ICETC
International Conference on Emerging Technologies for Communications
Kitakyushu, Japan, Nov 25-27, 2024

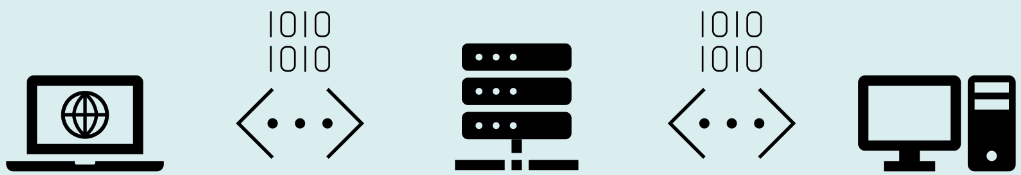
Quantum Internet

Winston Seah
School of Engineering and Computer Science

1897
VICTORIA UNIVERSITY OF
WELLINGTON
TE HERENGA WAKA

Classical Computing & Networking

- Classical computers
  - Store information in bits, either “0” or “1”
  - Deterministic & measurements do not change state
  - Two bits – 00, 01, 10 and 11
- Classical networks



Building Block of the Internet

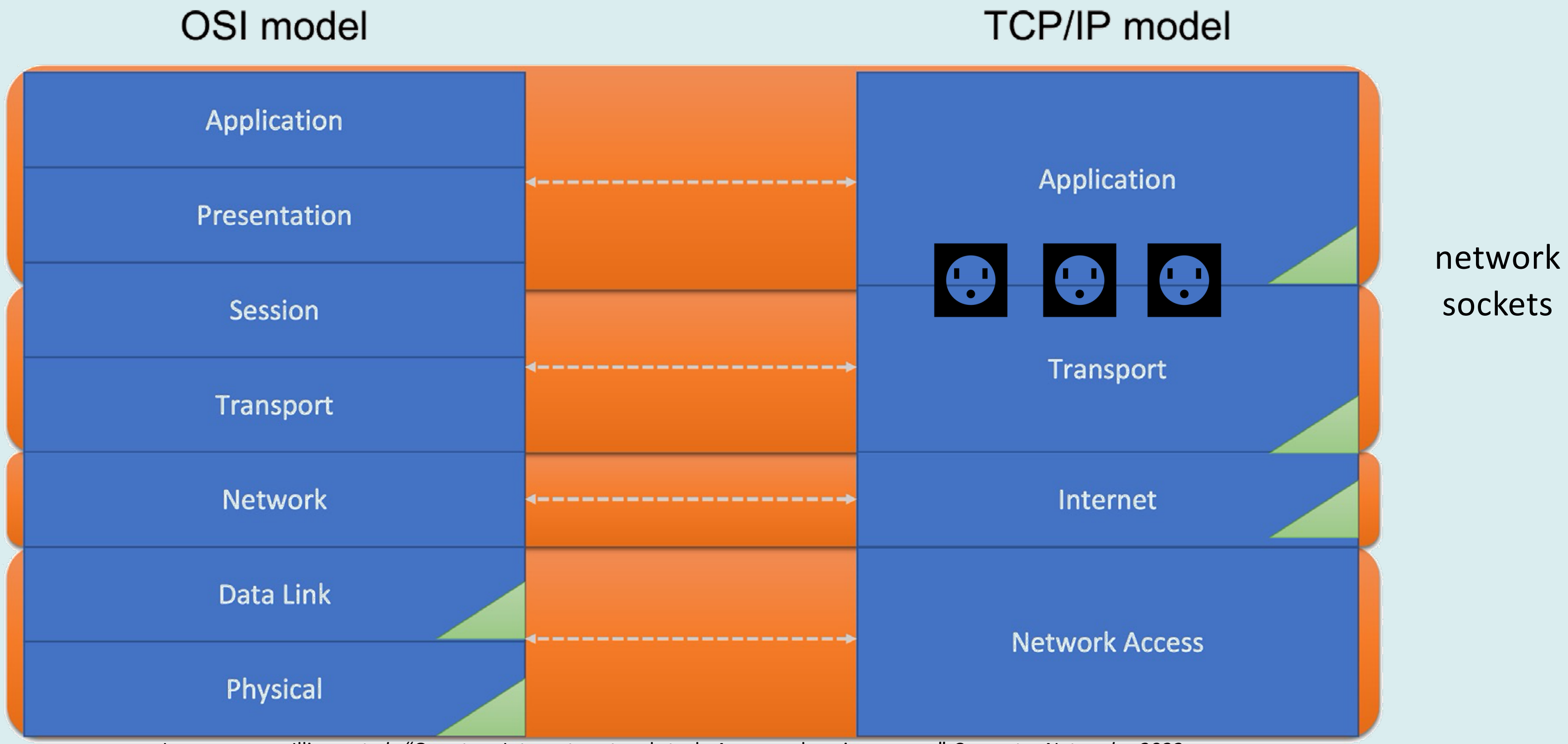


Image source: Illiano *et al.*, “Quantum Internet protocol stack: A comprehensive survey,” *Computer Networks, 2022.*

Emerging Networking Technologies

- 2000
  - Multipath virtual sink architecture for underwater sensor networks and underwater drones
  - Wireless sensor networks powered by ambient energy harvesting
- 2010 – nanoscale networks
  - Pulse arrival scheduling for nanonetworks under limited IoT access bandwidth (LCN 2017 best paper award)
- 2020 – quantum networks …

Emerging Networking Technologies

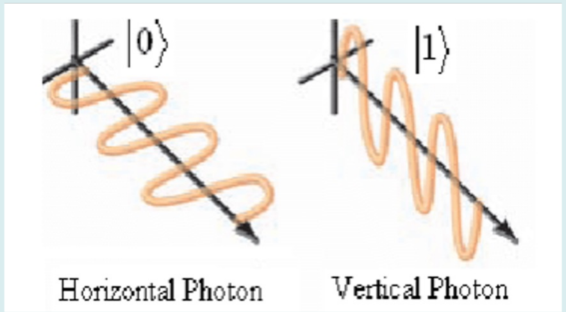
Unique features of underlying physical network:

- Underwater networks - Acoustic communications
  - Long delay, very high error rates,
- Energy-harvesting powered networks
  - Unpredictable energy supply
  - Challenges established theory – unslotted multiple access better than slotted multiple access
- Nanoscale networks
  - Pulse communication and severe resource constraints

