Entanglement Blocking in DLCZ-based Networks

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Abstract: Resource and performance dependent blocking mechanisms for entanglement routing in quantum networks are identified and characterized in simulations of a DLCZ architecture under different loss and resource availability conditions. © 2021 The Author(s)

1. Introduction

Recently, much interest has been directed toward realizing quantum networks that distribute quantum entanglement to enable distributed quantum computing. In these networks, photons carried in telecom fiber are entangled with quantum memories or registers and are used to perform operations such as quantum teleportation. Through purification and quantum error correction methods, these entanglement based processes can form quantum repeaters and extend quantum computing over long distances [1]. Recently the first experiment to show an entanglement bit rate above the rate loss limit was reported, an important step toward quantum repeater networks [2]. Although a number of different architectures and qubit technologies have been studied, most share similar basic processes such as the use of Bell state measurement for entanglement swapping and the coordinated transmission of entangled photons [3]. Recent studies have focused on the problem of routing entanglement through a network, which involves the scheduling of these processes to create entanglement between quantum memories along a path between two end nodes [4]. Depending on the technologies involved and system details, the entanglement routing can be very inefficient, requiring many parallel or time multiplexed transmission events. Various strategies to improve the entanglement bit rates have been proposed using analytical models for the entanglement probabilities [4, 5]. Other network control and management aspects of this problem also need to be studied considering the different qubit technologies, architectures, and network topologies or characteristics. In this work, we examine the blocking mechanisms that arise in the operation of such entanglement routing networks and their impact on network design and resource allocation. For this purpose, we developed a network simulation built on the Strawberry Fields simulator [6] for a Duan-Lukin-Cirac-Zoller (DLCZ) based entanglement distribution network [3]. Two different types of blocking mechanisms are identified and characterized through simulation.

The DLCZ architecture is composed of neutral-atom memories, which are entangled with photons using Raman interactions. Ensembles of neutral atoms, typically rare-earth atoms such as Cesium and Rubidium, are held in magneto-optical traps (MOT) and photons that are entangled with the atomic ensemble are emitted from the trap when stimulated by a read pulse. By performing a Bell state measurement (BSM) on the photons emitted from two such MOTs, the atomic qubit memories can be entangled. This process will succeed with probability $\frac{1}{2}p_c(1-p_c)^2(\eta_1+\eta_2)$, using a photon-number resolving detector (PNRD) in the BSM, where p_c is the probability that an entangled photon is generated in the MOT and η_1, η_2 are the optical losses including fiber propagation (see Fig. 1b) [7]. These 'line side' qubit memories also need to be entangled with other 'internal' or 'client side' qubits in order to perform teleportation or other quantum processing. This internal node entanglement can happen independently and prior to the line side entanglement operations. Furthermore, multiple line side photons can be emitted from a single qubit memory until a successful BSM result is recorded or the qubit memory lifetime expires and a new qubit needs to be created. In general, each qubit memory will support a finite number of entanglement attempts before the process must be restarted.

1.1. Entanglement Blocking

This process of entangling the internal qubits of two distant nodes introduces two distinct mechanisms that can cause entanglement routing to fail or to be blocked: *resource-dependent blocking* and *performance-dependent blocking*. Resource blocking is similar to wavelength blocking in classical optical networks in that the quantum memory or BSM device necessary to set up entanglement is already in use, preventing further entanglement events with that resource. Note that wavelength blocking on the fiber links generally does not occur in these systems because the transmitted photons are sent in pulses that must be precisely scheduled and therefore time interleaving and synchronization is built into the system. Thus, time slot blocking might occur, but continuous blocking of a wavelength is not expected. Performance blocking is analogous to impairment-based blocking in classical networks in that it results from noise or losses that cause the entanglement operation to fail. Performance blocking may also be dependent on a timeout mechanism or number of entanglement attempts limit and the finite qubit memory lifetime. The final qubit fidelities may also be have a fidelity threshold requirement. Repeated attempts or high noise levels can compromise the fidelity resulting in such performance-based blocking. It is important to note that these two very different categories of entanglement blocking mechanisms are also coupled by the network architecture. For example, optical switches can be used to allow flexibility in accessing different resources such as BSMs or memories, but they add loss that can lead to more performance based blocking.

