

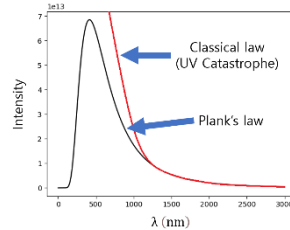
A vision and role of quantum internet

ITU Workshop (2023.07.25)

Korea University

Jun Heo

From Quantum physics to Quantum internet

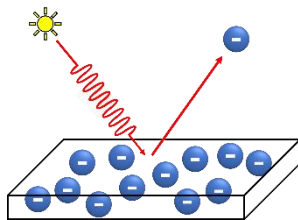


1900
Max Plank :
discovery of
Energy quanta

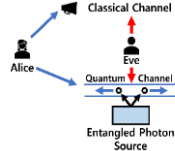
Quantum Physics

1927
Schrodinger, Born,
Heisenberg, Bohr :
Quantum physics

1905
Einstein:
Photoelectric effect



1991
Entanglement-
based QKD : E91



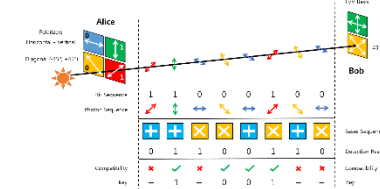
2003
Decoy method
(Hwang)

2019
OpenQKD (EU)
:QKD testbed

2022
QKD
commercial
service in
Korea
(KT, SKT)

2023

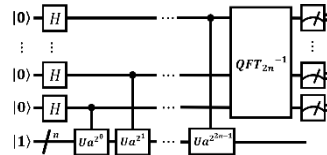
1984 The first QKD protocol BB84
Quantum communication (QKD)



Quantum computer

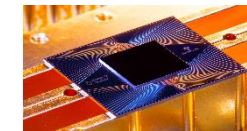
1980~1982 Feynman : concept of quantum computer

1994
Shor:
Quantum algorithm



2016
IBM quantum cloud
computing

2019
Google
quantum supremacy
(about 50 qubits)



IBM : 1121 qubit
quantum computer
(roadmap)

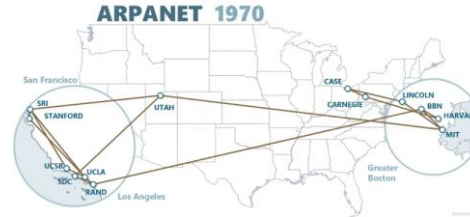
Quantum Internet

History of digital internet



1836
 Marconi:
 First long-
 distance
 communication

1858~1866
 Atlantic ocean
 undersea cable



1969
ARPANET :
 Origin of
 internet
 (supported
 by DARPA)

1973
TCP/IP protocol
 (packet based
 network)

1991
 WWW
 (world wide web)

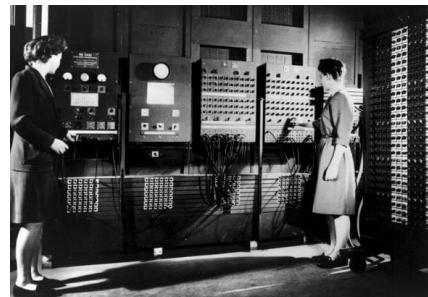


1993~1996
 Web browser

2023

**Digital Internet
 (AI /
 Metaverse)**

Digital Computer
 1945~ ENIAC



1981
 IBM
 (personal computer)



IBM PC 5150

1983
 Ethernet
 (first standard)

2007
 Apple (iPhone)



Internet : [global system of interconnected computer networks](#) that uses the [internet protocol \(TCP/IP\)](#) to communicate between networks and devices

Philosophy of digital internet

- ① Connecting internet [without changing the individual subnetworks](#)
- ② Resending packets for loss or error
- ③ Interconnecting subnetworks by gateway or router
- ④ [No global control](#)

TCP/IP

- IP: transfer packet
- TCP: flow control and packet-loss correction
- ["Separation of concern"](#)

