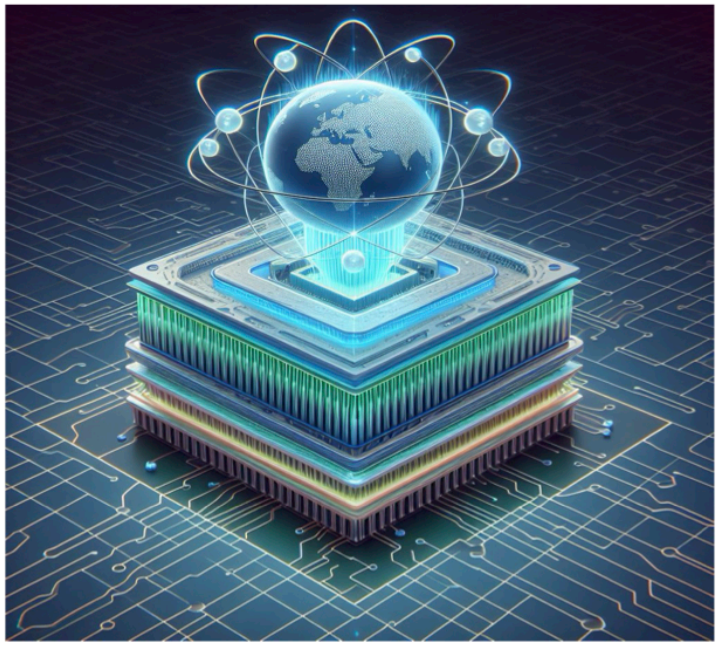
University of Naples
Federico II



FLY
Future Communications Laboratory
www.quantuminternet.it

Engineering quantum connectivity

the quest for a paradigm shift

Prof. Marcello Caleffi

Quantum Internet research group

FLY: Future Communications Laboratory

University of Naples *Federico II*

marcello.caleffi@unina.it

University of Naples
Federico II

OUTLINE

1. RESEARCH GROUP
2. QUANTUM INTERNET UNCONVENTIONAL FEATURES
3. ENGINEERING QUANTUM CONNECTIVITY

University of Naples *Federico II*

Quantum Internet research group

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

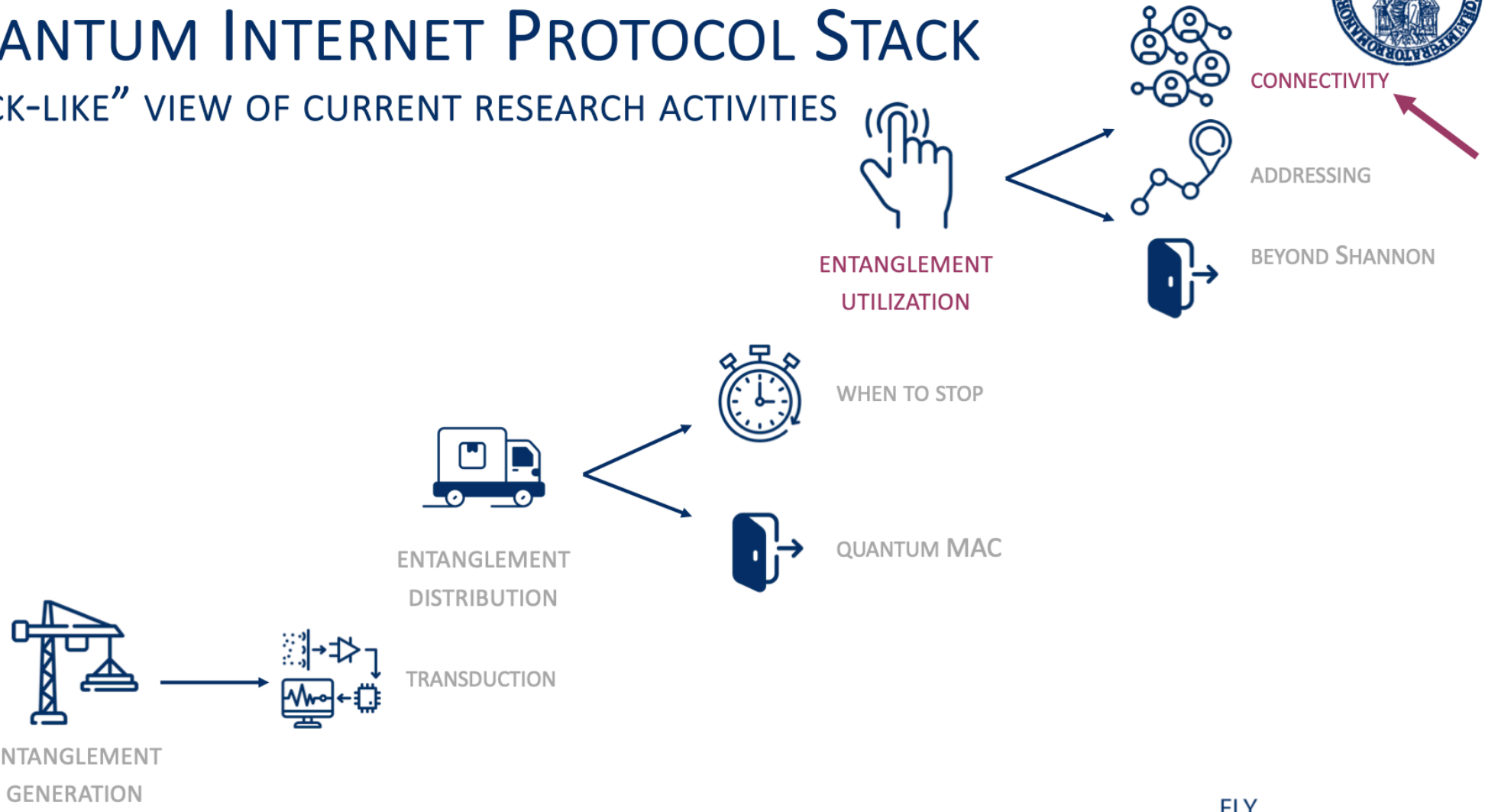
- Exploit currently available technology for **distributing entanglement** via metro-scale fiber network **with a communication-engineering perspective**
- Leveraging proof-of-concept demonstration as **feedback** for on-going **research activities**

- Images: flaticon.com

University of Naples
Federico II

QUANTUM INTERNET PROTOCOL STACK

"STACK-LIKE" VIEW OF CURRENT RESEARCH ACTIVITIES



University of Naples
Federico II

Outline

1. Research Group
2. Quantum Internet unconventional features
   - entanglement is not information
   - open issues
   - beyond physical connectivity
3. Engineering Quantum Connectivity

Quantum Internet unconventional features

Entanglement ≠ Information

	Classical Information	Quantum Information	Entanglement
Temporal constraints	**NO**	**YES: DECOHERENCE**	
Duplication constraints	**NO**	**YES: NO-CLONING**	**NO**
Singleton	**YES**		**NO**
Scope	**LOCAL**		**NON-LOCAL**
State	**NEARLY STATELESS**	**SOMEHOW STATEFUL (TIMING)**	**PROFOUNDLY STATEFUL**
Value	**LOCAL AND PRE-DETERMINED**		**GLOBAL AND DYNAMIC**
Operation and flow direction	**YES**	**FLEXIBLE**	
Classes	**NO**		**YES**

- **IN DEPTH-DISCUSSION** IN ***"QUANTUM INTERNET PROTOCOL STACK: A COMPREHENSIVE SURVEY"***, COMPUTER NETWORKS, 2022

University of Naples
Federico II

Outline

1. Research Group
2. Quantum Internet unconventional features
   - entanglement is not information
   - open issues
   - beyond physical connectivity
3. Engineering Quantum Connectivity

Quantum Internet unconventional features

Open issues and research directions

Latency and synchronization	Decoherence and tight sync for entanglement generation
Signaling	Entanglement tasks rely on classical signaling
Metrics	Quantum unconventional features plus quantum-classical interplay
Medium access and broadcast	Entanglement access control without broadcasting
Networking	Entanglement rules connectivity
Quantum path and quantum addressing	Quantum information carrier propagation
Quantum vs classical internet	Complex interplay yet to be fully understood
Industrial perspective and standards	Trade-off: basic research against industrialization

- ***"Quantum Internet Protocol Stack: A Comprehensive Survey"***, Computer Networks, 2022

Quantum Internet unconventional features

Open issues and research directions

Latency and synchronization	Decoherence and tight sync for entanglement generation
Signaling	Entanglement tasks rely on classical signaling
Metrics	Quantum unconventional features plus quantum-classical interplay
Medium access and broadcast	Entanglement access control without broadcasting
Networking	Entanglement rules connectivity
Quantum path and quantum addressing	Quantum information carrier propagation
Quantum vs classical Internet	Complex interplay yet to be fully understood
Industrial perspective and standards	Trade-off: basic research against industrialization

- Classical networks
  - Neighborhood ruled by physical connectivity
    - A persistent physical channel is mandatory
- Quantum networks
  - Neighborhood is dynamic and time-variant
    - Entanglement swapping
  - Connectivity can be engineered

• "Quantum Internet Protocol Stack: A Comprehensive Survey", Computer Networks, 2022

