Programmable Quantum Communications Networks

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Quantum Communications Networks Overview

A Classical Communications Network transfers bits from a sender to a receiver

A Quantum Communications Network transfers qubits from a sender to the receiver

Sender and receiver may be connected through

- A direct communication link (optical or free-space)
- through intermediary repeaters capable of transferring qubits

Bit vs Qubit

- A bit of information can have a value of 0 or 1
- A qubit exists in an indeterminate state
  - State becomes known after measurements

Quantum computers allow quantum operations on a collection of qubits

Quantum communications network allow transfer of qubit information between the sender and receiver

- Quantum entanglement is the basic mechanism for qubit information transfer

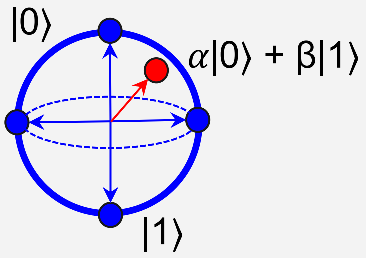
Quantum Communications

Superposition

A qubit exists in a superposition of two states of 0 or 1

Spin of an electron is measured as a vector of unit size

- $\alpha^2+\beta^2 = 1$
- $<\alpha, \beta>$ is qubit state



No-cloning

A qubit can not be duplicated

If a qubit is read, its state collapses to either 0 or 1

If a qubit is tampered with, its state changes

- Arbitrary state can not be copied

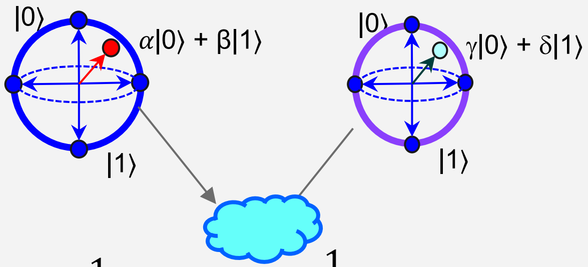
Provides a level of security in quantum transmissions

Entanglement

Two qubits can be entangled with each other

A change in state of one changes the state of another

Example two photons which can exist in a superposition of states between 0 and 1.



$$\frac{1}{\sqrt{2}}(\alpha\delta \pm \beta\gamma), \quad \frac{1}{\sqrt{2}}(\alpha\gamma \mp \beta\delta)$$

Quantum Networks

Can exist in many different flavors

– Send quantum information through polarization of the photon

– Send quantum information through encoding of the phase of photon

– Through entanglement of photons leveraging trapped ions, spins, photons or superconducting qubits.

Information sent on quantum channel needs to be validated

Net result:

