

Transferring Entanglement Between Different Dimensions

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Abstract

Quantum random walks have been an area of significant interest over the past two decades within quantum computation and information. They exhibit many desirable qualities that aid quantum computations and are extremely versatile for use in the design of quantum algorithms. In this report I analyse a recent publication that uses quantum walk dynamics in order to generate higher dimensional entangled states.

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1 Introduction

Quantum computing is an area of intense active research, with its sensational results often making it into mainstream media. Loosely speaking, it is a field that seeks to examine how quantum phenomena can be exploited to allow for greater and more powerful computations than currently possible using classical computers. Many schemes for quantum computation utilise qubits, the quantum analogue of the bit which is the unit of information in classical computing. The main difference between the bit and the qubit, is that the bit can only exist in one of two states at any one time, whereas the qubit, due to its quantum nature, can exist in superposition of both the possible states. Other models utilising qudits, which exist in superposition of d states rather than just two, have been proposed as they can unlock further advantages at the cost of being more complex to implement physically.

In addition to superposition, another well known quantum phenomena that is often taken advantage of in quantum computing is *entanglement*, correlations present in quantum systems that are far stronger than possible to find in classical systems. There are a variety of protocols that require the presence of entangled qubits in order to achieve results not possible with classical computers, for example superdense coding [1], quantum key distribution [2] and quantum teleportation [3]. Higher dimensional entanglement, entanglement between qudits, further enhances the power of quantum algorithms, for example superdense coding. As such the ability to possess and manipulate entangled states in higher dimensions has further benefits but again comes with its own challenges.

Quantum walks (QWs) are powerful tools in the landscape of quantum computing. Much like their classical analogues, they exhibit many properties that are desirable for computations and are an extremely useful building block for many algorithms designed for quantum computers [4]. Specific research interest into the quantum variant stems from their very significant divergences from the classical, including different spreading speeds and ability to traverse multiple paths at once. Their power is such that QWs can simulate any quantum computation and therefore are a model for universal quantum computing [5]. There is also evidence of robust performance even when the quantum computer is not perfectly isolated from its environment, and in certain situations it has been shown that decoherences due to interactions with the environment is beneficial for a given computation [6]. Quantum walks are divided into two categories, *discrete* and *continuous* time, these labels describing the nature of the evolution of the walker as the quantum walk progresses. Continuous time QWs have been shown to solve a wide range of problems in a number of different settings, in some cases exponentially faster than a classical computer is able to [7].

A potential solution to the demanding task of generating higher dimensional entanglement has been proposed [8] which uses the dynamics of discrete QWs to transfer lower dimensional entanglement between qubits, which is far simpler to generate, into the high dimensional qudits. Whilst this scheme can be used to some moderate degree of success, I will present an alternative devised to operate in a similar setting but utilising ancilla-based quantum computing (AQC) to instead transfer entanglement optimally.

In this report, a primer on entanglement, and two models of quantum computing, quantum walks and ancilla-based quantum computing, is given in section 2. Following this, section 3 will focus on the protocol that uses discrete QW dynamics to facilitate the transfer of entanglement, in particular analysing its efficiency in achieving the aim of entanglement transfer. The AQC scheme for entanglement transfer is presented in section 4. Further uses of the AQC scheme beyond the transfer of entanglement are also presented in this section. Finally, a discussion on the results presented in the report, further work and a brief summary is presented in section 6.

MOVE TO WHEN NEEDED As mentioned above, discrete time quantum walks are much more suited for the purposes of this report, therefore future references to quantum walks will be assumed to be the discrete variant unless stated otherwise. We will also use QW to denote (discrete) quantum walk. MOVE TO WHEN NEEDED

2 Background

2.1 Quantum Computation

2.1.1 Qubits

A qubits can be described by a state belonging to a Hilbert space \mathcal{H} of dimension two. A common basis for \mathcal{H} is *computational basis*, labelled by $|0\rangle$ and $|1\rangle$. Naturally we can also use other bases for describing our qubit state. A common alternative is the basis $\{|+\rangle, |-\rangle\}$. This basis is best known as the *Hadamard basis*, as $|+\rangle$ and $|-\rangle$ are equal to $H|0\rangle$ and $H|1\rangle$, where H is the Hadamard transform given by

$$|+\rangle = H|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \quad (1)$$

$$|-\rangle = H|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle). \quad (2)$$

