Entangling unitary gates on distant qubits with ancilla feedback

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By using an ancilla qubit as a mediator, two distant qubits can undergo a non-local entangling unitary operation. This is desirable for when attempting to scale up or distribute quantum computation by combining fixed static local sets of qubits with ballistic mediators. Using a model driven by measurements on the ancilla, it is possible to generate a maximally entangling CZ gate while only having access to a less entangling gate between the pair qubits and the ancilla. However this results in a stochastic process of generating control phase rotation gates where the expected time for success does not correlate with the entangling power of the connection gate. We explore how one can use feedback into the preparation and measurement parameters of the ancilla to speed up the expected time to generate a CZ gate between a pair of separated qubits and to leverage stronger coupling strengths for faster times. Surprisingly, by choosing an appropriate strategy, control of a binary discrete parameter achieves comparable speed up to full continuous control of all degrees of freedom of the ancilla.

I. INTRODUCTION

The ability to harness quantum phenomena for information processing purposes underlies quantum computation (QC). There are several different underlying computation models, including gate-based [1], measurement-based [2], adiabatic [3] and topological models [4]. Their interest in not only due to their suitability to different physical substrates for implementation but also on a more fundamental level as to the sets of resources necessary or sufficient for universal QC.

Recently a subset of schemes have arisen based around the use of ancilla systems, such as the ancilla-driven [5, 6], ancilla-control [7] and quantum bus [8] proposals, where logical operations are generated by interacting the qubits of the main register with an ancilla system then performing operations on that ancilla system. The various ancilla schemes are distinguished by their differing requirements of the interaction between register and ancilla, the operations on the ancilla and the number of required interactions. For example, the ancilla-control scheme for implementing a single qubit unitary on a register qubit requires being able to perform that unitary on the ancilla [7]; the ancilla-driven scheme requires only arbitrary rotations about a single axis, provided the appropriate measurement basis is available for measurements on the ancilla [5].

Ancilla driven quantum computation is particularly suited to the use of hybrid physical systems [9, 10] where there is a memory register optimised for stability and long coherence times and a short lived but easily manipulated ancilla system such as NV centre nuclear-electron spins. The model of weaker or arbitrary interaction strength is suited for when the interaction is not tunable such as when dealing with scattering between flying and static qubits [11]. A stable memory register may be the product of a particularly well chosen physical system but also it could be due to the use of nodes of qubits that are engineered to perform error-correction and fault tolerance codes locally as in several proposals for networked quantum computation [12]. A distributed design may also aid in parallelising circuit design for a time speed up or in aiding scalability of a physical implementation [13, 14].

In these cases different local nodes of qubits may have to be connected by a different physical medium, such as a photon or coherent beam system [15]. Therefore it is useful to consider ancilla schemes in the context of distributed or networked quantum computation where non-local operations are applied over relatively large separations that inhibit coordination.

The problem of entangling a physically separated pair has been considered before with methods such as the Barrett-Kok double heralding approach [16] where entangled states are generated through projecting the system via photon pair measurements or Lim, Barrett et al [17]'s repeat-until-success method through Bell basis measurements. In contrast, the operation on the qubit pair in Ancilla Driven Quantum Computation remains a reversible, commutable unitary gate that also requires only single qubit measurements and does not require maximum entanglement with the ancilla. This means that the process can be used in frameworks other than the generation of cluster states for measurement based quantum computation and can use non-maximal ancilla-register interactions. However in the latter case, the process for generated an entangling gate becomes stochastic.

This paper examines the use of feedback of ancilla measurement results into subsequent generations. The application of control over the ancilla state is also used to speed up this stochastic process and to make it behave according to a well defined statistical behaviour. This occurs in the broader theme of how we can trade off the requirement of some resources at a cost of an increased time to implement specific operations.