QUANTUM INTERNET UNCONVENTIONAL FEATURES

OPEN ISSUES AND RESEARCH DIRECTIONS

LATENCY AND SYNCHRONIZATION

SIGNALING

METRICS

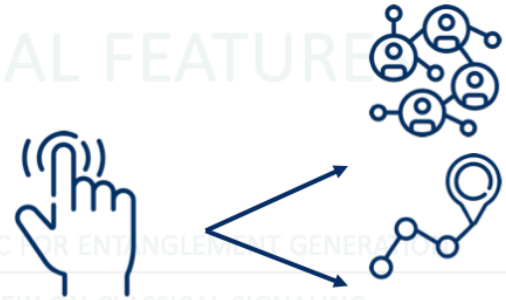
MEDIUM ACCESS AND BROADCAST

NETWORKING

QUANTUM PATH AND QUANTUM ADDRESSING

QUANTUM VS CLASSICAL INTERNET

INDUSTRIAL PERSPECTIVE AND STANDARDS



ENTANGLEMENT UTILIZATION

DECOHERENCE AND TIGHT SYNC FOR ENTANGLEMENT GENERATION

ENTANGLEMENT TASKS RELY ON CLASSICAL SIGNALING

QUANTUM UNCONVENTIONAL FEATURES PLUS QUANTUM-CLASSICAL INTERPLAY

ENTANGLEMENT ACCESS CONTROL WITHOUT BROADCASTING

ENTANGLEMENT RULES CONNECTIVITY

QUANTUM INFORMATION CARRIER PROPAGATION

COMPLEX INTERPLAY YET TO BE FULLY UNDERSTOOD

TRADE-OFF: BALANCE RESEARCH AGAINST INDUSTRIALIZATION

ENTANGLEMENT DISTRIBUTION

TRANSDUCTION

ENTANGLEMENT GENERATION

- CLASSICAL NETWORKS
  - NEIGHBORHOOD RULED BY PHYSICAL CONNECTIVITY
  - A PERSISTENT PHYSICAL CHANNEL IS MANDATORY
- QUANTUM NETWORKS
  - NEIGHBORHOOD IS DYNAMIC AND TIME-VARIANT
  - ENTANGLEMENT SWAPPING
  - CONNECTIVITY CAN BE ENGINEERED

"QUANTUM INTERNET PROTOCOL STACK: A COMPREHENSIVE SURVEY", COMPUTER NETWORKS, 2022

University of Naples
Federico II

Outline

1. Research Group
2. Quantum Internet unconventional features
   - entanglement is not information
   - open issues
   - beyond physical connectivity
3. Engineering Quantum Connectivity

Quantum Internet: How?

Beyond physical connectivity

⇨ VIRTUAL CONNECTIVITY	TIME-VARIANT (DEPLETABLE) CONNECTIVITY REGARDLESS OF INSTANTANEOUS CONDITIONS
AUGMENTED CONNECTIVITY	
ON-DEMAND CONNECTIVITY	

- PHYSICAL CONNECTIVITY
  - REQUIRES THE AVAILABILITY OF A PHYSICAL CHANNEL
    - DEPENDS ON THE INSTANTANEOUS CONDITIONS OF PROPAGATION
  - WIDELY ASSUMED:
    - TEMPORAL DYNAMICS WAY LARGER THAN NETWORK FUNCTIONALITIES RUN TIMES

- VIRTUAL CONNECTIVITY
  - ENABLED BY ENTANGLEMENT
  - PHYSICAL CHANNEL REQUIRED ONLY FOR ENTANGLEMENT DISTRIBUTION
    - NOT NEEDED FOR ACTUAL TELEPORTATION
  - TEMPORAL DYNAMICS
    - SHORTER THAN NETWORK FUNCTIONALITIES
    - ENTANGLEMENT DEPLETED BY USE
      - TIME-CONSTRAINTS

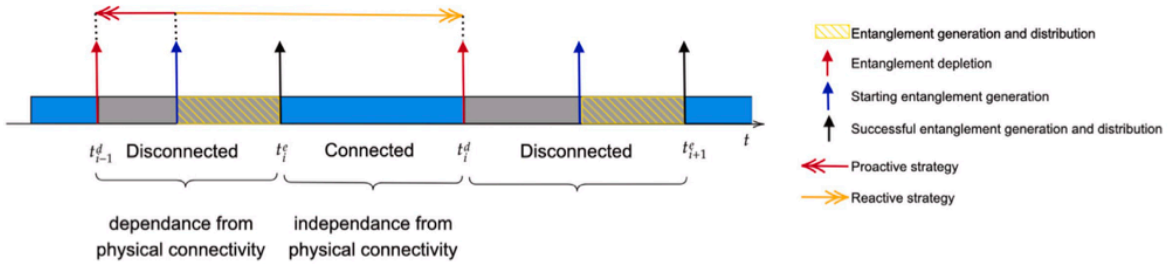
- *"Quantum Internet: A Comprehensive Survey"*, Computer Networks, 2022

University of Naples Federico II

Quantum Internet: How?

Beyond physical connectivity

⇨ Virtual connectivity	Time-variant (depletable) connectivity regardless of instantaneous conditions
Augmented connectivity	
On-demand connectivity	



- Entanglement generation and distribution
  - Proactive schemes
    - Early distribution of entanglement resources before actual need arises
  - Reactive schemes
    - On-the-fly distribution, when needed

- *"Quantum Internet Protocol Stack: A Comprehensive Survey"*, Computer Networks, 2022

Quantum Internet: How?

Beyond physical connectivity

Virtual connectivity	Time-variant (depletable) connectivity regardless of instantaneous conditions
⇨ Augmented connectivity	Independent from physical node location
On-demand connectivity	

- Entanglement swapping
  - Overcomes limitation of physical connectivity
    - Bounded by the physical distance among the network nodes
  - Enabling
    - Direct virtual link
    - Between remote nodes
- Augmented connectivity
  - Swapping increases the connectivity between nodes
    - More than linearly
  - No free meals
    - The more swapping, the higher EPR cost
    - Constraints increase

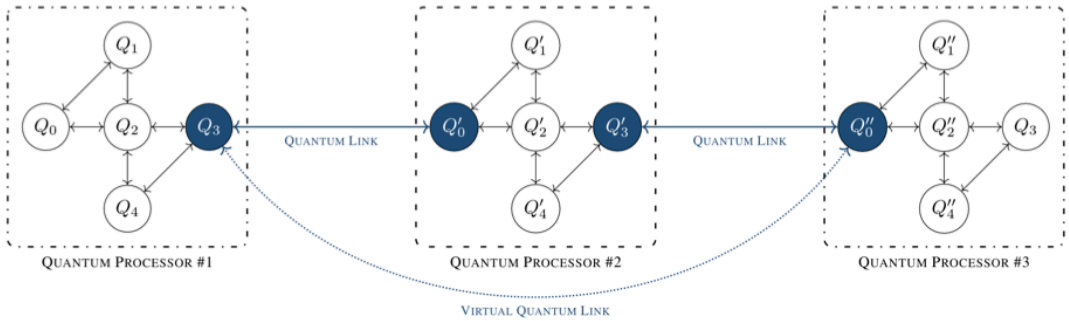
- "Quantum Internet Protocol Stack: A Comprehensive Survey", Computer Networks, 2022

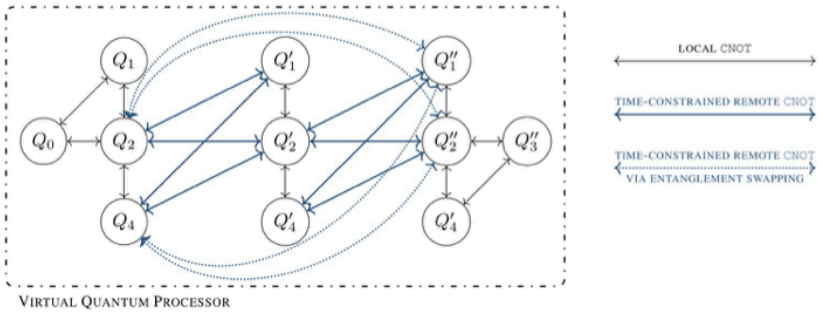
University of Naples
Federico II

QUANTUM INTERNET: HOW?

BEYOND PHYSICAL CONNECTIVITY

VIRTUAL CONNECTIVITY	TIME-VARIANT (DEPLETABLE) CONNECTIVITY REGARDLESS OF INSTANTANEOUS CONDITIONS
⇒ AUGMENTED CONNECTIVITY	INDEPENDENT FROM PHYSICAL NODE LOCATION
ON-DEMAND CONNECTIVITY	





- ***"COMPILER DESIGN FOR DISTRIBUTED QUANTUM COMPUTING"***, COMPUTER NETWORKS, 2022

Quantum Internet: How?

Beyond physical connectivity

Virtual connectivity	Time-variant (depletable) connectivity regardless of instantaneous conditions
Augmented connectivity	Independent from physical node location
⇨ On-demand connectivity	

- Bipartite entanglement
  - i.e., EPRs
  - creates half-duplex unicast link
  - identities of source-destination pair
    - fixed
      - but roles can be swapped

- Multipartite entanglement
  - i.e., GHZ states
  - enables distillation of different EPR pairs
    - differing in the identities of the source-destination pair
  - virtual neighbors chosen at runtime
    - depending on the communication needs

- "Quantum Internet Protocol Stack: A Comprehensive Survey", Computer Networks, 2022

Quantum Internet: How?

