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Dynamic Quantum Network: from Quantum Data Centre to Quantum Cloud Computing

Reza Nejabati, Rui Wang, Dimitra Simeonidou
High Performance Networks Group, Smart Internet Lab, University of Bristol, Woodland Road, Bristol, United Kingdom
reza.nejabati@bristol.ac.uk

Abstract: This paper presents challenges and solutions for creating a dynamic entangled quantum network as the main technology enabler for realizing scalable quantum data centres and future quantum cloud computing infrastructure serving a large number of users.

1. Introduction

Quantum cloud computing is defined as an infrastructure that enables a large number of users to securely access remote quantum computing facilities in the same way that today's Google and Amazon cloud computing services serve their users [1]. A quantum data centre (QDC) aims to scale quantum computing power by utilising several few-qubit quantum processors (QP) in a networked fashion resembling the structure of today's classical mega data centres of Amazon and Google.

The fundamental technological ingredients for realising the vision of quantum cloud computing and quantum data centre are quantum processors, communication of the processors and dynamic quantum networking between them [2]. With successful demonstrations from the likes of IBM Q, Google's Bristlecone, Rigetti's Aspen and PsiQuantum, quantum computing is witnessing its first generation of quantum processors composed of ~100 qubits [3]. Also, over the past decade, quantum networking has been matured with some commercial products are becoming available. However, so far most of the efforts in quantum networking have been dedicated to developing technologies for point-to-point quantum secure connection known as quantum key distribution (QKD) using dedicated fibre, satellite, or optical wireless links [4].

Despite the progress, still there is a need for significant research to develop solutions that allow deployment of networked quantum processors in the form of a quantum data centre and provide remote access to it to serve multiple users and services at the same time (quantum cloud computing). This paper discusses challenges and possible solutions from a networking perspective for creating a quantum data centre and providing quantum computing as a secure cloud service.

2. A Quantum Network Supporting Multitenancy

To support cloud computing, classical data centres utilise technologies for sharing computing resources among multiple applications and users. This concept is called multitenancy [5]. A key technology enabler for multitenancy is a flexible data centre interconnection network that enables dynamic and on-demand clustering of computing resources into multiple co-existing slices like containers, each serving a different application. To mimic this concept, a quantum data centre should utilise a quantum interconnection network that allows clustering and allocation of qubit processors to different applications and users. Achieving this while preserving the quantum state between connected quantum processors is a major challenge and require a dynamically reconfigurable quantum network supporting entanglement distribution and teleportation.

3. Intra -Data Centre Quantum Network

A quantum datacentre comprising of several few-qubit quantum processors requires two types of co-existing interconnected networks. One network is a classical interconnected network supporting classical communication between quantum processors. Such a network supports classical information exchange between processors, for example exchange of measurement information between qubit processors, that are required for the execution of the quantum algorithms. The second network is a quantum network supporting entanglement distribution and teleportation. This network interconnects quantum processors at the quantum state level. Such a network shall be able to support entanglement distribution, qubit teleportation or gate teleportation for remote operation between qubit processors. Another important aspect is the architecture and topology of the interconnect networks. They directly affect the performance and efficiency of the quantum data centre. Important aspects include: 1) Network topology for achieving the optimum quantum algorithm execution with the on-demand connections between quantum processors. For example, different entanglement-based wavelength-division multiplexing (WDM) optical network topologies such as ring, star, semi-mesh, and full mesh; 2) Placement of measurement modules in the network. Measurement modules perform necessary measurement operations such as bell state measurement for entanglement generation between quantum processors. These modules can be embedded in the network and shared between processors; 3) Computing qubit to communication qubit ratio. Each quantum processor must include some communication qubits or flying qubits for connection to other quantum processors. Increasing the degree of connectivity between quantum processors will require reservation of a higher number of qubits within a quantum processor as communication qubits. Furthermore, a quantum transducer [6] that interfaces flying qubits and stationary communication qubits is required for each quantum link. This will further pose a challenge to operation and management of the quantum network with a low computing qubit to communication qubit ratio.

4. Inter -Data Centre Quantum Network

Data centre warehouses benefit from a controlled environment. This allows achieving the high level of precision required, e.g. phase and temperature stability, for proper operation of a dynamic entanglement intra data centre network. However, an efficient and reliable transfer of quantum states with a high success rate over a long distance is a challenging problem without any realistic solution in prospect for the near future. Therefore, is no realistic solution for interconnecting two or more geographically distributed quantum data centres at the quantum state level. The only viable solution is to connect them at the classical information level.

5. Multi-tenant secure Quantum Cloud Computing

Sharing quantum computing power in the form of a data centre between multiple users and applications at scale requires mechanisms that guarantee security and isolation between tenants both at the access level and also within the data centre. The intra data centre quantum network is inherently secured benefiting from the no-cloning principle of quantum entangled photons. However, the intra data centre classical network as well as the access network to the quantum data centre need to be secured. The intra data centre classical network can also utilise entanglement photon resources of quantum entangled interconnected network to implement QKD protocol for securing classical information exchange between qubit processors. The access network also can be secured either using QKD protocol or other security mechanisms such as universal blind quantum computing or post-quantum cryptography.