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II. ANCILLA DRIVEN OPERATIONS

In an ancilla driven model, a qubit in a memory register interacts with an ancilla qubit in a prepared state, then the ancilla is measured and the resulting back-action on the register is unitary depending on the parameters of the preparation, interaction and measurement. If the interaction is locally equivalent to $e^{-i\frac{\pi}{4}\sigma_z\otimes\sigma_z}$ (CZ type) or $e^{-i\frac{\pi}{4}(\sigma_x\otimes\sigma_x + \sigma_y\otimes\sigma_y)}$ (CZ.SWAP type) then one can generate an arbitrary rotation angle $\beta$ on the register qubit by performing a rotation by $\beta$ in the ancilla before measurement. E.g. Using a CZ gate and an ancilla prepared in the $|+\rangle$ state, performing a rotation about the $\hat{z}$ axis, $R_z(\beta)$, on the ancilla then measuring in the 0/1 basis; this enacts $Z^j R_z(\beta)$, where $j = 0, 1$ is the measurement result, on a single register qubit.

Rotations about a single axis will of course not be able to generate any arbitrary single qubit unitary. However if the interaction is $(H_A \otimes H_R).CZ$, where we have included Hadamard local gates as part of the interaction, then by accounting for the extra local effects on the ancilla by applying $J(\beta) = H_A e^{-i\frac{\pi}{2}\sigma_z}$ instead before the measurement, $X^j J(\beta)$ acts on the register. The class $J(\beta)$ allows one to feedback the measurement results to commute through the Pauli correction into a single post-correction and to apply any single qubit unitary (up to global phase), $U \equiv J(0)J(\alpha)J(\beta)J(\gamma)$ for some $\alpha, \beta, \gamma$ [18].

Crucially, by applying this same interaction between the ancilla and two subsequent register qubits, a CZ gate can be generated on the register, up to local gate corrections, thus providing the resources for universal quantum computation.

However if the interaction is instead equivalent to $e^{-i\alpha \sigma_x \otimes \sigma_x}$ or $e^{-i(\alpha \sigma_x \otimes \sigma_x + \alpha' \sigma_y \otimes \sigma_y)}$ for $0 < \alpha < \frac{\pi}{2}$ then the rotation angle $\beta$ remains random in a way without simple post-corrections [19]. This applies also for the two qubit entangling gate: a gate locally equivalent to a Control $\gamma$ rotation, $C(\gamma)$, is generated with random $\gamma$ depending on the measurement result.

It may however be possible to generate a chosen $C(\gamma)$ gate if a probabilistic achievement time is allowed. Any gate generated by the use of a connection interaction in the local equivalence class of $e^{-i\alpha \sigma_x \otimes \sigma_x}$ will also be able to be diagonalised in the computational basis by local unitary gate operations. If the local operations can be directly created, or created by the use of well engineered qubits and interactions in a local node, then the diagonalised products of each generation will all commute and the random behaviour will map to a random walk on a circle. The gates generated would be of the general form $\text{diag}(e^{i\theta_1}, e^{i\theta_2}, e^{i\theta_3}, e^{i\theta_4})$ which is locally equivalent to a Control-$R_z(\Phi)$ gate where $\Phi = \phi_4 - \phi_3 - \phi_2 + \phi_1$. The angles are mapped to a point on a circle. So at each time interval, an angle is randomly gated to represent the gate generation and is added to the sum of all previous gate generations; if the new sum lies with a target region, given by $\pi \pm \epsilon$, for some chosen error $\epsilon$, the operations are halted.
III. UNGUIDED BEHAVIOUR OF RANDOM GENERATION

The probabilistic nature of the generation of gates in this scheme leaves us with the problem of understanding the statistics of the time it takes to reach any arbitrary gate.

We simulated the creation of a CZ equivalent gate by use of the circuit in figure 3 with the choice of $U_1=I$, $U_\alpha = R_x(\frac{\pi}{2})$ and $U_\rho = H$ i.e. preparation and measurement in the $X$ eigenstate basis. These settings are not unique to the gates generated. This was performed 10,000 times, with an error bound of $\pi/100$ and the resulting distribution is displayed in figure 4.

The distribution of hitting times, when put into sufficiently broad bins, can be described by an exponential tail. One of the results is an irregular angle that depends on the coupling strength while the other is $\pi$-dependent. Using the mean hitting time is 74.1, the standard deviation is 74.5.