– A random number is known at sender and receiver

– Transmission is highly secure

– The value of random number is not predetermined

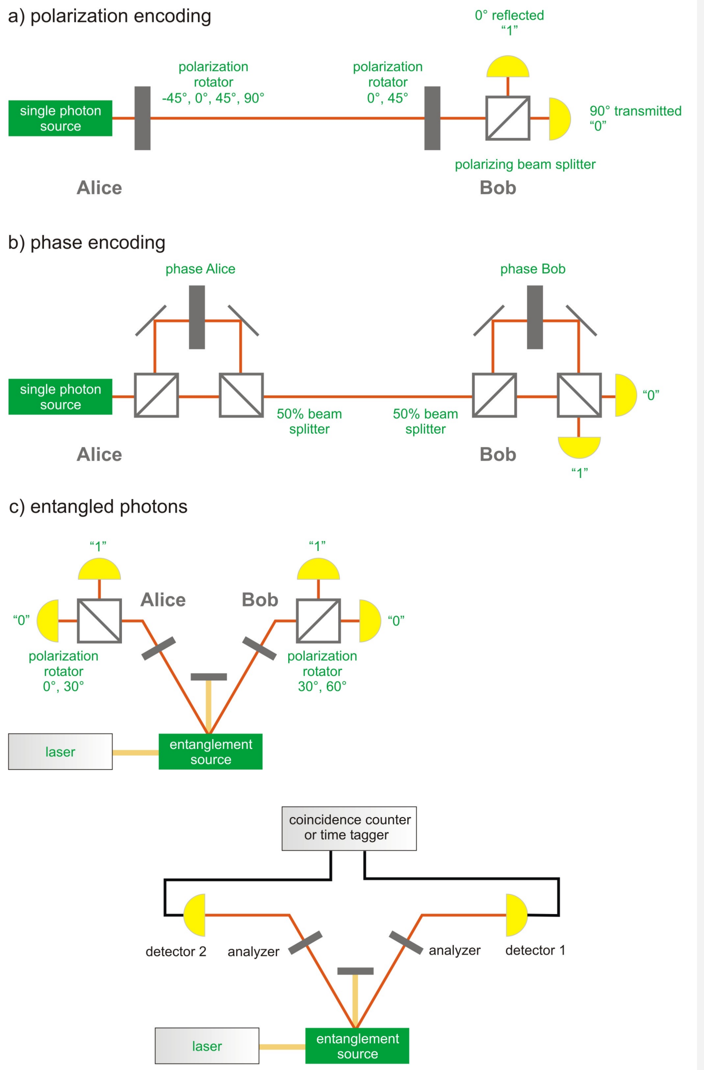


Image from URL: https://www.picoquant.com/applications/category/quantum-optics/quantum-communication

Evolution of Quantum Networks

Experimental

- Within labs
- Show Viability
- Small Networks
- Easy setup main challenge
- Goal: Successful xmission and reception

Standalone

- Several Nodes and repeaters
- Medium size-nodes
- Multiple nodes communicating at same time
- Goal: support limited applications

Complement

- In production
- Complements a classical net
- Size: S → L
- Goal: Operations
- Challenge: Provide enhancements over classical network.

Functional

- In production
- No classical net
- Goal: Operations
- Challenge: Routing and flow control on the quantum switches

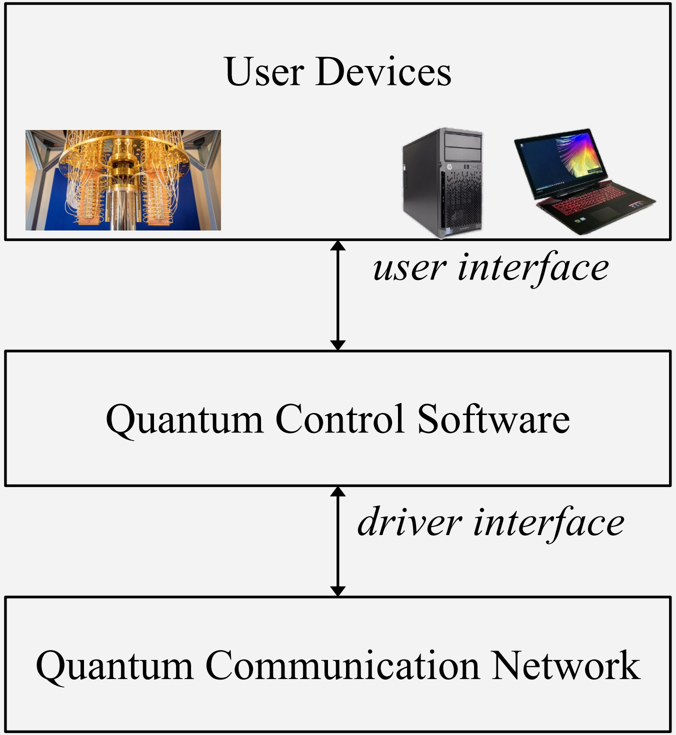
Interoperate

- Many quantum networks
- Coexist and interoperate with many classical networks
- Challenges: Operations, Management, Control