Beyond physical connectivity

Virtual connectivity	Time-variant (depletable) connectivity regardless of instantaneous conditions
Augmented connectivity	Independent from physical node location
⇨ On-demand connectivity	Enabling half-duplex unicast link between nodes chosen at run-time

- Bipartite entanglement
  - i.e., EPRs
  - creates half-duplex unicast link
  - identities of source-destination pair
    - fixed
      - but roles can be swapped

- Multipartite entanglement
  - i.e., GHZ states
  - enables distillation of EPR pairs
    - differing in the identities of the source-destination pair
  - between virtual neighbors chosen at runtime
    - depending on the communication needs

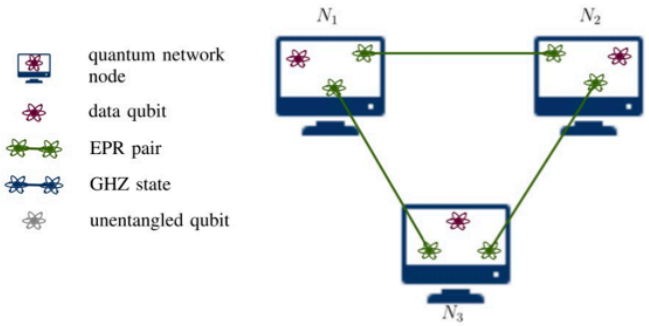
- "Quantum Internet Protocol Stack: A Comprehensive Survey", Computer Networks, 2022

QUANTUM INTERNET: HOW?

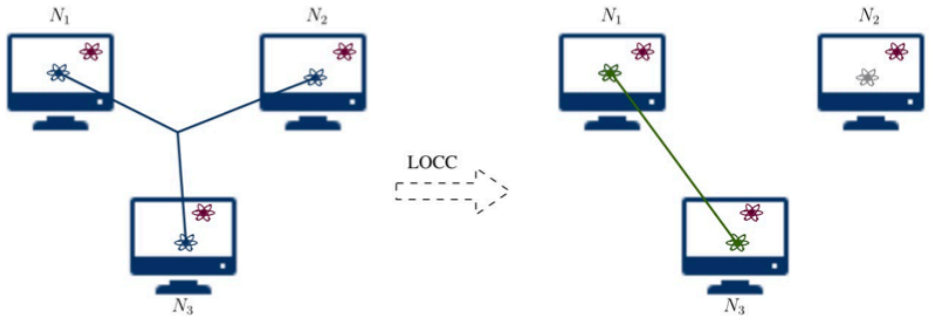
BEYOND PHYSICAL CONNECTIVITY

VIRTUAL CONNECTIVITY	TIME-VARIANT (DEPLETABLE) CONNECTIVITY REGARDLESS OF INSTANTANEOUS CONDITIONS
AUGMENTED CONNECTIVITY	INDEPENDENT FROM PHYSICAL NODE LOCATION
⇒ ON-DEMAND CONNECTIVITY	ENABLING HALF-DUPLEX UNICAST LINK BETWEEN NODES CHOSEN AT RUN-TIME

EPR-BASED CONNECTIVITY



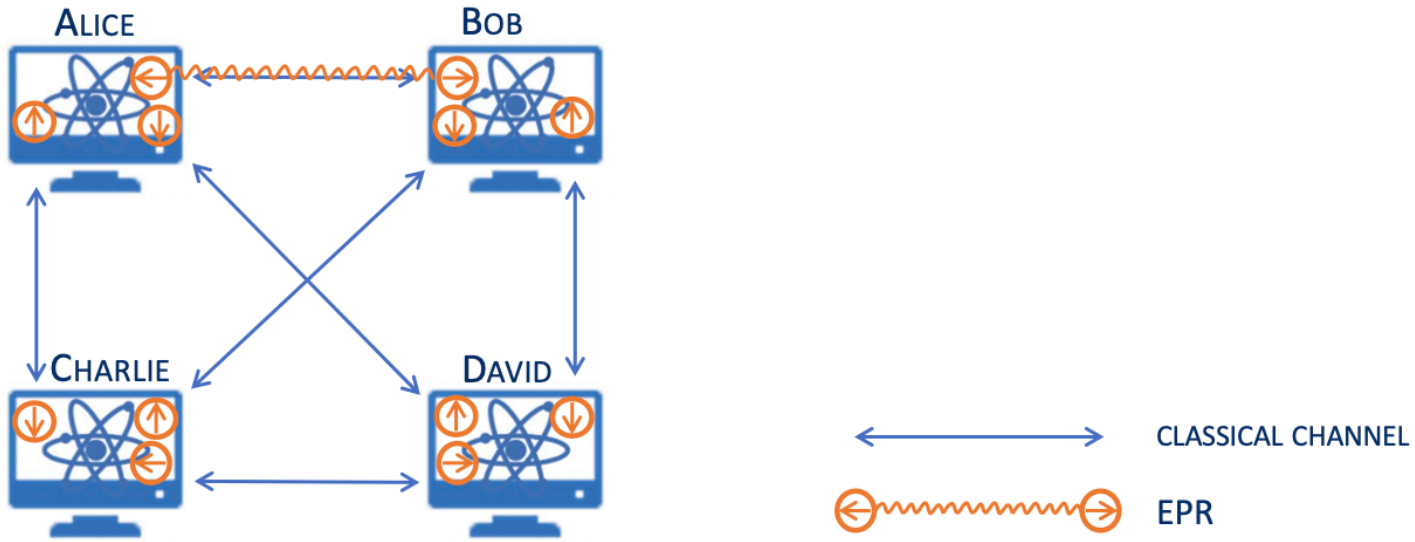
ON-DEMAND CONNECTIVITY



- ***"QUANTUM INTERNET PROTOCOL STACK: A COMPREHENSIVE SURVEY"***, COMPUTER NETWORKS, 2022

QUANTUM INTERNET: HOW?
BEYOND PHYSICAL CONNECTIVITY

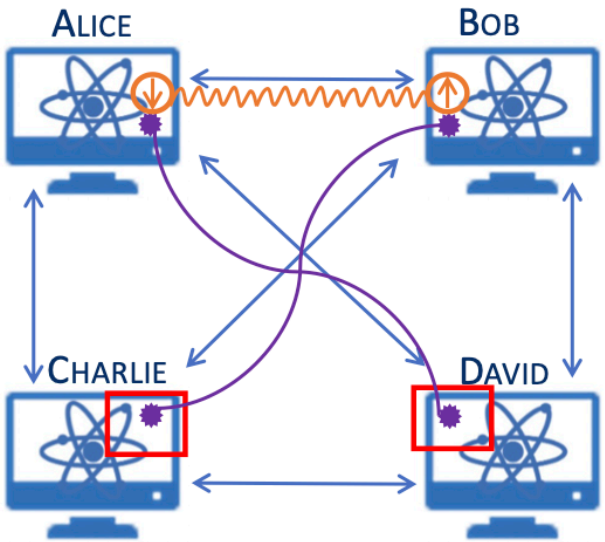
EPR CONNECTIVITY: NODE IDENTITIES FOR VIRTUAL LINK SELECTED A-PRIORI



- S. CHEN, J. ILLIANO, A.S. CACCIAPUOTI AND M. CALEFFI, "***SCALING QUANTUM NETWORKS: INTER-QLANS ARTIFICIAL CONNECTIVITY***", IEEE QCE, 2024.

QUANTUM INTERNET: HOW?
BEYOND PHYSICAL CONNECTIVITY

MULTIPARTITE ENTANGLEMENT: ON-DEMAND SELECTION OF NODE IDENTITIES FOR VIRTUAL LINK



- S. CHEN, J. ILLIANO, A.S. CACCIAPUOTI AND M. CALEFFI, "***SCALING QUANTUM NETWORKS: INTER-QLANS ARTIFICIAL CONNECTIVITY***", IEEE QCE, 2024.