IV. STRATEGIES FOR GUIDED GATE GENERATION

In the ancilla-driven scheme, an ancilla is prepared in a specific basis, undergoes an interaction with one register qubit using a specific connection interaction, the ancilla is then interacted with the second register qubit and then measured in an appropriate basis. The ancilla is controlled by the choice of preparation state and measurement basis provided that any local unitary actions on the ancilla in the intermediate time between interactions account for the conditions for a unitary, entangling generated gate on the register. This restriction results in only two degrees of freedom. In the context of a spatially separated pair in a distributed network, the two parameters can be seen as one requiring the preparation of the ancilla performed by Alice and the other the measurement performed by Bob. If you have only 1 degree of freedom then the task of setting up the strategy can be placed on only one partner. Alice could prepare a sequence of qubits and then send them to Bob. Bob then only has to measure them in a fixed basis with minimal instructions about what to do after a certain measurement result. We also consider how a strategy might affect the complexity of Bob’s instructions. Since Bob only has two measurement results, he must at some point receive a string of binary with the instruction to stop at the point when the instructions don’t match the string; perhaps those so interested could examine all possible strings and the entropy of instructions for particular strategies, we will just be focusing on a question surrounding a simple case where the stopping condition is always the same measurement result for Bob. If Bob was looking for signals coming out of two ports, Bob would just wait until he one of those ports thus we call this a “one port” strategy. This might also be important in an experimental context if the measurement process is prone to a particular measurement bias.

So we consider

- What if we have control over only 1 degree of freedom instead of 2?
- What if we use only 1 port instead of 2?

The distribution of hitting times, when put into sufficiently broad bins, can be described by an exponential tail distribution of hitting times in the case without feedback, we expect that an important feature of the hitting time statistic is the minimum number of steps required to create a finite probability of hitting the target. In the following section, we discuss strategies based around the principle of optimising the probability of success in a minimal number of steps. Because there is always a probability of generating CZ with any coupling by preparation and measurement in the $X$ eigenstate basis, it is possible to perform a “one step” strategy: maximise the probability to hit the target in the next step.
Since the process is probabilistic, we are interested not just in the expected number of ancilla one side may have to send to another but more the total number that have to be prepared to ensure a certain probability of success. This also can be seen as a division of tasks- Alice prepares a number of ancilla qubits such that \( P(n < N) \geq 0.999 \) and transmits them to Bob who then has to carry out the instructions for when to stop permitting the ancilla to interact with his qubit. Based on approximately geometric behaviour, the expectation time is linearly inverse to the probability per time interval and naturally linear with the time interval. So if the time interval is increased by \( n \) steps, the probability needs to be increased by \( n \).

The value of \( N \) can also be approximated by a linear multiple of the expectation value so they enforce a restriction on when a “multi step” strategy is viable- a two step strategy should double the probabilities and so on.

A. The one step strategy

At each step set the conditions so that one measurement result generates a gate which corresponds to the angle difference between the present point on the circle and the point \( \pi \). If this measurement does not occur, find the distance between the present point and the point \( \pi \) and attempt to generate that gate. Upon every failure, find the new distance between the target and the current point and attempt to generate that gate.

![FIG. 5: The probability tree of the “one step” strategy. The first step will always require generating a CZ equivalent gate, the other result will be dependent on the coupling and will then dictate all future conditions. The conditions are reset at each step with each new ancilla.](image)

Understanding the setting of the conditions of the gate generation can be understood with a minor review of the Bloch sphere picture of the entanglement condition (see figure 6). Since the non-local part of the Cartan decomposition of the connection interaction is diagonal in the computational basis, the ancilla before measurement has evolved as \( |a\rangle \sum_{ij} c_{ij} |i\rangle |j\rangle \rightarrow \sum_{ij} |a_{ij}\rangle |i\rangle |j\rangle \). The final states \( |a_{ij}\rangle \) will be

\[
\cos \left( \frac{\theta - (-1)^j 2\beta}{2} \right) |0\rangle + e^{i(-1)^j 2\alpha} \sin \left( \frac{\theta - (-1)^j 2\beta}{2} \right) |1\rangle
\]

These will map to four points on the Bloch sphere. The angle \( \beta \) must be set by operations before and after the first interaction, the angle \( \theta \) is set before the second interaction and must be known so that a measurement can be applied which is mutually unbiased to all four points.