6. Dynamic Entanglement-Based Networking for Intra-Data Centre

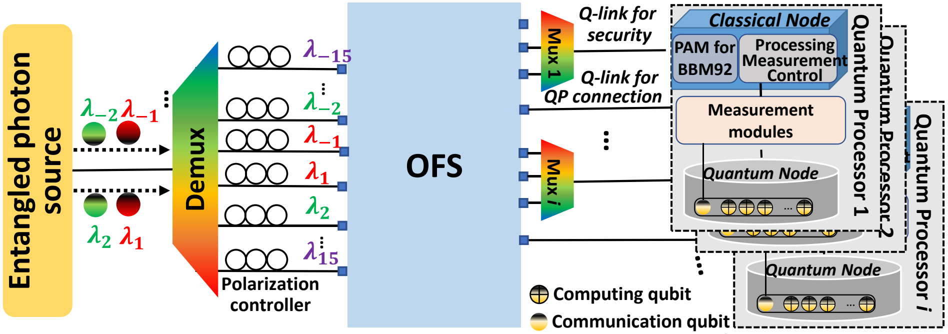

Figure 1: Dynamic intra quantum datacenter network with SPDC for both entanglement generation and distribution between QPs and quantum secured communications.

Fig 1 shows a possible solution for creating a dynamic entangled quantum network for interconnecting qubit processors within a data centre and also providing entangled photons for implementing QKD for securing the classical information exchange. Such a network requires a broadband entangled photon source via spontaneous parametric down-conversion (SPDC) process, often producing polarisation entangled photons. It also requires a DEMUX which divides the broadband entangled photon spectrum into multiple entangled channels; an optical fibre switch (OFS) for dynamically distributing entangled photos between qubit processors; When a pair of entangled photons reach both QPs successfully, the measurement modules will perform teleportation protocol by applying certain quantum gates with the assist of classical measurement outcome information. The entangled photons can also be used for QKD with MUX to combine the entangled photons such that the polarisation analysis module (PAM) at the classical part is able to measure in the necessary orthogonal bases to perform the BBM92 QKD protocol [7], [8]. The proposed architecture realises a completely reconfigurable intra data centre quantum network which can be configured into any arbitrary topology with dynamicity in time and wavelength. An important aspect in the operation of such a dynamic network is to arrange bipartite entangled communication with high entangled fidelity for qubit processors interconnection and low QBER for quantum-secured classical connections.

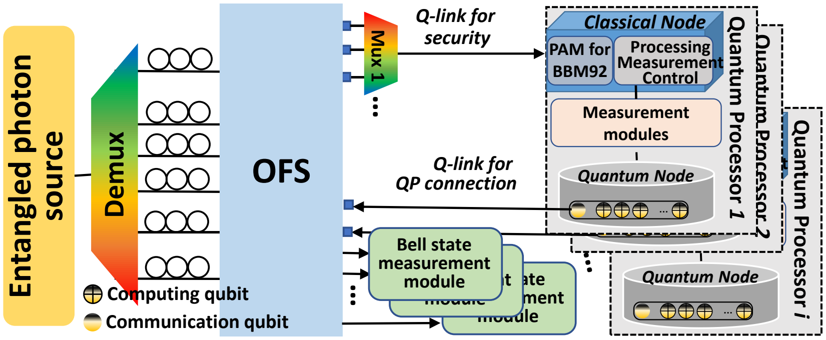

Figure 2: Dynamic intra quantum datacenter network with BSM to provide entanglement for QP and SPDC for quantum secured communications.

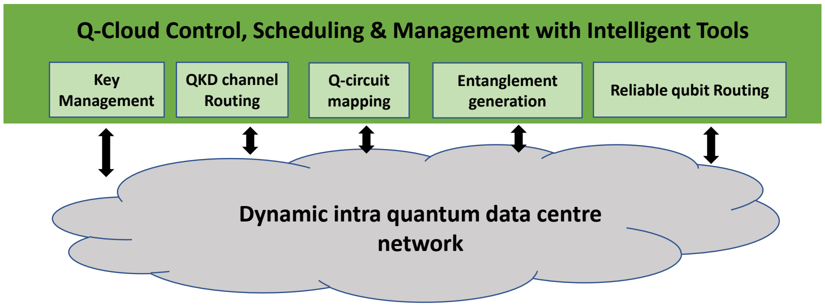

Figure 3: Control and management plane for quantum data centre network

Another approach to realise interconnections between QPs is illustrated in Fig. 2. Two flying qubits which are entangled with their own stationary communication qubits of quantum transduces in two QPs are routed to a Bell state measurement (BSM) module via OFS. BSM projects the state of stationary qubit into entangled state. This allows entanglement swapping between two stationary qubits at two separate QPs. The entangled photons from broadband entangled source via SPDC process will only provide as QKD for secured classical information transmission in this case, as compared to the scheme above. The complexity of the control of such a dynamic entanglement quantum network increases exponentially with the size of the data centre and the number of its qubit processors. A practical way to manage such a network is to utilise intelligent tools such as machine learning techniques. DNN model has been implemented in [9] to predict QBER of quantum links according to assigned wavelength, beam splitter and coincidence window in a quantum network. This will allow other tools to implement effective routing and resources assignment schemes of the quantum data centre network. Similar tools will be required to predict the fidelity of quantum links for QP interconnection. Further functions and moules are required to support the efficient and necessary operation of intra quantum data centre network, as illustrated in Fig. 3.

7. Conclusion

A dynamic entangled quantum network empowered by machine learning control mechanism is the fundamental technology enabler for creating a scalable quantum computing power in form of a quantum data centre. Such a datacentre comprises a network of multiple qubit processors. A quantum datacentre is also the basic building block for realising future quantum computing services in form of quantum cloud computing. Quantum cloud computing enables sharing of the computing power of the quantum data centre between multiple users and applications.

8. References

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