University of Naples
Federico II

OUTLINE

1. INTRO
2. QUANTUM INTERNET UNCONVENTIONAL FEATURES
3. **ENGINEERING QUANTUM CONNECTIVITY**

ENTANGLEMENT GENERATION

TRANSDUCTION

ENTANGLEMENT DISTRIBUTION

WHEN TO STOP

QUANTUM MAC

ENTANGLEMENT UTILIZATION

CONNECTIVITY

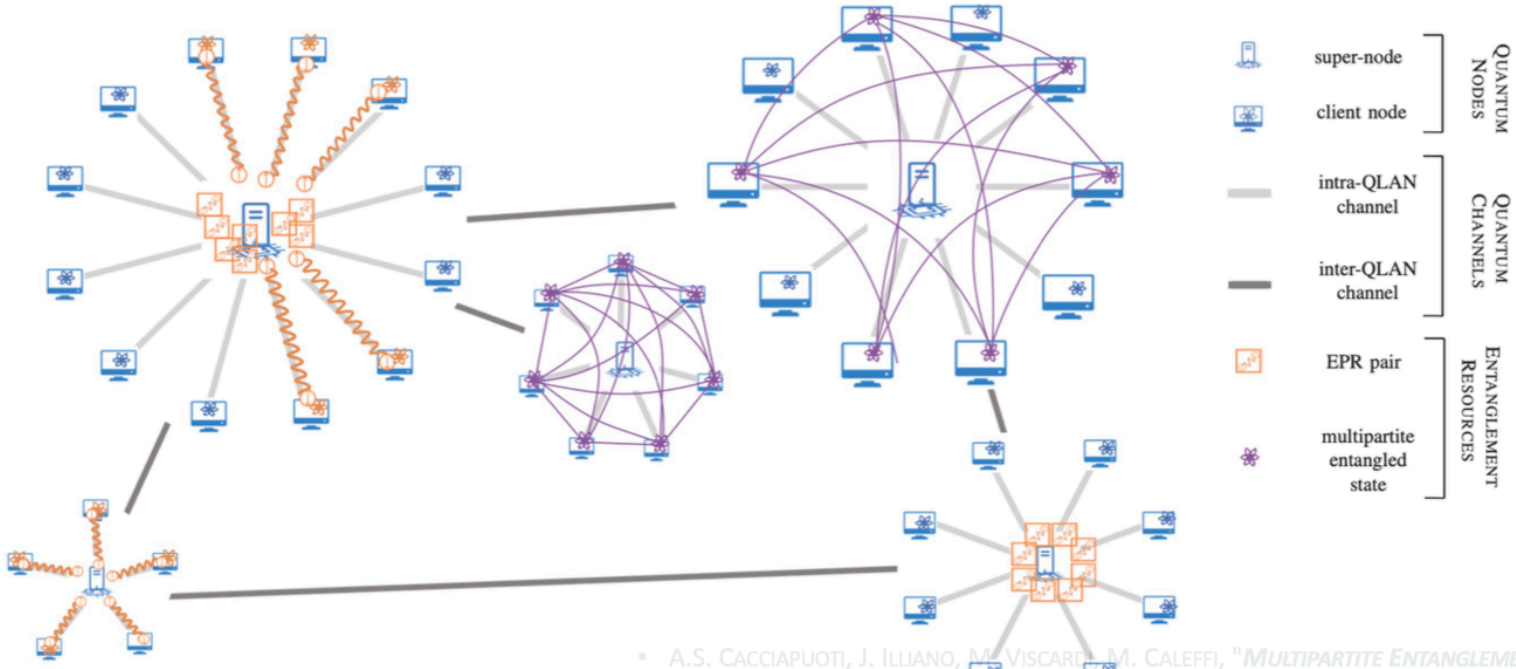
ADDRESSING

BEYOND SHANNON

ENGINEERING QUANTUM CONNECTIVITY

QUANTUM NETWORK ARCHITECTURE

INTERCONNECTION OF MULTIPLE QLANS



- A.S. CACCIAPUOTI, J. ILLIANO, M. VISCARDI, M. CALEFFI, "*MULTIPARTITE ENTANGLEMENT DISTRIBUTION IN THE QUANTUM INTERNET: KNOWING WHEN TO STOP!*", IEEE TRANS. ON NETWORK AND SERVICE MANAGEMENT, 2024.

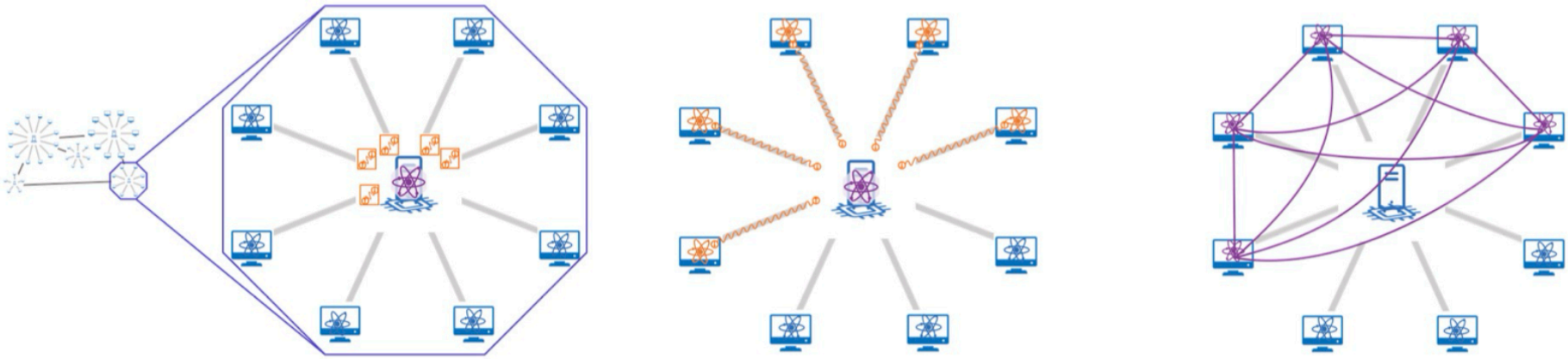
WITHIN A QLAN

• F. MAZZA, M. CALEFFI, A.S. CACCIAPUOTI, "***INTRA-QLAN CONNECTIVITY: BEYOND THE PHYSICAL TOPOLOGY***", ARXIV.2406.09963, 2024.

ENGINEERING CONNECTIVITY 1/2: INTRA-QLAN

QUANTUM NETWORK ARCHITECTURE

ZOOMING ON A SINGLE QLAN



(a) The super-node generates the EPR pairs (orange squares) and the multipartite entangled state (purple atom).

(b) The super-node distributes the EPR pairs to the targeted clients through the physical quantum channel (gray line).

(c) By exploiting the distributed EPR pairs, the multipartite entangled state is teleported to the targeted client nodes.

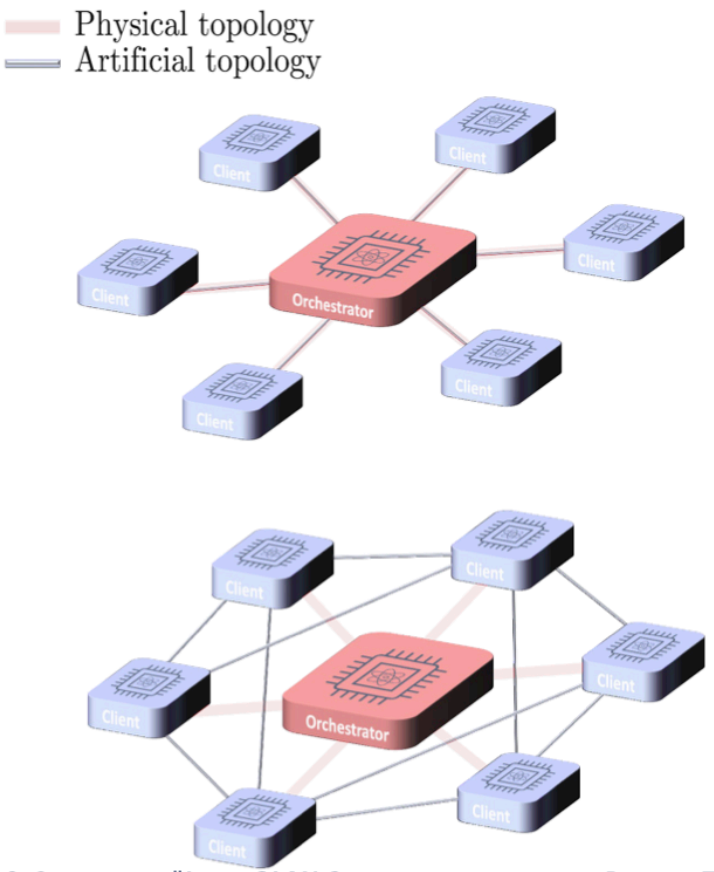
- A.S. CACCIAPUOTI, J. ILLIANO, M. VISCARDI, M. CALEFFI, "***MULTIPARTITE ENTANGLEMENT DISTRIBUTION IN THE QUANTUM INTERNET: KNOWING WHEN TO STOP!***", IEEE TRANS. ON NETWORK AND SERVICE MANAGEMENT, 2024.

University of Naples
Federico II

Engineering Connectivity 1/2: Intra-QLAN

Goals

- What
  - Design principles for quantum networks
    - covering limited geographic area
- How
  - Leveraging entanglement-based connectivity.
    - by defining a simple and feasible structure
  - to engineer artificial connectivity on-demand
- Why
  - Overcoming the limitations induced by physical topology.
  - Creation of on-demand entanglement-based links.
  - Lightweight clients.