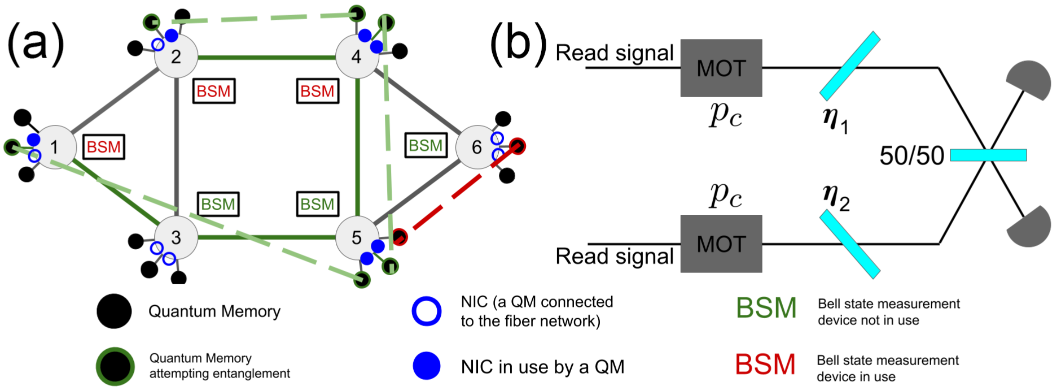


Fig. 1: (a) Network setup with pairs attempting entanglement(green dashed) and *blocked* connections (node 5 to node 6, red). (b) DLCZ simulation model for entangling line side NICs (MOT). A 'read' pulse is sent into each MOT to stimulate the release of a photon from the ensemble inside, which is then sent to the BSM. We take $p_c = 0.05$ in this work

2. Simulation Model

In order to better understand the different entanglement blocking mechanisms, we set up the DLCZ-based network simulation shown in Fig. 1. We separate internal quantum memories (QM) from line side quantum memories acting like a network interface card (NIC). Each node has 5 QMs, 3 NICs and 1 or no BSMs. The numbered nodes are optical switches that connect the QMs, NICs, and BSMs. The distances L between nodes are varied and losses correspond to standard single mode fiber.

We use `StrawberryFields` [6] to simulate the qubit operations in the nodes, reducing links to basic photonic quantum states being mixed and then detected on a photon number resolving detector (PNRD). Our simulation runs using the procedure outlined in Fig. 2a, where at each timestep every memory has a chance to make an entanglement request with another randomly selected memory (probability p_{req}). If a route exists, the request is added to a queue along with the optimal BSM device for the pair to use; otherwise it is resource blocked. The route is established by assigning a NIC to the connection at each end node and identifying a path through the network, which may traverse multiple nodes through the fiber switches. After the traffic is generated, at each timestep every pair from the queue performs one entanglement attempt via the channel model in Fig. 1. Using `StrawberryFields`, an entangled photon is created at each memory and transmitted to the designated BSM device. If the outcome of the Bell state measurement is successful, all allocated network resources for the pair are released as the teleportation between QMs is complete. Otherwise the node pairs will continue to attempt entanglement M times before a performance blocking event occurs and the network resources are released.

Several assumptions are made in this simulation: only transmission and switching losses are taken into account, the probability of success is only a function of the total losses between the MOTs and the BSM, and we approximate the states leaving the MOTs with a coherent state that maximizes fidelity with the true state.