Quantum Basics

Quantum bits, **qubits** – superposition of “0” or “1”

- State of A, one-qubit system
  $|A\rangle = a_0|0\rangle + a_1|1\rangle$ where $a_0, a_1 \in \mathbb{C}$
  a_0, a_1 – probability amplitudes to measure “0” or “1”



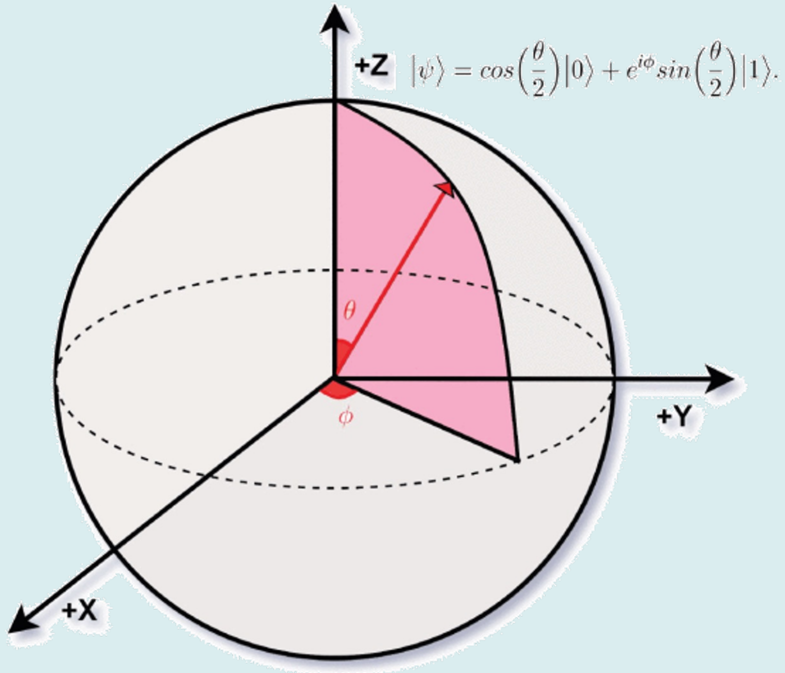
- Probability of measuring $|0\rangle$ is $|a_0|^2$ and $|1\rangle$ is $|a_1|^2$, and $|a_0|^2 + |a_1|^2 = 1$

Quantum Basics

Quantum bits, **qubits** – superposition of “0” or “1”

- Two qubit example
  $|A\rangle = a_{00}|00\rangle + a_{01}|01\rangle + a_{10}|10\rangle + a_{11}|11\rangle$
  where $|a_{00}|^2 + |a_{01}|^2 + |a_{10}|^2 + |a_{11}|^2 = 1$
- n classical bits are only ever in ONE of the 2^n possible states at any given moment, an n-qubit register can be in a superposition of ALL of the possible states.

Quantum Basics



How to make qubits?

- Non-solid state
  - Photons
  - Trapped ions
- Solid state
  - Superconductors
  - Nitrogen-Vacancy-Centres or NV-Centres in diamond
  - Semiconductor Quantum Dots
    - quantum dot → single electron transistor, very similar to classical field effect transistor

Quantum Basics

Quantum measurement

- Measuring/reading a classical bit "0" or "1" is easy and *repeatable*.
- Measuring/reading a qubit's state, "0" or "1" is also possible, BUT it is an *irreversible operation*
- "Reading" a qubit will "destroy" it.
- Cannot read a qubit more than once!

Quantum Basics

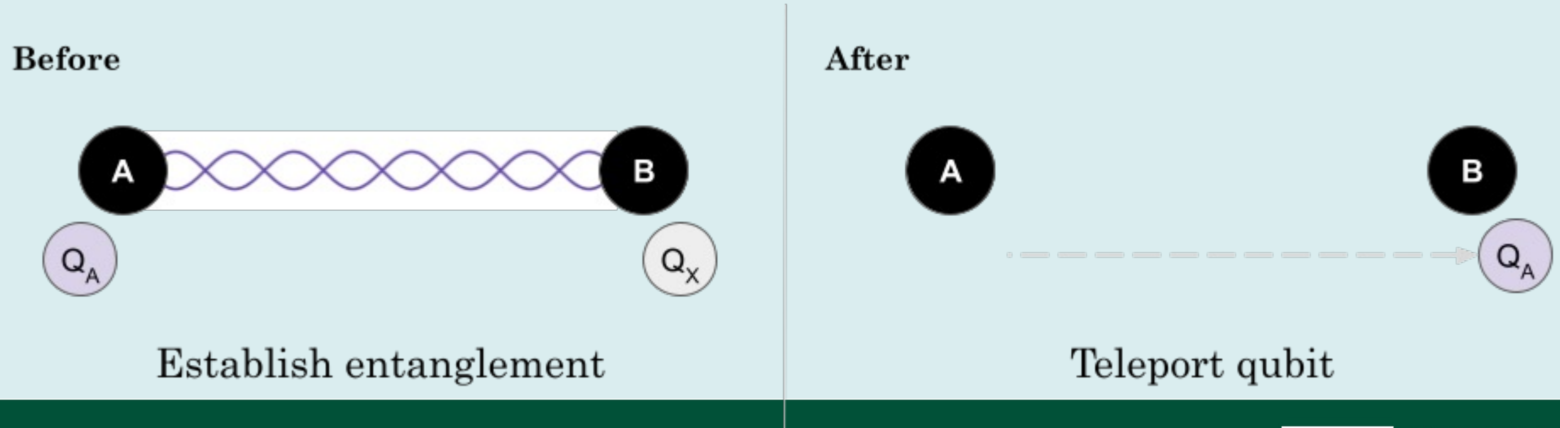
No-cloning theorem

- Qubit can be directly transmitted to a remote node via an optical fiber link or free space optical
- But, if photon is lost due to attenuation or it is corrupted by noise,
  - it cannot be recovered by some form of measurement or by re-transmitting a copy of the original information.
  - classical communication / networking approaches are NOT applicable!!!

Quantum Basics

Entanglement

- links qubits together such that the state of one instantly affects the other – no matter the distance.
- reliable way to transport a qubit from point-to-point.