Qubits can also be written out in vector form, and the most common choice for this is to assign the computational basis states as

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \quad (3)$$

Therefore the Hadamard transform and associated basis states are given by

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (4)$$

$$|+\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}, |-\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix}.$$

2.1.2 Qudits

In quantum computing, or indeed classical computing, there is no physical constraint that necessitates the use of two level qubits or bits. In classical computing, the bit can be generalised to a unit that takes on one of d states, known as the *dit*. Similarly, the quantum

dit is the *qudit*, which can be in superposition of up to d states. Many aspects of quantum computing specific to qubits generalise nicely to qudits. The computational basis is now extended from $\{|0\rangle, |1\rangle\}$ to $\{|i\rangle\}_{i=0}^{d-1}$. To distinguish kets representing belonging to Hilbert spaces of different dimension, the notation $|\cdot\rangle_d$ will be used to denote a state belonging to a Hilbert space \mathcal{H}_d where denotes a Hilbert space of dimension d . For compactness, operators will not have their dimension explicitly labelled, since they belong to the same Hilbert space as the state they are acting on. Similar to qubits, there are many different bases that can be used to describe our qudit states. The d dimensional analogue to the Hadamard transform is the *quantum Fourier transform* is given by

$$F|x\rangle_d = \frac{1}{2^{\frac{d}{2}}} \sum_{y=0}^{d-1} \omega^{xy} |y\rangle_d, \quad (5)$$

where $\omega = e^{i\frac{2\pi}{d}}$, i.e. it is the d^{th} root of unity. Therefore the Fourier basis can be generalised to the set of states $\{|+_i\rangle\}_{i=0}^{d-1}$, where

$$|+_i\rangle_d = F|i\rangle_d. \quad (6)$$

Note that in the case $d = 2$, $F = H$, hence the Hadamard transform is actually a quantum Fourier transform.

Again, qudits can also be written as vectors, with the computational basis states again assigned as

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \\ \vdots \\ 0 \end{pmatrix}, \dots, |d-1\rangle = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 1 \end{pmatrix}. \quad (7)$$

The Fourier transform can also be given as the matrix

$$F = \begin{pmatrix} 1 & 1 & \dots & 1 \\ 1 & \omega & \dots & \omega^{d-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \omega^{d-1} & \dots & \omega^{(d-1)^2} \end{pmatrix}, \quad (8)$$

and the associated Fourier basis states are found by applying the matrix representation of F to the computational basis state vectors.

2.1.3 Collections of Qudits

Qudits considered in isolation are not overly useful for quantum computations and in general a collection of qudits is needed for a given algorithm. The Hilbert space of a collection of n qudits, which are not necessarily all of the same dimension, is found by taking the tensor product, \otimes , of the Hilbert spaces of each of the individual qudits

$$\mathcal{H} = \mathcal{H}_{d_0} \otimes \mathcal{H}_{d_1} \otimes \dots \otimes \mathcal{H}_{d_{n-1}}. \quad (9)$$

The computational basis state for the combined Hilbert space is found by taking all possible tensor product combinations of the basis states for each constituent Hilbert space. The state

$$|0\rangle_{d_0} \otimes |0\rangle_{d_1} \otimes \cdots \otimes |0\rangle_{d_{n-1}} \quad (10)$$

is an example of such a basis state. Notationally, this state can be further simplified by the omission of the tensor product symbol,

$$|0\rangle_{d_0} |0\rangle_{d_1} \cdots |0\rangle_{d_{n-1}}. \quad (11)$$

If the kets are of the same dimension then this can be further compactified by contracting them,

$$|0\rangle_d |0\rangle_d \cdots |0\rangle_d = |00 \dots 0\rangle_d. \quad (12)$$

Since tensor products distribute over sums, when combining states in superposition they must also be distributed over. For example with two qudits,

$$(|0\rangle_d + |1\rangle_d) \otimes |2\rangle_d = (|0\rangle_d + |1\rangle_d) |2\rangle_d \quad (13)$$

$$= |02\rangle_d + |12\rangle_d \quad (14)$$

Recall also from the properties of the tensor product that it is not commutative, therefore care must be taken in ensuring that the order of qudits is preserved throughout,

$$|01\rangle_2 \neq |10\rangle_2. \quad (15)$$

In this report all three notational methods are used, with clarity given due preference over compactness. The subscripts are often dropped when the meaning is clear.