Given any coupling strength, at the start of the strategy, the first attempt to generate \( CZ \) is performed the same way: the ancilla is prepared in the \( + \) state and then measured in the \( |\pm\rangle \) basis with the “-” (port 1) result generating a gate equivalent to \( CZ (C(\pi)) \). The “+” (port 0) result would generate a blow back gate \( C(\Phi_0) \).

There is a sense of direction with the gate generation; one port gives \( C(-|\Phi_0\rangle) \), the other \( C(+|\Phi_1\rangle) \), clockwise or anticlockwise around the circle that represents the \( C(\gamma) \) group. One can simply switch the direction association of the ports by performing a bit flip either immediately before or after transmission from Alice to Bob, so we will ignore the exact sign requirements in the notation from here on and simply note the need to flip. Having trav-
eled “clockwise”, the best next step is to continue in that
direction and generate $C(\pi - \Phi_0)$. If $\Phi_0$ is small then
$\pi - \Phi_0$ will be large enough that it can only be generated
from port 1, the port with larger $\Phi$ but smaller proba-
bilities upper-bounded by $\frac{1}{2}$. Another feature of port 1 is
that the probability increases as the preparation and
measurement variables $(\beta, \theta)$ are increased and for a fixed
$\Phi_1, \theta$ increases with $\beta$. Therefore the for optimal proba-
bility, it is only needed to fix one of these parameters to
the maximum and vary the other. So an 1 port strategy
is effectively also a 1 degree of freedom strategy where
the only task is finding the gate and the parameters for
the next step.

At every step $n$, there is one gate that matches success
$C(\Phi_{1,n})$ and a failure gate $C(\Phi_{0,n})$, therefore to be at step
$n$, the current action on the register system is the product
of previous failures $C(-\Phi_{0,1} + \Phi_{0,2} + ... + \Phi_{0,n-1})$. The
next gate to be generated for success must be $C(\pi - (\Phi_{0,1} - \Phi_{0,2} - ... - \Phi_{0,n-1})$.

The magnitude of the angle $\Phi$ of both ports increases
with the probability of success of $\Phi_1$. So because the
largest angle to be generated is $\pi$ in the first step, the first
step has the highest probability of success and also the
highest value of the failure gate $\Phi_0$. Therefore $\pi - |\Phi_{0,1}|$
is the smallest value and has the smallest probability of
success. These two first values provide a bound on the
behaviour of the strategy. The cumulative distribution
function based measure, $P(n < N)$, can be compared
to the CDF of constant probability for each step using
the extreme probabilities: $1 - (1 - p_2)^n < P(n < N) < 1 - (1 - p_1)^n$.

This also means that the first step provides the thresh-
hold for when a two port strategy is viable: when is
$\pi - |\Phi_{0,1}|$ small enough that it can be generated from
port 0? Since $\Phi_{0,1}$ is also the maximum $\Phi_0$, it must be
when $\Phi_{0,1} = \frac{\pi}{2}$. Port 0 has a different $(\beta, \theta)$ for fixed
$\Phi_0$ relationship and it’s probabilities are optimised away
from the fixed measurement conditions so this is also the
threshold for when a 2 degree of freedom strategy can be
involved.

B. The “flip-undo” strategy

Up until now we have discussed the ability to manip-
ulate the ancilla with the assumption that we can ex-
ercise any arbitrary single qubit unitary gate. This is
in line with the requirements of the ancilla-driven and
ancilla-control schemes. However we have also developed
a scheme for exploring what can be done with as simple
an action on the ancilla as possible: we have only avail-
able to us a fixed preparation state, a fixed measurement
basis and the choice of whether or not to implement a bit
flip gate, $X$- specifically the bit flip required to change
the sense of direction of the ports. What this provides
is the ability to attempt to undo a previous action hence
the designation the “flip-undo” strategy.

After attempting to generate a $C(\pi)$ gate in a single
step, if the result failed, attempt to go back to the origin.
Whether you have arrived at the origin or not, attempt
to generate a $C(\pi)$ gate with the product of the next
generation. If one fails again, repeat the process from
the second step. Repeat until success.