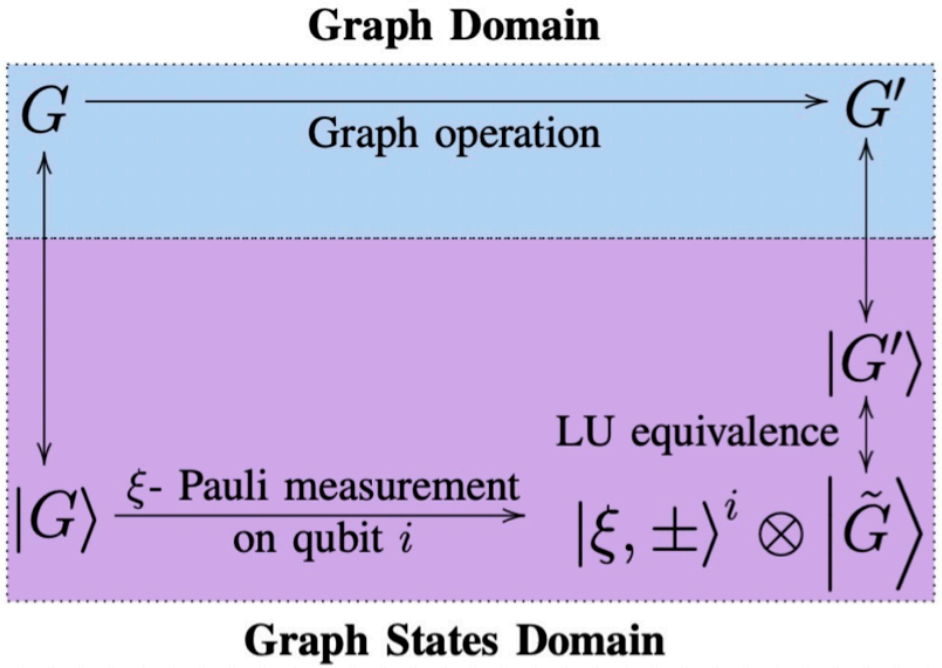


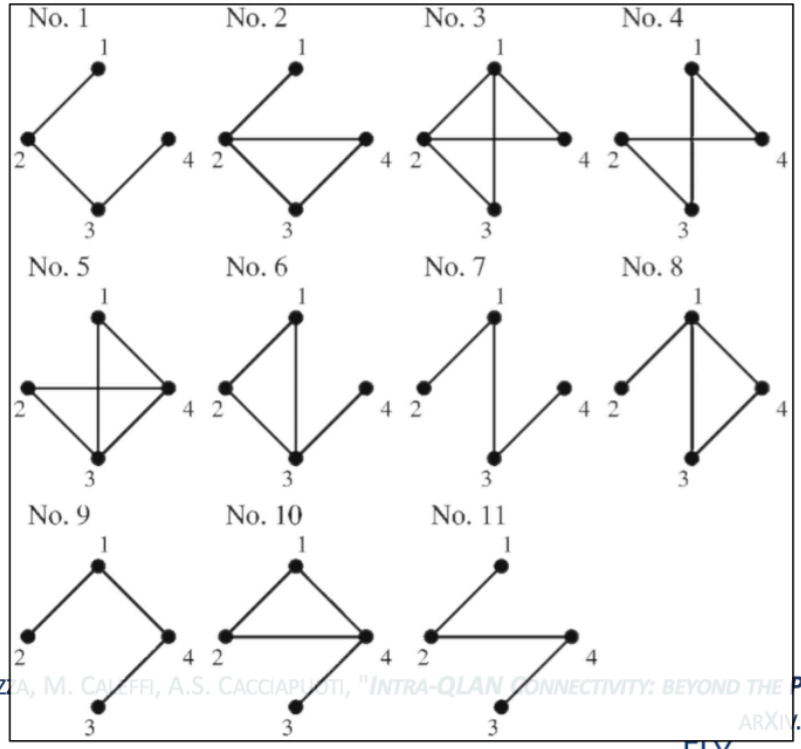
- F. Mazza, M. Caleffi, A.S. Cacciapuoti, "***Intra-QLAN Connectivity: beyond the Physical Topology***", arXiv.2406.09963, 2024.

ENGINEERING CONNECTIVITY 1/2: INTRA-QLAN

MULTIPARTITE RESOURCE

GRAPH STATES



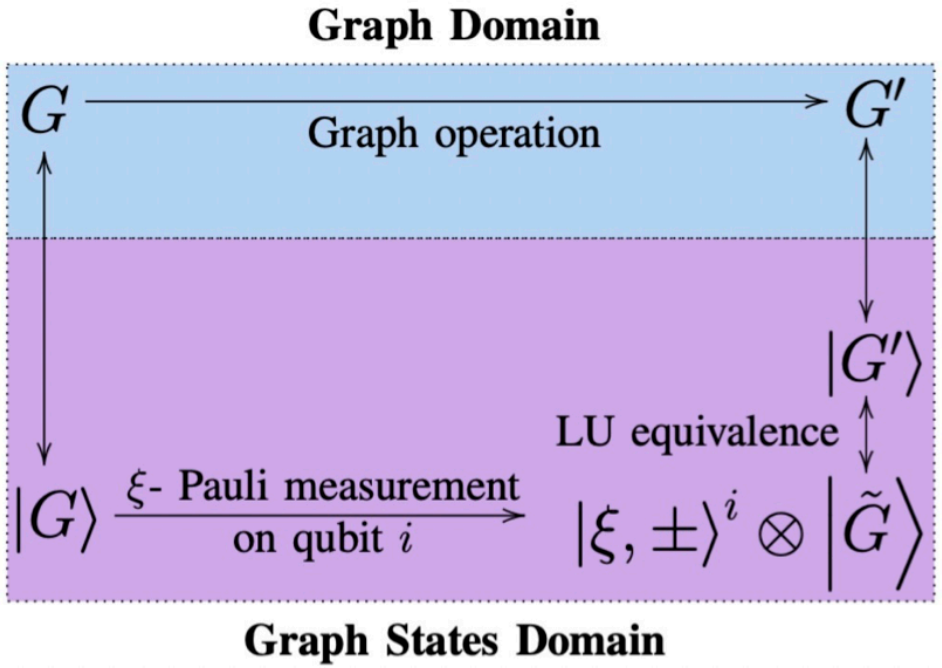


- F. MAZZA, M. CALEFFI, A.S. CACCIAPUOTI, "*INTRA-QLAN CONNECTIVITY: BEYOND THE PHYSICAL TOPOLOGY*", ARXIV:2406.09963, 2024.

ENGINEERING CONNECTIVITY 1/2: INTRA-QLAN

MULTIPARTITE RESOURCE

GRAPH STATES



CLASSICAL SIGNALING

- $|G\rangle \xrightarrow{\xi-Pauli\ measurement} |\xi,\pm\rangle^i \otimes |G'\rangle$

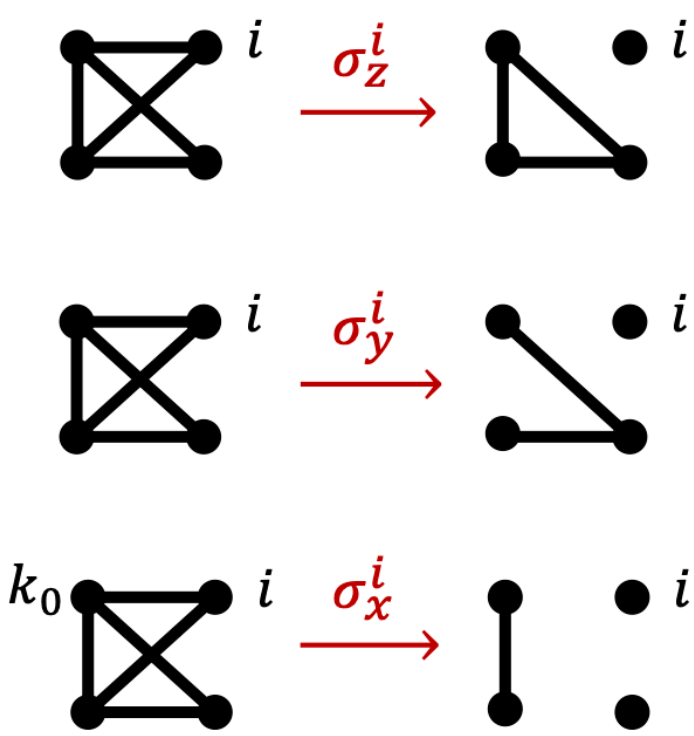
$$G' \equiv \begin{cases} G - i & if\ \sigma_\xi^i = \sigma_z \\ \tau_i(G) - i & if\ \sigma_\xi^i = \sigma_y \\ \tau_{k_0}\left(\tau_i\left(\tau_{k_0}(G)\right) - i\right) & if\ \sigma_\xi^i = \sigma_x. \end{cases}$$

- F. MAZZA, M. CALEFFI, A.S. CACCIAPUOTI, "*INTRA-QLAN CONNECTIVITY: BEYOND THE PHYSICAL TOPOLOGY*", ARXIV.2406.09963, 2024.

ENGINEERING CONNECTIVITY 1/2: INTRA-QLAN

MULTIPARTITE RESOURCE

GRAPH STATES



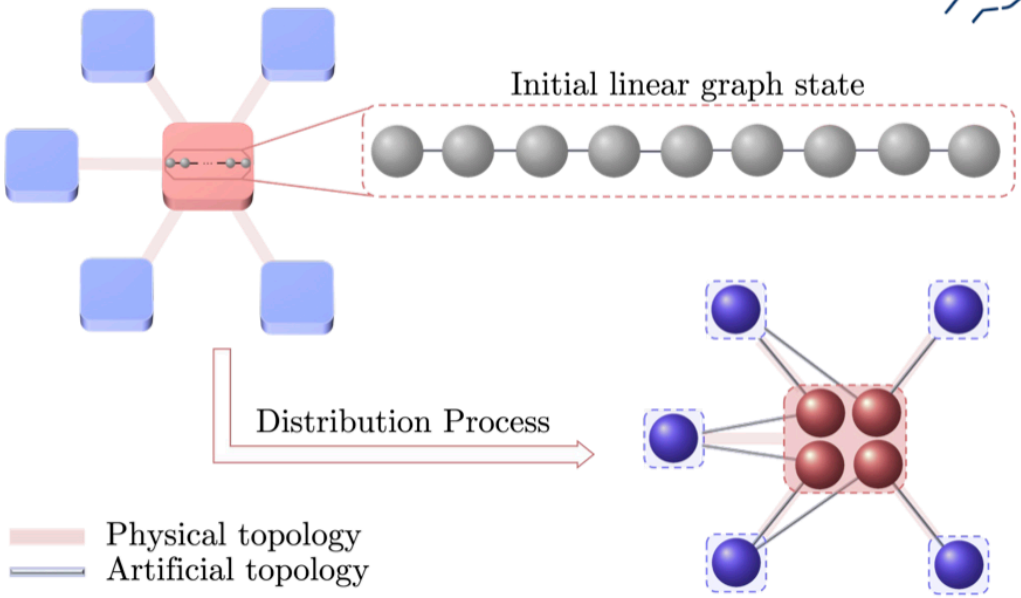
- $|G\rangle \xrightarrow{\xi-Pauli\ measurement} |\xi, \pm\rangle^i \otimes |G'\rangle$

$$G' \equiv \begin{cases} G - i & if\ \sigma_\xi^i = \sigma_z \\ \tau_i(G) - i & if\ \sigma_\xi^i = \sigma_y \\ \tau_{k_0}\left(\tau_i\left(\tau_{k_0}(G)\right) - i\right) & if\ \sigma_\xi^i = \sigma_x. \end{cases}$$

- F. MAZZA, M. CALEFFI, A.S. CACCIAPUOTI, "*INTRA-QLAN CONNECTIVITY: BEYOND THE PHYSICAL TOPOLOGY*", ARXIV.2406.09963, 2024.