2.1.4 Operators

There are a wide variety of other operators beyond those introduced above that equate to a change of bases. One of the most common is the (Pauli) X , or NOT, operator. As the second name implies, in the qubit setting acts in the same way as the classical NOT operator,

$$|0\rangle \mapsto |1\rangle \quad (16)$$

$$|1\rangle \mapsto |0\rangle. \quad (17)$$

More generally in the qudit setting,

$$X |i\rangle_d = |i + 1 \bmod d\rangle_d. \quad (18)$$

However, there are other gates that do not have a classical analogue such as the the (Pauli) Z gate. In the qubit setting acts Z as the identity on $|0\rangle$ and applies a relative phase to $|1\rangle \mapsto -|1\rangle$. Again this can be generalised to the qudit setting

$$Z |i\rangle_d = \omega^i |i\rangle_d, \quad (19)$$

where ω is again the d^{th} root of unity. Both of these operators are sometimes referred to as Pauli operators as their matrix representations in the computational basis are given by the Pauli matrices σ_x and σ_z . There is also the Y operator corresponding to the Pauli σ_y matrix but this is often omitted from consideration as

$$ZX = iY. \quad (20)$$

Hence when designing a set of operators for a quantum computer, there is no theoretical need for Y as it already exists up to a global phase, which is essentially irrelevant. The final operation to be introduced in the section is the $C-U$, or controlled- U operator, where U is any unitary operation. This operator is distinct from the others previously introduced in that it acts on two qudits rather than just one, although it only directly alters the state of one of the two qudits. In the qubit setting, one qubit is designated as the control qubit and the other the target. If the control qubit is in the state $|0\rangle$, then nothing happens to the target qubit. If the control qubit is in the state $|1\rangle$, then the operator U is applied to the target qubit. Written mathematically, where the left hand qubit is the control, the right hand qubit is the target in some arbitrary qubit state $|\psi\rangle$,

$$C-U(|0\rangle \otimes |\psi\rangle) = |0\rangle \otimes |\psi\rangle \quad (21)$$

$$C-U(|1\rangle \otimes |\psi\rangle) = |1\rangle \otimes U|\psi\rangle. \quad (22)$$

To extend this to the qudit setting, first note that equations 21-22 can be compactly written as

$$C-U(|x\rangle \otimes |\psi\rangle) = |x\rangle \otimes U^x |\psi\rangle. \quad (23)$$

This equation now is well-defined for qudits, where instead of just taking values 0 or 1, x can now take values from $\{0, 1, \dots, d-1\}$. Note that this definition applies also when the dimensions of the control and target are not equal, provided that the action of U on the target is well-defined

$$C-U(|x\rangle_d \otimes |\psi\rangle_{d'}) = |x\rangle_d \otimes U^x |\psi\rangle_{d'}. \quad (24)$$

In this report, unless otherwise stated, it is assumed that control qudits are always on the left and target qubits on the right.

It is sometimes necessary to have operators that act on single qudits in a collection of n qudits. These can be expressed by taking the tensor product with the identity acting on the other qudits in the collection. For example, the operator that acts with an X on the qudit of index 1 in the state $|\psi_0\rangle \otimes |\psi_1\rangle \otimes |\psi_2\rangle$ is given by

$$I \otimes X \otimes I. \quad (25)$$

2.1.5 Circuits and Gates

When describing a circuit that implements a series of operators on our qudits, it is often much clearer and simpler to use a circuit diagram. Straight lines in the circuits represent qubits/qudits. Operations on qudits are represented by gates placed on the straight lines





Operator	Gate
(Pauli) X	
(Pauli) Z	
Hadamard	
QFT	

Table 1: Table of operators and their gate representations in quantum circuits.