Rich killer application of internet

- Military (early stage), E-mail
- WWW, Game, E-commerce

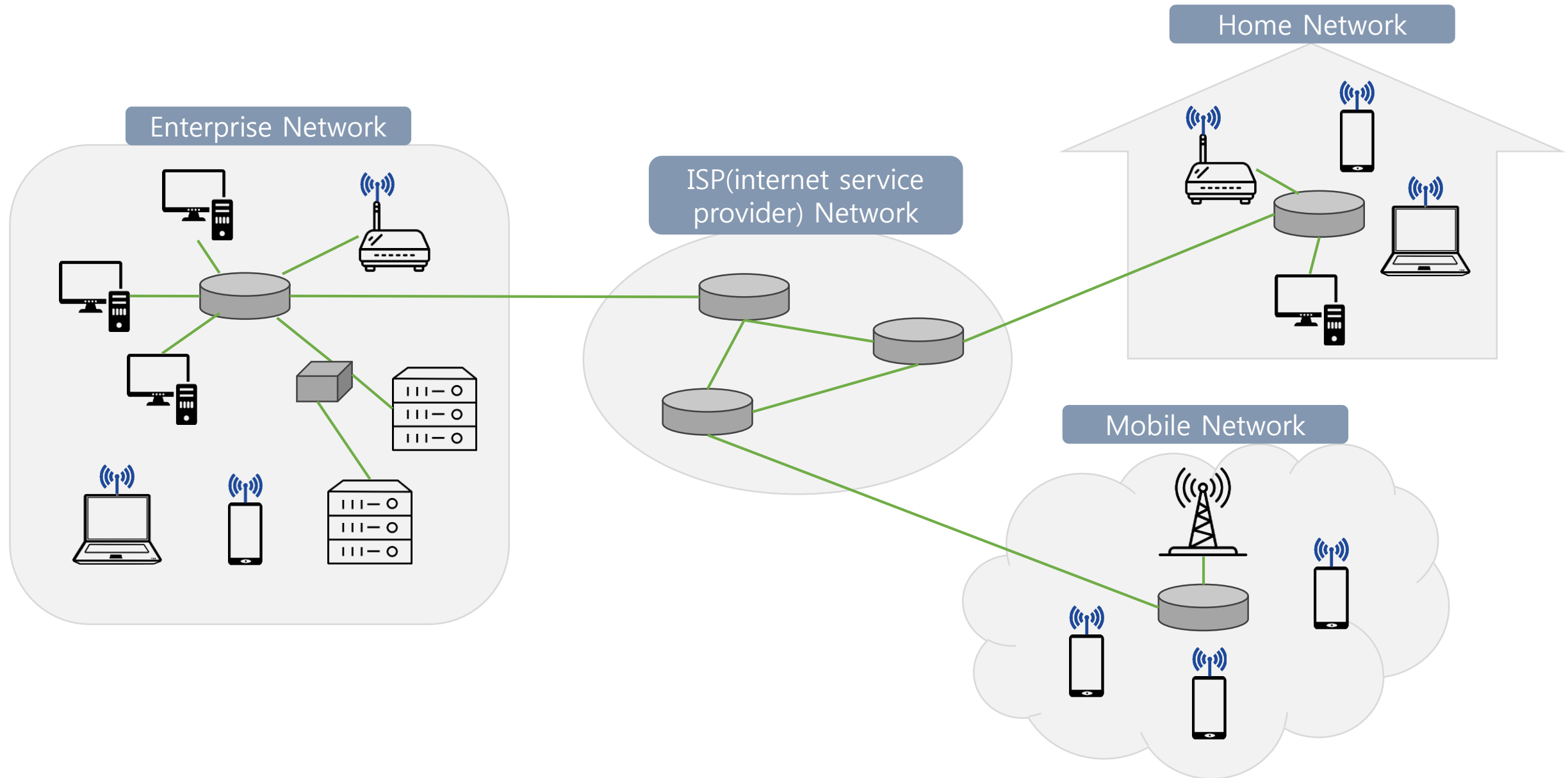
Quantum Internet : a network of quantum computers that send, compute, and receive information in quantum states.

“The quantum internet will not replace the modern or classical internet; instead, it will provide new functionalities such as quantum cryptography and quantum cloud computing.” (Chicago News Dec 8, 2022)

Role of quantum internet

- ① Secure digital internet : QKD, Blind computing etc.
- ② Enhancement of quantum computing capability : distributed quantum computing
- ③ Collecting and processing ultra-precision sensing data : quantum cloud computing with quantum sensors
- ④ New functionalities using entanglement (teleportation, non-local quantum operation, repeater ...)