Quantum Basics

Entanglement analogy

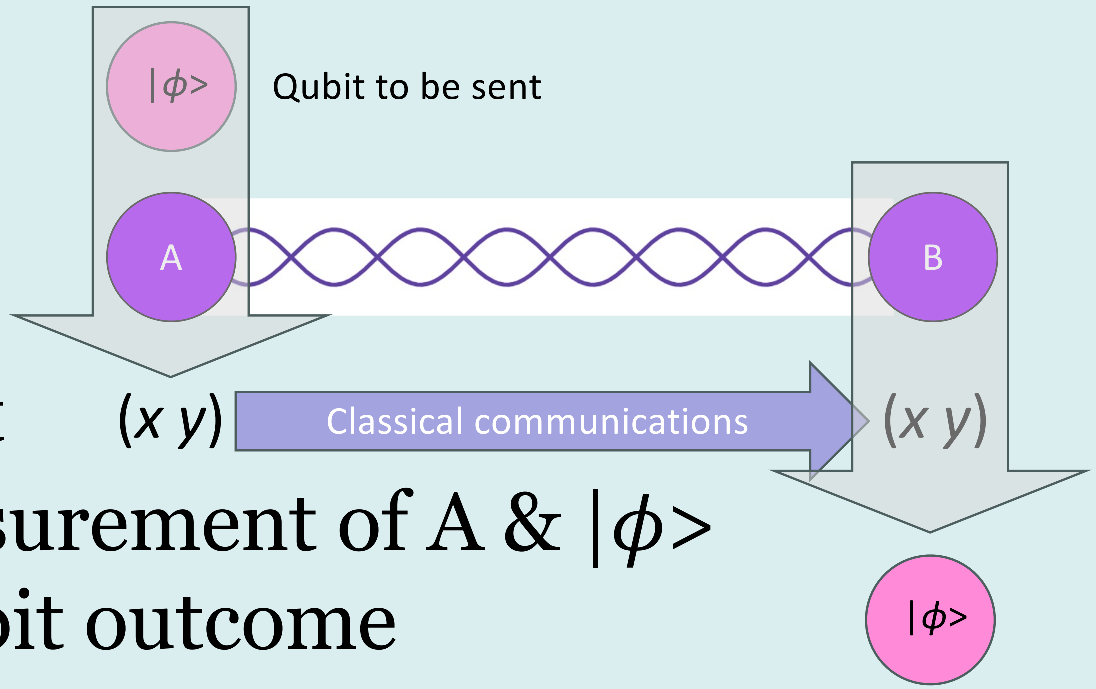
- Imagine a Mystery Kit Kat (plain packaging)
  - Two flavours of chocolate = DARK, WHITE
  - Break in half without revealing contents
  - Give on half to Alice and other half to Bob

Quantum Basics

Teleportation

- Suppose two qubits A and B are “entangled”
- If A is measured, then B will immediately have the same state as A
- No matter how far apart A and B are !!!
- How to transmit information?

Quantum Basics



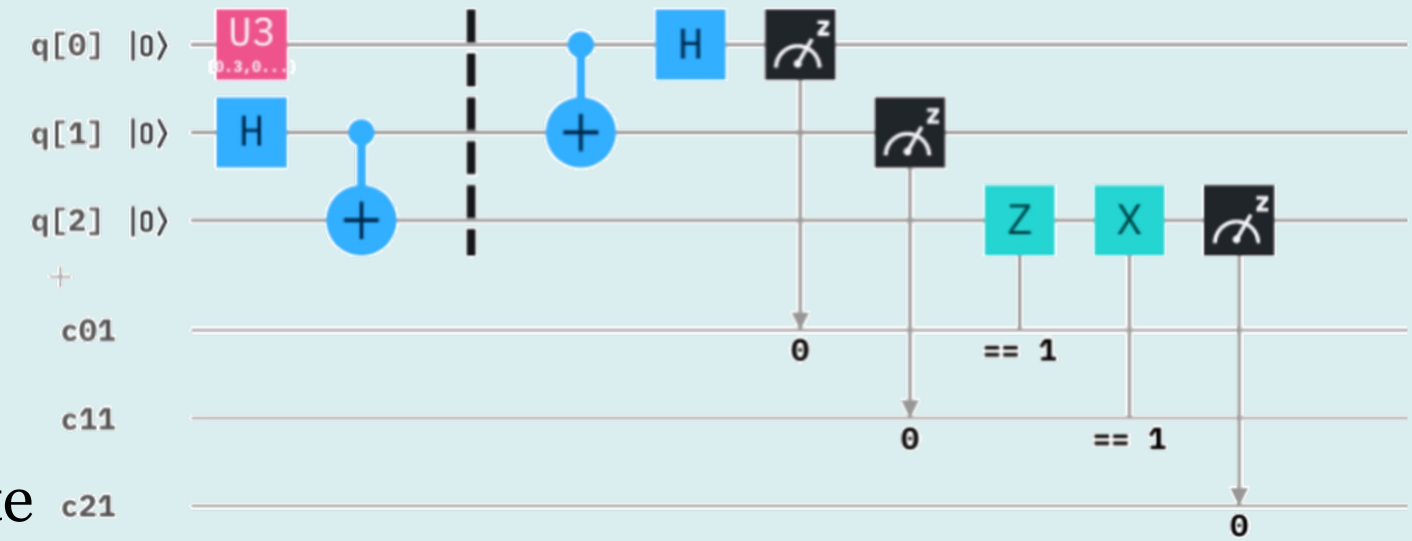
Teleportation

- Create entanglement
- Perform a joint measurement of A & |ϕ> giving a classical 2-bit outcome
- Send 2-bit outcome to B
- Measure B, then depending on the 2-bit value, B applies one of 4 *actions* to obtain |ϕ>