3. Results and Discussion

Fig. 2b shows the ratio of the total number of blocked requests to the total number of attempts as a function of the maximum number of attempts M before performance blocking occurs. A total of 10^5 time steps are run for three distances L using the simulation parameters shown in the figure. At this very low request rate, blocking is almost entirely due to performance. Complete blocking occurs for a small number of attempts. As the number of attempts increases, eventually the blocking probability drops to a low constant value determined by the small probability of resource blocking. This transition requires more attempts for longer distances due to higher losses.

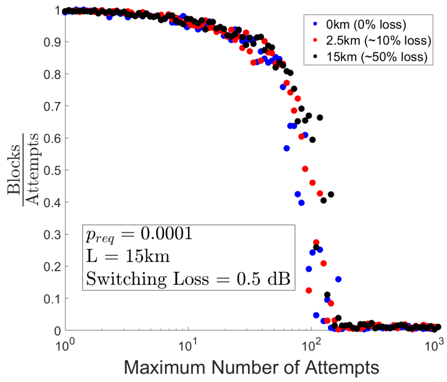
Increasing quantum network traffic demand or request probability will increase resource blocking. Fig. 3a shows the fraction of performance blocking to the total number of blocked requests as a function of the entanglement request rate.

In Fig. 3b, the fraction of blocking due to performance increases as the losses increase due to longer distances between the nodes, shown for different switch losses. As the switch loss increases the transition becomes less

Algorithm 1 Simulation

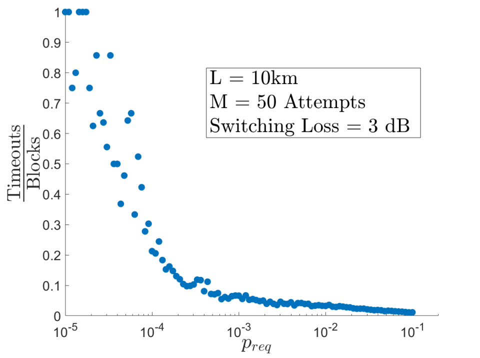
```
t=1
while t ≤ T do
  t → t+1
  for each QM do
    Generate 0 ≤ r ≤ 1
    if r < p_req then
      Pick 2nd QM randomly
      if chosen QMs are not already in use then
        if there is a BSM node along some path between them then
          Pick best path and add request to queue
        else
          Mark request as blocked and delete it
  for each request in the queue do
    Use StrawberryFields to simulate one entanglement attempt
    if only one photon is seen at the BSM node then
      Release hold on resources being used and remove request from queue
      Mark request as success
    else
      Decrement attempts remaining for this request
      if request has exceeded M attempts then
        Release hold on resources and remove request from queue
        Mark request as blocked
```

(a) The simulation algorithm

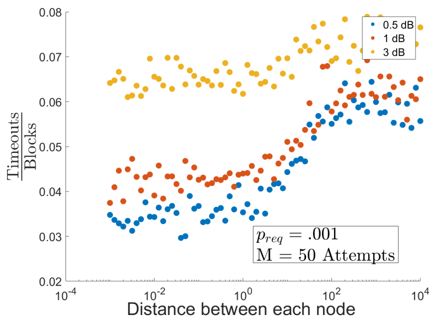


(b) Percentage of requests blocked

Fig. 2: (a) Entanglement establishment process during each timestep. (b) fraction of requests blocked due to performance blocking versus the maximum allowed attempts M



(a) Percentage of blocks that are timeouts vs p_{req}



(b) Percentage of blocks that are timeouts vs L (km)

Fig. 3: (a) Fraction of blocked attempts due to performance blocking for increasing entanglement request probability, p_{req}, (b) dependence of fraction of performance blocking on node distance (loss).

apparent as the switching loss dominates. In this case, BSMs were only available at two nodes in the network, which requires both longer transmission distances to reach the BSMs and lower availability of BSMs, increasing resource blocking.

In this work resource and performance blocking mechanisms were identified and characterized in DLCZ based entanglement distribution networks. These results provide an important starting point for the understanding of entanglement blocking and the relevant trade-offs involved in quantum network design.

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