Network architecture of digital internet



Digital internet vs. Quantum internet

Similarities

- network of network
- Separation of concern by protocol stack (suboptimal but effective)

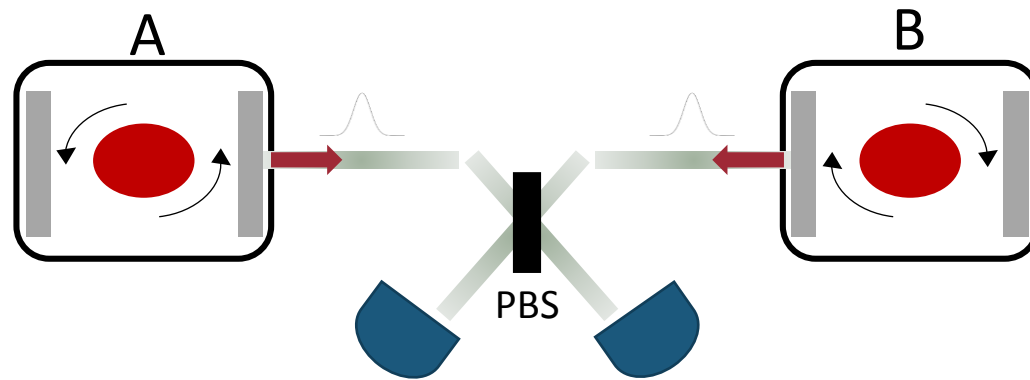
difference

- Superposition / measurement-irreversible / no-cloning properties / Entanglement (different protocol stack required)
- **Entanglement is a key factor for quantum internet**
 - ① teleportation
 - ② QKD w/ entanglement
 - ③ Blind computing (secure cloud computing)
 - ④ **Entanglement based non-local quantum operation (distributed computing)**
 - ⑤ **Repeater (enlarge transfer distance)**

	bit	qubit	entanglement
Time constraints	no	yes	yes
copy	yes	no	yes/no
scope	local	local	non-local

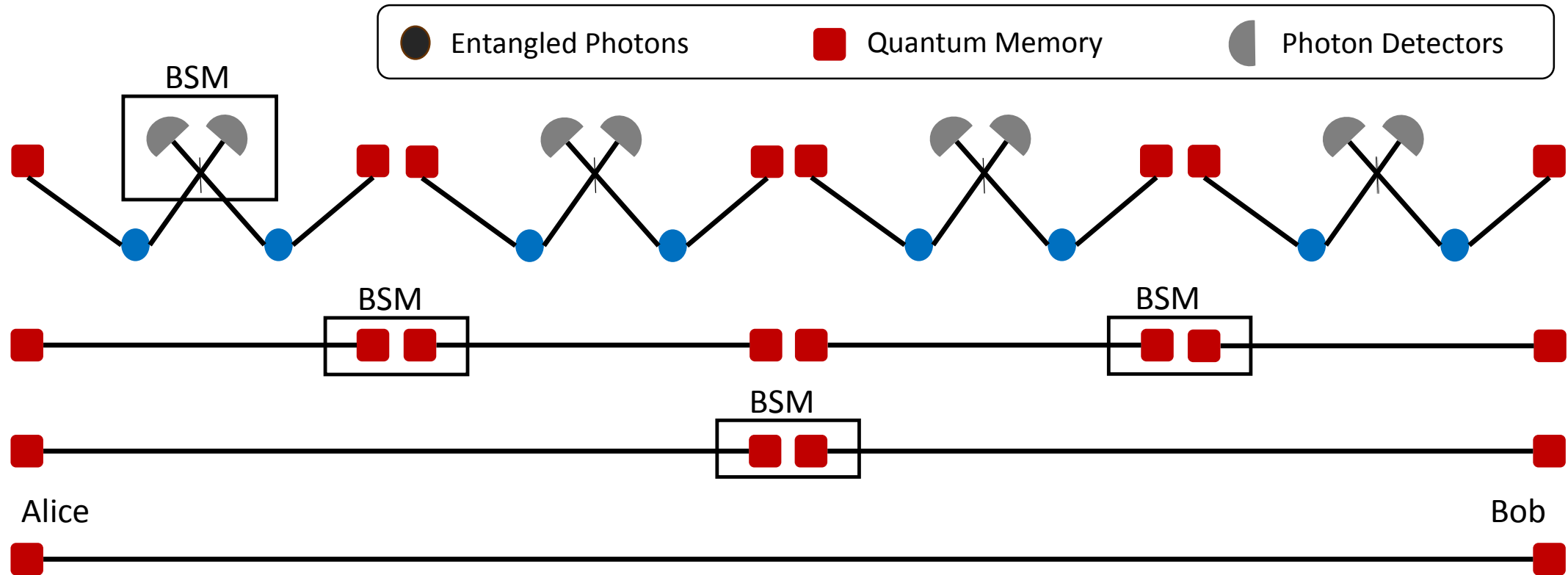
① Quantum entanglement generation

- **Goal** : share entanglement between two separate ends A and B
for secure communication, quantum teleportation, entanglement swapping etc.