Quantum Basics

Teleportation

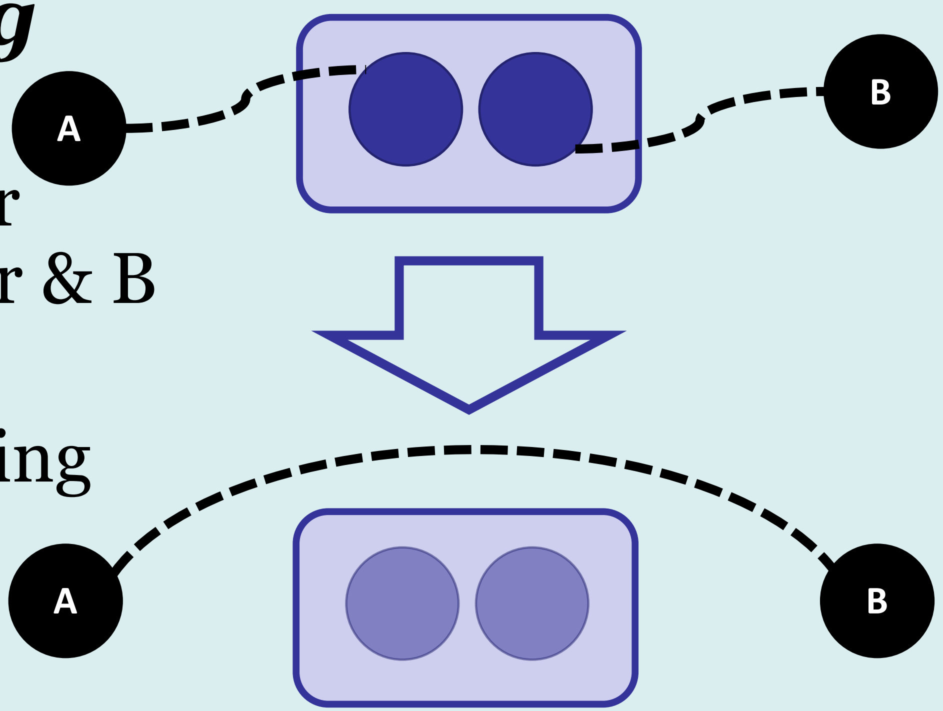
1. Measure B.
2. If (x y) =
    00 – do nothing
    01 – apply X gate
    10 – apply Z gate
    11 – apply ZX gate



Quantum Basics

Entanglement swapping

- Generate entanglements between qubits in A & repeater and between qubits in repeater & B
- Entanglement swap between qubits in repeater → two existing pairs of entanglement destroyed but new entanglement created



Quantum Internet

- *Global network interconnecting heterogeneous quantum networks, able to transmit qubits and to generate and distribute entangled states*
- Sits side-by-side with classical internet
- Supports distributed quantum application protocols with highest fidelity & efficiency

Quantum Internet

- Application classes as defined by Quantum Internet Research Group (QIRG) of Internet Engineering Task Force (IETF) :
  - quantum cryptography – quantum key distribution, fast Byzantine negotiation (consensus/mining in blockchains), quantum money (suggested in 1970s)
  - quantum sensing – network clock synchronization, extending baseline of telescopes
  - quantum computing – distributed quantum computing, secure with privacy preservation

Internet Protocol Stack

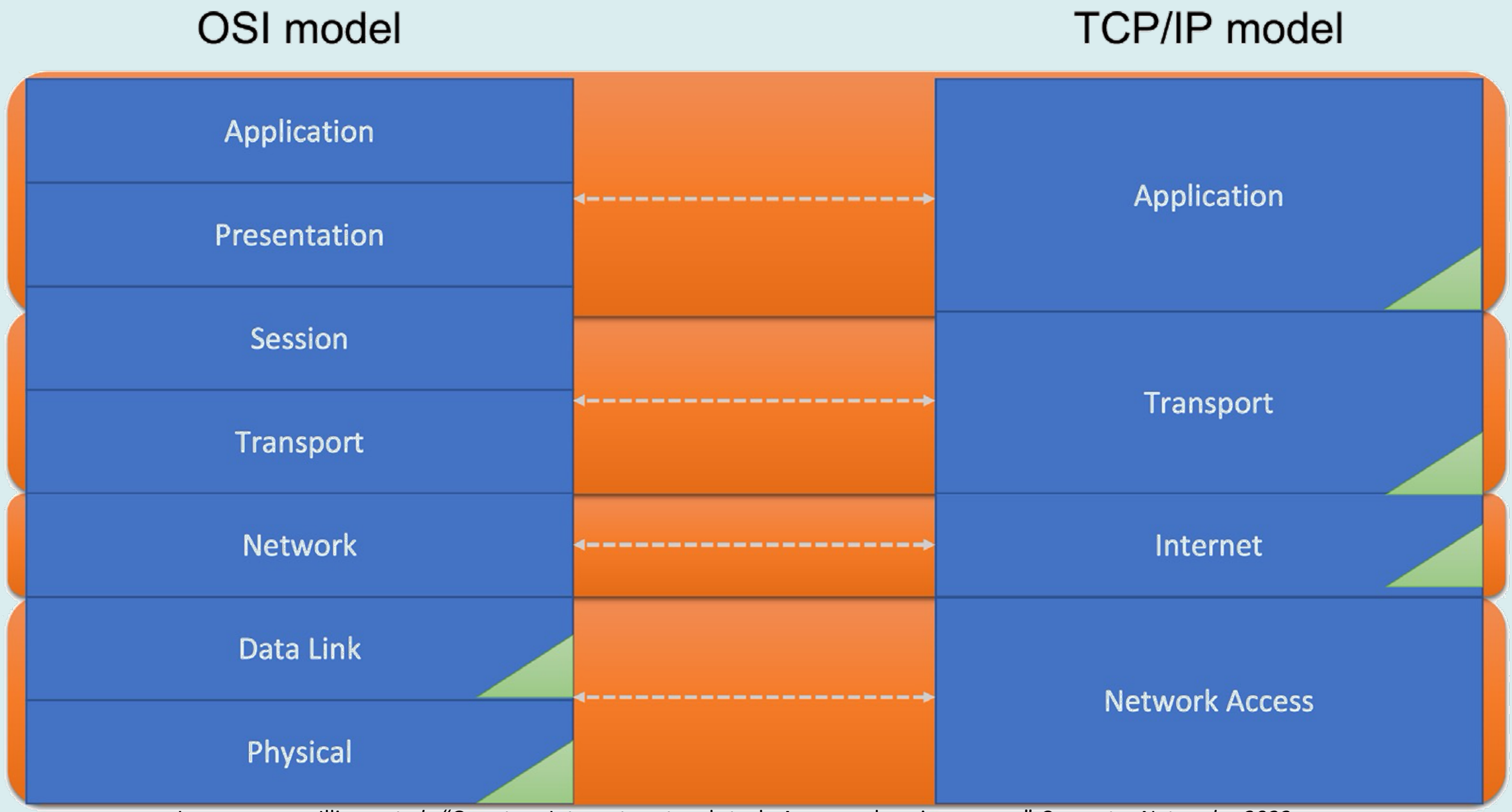


Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Quantum Internet Protocol Stack

"by simply replacing or extending some classical protocols to their quantum counterpart, without any global modification of the overall protocol stack. Unfortunately, this approach is doomed to fail…"

– Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks*, 2022.

