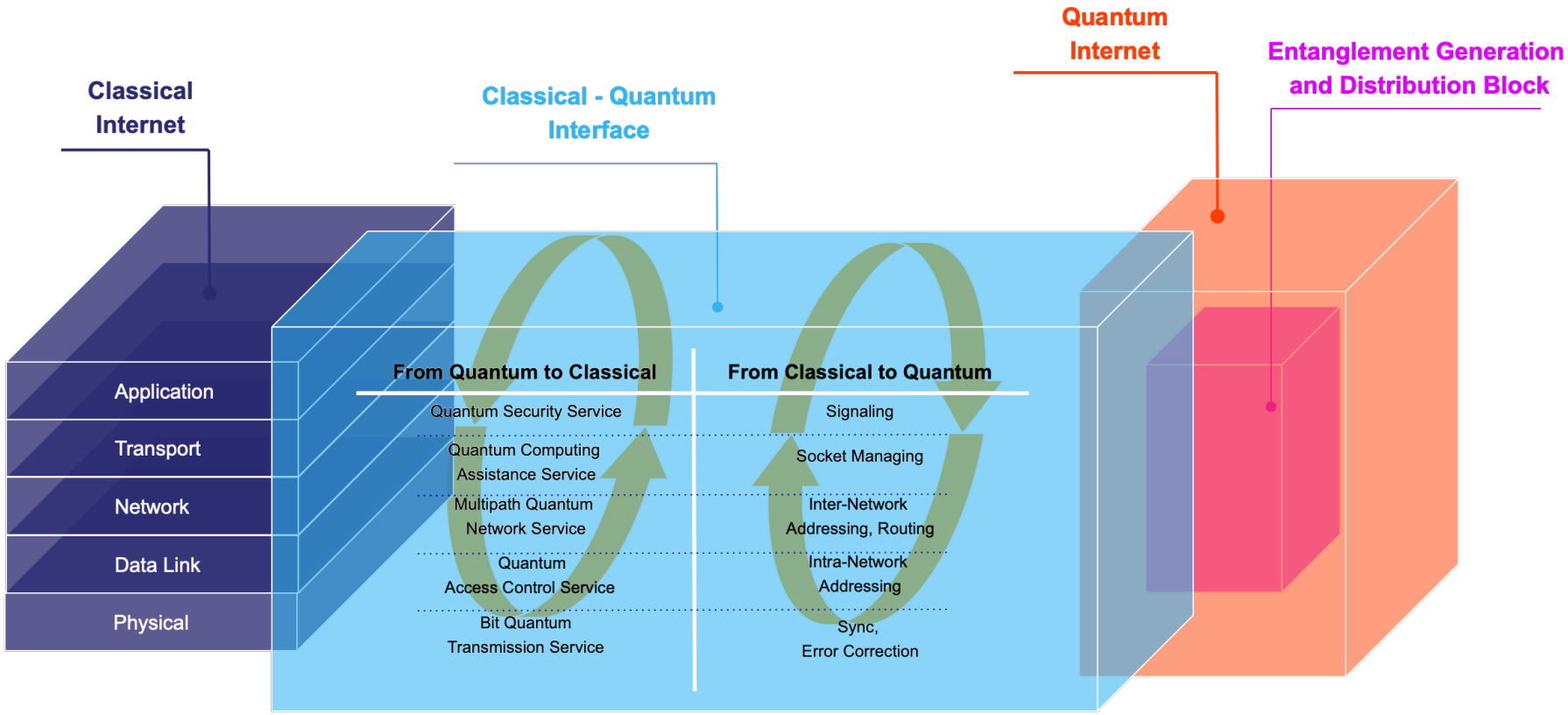
- State probability $P(S_j^M)$with j = n, versus failure distribution probability q, for different values of n and distribution attempts M.

EAC performance evaluation



- EAC contention-resolution probability for noisy entanglement distribution towards n = 8 contending nodes.

Classical—Quantum Interface



- The Quantum Internet cannot operate indipendently or autonomously from the classical Internet
- Cross-layer interactions between classical Internet and Quantum Internet

A. S. Cacciapuoti, J. Illiano, S. Koudia, K. Simonov, M. Caleffi, "*The Quantum Internet: Enhancing Classical Internet Services one Qubit at a Time*", IEEE Network, vol.36, no.5, p 6-12, September/October2022

Thank you for your attention