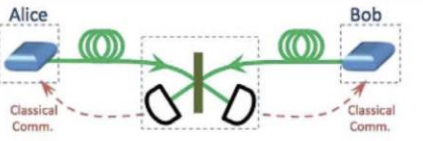
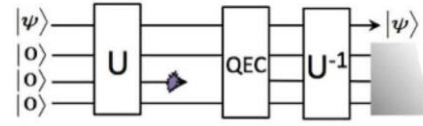
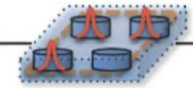
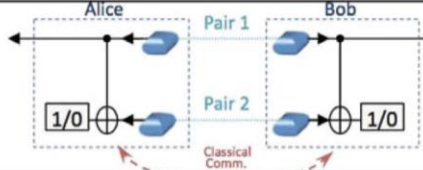
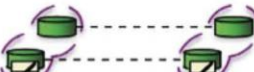
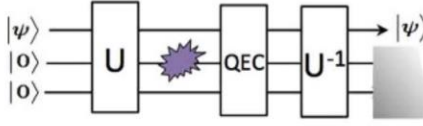
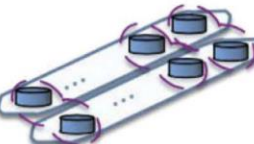


② Quantum repeater

- Goal : generating long-distance entanglement by short-distance entanglement and entanglement swapping



② Quantum repeater

Errors	Approaches	Examples	Schematics	1G	2G	3G
Loss Error	Heralded Entanglement Generation (HEG)			✓	✓	
	Quantum Error Correction (QEC)					✓
Operation Error	Heralded Entanglement Purification (HEP)			✓		
	Quantum Error Correction (QEC)				✓	✓

Elements:

 Remotely entangled qubit

 Flying qubit (photons)

 CNOT gate

 Qubit in an encoded block

 Measurement (X/Z)

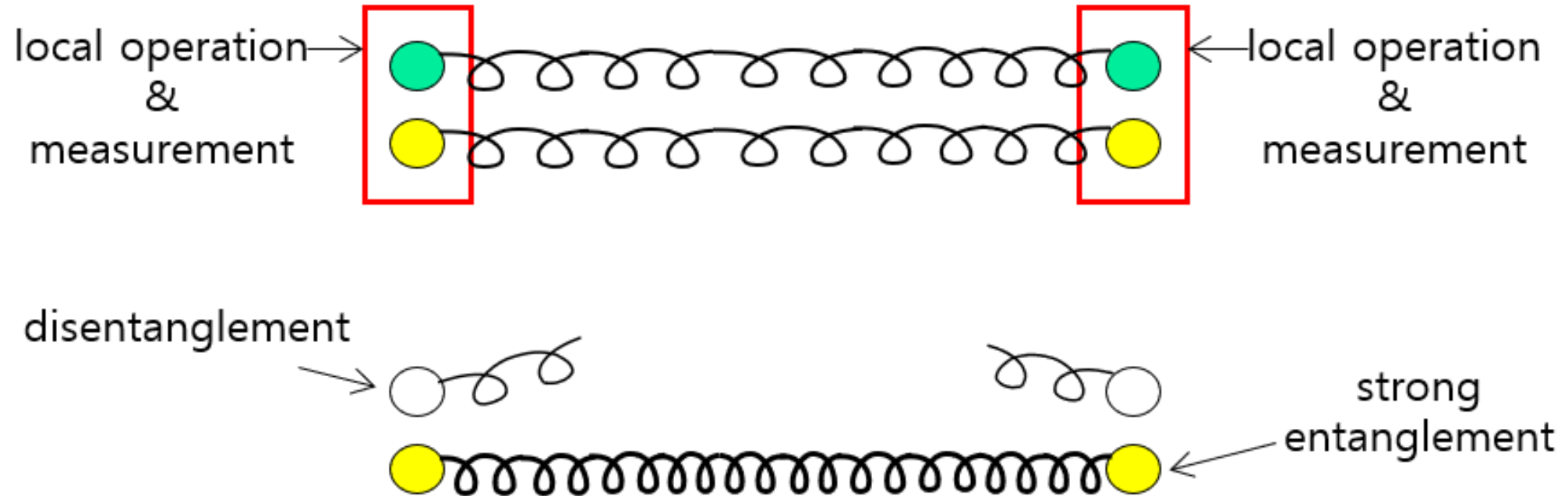
 Teleportation-based Error Correction

Figure 1. A list of methods to correct loss and operation errors. Depending on the methods used to correct the errors, QRs are categorized into three generations.