Quantum Internet Protocol Stacks

Proposals:

- Van Meter *et al.*
- Wehner *et al.*
- others

Quantum Stack by Van Meter *et al.*

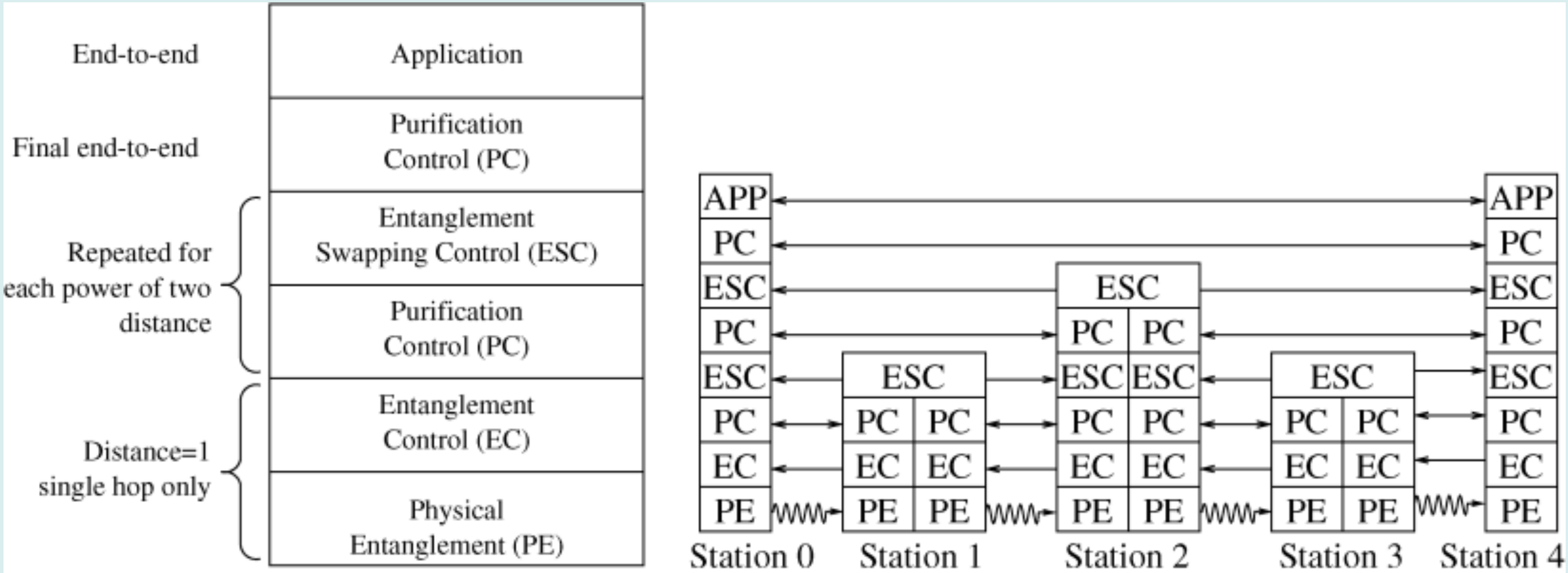


Image source: Van Meter *et al.*, “System Design for a Long-Line Quantum Repeater,” *IEEE Trans on Networking*, 2009.

Quantum Stack by Van Meter *et al.*

Quantum Recursive Network Architecture

- Proposed in 2011
- Recursive executions of PC/ESC
  → *single individual link represented by a high-fidelity entanglement shared between source and destination nodes*

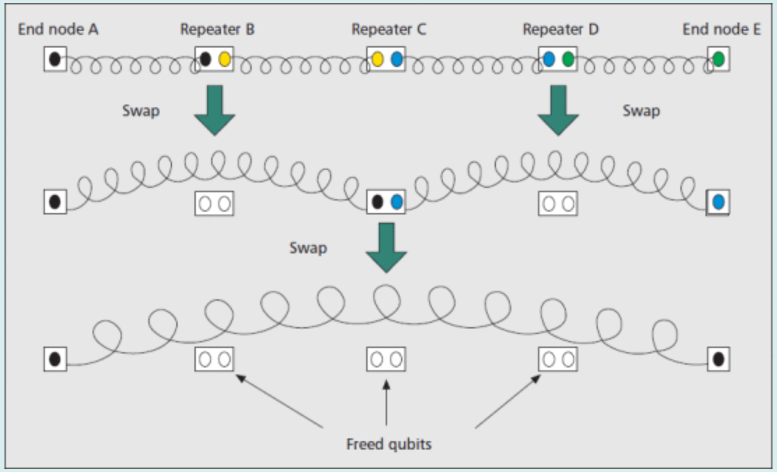


Image source: Van Meter *et al*. "Designing quantum repeater networks," *IEEE Communications Magazine*, 2013.