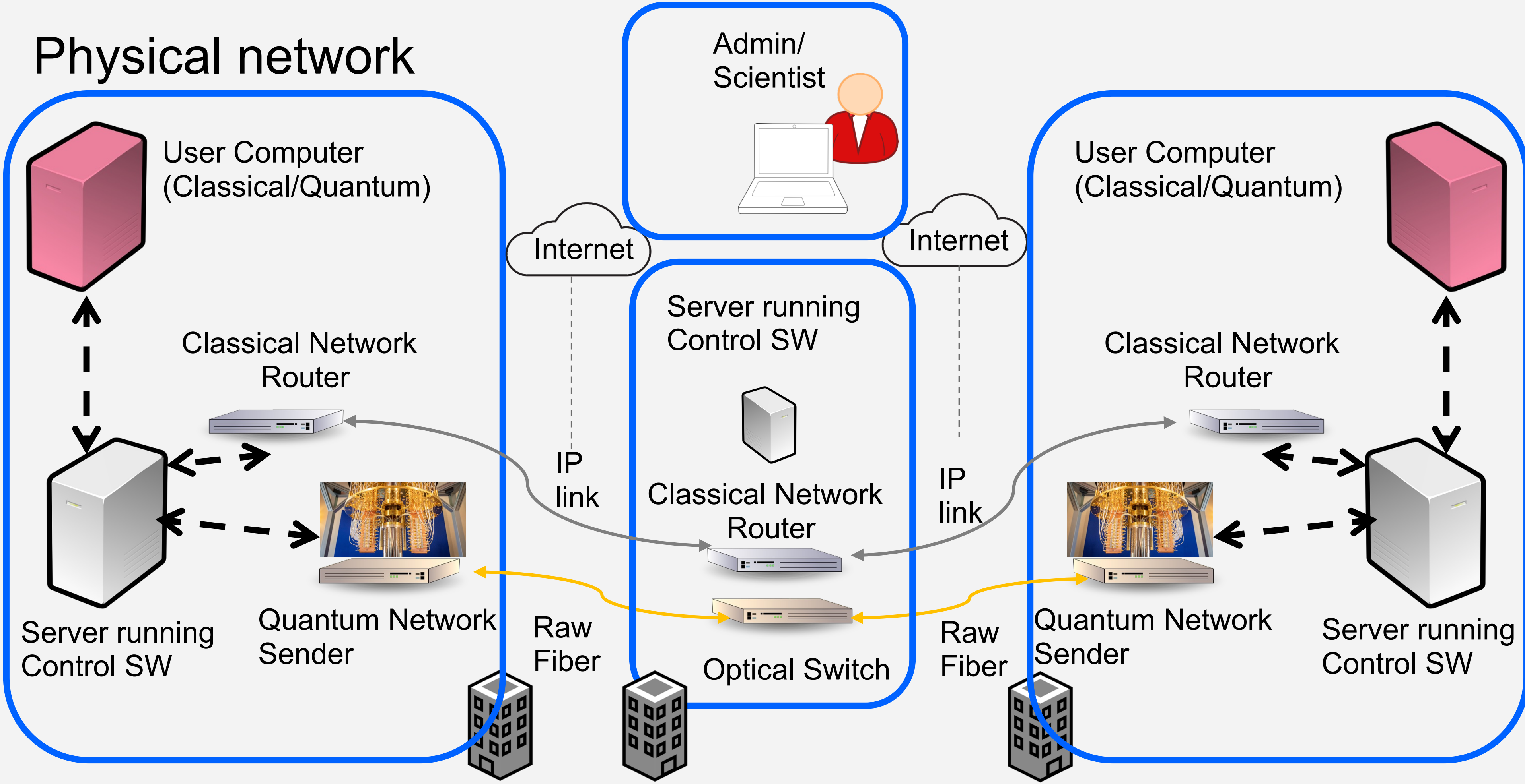
Quantum Control Software

Implement a Control Software stack for Quantum Communications Networks

- Simplify the operations and control of Quantum Communication links
- Enable better integration of Quantum networks with existing classical networks
- Provide support for all stages of quantum networks
  - Currently mostly Experimental
  - Eventually towards interoperable quantum networks
- Provides programmability of quantum network



Physical network



Who’s the User?

Experimental

- The scientist who is running the experiments
- Primary Goal: Consistent Configuration of Experiments

Other Issues:

- Link to sw on user computer
- Security exposure due to remote scientist

Standalone

- Software on the user computer
- Primary Goal: Transfer of Qubits

Other Issues:

- Management Information
- Multiple Network Flows support

Complement

- Software on the user computer
- Network Admin
- Primary Goal: Simplify usage of network

Other Issues:

- Routing Setup
- Fault Tolerance

Functional

- Software on the user computers
- Network Admin
- Primary Goal: Smooth Operations
- Other Issues:
- Security Mgmt
- Capacity Plan
- Performance
- Full Mgmt