[ref] S. Muralidharan, L. Li, J. Kim, N. Lutkenhaus, M. D. Lukin, and L. Jiang. Optimal architectures for long distance quantum communication. Scientific Reports, 6:20463, 2016.

③ Entanglement purification (distillation)

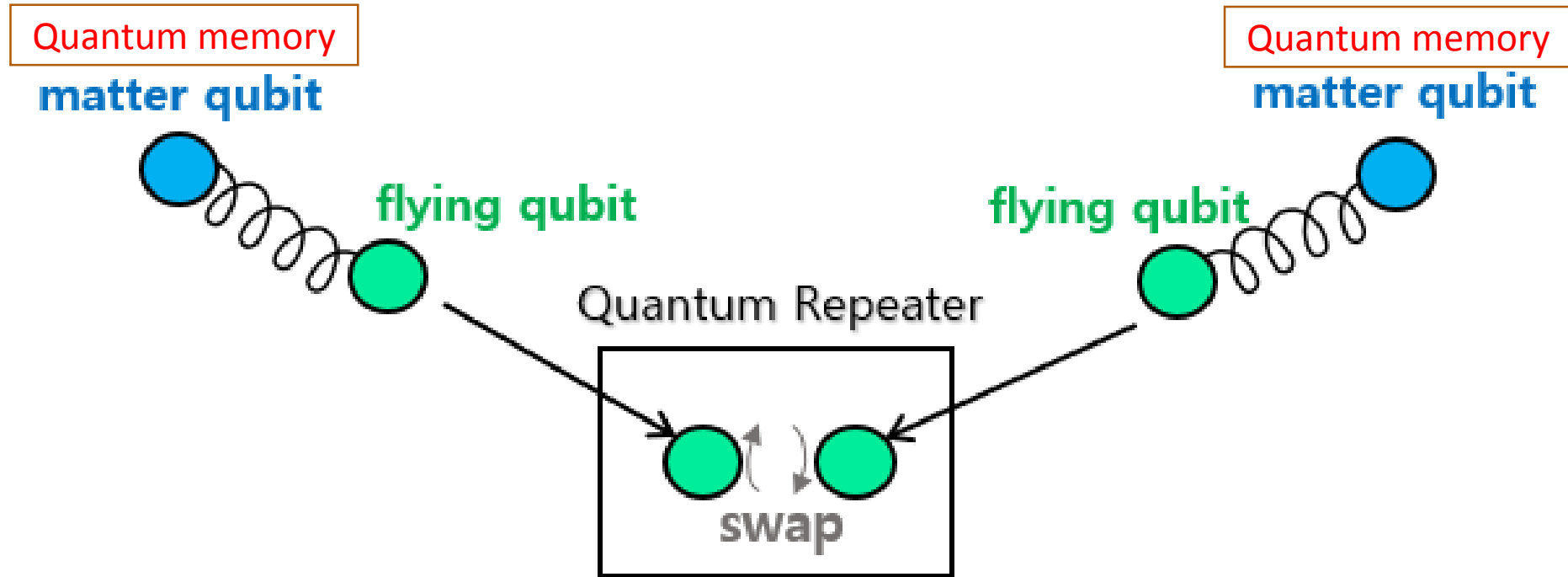
- **Goal** : purifying noisy or mixed entanglement qubits to have maximally entangled qubits