- Like *network of networks* → the Internet

Quantum Stack by Van Meter *et al.*

- Entanglement distribution among quantum nodes requires *virtual/physical network topology* and *coordination among nodes*
- In 2019, proposed a *bootstrap protocol* for:
  - supporting coordinated autonomous decision-making in quantum operations over a network
  - quantifying achievable fidelity, accounting for classical control messages

Quantum Internet Protocol Stacks

Proposals:

- Van Meter *et al.*
- Wehner *et al.*
- others

Quantum Stack by Wehner *et al.*

- Layered model for quantum networks, based on *bipartite entanglement*
- Physical and link layer functionalities and protocols
- For NV centres in diamond
- later revised to be underlying platform independent

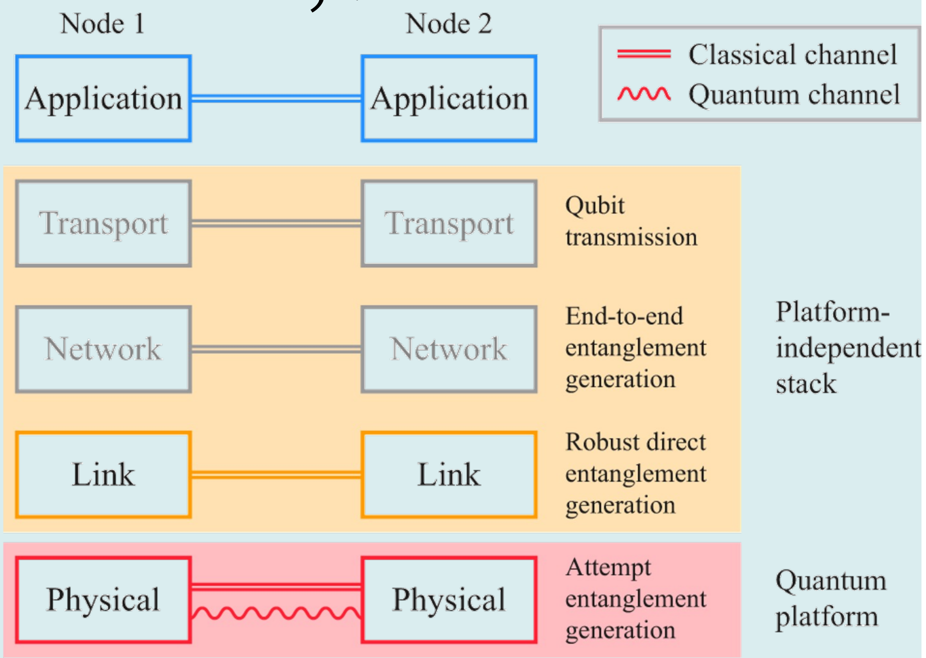


Image source: Pompili *et al.*, *npj Quantum Inf* , 2022.

Quantum Stack by Wehner *et al.*

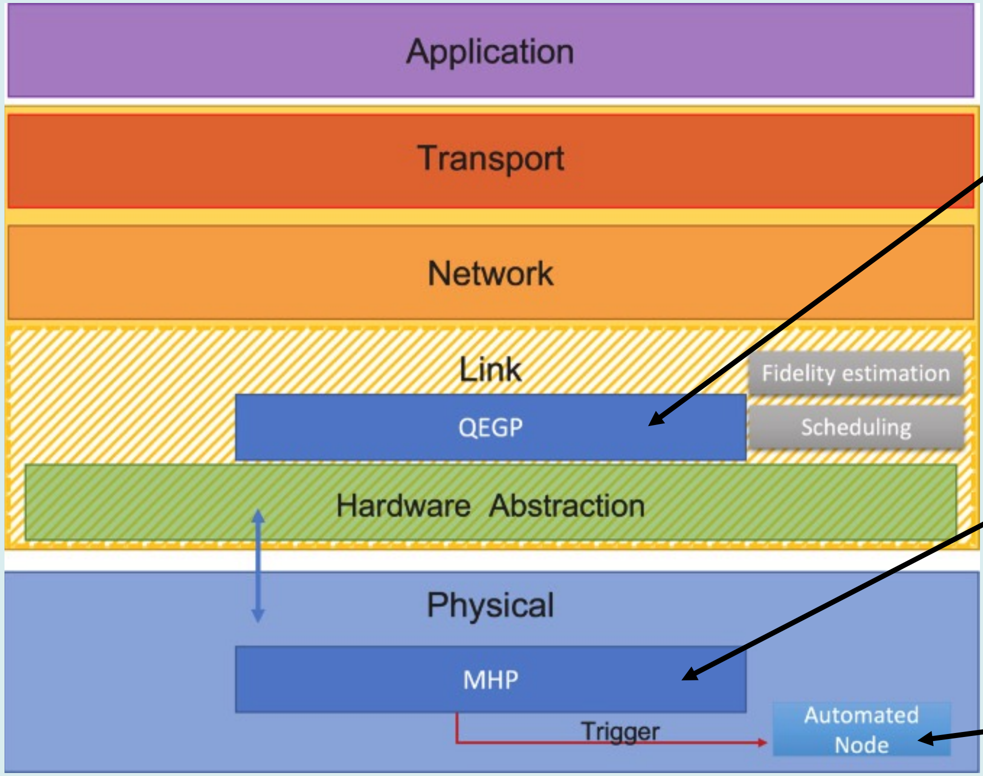


Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Gets inputs from upper layers:

- remote node ID, #entangled pairs, minimum fidelity, request type, measurement basis, etc.

Instructs lower layer protocols through Hardware Abstraction Layer

- Coordinates automated nodes;
- Polls the link layer to determine whether entanglement generation is required or not in a given time slot.

- Devices triggered to generate entanglement.