Engineering Connectivity 1/2: Intra-QLAN

QLAN prototype for multipartite entanglement



Simple centalized physical topology: **orchestrator** node.

- It **generates** and **distributes** a multipartite entangled state.
- It is **physically connected** to all the clients.
- It implements the **network logic** through local Pauli measurements.

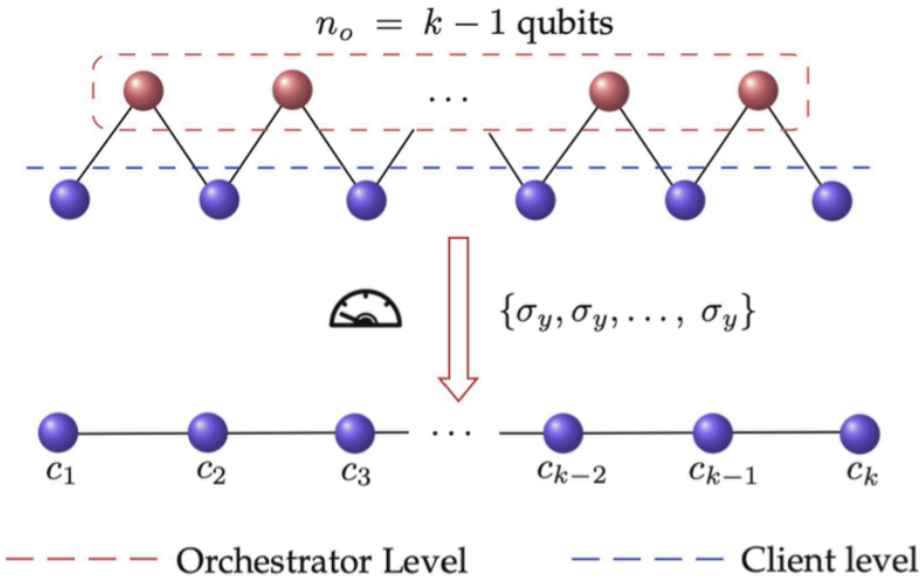
It imposes a hard constraint on the admissible **physical QLAN topology,** which is compelled to be a **star** topology.

- F. Mazza, M. Caleffi, A.S. Cacciapuoti, "***Intra-QLAN Connectivity: beyond the Physical Topology***", arXiv.2406.09963, 2024.

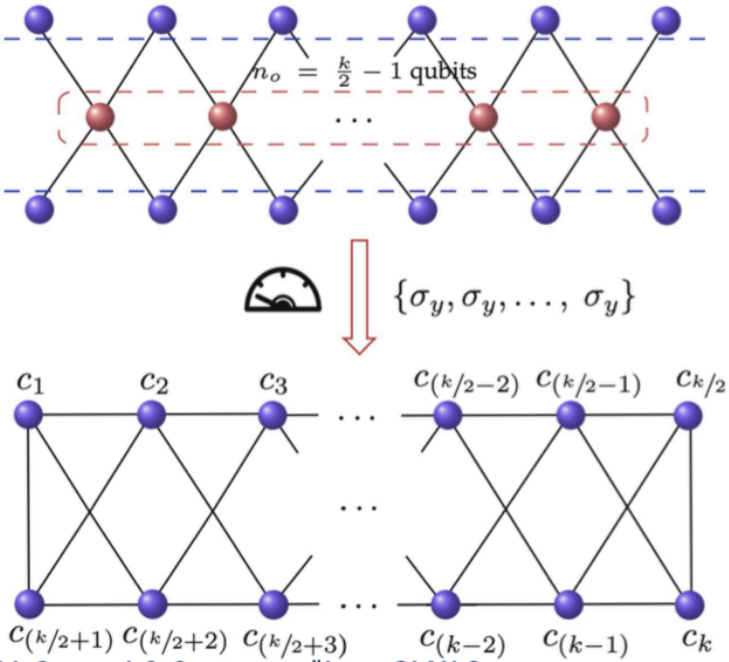
ENGINEERING CONNECTIVITY 1/2: INTRA-QLAN

RESULTS: ON-DEMAND TOPOLOGY ENGINEERING

FROM STAR TO BUS



FROM STAR TO RING

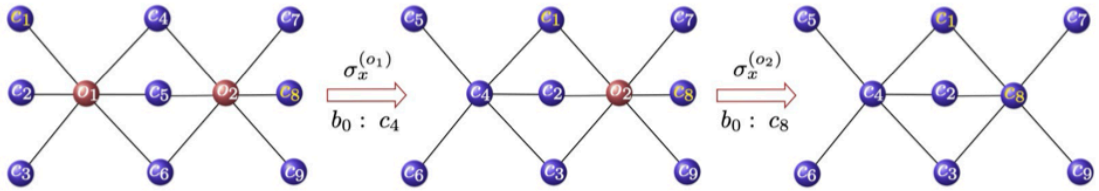


- F. MAZZA, M. CALEFFI, A.S. CACCIAPUOTI, "***INTRA-QLAN CONNECTIVITY: BEYOND THE PHYSICAL TOPOLOGY***", ARXIV.2406.09963, 2024.

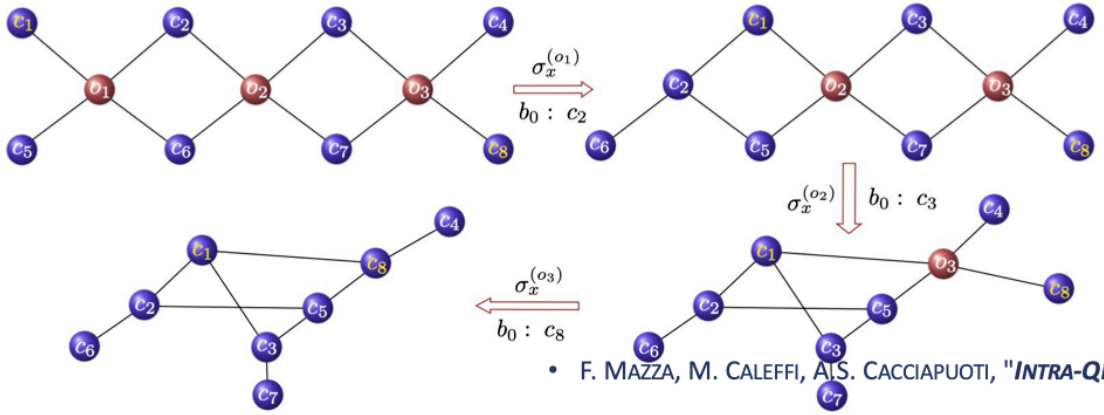
ENGINEERING CONNECTIVITY 1/2: INTRA-QLAN

RESULTS: ON-DEMAND TOPOLOGY ENGINEERING

MANIPULATING NODES PROXIMITY ON-DEMAND: ENTANGLEMENT ROLLING



(b) Example of entanglement rolling with generalized tree-like topology and $k_c = 6$, $n_o = 2$ and $\hat{k}_b = 3$. In this example, clients c_1 and c_8 have a proximity $d(c_1, c_8) = 2$.



- F. MAZZA, M. CALEFFI, A.S. CACCIAPUOTI, "*INTRA-QLAN CONNECTIVITY: BEYOND THE PHYSICAL TOPOLOGY*", ARXIV.2406.09963, 2024.