Key elements of Quantum Network

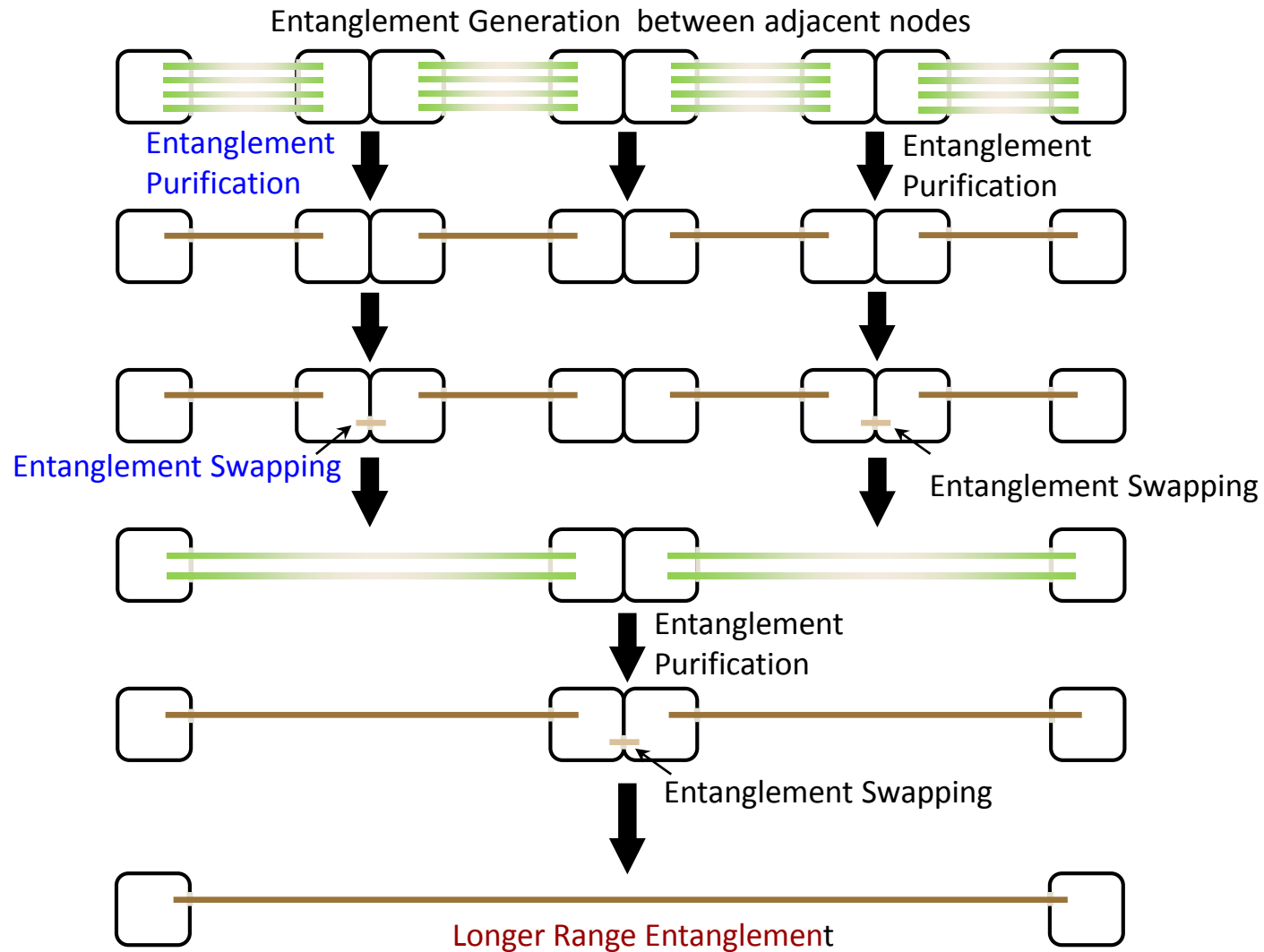
④ Quantum memory for quantum network

- **Goal** : maintaining entanglement while distributing entanglement

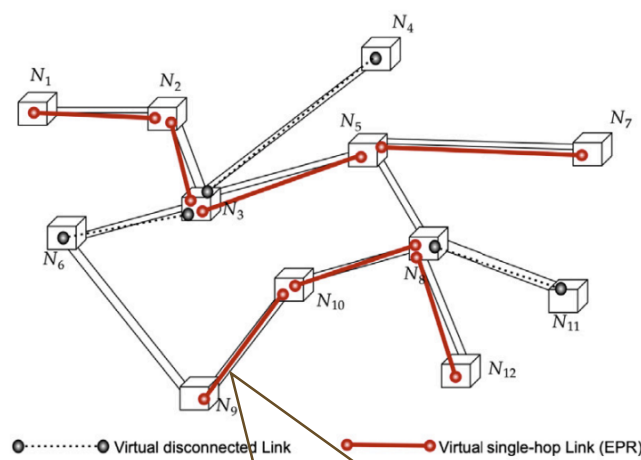
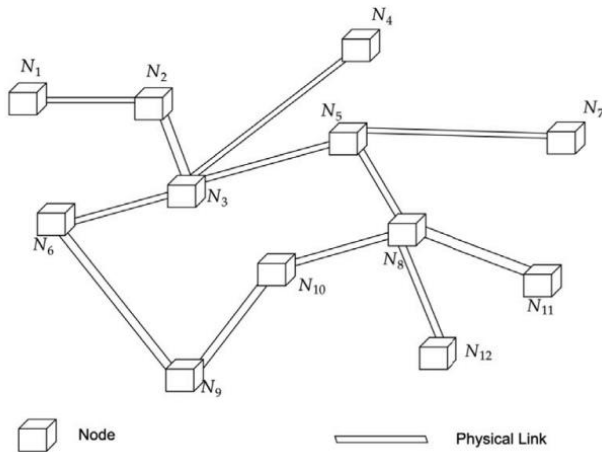


