Linear optical measurement-based quantum computation with gain tuning

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Any continuous-variable computation is accompanied by Gaussian noise that distorts the information in the system and requires specifically tailored error correction and fault tolerance schemes to be applied. We show that performing arbitrary linear optics gates via measurement-based quantum computation on an entangled resource state known as the quad-rail lattice can be modelled by a loss channel rather than by a Gaussian noise model. We do this by incorporating gain tuning into our system, which has been shown to convert a teleportation channel into a loss channel. Depending on the architecture or encoding of the system, a loss channel could be more suitable. For example, in the case where we encode a qubit with a single photon distributed between two modes. In this encoding, we show that we are able to achieve all single-qubit rotation operations within a loss channel framework.

Measurement-based quantum computation (MBQC) [1] is a well-established and highly pursued implementation of a quantum computer. In this model, a series of adaptive, single-qubit measurements on an entangled resource state (generally called a cluster state) are sufficient to perform any quantum computation. In the realm of continuous-variable MBQC [2], the cluster state is canonically realised analogously to the discrete-variable (qubit) case except the qubits are replaced by modes (infinite dimensional quantum states). The canonical implementation of such states is physically difficult to perform and not particularly scalable, motivating the use of an alternate implementation [3] which relies on less experimentally-taxing physical resources and has been recently demonstrated to be highly scalable [5]. We call the resource state for such implementations the *quad-rail lattice*. We can represent cluster states within a graphical framework [4]; in Figure 1 we depict a canonical continuous-variable cluster state (top) as well as the quad-rail lattice (bottom) graphically.

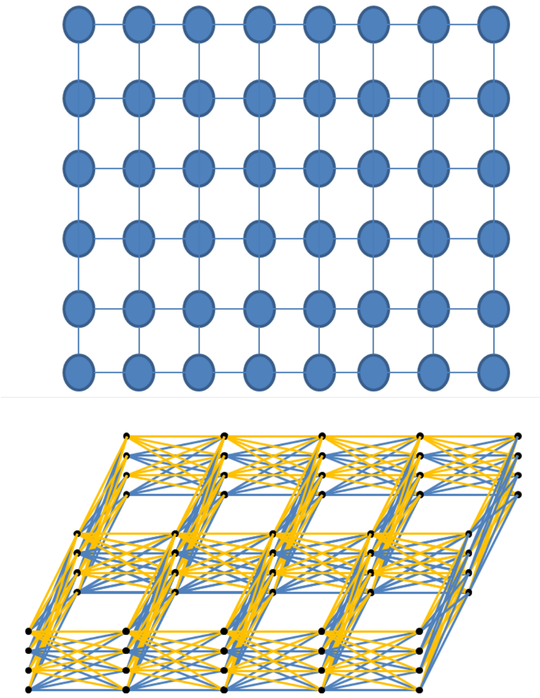

Figure : Graphical representation of the canonical continuous-variable cluster state (top) and the more physically-motivated quad-rail lattice (bottom). The details of this mapping can be found in [3].

A significant hurdle faced by continuous-variable implementations of MBQC is inherent Gaussian noise that is due to the fact that modes are approximations of ideal continuous-variable eigenstates. A well-known result in continuous-variable quantum teleportation is that by gain tuning (tuning the correction operator in the teleportation scheme) [6] a teleportation network can be modelled as a pure loss channel. There has been recent interest in hybrid models of computation [7], whereby gain tuning is used to achieve high fidelity teleportation of qubits which are encoded in modes. In Figure we illustrate the effect of a regular teleportation network (a) and a gain-tuned teleportation network (b) on an input coherent state. These illustrations emphasise that a loss channel simply reduces the numbers of photons in the state (according to some probability that is proportional to the squeezing parameter of the entangled resource state), while a Gaussian noise channel blurs the state in phase space.