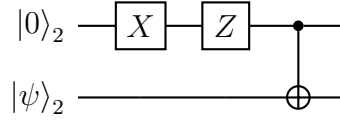


Figure 1: An example of a circuit schematic representing the expression given in equation 26.

corresponding to the qudits we wish to act on. A table of gates relevant for this report is given in table 1.

When reading a circuit, time flows from left to right and a gate must finish its operation on a qudit before the next gate on the same qudit is enacted. Figure 1 is an example of a two qubit circuit implementing the following series of operations

$$C-X(Z \otimes I)(X \otimes I)(|0\rangle_2 \otimes |\psi\rangle_2). \quad (26)$$

2.2 Entanglement

Entanglement is a property of quantum systems that is the source of many of the remarkable results displayed by quantum algorithms. Essentially it is the presence of correlations in a quantum system that is stronger than possible classically. Although entanglement can exist between multipartite systems, such as in the case of GHZ states or W states, in this report only bipartite entanglement will be discussed. Therefore, all references to entanglement are specifically referring to bipartite entanglement. Generalising entanglement to higher dimensions in the bipartite setting is done by having entanglement between qudits as opposed to qubits. There is no requirement for the dimensions of the entangled qudits to be matching. For example,

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_2 \otimes |0\rangle_3 + |1\rangle_2 \otimes |1\rangle_3), \quad (27)$$

is a entangled state between a qubit and a qutrit ($d = 3$).

2.2.1 Measuring entanglement

In order to analyse the efficiency of an entanglement transfer protocol, it is useful to have a method of measuring entanglement, of which numerous methods have been proposed and

are used. For a full mathematical discussion on entanglement quantification, see [9]. In this report, the measure of entanglement used is the *logarithmic negativity*, first presented by Vidal [10].

Definition 2.1 (Logarithmic Negativity). *Let ρ be a density matrix describing a bipartite quantum system $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$. The logarithmic negativity, $E_N(\rho)$, of ρ is defined as*

$$E_N(\rho) = \log_2 \|\rho^{\Gamma_A}\|_1. \quad (28)$$

where ρ^{Γ_A} denotes the partial transpose of ρ with respect to the subsystem \mathcal{H}_A and $\|X\|_1 = \text{Tr}(\sqrt{X^\dagger X})$ denotes the trace norm of X .

The logarithmic negativity is also referred to as the log negativity. It is an appropriate choice for the purpose of this report as it is an entanglement measure that is computable for mixed as well as pure states, and satisfies (strong) additivity

$$E_N(\rho \otimes \sigma) = E_N(\rho) + E_N(\sigma). \quad (29)$$

A proof for this is given in [10].

This usefulness of this can be demonstrated with the use of the following claim.

Claim 2.2. *A maximally entangled state in $d \times d$ dimensions has a log negativity of $\log_2 d$.*

Proof. First, note that for a Hilbert space of dimension $d \times d$, the state

$$|\psi\rangle = \frac{1}{\sqrt{d}} \sum_{j=0}^{d-1} |j\rangle \otimes |j\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B \quad (30)$$

is maximally entangled, since its reduced density matrix in either subspace is maximally mixed. So to quantify the entanglement of any maximally entangled state it is sufficient to calculate the log negativity of the density matrix, ρ associated with $|\psi\rangle$. Since $|\psi\rangle$ is a pure state

$$\rho = |\psi\rangle \langle \psi| \quad (31)$$

$$= \frac{1}{d} \sum_{j,k} |j\rangle \langle k| \otimes |j\rangle \langle k| \quad (32)$$

To calculate $E_N(\rho)$ we need the partial transpose on one of the subspaces, the choice of which is irrelevant since they are both equally entangled with one another. So choose to find the partial transpose in \mathcal{H}_A .

$$\rho^{\Gamma_A} = \frac{1}{d} \sum_{j,k} |k\rangle \langle j| \otimes |j\rangle \langle k| \quad (33)$$

From this we wish to calculate the trace norm $\|X\|_1 = \text{Tr}(\sqrt{XX^\dagger})$.