Note: Quantum Repeater without memory has been researched in all photonic quantum process

Combination of key elements of Quantum Network



Quantum internet : virtual connectivity



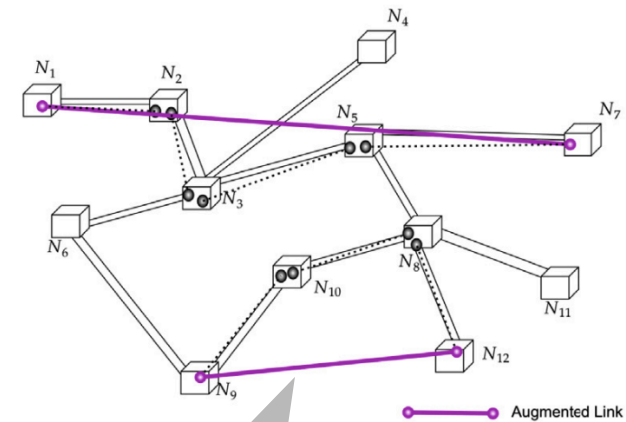
Virtual connectivity

Virtual connectivity

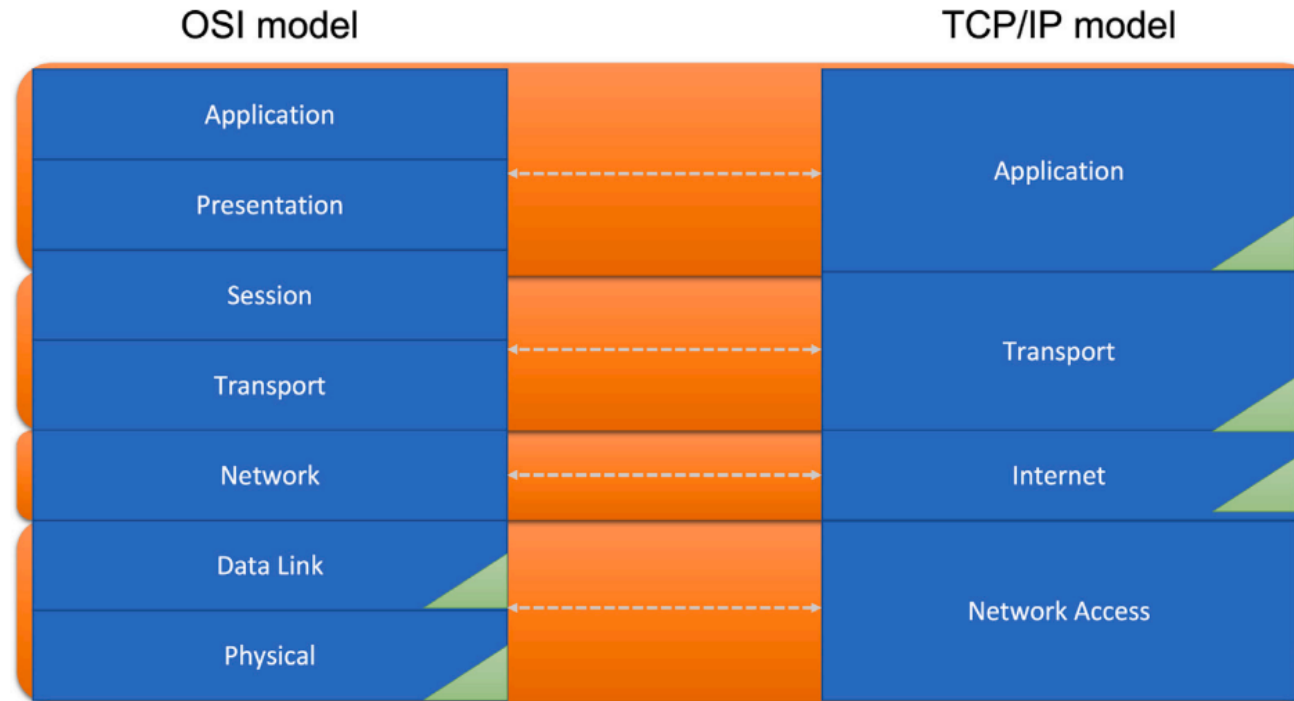
- Connection due to entanglement sharing along the physical link
- Disconnection due to depletion of entanglement sharing