Open issues and research directions

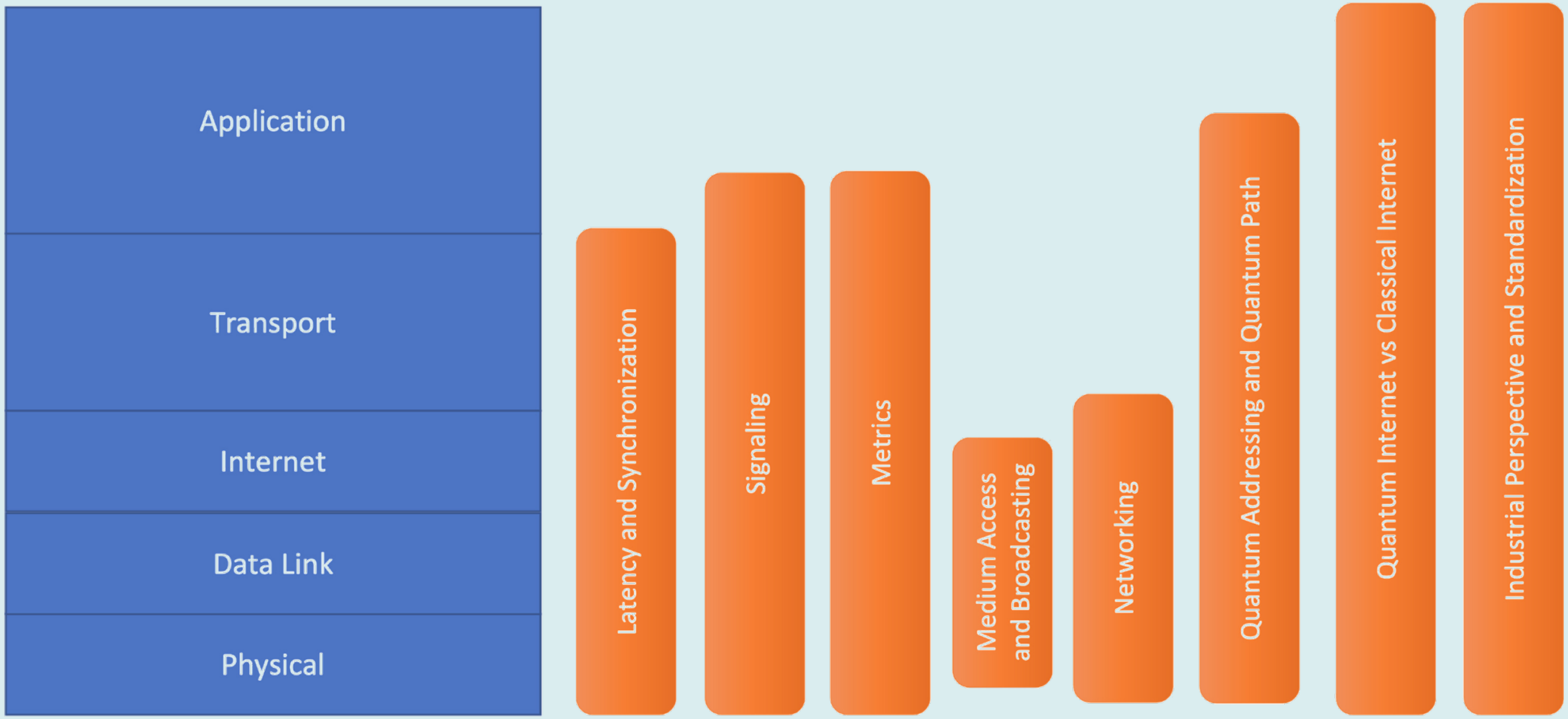


Image source: Illiano *et al.*, "Quantum Internet protocol stack: A comprehensive survey," *Computer Networks, 2022.*

Open Issues – Standardization

- Lack of unified quantum internet protocol stack
- International projects and standardization efforts (e.g., in ITU, IETF, IEEE, GSMA, ETSI) for:
  - architectures, interfaces and protocols
  - interoperability between quantum networks
  - seamless interworking with current infrastructures

Open Issues – Signaling vs Data

- Coordination is critical and exchange of control information still relies on classical internet
- Telecommunication networks have dedicated signaling channels
- Classical internet carries both data and signaling in-band
- Entanglement needs qubits on nodes → less qubits on nodes for quantum data

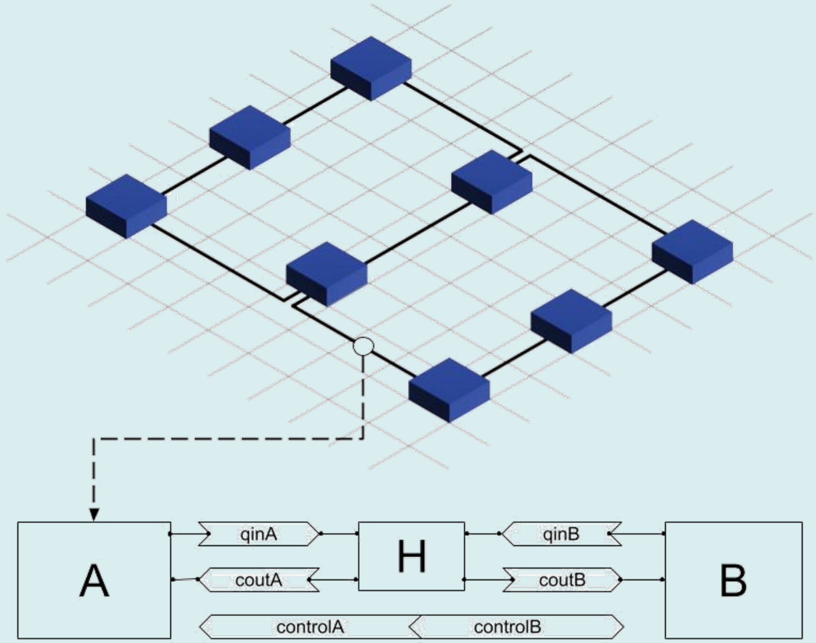
Open Issues – Medium Access

- How to arbitrate / coordinate access to virtual link → utilization of entanglement as resource?
- Two or more nodes share an entanglement
  - Which node to use and when?
  - Entanglement Access Control (EAC) protocol
  - Much harder with multiparty entanglement
- No-broadcasting theorem – unknown quantum state cannot be broadcast to two / more receivers

Ongoing Research

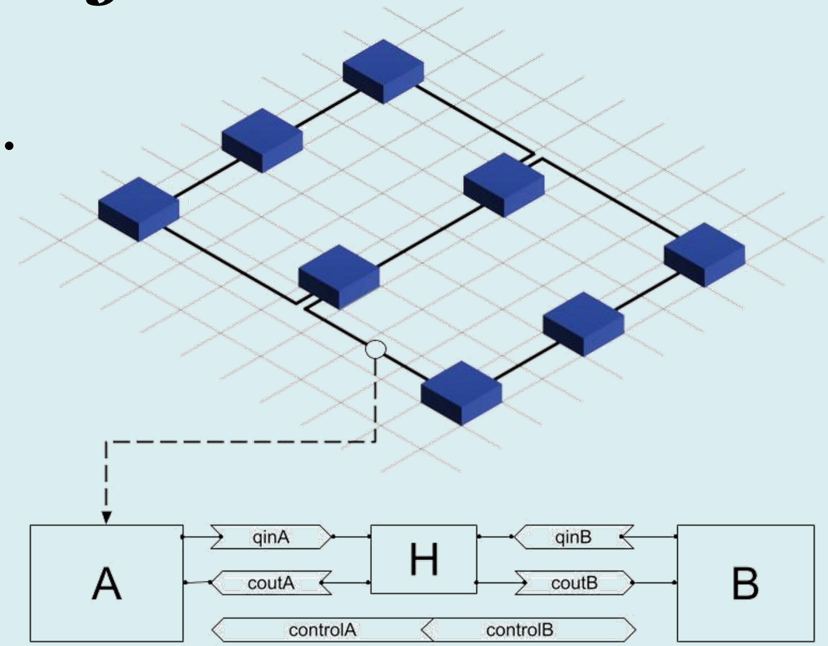
Synchronization Control-Plane Protocol for Quantum Link Layer

- QLL role – create entanglements between adjacent nodes, using heralded entanglement generation.
- QEGP and MHP handles the generation of entanglements between two nodes.