![FIG. 7: The probability tree of the “flip-undo” strategy re-
ceives all possible points in the strategy after 2 steps. After
the first step, it can be seen as a repeat-untił-success strategy
where the time to repeat is 2 gate generations.](image)

The inspiration for this scheme comes from question-
ing why the two qubit gate is equivalent to $C(\gamma)$ and not
$C(-\gamma)$. The answer comes from the Bloch sphere picture
of the four possible states of the ancilla after interaction
and their orientation. In the middle of the procedure, it is
only two states dependent on the first register qubit:
$\sum_i |a_i\rangle |i\rangle \sum_j c_{ij}^* |j\rangle$. On the Bloch sphere, these will be
two points, one above the other on the same vertical
plane, in order for the conditions for the gate to be uni-
tary and entangling to be fulfilled. Which is above which
determines the sign of the rotation angle. So if one was
able to flip the orientation the sign would change. This
can be done by introducing an $X$ gate on the ancilla in
between the two connection interactions.

It should seem obvious that in a case where either $C(\pi)$
or $C(\gamma)$ is generated and the target is $CZ = C(\pi)$ that it
is preferable to label a result $C(\gamma)$ a failure and attempt
to undo it in order to try again to generate $CZ$ directly.
Yet that then creates a possible result where the sequence
product is $C(\pi)C(\gamma) = C(\pi + \pi)$. Again the apparent
best decision is to attempt to undo $C(\gamma)$ as this will now
immediately lead to the target gate. In the following step,
the only two possible product sequences must result in
$C(\pi)$ or $C(\gamma)$ which makes employing this strategy form
a closed loop.

Now that there is a description and probability tree
for a finite number of points on the circle, we can find an
exact description of the time statistics using the recursive
relationships between the expectation times at different
points, if we take the probability of generating $C(\pi)$ in the first step to be $p$:

\[
\hat{n} = p + (1 - p)(\hat{n}_1 + 1) \\
\hat{n}_1 = p(\hat{n}_2 + 1) + (1 - p)(\hat{n} + 1) \\
\hat{n}_2 = p(\hat{n} + 1) + (1 - p) \\
\Rightarrow \hat{n} = 1 + \frac{1}{p}
\]

Another way to look at it is that after the probability of success in the first step, there is a 2 step time interval which results in a probability of success of $2p(1 - p)$ which can be repeated. So an exact geometric distribution tail is formed where the expected time is $2\frac{1}{2p(1-p)}$ and so $\hat{n} = p + (1 - p).\left(\frac{1}{p(1-p)} + 1\right) = 1 + \frac{1}{p}$. The cumulative density function is given by $1 - (1 - p)(1 - 2p(1 - p))^k$ where the number of transmitted ancilla qubits is $2k + 1$.

V. NUMERICAL RESULTS

We found the parameters and resulting probabilities for continuing with the one-step strategy for 500 steps for a range of coupling strengths of the connection interaction. The full range for $0 < \alpha < 2\pi$ was covered for the 1 port 1 degree of freedom strategy where the degree of freedom was represented by the preparation parameter $\beta$. We then found more values for the range of coupling strengths that starts just before the threshold for the two port strategy. In this range we then found the values for a two port strategy where one could only vary $\beta$ and perform no optimisation of port 0 and then found them again for when optimisation over $\beta$ & $\theta$ is allowed. Finally we checked for just the one port strategy, the probabilities for each step when the measurement parameter is the allowed degree of freedom rather than the preparation and this did turn out to give the exact same results.

The order of improvement between different one-step strategies is less than a single step in the expectation time. The 1 port strategy tends towards an expectation number of 2 while the 2 port/ 2 degree of freedom strategy tends toward 1.5 ; the 2 port/ 1 d.o.f. approach has a peak in improvement near the middle of the range but at very close to the maximum coupling returns back to the 1 port strategy. This scale of improvement can be expected from the behaviour of the probability of either port. As $\alpha \rightarrow \frac{\pi}{2}$, $\Phi_{0,1} \rightarrow -\pi$, $\tau - |\Phi_{0,1}|$ becomes very small and thus the probability out of port 0 in the second step tends to 1. Any consideration of multi-step strategies in this range is therefore of limited advantage; the behaviour where failure in the first step improves the probability of success in the second step which we would expect to be a feature of any two step strategy is already a feature of the one step strategy with two ports and access to both parameters.