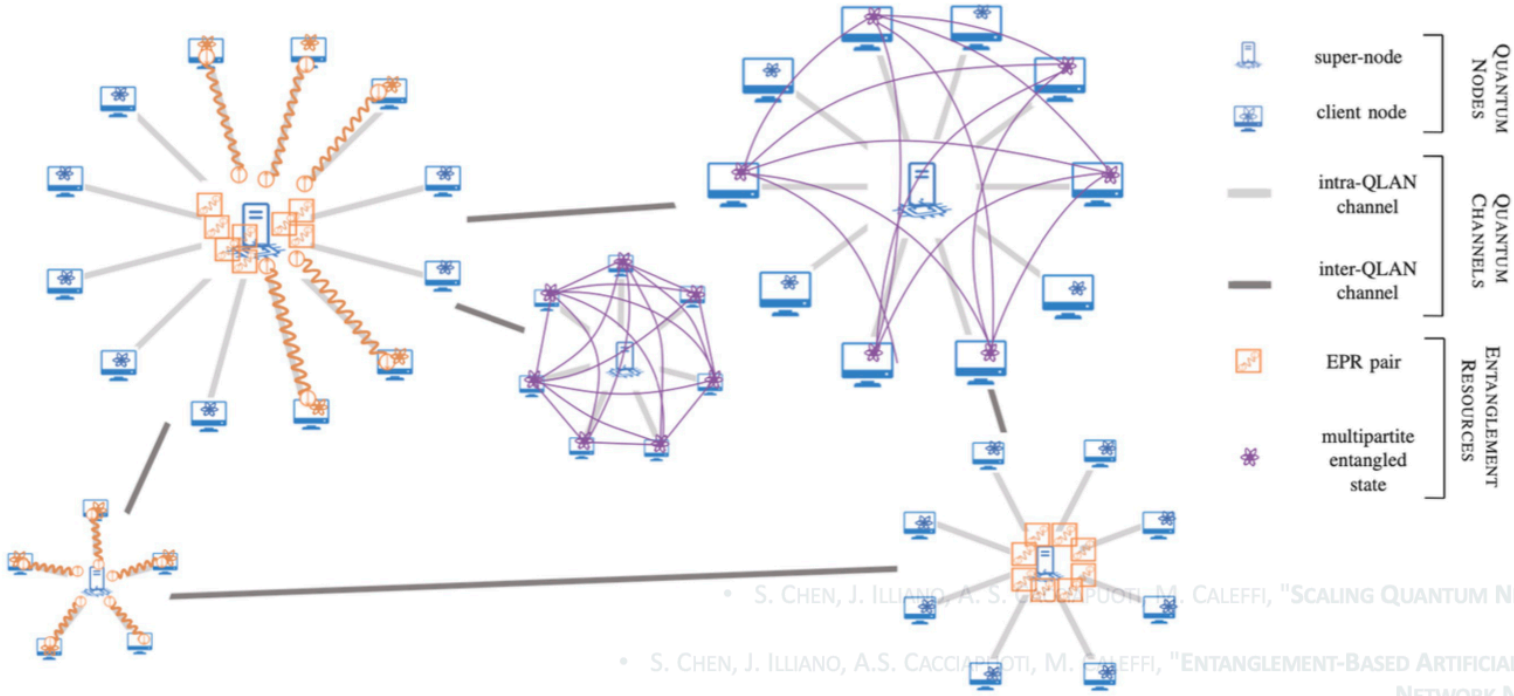
BETWEEN QLANS

- S. CHEN, J. ILLIANO, A. S. CACCIAPUOTI, M. CALEFFI, "**SCALING QUANTUM NETWORKS: INTER-QLANS ARTIFICIAL CONNECTIVITY**", IEEE QCE, 2024.
- S. CHEN, J. ILLIANO, A.S. CACCIAPUOTI, M. CALEFFI, "**ENTANGLEMENT-BASED ARTIFICIAL TOPOLOGY: NEIGHBORING REMOTE NETWORK NODES**", ARXIV.2404.16204, 2024.

Engineering Connectivity 2/2: Inter-QLAN

Goal

On-demand connectivity between nodes belonging to different QLANs



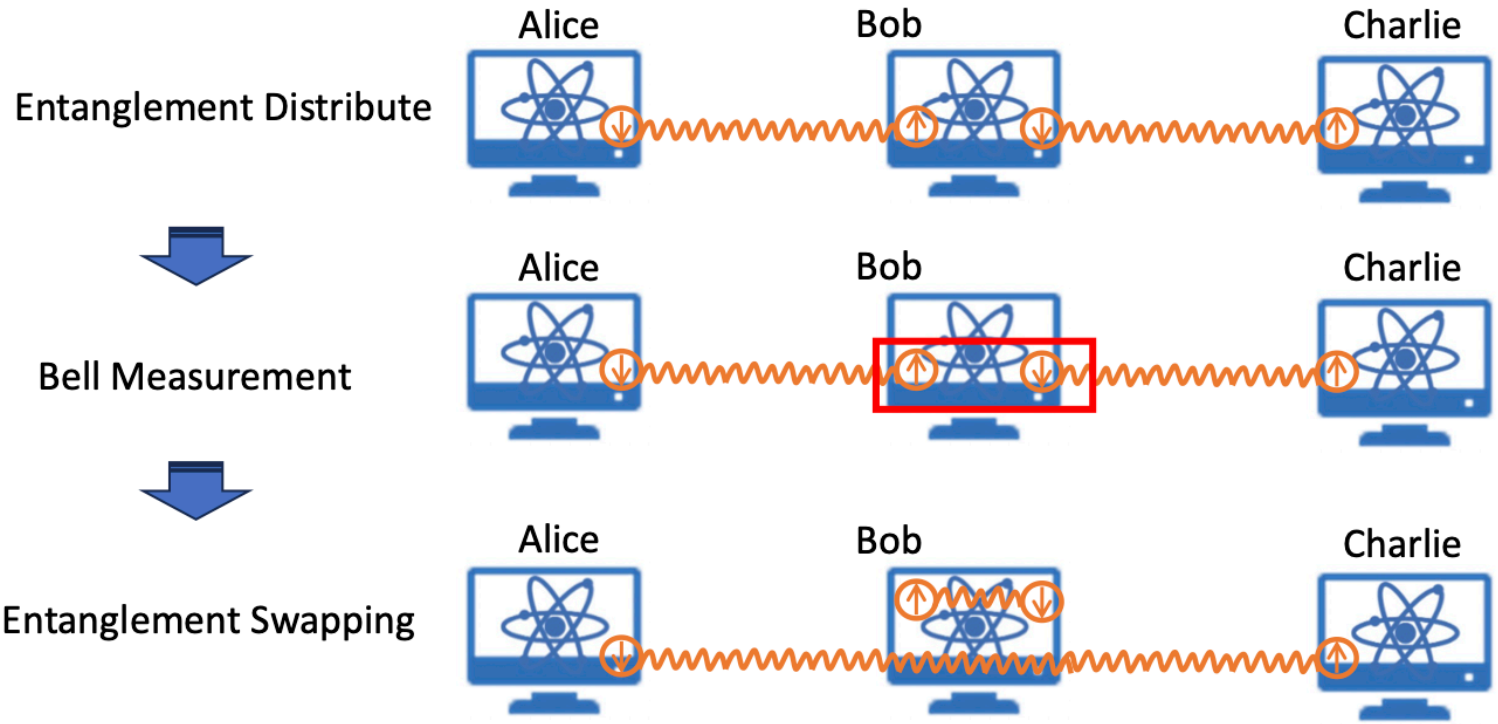
- S. Chen, J. Illiano, A.S. Cacciapuoti, M. Caleffi, "Scaling Quantum Networks: Inter-QLANs Artificial Connectivity", IEEE QCE, 2024.
- S. Chen, J. Illiano, A.S. Cacciapuoti, M. Caleffi, "Entanglement-Based Artificial Topology: Neighboring Remote Network Nodes", arXiv.2404.16204, 2024.

ENGINEERING CONNECTIVITY 2/2: INTER-QLAN

OLD-SCHOOL

Bipartite entanglement Bell measurement

SWAPPING AND PURIFICATION



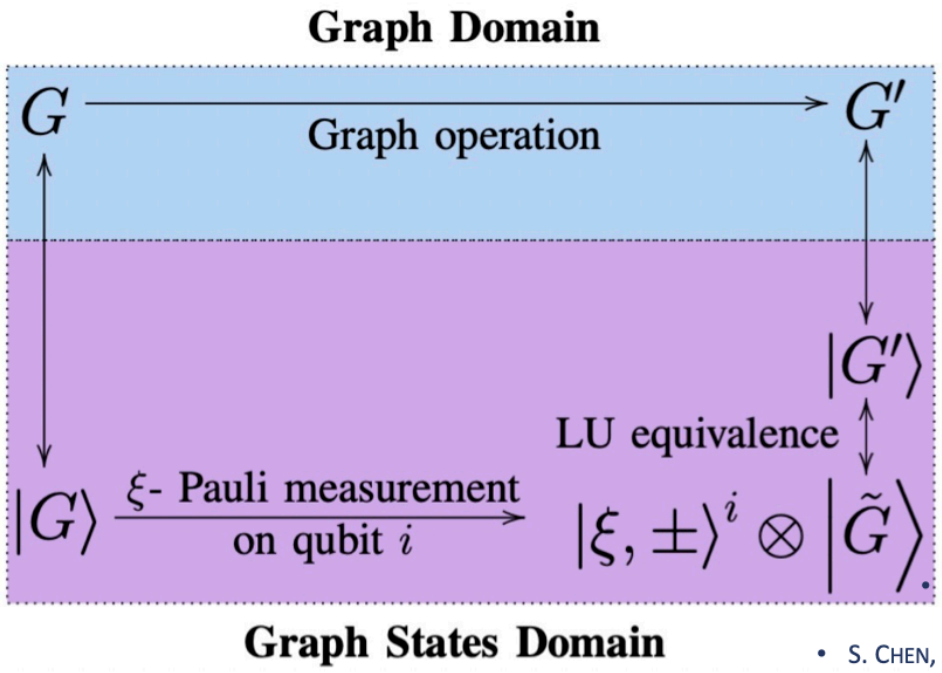
- M. CALEFFI, "OPTIMAL ROUTING FOR QUANTUM NETWORKS", IEEE ACCESS, VOL. 5, PP. 22299-22312, OCTOBER 2017.