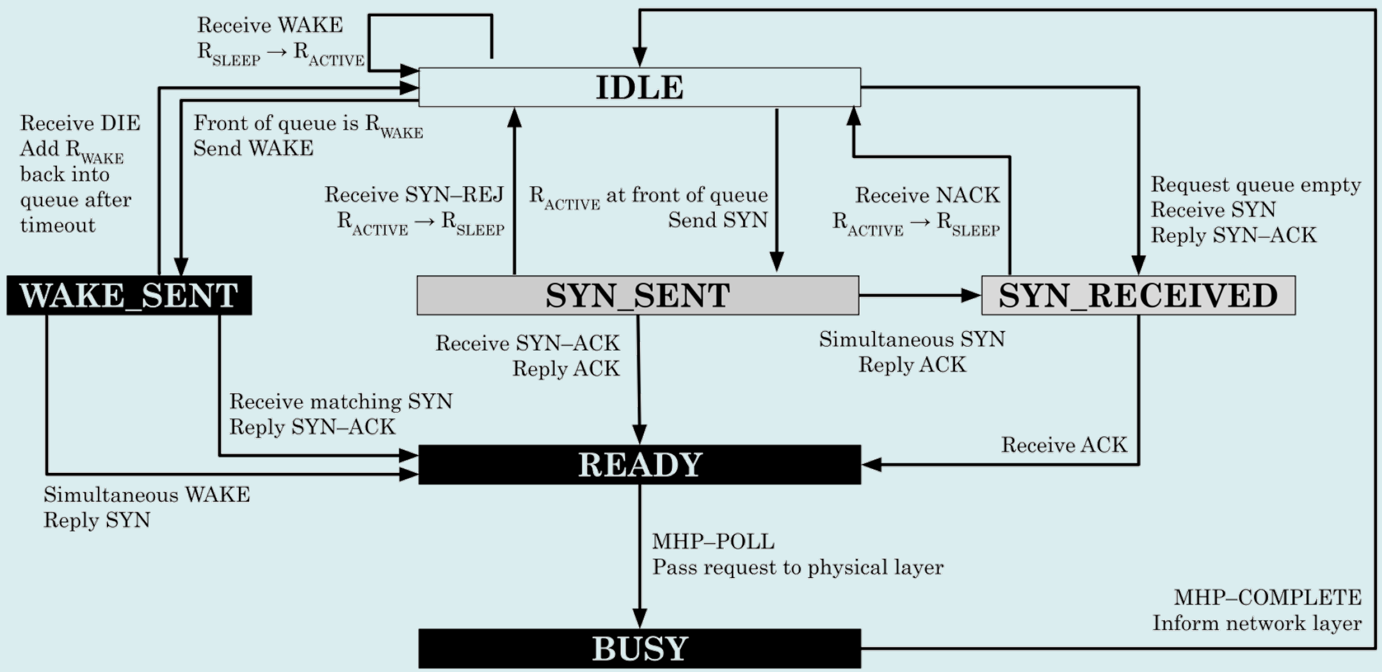


Eventual Synchronization Protocol

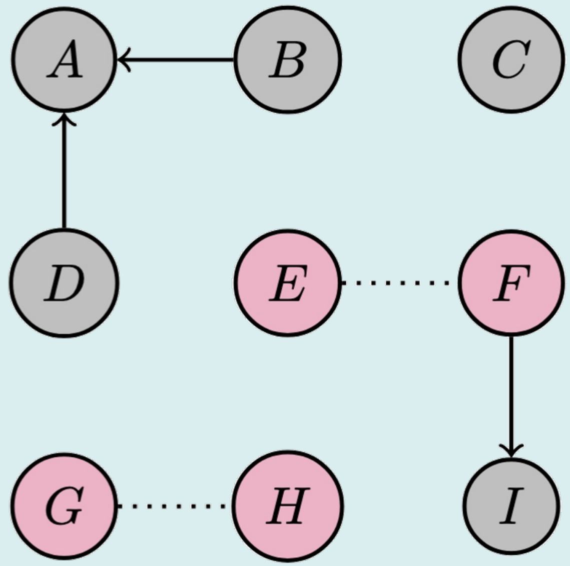
- **ESP** – ***Control Plane Protocol that enables nodes to synchronize before making an entanglement***.
- Quality of the generated entanglement, referred to as fidelity, F, where $F \in [0, 1]$.
  $F = 1$ is the ideal state
- Fidelity directly affects the functionality of higher-level services that utilize these entanglement.
- In practice, only $F > 0.5$ is useful.



Eventual Synchronization Protocol



E, *F*, *G*, and *H* are **BUSY**. *C* and *I* are **IDLE**. *B* and *D* are in **SYN_SENT**. *F* has a queued **WAKE** request for *I*.



Open Issues – Networking

- Given *no-cloning* theorem, how to provide basic networking functionalities – neighbour discovery, path discovery, forwarding and routing
- Entanglement-based communications vs direct transmission
- Entanglement generation and entanglement-aware routing
- Error control and correction for reliability

Acknowledgements

- Dr Del Rajan, PhD.
  for introducing me to quantum networking
- Royal Society of New Zealand
  for James Cook Research Fellowship to conduct fulltime research for 2 years on *Quantum Networking Protocols and Algorithms*
- Brandon Ru
  for contributions to synchronization protocol

Questions???

My contact details:

Email: winston.seah@ecs.vuw.ac.nz

Research group website:

https://ecs.wgtn.ac.nz/Groups/WiNe/WirelessNetworksResearchGroup