$$\rho^{\Gamma_A} (\rho^{\Gamma_A})^\dagger = \frac{1}{d^2} \sum_{j,k} |k\rangle \langle k| \otimes |j\rangle \langle j| \quad (34)$$

$$= \frac{1}{d^2} I_d \otimes I_d \quad (35)$$

$$= \frac{1}{d^2} I_{d^2} \quad (36)$$

$$\implies \|\rho^{\Gamma_A}\|_1 = \frac{1}{d} \text{Tr}(I_{d^2}) \quad (37)$$

$$= \frac{1}{d} \cdot d^2 \quad (38)$$

$$= d \quad (39)$$

Therefore, this gives

$$E_{\mathcal{N}} = \log_2 \|\rho^{\Gamma_A}\| \quad (40)$$

$$= \log_2 d. \quad (41)$$

□

This combined with the strong additivity condition is what makes the choice of log negativity an apt one. In comparing how efficient the transfer of entanglement from the Bell pairs to a qudit pair, the log negativity allows for direct comparison of the entanglement transferred into the two qudit system, and the entanglement of the resultant state of the qudit pair. If the entanglement in n Bell states is transferred, then the final state of the qudit pair has log negativity n in the case of optimal transfer.

2.3 Quantum Random Walks

Quantum random walks, as mentioned in section 1, are a model for universal quantum computation, meaning that any computation that is possible for a quantum computer can be simulated by a QW. Like much of quantum computing, QWs can be motivated from a classical predecessor, the *classical random walk*. Here the classical random walk is used specifically to motivate the discrete QW since the protocol presented in section 3 makes use of such a QW. Hence all future references to QWs are assumed to be of the discrete variant.

2.3.1 Motivation from the Classical Random Walk

In the classical random walk, a walker is constrained to moving up and down a discrete number line, starting their walk at the origin. To determine whether to take a step to the left (-1) or the right (+1), the walker flips an unbiased coin, moving to the right if the coin lands on heads and to the left if the coin lands on tails. This process of flipping a coin and taking a step can be repeated until a desired stopping point is reached, e.g. after a given

number of coin flip. The walk can also continue on forever and in this limit, the walker will reach every point on the number line. In this report, however, only finite length walks are considered. Without much thought it can be concluded that after T steps the walker can be at most $\pm T$ steps away from the origin, corresponding to the case where every step taken is in the same direction. The probability distribution describing the probability of the walker being in any given position away from the origin is given by a binomial distribution, an example of which is shown in orange in figure 2 for 100 coin flips.

2.3.2 Quantum Walk on a Line

Having described the classical random walk, it can now be ‘quantised’ into a *quantum random walk*. The QW is considered as a composite system of the coin, belonging to the Hilbert space \mathcal{H}_C and walker, \mathcal{H}_W ,

$$\mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_W. \quad (42)$$

Note that this use of subscript does not depart from the earlier usage to indicate the dimension of the Hilbert space, since the \mathcal{H}_C is spanned by two states (the ‘heads’ state and the ‘tails’ state), and \mathcal{H}_W is spanned by all the points on the number line to be walked upon, so can be thought of as an unspecified d dimensional space. Therefore the labels C and W , also serve to indicate the dimension of the labelled space.

To aid distinguishability between coin states and position states, they are labelled by

$$\langle \mathcal{H}_C \rangle = \{|\uparrow\rangle, |\downarrow\rangle\} \quad (43)$$

$$\langle \mathcal{H}_W \rangle = \{|k\rangle \mid -T \leq k \leq +T, k \in \mathbb{Z}\}, \quad (44)$$

where $\langle U \rangle$ denotes a set of states which span U , and T again is the number of ‘coin flips’ (see below). Therefore, the states $|\uparrow\rangle, |\downarrow\rangle$ take the place of heads and tails on our quantum ‘coin’. Note in particular that there is no constraint placed on the dimensionality of \mathcal{H}_W , and therefore the walker can be taken to be a qudit, whereas $\dim \mathcal{H}_C = 2$ and the coin is taken to be a qubit. Now that the Hilbert space of the system has been constructed, operators are required in order for the system to evolve. In the classical random walk, the first operation needed was a coin flip so in similar fashion the quantum walk too needs a coin flip operator, $C \in \mathcal{H}_C$ (not to be confused with the C - U controlled-unitary operator). There is a continuum of choices for C , and indeed QWs can be constructed on a whole host of different graphs - see for a greater discussion [11]. For walks on a line, constraining the coin to have real coefficients leaves the Hadamard coin as the only choice of coin available. This takes on the same form as the Hadamard transform defined in Section 2.1.5 and is given here via an alternative expression,