ENGINEERING CONNECTIVITY 2/2: INTER-QLAN

OUR APPROACH

CLASSICAL SIGNALING

GRAPH STATES



- $|G\rangle \xrightarrow{\xi-Pauli\ measurement} |\xi,\pm\rangle^i \otimes |G'\rangle$

$$G' \equiv \begin{cases} G - i & if\ \sigma_\xi^i = \sigma_z \\ \tau_i(G) - i & if\ \sigma_\xi^i = \sigma_y \\ \tau_{k_0}\left(\tau_i\left(\tau_{k_0}(G)\right) - i\right) & if\ \sigma_\xi^i = \sigma_x. \end{cases}$$

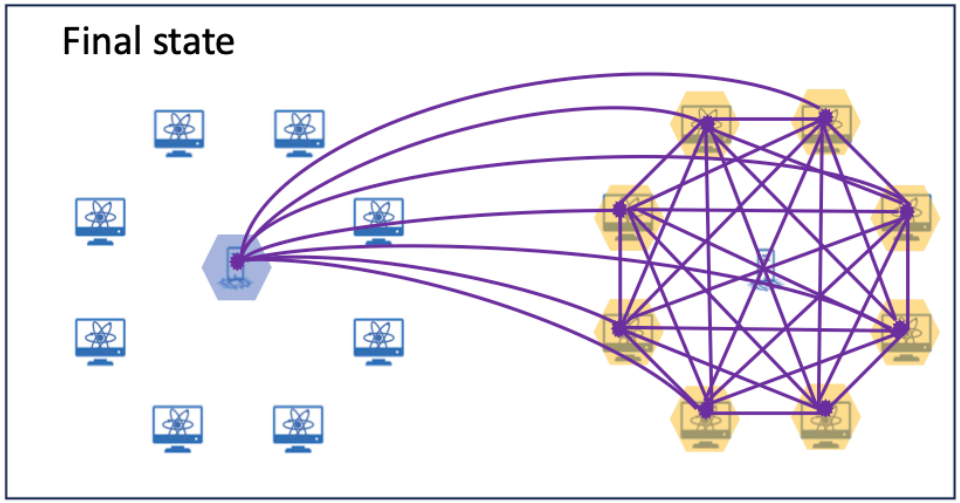
S. CHEN, J. ILLIANO, A. S. CACCIAPUOTI, M. CALEFFI, "SCALING QUANTUM NETWORKS: INTER-QLANS ARTIFICIAL CONNECTIVITY", IEEE QCE, 2024.

- S. CHEN, J. ILLIANO, A.S. CACCIAPUOTI, M. CALEFFI, "ENTANGLEMENT-BASED ARTIFICIAL TOPOLOGY: NEIGHBORING REMOTE NETWORK NODES", ARXIV.2404.16204, 2024.

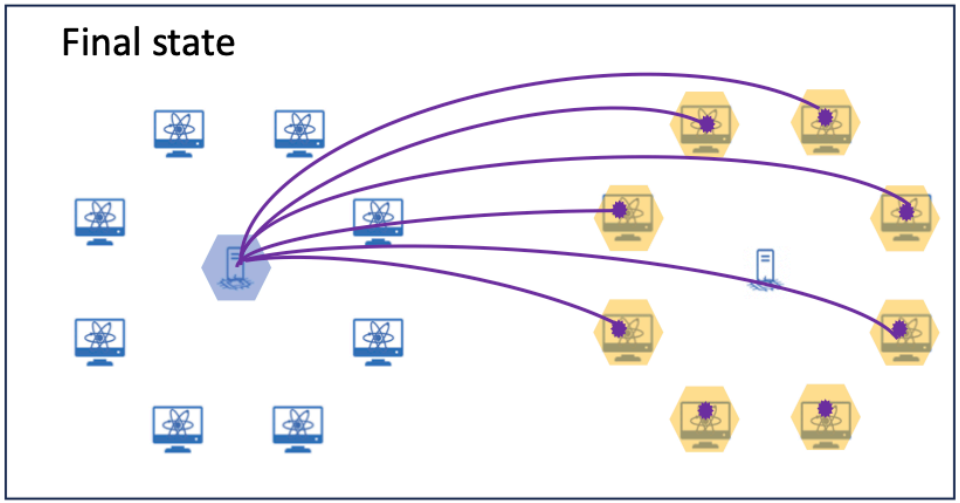
ENGINEERING CONNECTIVITY 2/2: INTER-QLAN

COMMUNICATION ARCHETYPES

HIERARCHICAL PEER-TO-PEER



CLIENT HAND-OVER

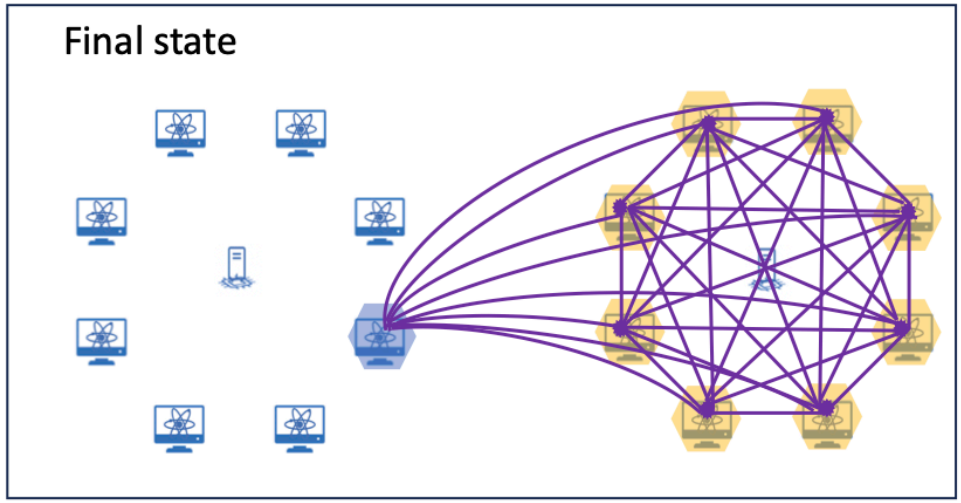


- S. CHEN, J. ILLIANO, A. S. CACCIAPUOTI, M. CALEFFI, "**SCALING QUANTUM NETWORKS: INTER-QLANS ARTIFICIAL CONNECTIVITY**", IEEE QCE, 2024.
- S. CHEN, J. ILLIANO, A.S. CACCIAPUOTI, M. CALEFFI, "**ENTANGLEMENT-BASED ARTIFICIAL TOPOLOGY: NEIGHBORING REMOTE NETWORK NODES**", ARXIV.2404.16204, 2024.

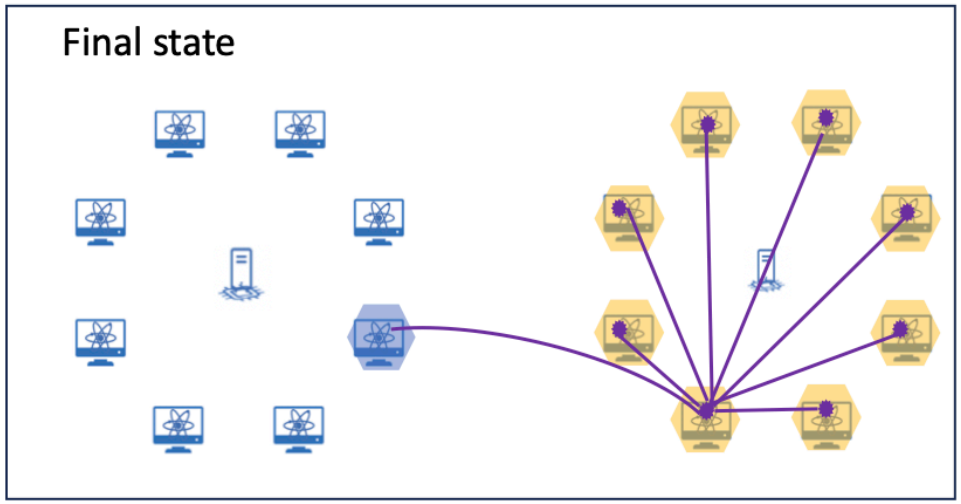
ENGINEERING CONNECTIVITY 2/2: INTER-QLAN

COMMUNICATION ARCHETYPES

GENUINE PEER-TO-PEER



ROLE DELEGATION



- S. CHEN, J. ILLIANO, A. S. CACCIAPUOTI, M. CALEFFI, "**SCALING QUANTUM NETWORKS: INTER-QLANS ARTIFICIAL CONNECTIVITY**", IEEE QCE, 2024.
- S. CHEN, J. ILLIANO, A.S. CACCIAPUOTI, M. CALEFFI, "**ENTANGLEMENT-BASED ARTIFICIAL TOPOLOGY: NEIGHBORING REMOTE NETWORK NODES**", ARXIV.2404.16204, 2024.

CONCLUDING

Engineering Connectivity

Concluding

- Entanglement enables an artificial network topology
  - That can be manipulated on-demand
  - Simply, by measuring qubits
  - Without further quantum resources
    - I.e., LOCC
- Neighborhood is up to you

Open Issues

- Classical communications
  - Is really an issue?
- Trade-off initial resources vs final connectivity
  - What's the best entangled state to start with?
- Physical vs artificial connectivity
  - Impact on network design

University of Naples
Federico II

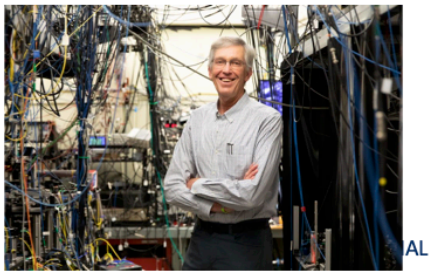
HOW DEEP IS THE ~~RABBIT~~ QUANTUM HOLE?

CONCLUDING

- WE JUST STARTED SCRATCHING THE SURFACE OF QUANTUM NETWORKING

"... IF YOU WANT TO BE ON THE CUSP OF THE FUTURE, YOU HAVE TO BE WILLING TO FAIL ... YOU BETTER BELIEVE IT'S SCARY. BUT IT'S AN EXHILARATING INTELLECTUAL ADVENTURE ... SO IF YOU KNOW WHAT YOU'RE DOING, DON'T DO IT!"

JEFF KIMBLE (1949, 2024)



- Images: flaticon.com, lewiscarroll.org

THANKS FOR YOUR ATTENTION

Questions or comments?