The viability of a multi-step strategy at the lower coupling step range can be examined using the lower bound on the probabilities of success in each step found from the probability in the second step. This value describes the behaviour of a geometric distribution that bounds the behaviour of the one step strategy; for a multi-step strategy to be effective it must at least improve upon this and since a multi-step strategy takes place over $n$ steps, it must improve the probability by at least a factor of $n$ yet this will be limited by the maximum value of 1. In figure 11 we can see what the maximum possible number of steps for a multi-step strategy could be for any improvement to be possible.

The most striking result is that the “flip-undo” strategy has very little cost in the expectation time com-
FIG. 10: A comparison of strategies for different numbers of degrees of freedom at high coupling strengths. The solid red curve represents the 1 port/1 d.o.f. approach, the dotted black curve is the 2 port/1 d.o.f. strategy and the dashed blue curve is the 2 port/2 d.o.f. strategy. The threshold occurs at approximately $0.73\frac{\pi}{4}$.

FIG. 11: The maximum number of steps in a strategy as allowed by the hard limit of $\frac{1}{p}$ for a given coupling, displayed over the top half of the range of coupling strengths. Compared to the one-step strategy. The gap between it and the 1 port approach only approaches a maximum of one step however the effect is more significant when considering the minimum number of ancilla required to secure $P(n = N) \geq 0.999$ but the relative effect is diluted as the coupling strength gets weaker.

VI. CONCLUSION

In summary, we have analysed a implementation of a maximally entangling gate between distant qubits mediated by interaction with flying ancilla with an arbitrary but fixed coupling strength. Due to the stochastic nature of the measurements and the non-determinism of the induced gate sequence, the time required for success is random [19]. By use of feedback on the ancilla preparation or the measurement basis, some improvements can be made over a stationary random walk strategy.

We have examined how the addition of local unitary gate control on the ancilla qubit can speed up the expected time for implementation and reduce the total number of ancilla qubit required for a given fidelity. What has been found is that the improvement from control over additional degrees of freedom is small which may be important in the context of distributed or networked quantum computation.

If the task is distributed between two separated devices, co-ordination between the devices only allows for some speed up past a threshold coupling strength. The eventual speed is small and indeed the benefits of applying any control and feedback can be mostly realised by the inclusion of only one single extra operation on the ancilla: the ability to choose to apply a bit flip. The dominant factor appears to be the group structure of the gates that are generated during the process and the ability to apply a bit flip to the ancilla ensures that only four possible gates can be generated which leads to a speed up over the generation of a continuous group.

Yet to be investigated are using interactions of the class $e^{-i(\alpha_x \sigma_x \otimes \sigma_x + \alpha_y \sigma_y \otimes \sigma_y)}$ to generate gates in its own class. However the abelian structure and single parameter of the $C(\gamma)$ gates has been a large part of the simplification of the analysis and possible speed up and one would expect that by having a two-parameter target, one would square the order of the expectation times. A two parameter interaction would be better created by applying two single parameter interactions with local unitary gates between them.

The strategies employed seek to minimise the communication between two parties attempting to generate a shared entangling gate. The strategy can be worked out by A and instructions transmitted to B before sending any ancilla; the local post-corrections can be commuted through so B’s instructions can be transmitted after all have been sent. This allows us to envisage a scenario in which A sends B a packet of $N$ ancillae where $P(n < N) \geq 0.999$. This avoids latency in classically transmitting results and instruction between ancillae. This does however require that any potential implementation allows for B to be able to feed the ongoing measurement results into a pre-interaction local operation in some strategies. Once B has hit the target gate, B would have to be able to prevent further interactions (whether by turning the interactions off or applying an appropriate pre-correction) for the rest of the ancillae in the transmitted packet. Thus times allowing for local corrections will limit the transmission rate. Considering the minimal speed up from doing otherwise, this speaks to the advantage of keeping to a one degree of freedom strategy.
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