Interoperate

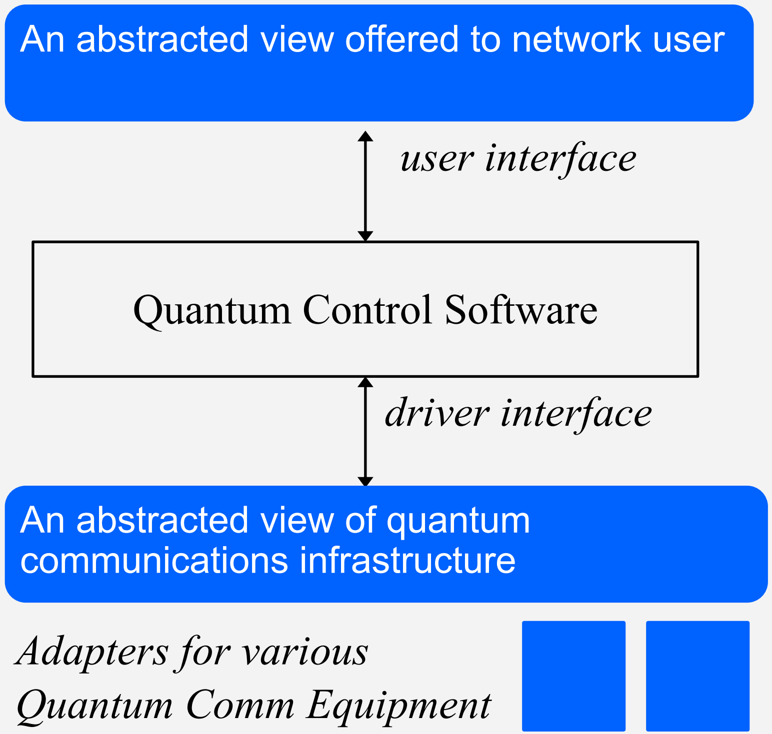
- Software on the user computers
- Network Admin
- Primary Goal: Internetworking
- Other Issues:
- Standard Protocols

Abstracting the design of Control Software

Control Software should assume an abstraction of the Quantum Network Equipment underneath it

- Adapters implement the abstraction on real equipment

Control software should export an abstracted view of the Quantum+Classical Network to the User



Functions of Control Software

Typical Computer Network Software Architecture calls for three distinct planes:

- Data Plane: defines the layers and usage interface of the network
- Control Plane: does the orchestration and configuration of the network elements
- Management Plane: monitors the network and performs FCAPS (traditional) or ITSM workflows for network management.

Design Choice:

- Should the control software do only the control plane, all three functions, or a subset of the functions.

Current thinking for programmability of network:

- Perform all control plane functions and a limited set of management functions
  - Sufficient to satisfy the needs for initial 3 stages of quantum network evolution
- Assume data plane puts quantum network as a link layer below IP
  - akin to MPLS/WiFi/Cellular

Abstractions in Driver Interface

End-node:

– interacts with the control software to send or receive a series of entangled qubits.

Intermediary Node:

– interacts with the control software to setup its configuration for relaying or the change the configuration of its links.

Link:

– provides a communication channel between the end-node(s) and intermediary node(s)

End-Node Properties:

– Configurations for generating/sending entangled qubits

– Commands for entangled qubits interacting with local qubits

– properties of connected links

– ambient conditions (temp, light intensity, etc.)

Intermediary Node Properties:

– Configurations to set up paths to transfer entangled qubits

– Link Properties and ambient conditions

Abstractions for User Interface

Connection

- A connection between two end-nodes
- Can be through one or more intermediaries
- Establishes the two nodes to communication
- Similar to Virtual Circuit concept

Implementation

- Exchange of configurations on classical network to configure all network nodes in its way

Message

- An interaction between two end-nodes of connection
- Results:
  - A common random number being read by both end-nodes if user is a classical computer
  - A set of entangled qubits delivered to both end-nodes if end-nodes are quantum computers

Implementation

- Xfer of entangled qubits followed by validation on classical network

Other Considerations

Experimental Stage:

– Security Exposures to experiments/quantum setup due to remote access

– Need to sanity-check the configuration of any command

  • Control speed of message transfer to be safe

  • Control adjustments in ambient settings to be safe

Stand-alone Stage: (Experimental Stage +)

– Network Control: follow a SDN like paradigm for managing everything together

– Centralized Controller manages consistency among the paths and avoid resource conflict

  • Avoid resource conflicts in switch configuration

Next Steps

Details of Interfaces

Missing Requirements

- User interviews to assess gaps to address

Implementation

- Initially on a Simulation Environment
- Eventually link to a real environment.

Open Questions

- Best exploitation of the quantum network and classical network in a complementary manner
- Solutions that can leverage the concurrent random number generated in quantum networks with classical network communications

Acknowledging folks who educated me about quantum networks:

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