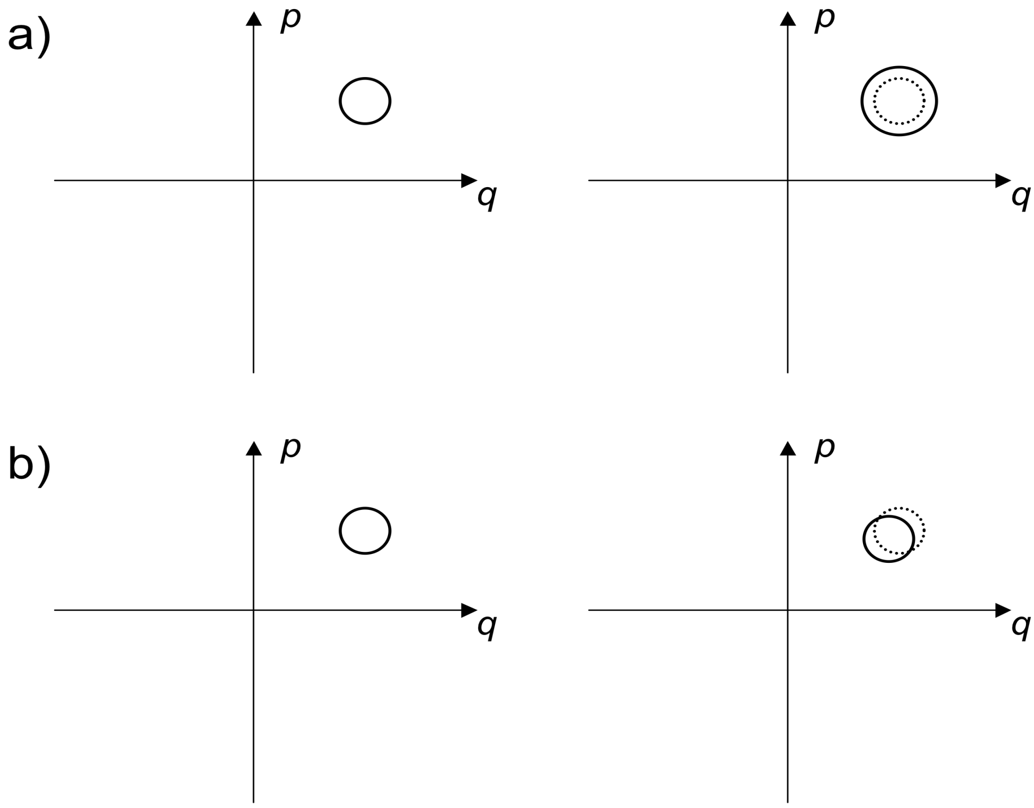

Figure 2: a) Phase space depiction of what a regular teleportation network does to an input coherent state. The left picture depicts the state before the channel while the right picture depicts the original state in dashed lines and the output state in black. As we see, noise has been introduced to the system and the coherent state shape widens. b) Phase space depiction of what a gain-tuned teleportation network does to an input coherent state. The left picture depicts the state before the channel while the right picture depicts the original state in dashed lines and the output state in black. As we see, the shape of the state has not changed but it has moved closer to the origin (lost photons). The degree of movement towards the origin is comparable to the size of the blur.

This work combines these two seemingly separate aspects of continuous-variable information science: the quad-rail lattice and the gain tuning result. What allows us to apply gain tuning to the quad-rail lattice is the fact that the quad-rail lattice can be interpreted as a teleportation network simply by a change of mode definitions [7].

We show that any series of linear optics gates (beamsplitters and phase shifters) can be implemented on the quad-rail in a way that utilises the gain-tuning result and allows for the computation to be modelled as a loss channel. To show this, we use interferometric symmetries of entangled Gaussian states to prove that each of the measurement schemes corresponding to these gates can be interpreted as a regular teleportation network followed by the unitary gates. This allows us to model a linear optics computation on the quad-rail lattice with a loss channel (rather than Gaussian noise).

A loss channel noise model could be advantageous when considering a qubit encoded within the quad-rail lattice. If we distribute a single photon between two modes of the quad-rail lattice:
$|\psi\rangle=\alpha|0,1\rangle+\beta|1,0\rangle$, the channel either destroys the single photon, leaving a vacuum state as output, or the photon 'survives' the channel and the teleported state is preserved with no Gaussian noise applied to it. The density matrix of the final state is thus: $\rho= \tanh^2 r \; |\psi\rangle\langle\psi| + (1- \tanh^2 r)|0\rangle\langle 0|$,

where r is the squeezing parameter of the entangled resource states. In the qubit mapping, a beamsplitter gate corresponds to a rotation about Y and the phase-shift gate corresponds to a rotation about Z. Our results thus imply that any single-qubit unitary can be applied on the quad-rail lattice within the loss channel noise model framework rather than with Gaussian noise. Our results motivate the investigation of error-detecting loss codes for MBQC with continuous variables as well as exploring hybrid models of computation and could potentially be applied to existing models of universal quantum computation that require linear optics gates, such as the KLM scheme [8].

References

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