Augmented connectivity

- Defining new neighborhood(=quantum link) due to entanglement swapping regardless of physical link

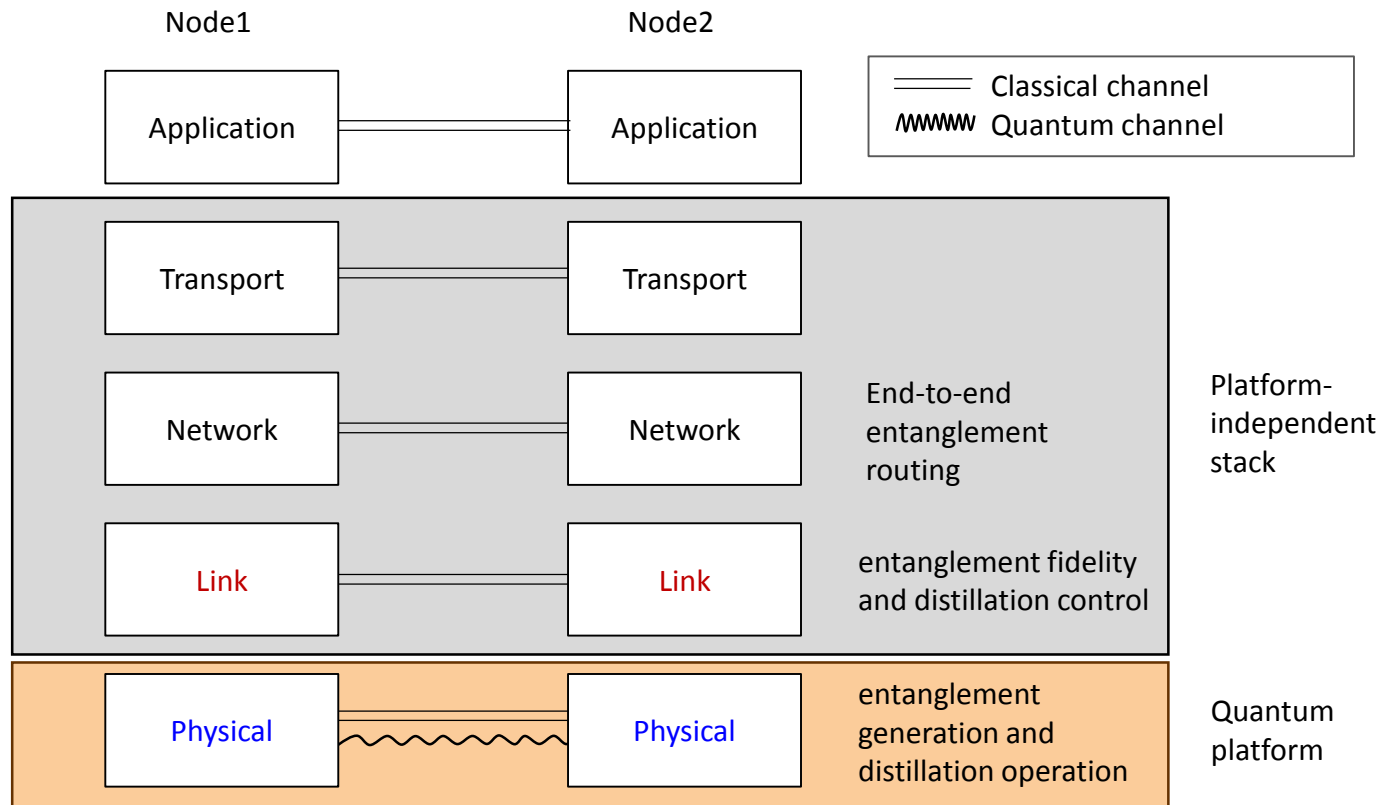


Augmented connectivity



- OSI model : universal network protocol stack
- TCP/IP model : protocol stack for internet

Quantum internet protocol stack (proposed)



[ref] M. Pompili et al, "Experimental demonstration of entanglement delivery using a quantum network stack," *npj Quantum Information* 5.1, 2022.

[ref]: W. Kozlowski, S. Wehner, Towards large-scale quantum networks, in Proc. of ACM NANOCOM '19, 2019

① Technical challenges : commercial quantum repeater and computer

- ✓ Quantum memory
- ✓ Entanglement generator and swapping
- ✓ Development of Quantum computer

② Killer application

- ✓ Security
- ✓ Quantum sensing
- ✓ Quantum computing

③ Standardization

- ✓ what layer in protocol stack ?
- ✓ what technology (hardware and software) ?
- ✓ How cooperate with digital internet ?