$$H = \frac{1}{\sqrt{2}} \left[|\uparrow\rangle \langle \uparrow| + |\uparrow\rangle \langle \downarrow| + |\downarrow\rangle \langle \uparrow| - |\downarrow\rangle \langle \downarrow| \right] \quad (45)$$

$$= \frac{1}{\sqrt{2}} \left[(|\uparrow\rangle + |\downarrow\rangle) \langle \uparrow| + (|\uparrow\rangle - |\downarrow\rangle) \langle \downarrow| \right] \quad (46)$$

where $|0\rangle \rightarrow |\uparrow\rangle$ and $|1\rangle \rightarrow |\downarrow\rangle$. As before, if the coin state is $|\uparrow\rangle$ then it becomes an equal superposition of $|\uparrow\rangle + |\downarrow\rangle$, if the coin state is in $|\downarrow\rangle$ then we get an equal superposition of

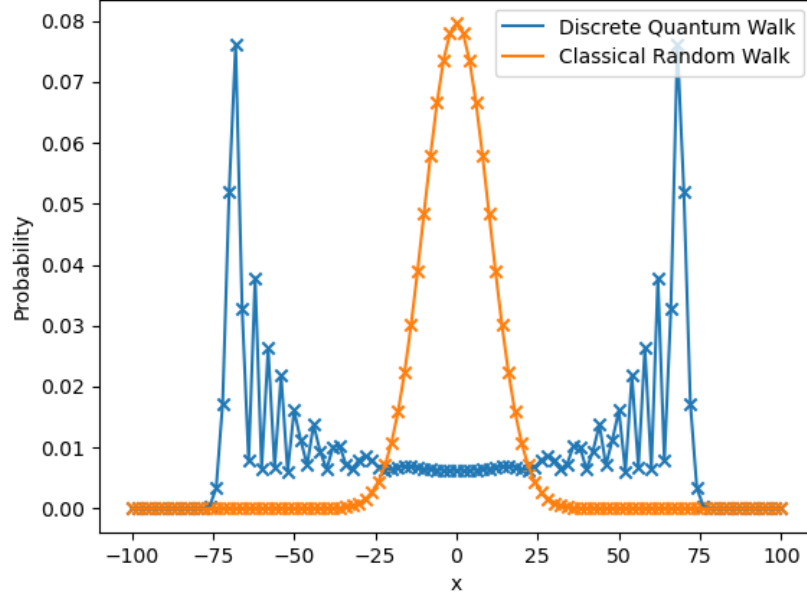


Figure 2: The probability distributions of a classical and quantum walk on a line, both originating at the origin. The quantum walk coin is initially in the $\frac{1}{\sqrt{2}}(|\uparrow\rangle + i|\downarrow\rangle)$ state. Odd points have been omitted as they all have zero probability.

$|\uparrow\rangle - |\downarrow\rangle$ and this is made particularly clear by equation 46. Following this, a shift operator $S \in \mathcal{H}$ is needed to move the walker dependent on the state of the coin.

$$S = \sum_k |\uparrow\rangle \langle \uparrow| \otimes |k+1\rangle \langle k| + |\downarrow\rangle \langle \downarrow| \otimes |k-1\rangle \langle k|. \quad (47)$$

Again, representing S in this way makes manifest its effect on the walker. If the coin state is $|\uparrow\rangle$, the walker takes a step in the $+1$ direction, if it is $|\downarrow\rangle$ then a step in the -1 direction is taken. The probability distribution of such a walk is plotted in blue in fig 2, where the initial coin state is $|\downarrow\rangle$, and is compared to a classical random walk.

Whilst the above choice of S is the most common on the number line, there are alternatives such as

$$\tilde{S} = \sum_k |\uparrow\rangle \langle \uparrow| \otimes |k\rangle \langle k| + |\downarrow\rangle \langle \downarrow| \otimes |k+1\rangle \langle k|. \quad (48)$$

The subtle difference between \tilde{S} and S is that \tilde{S} can only move in the $+1$ direction of the number line and has no ‘left moving’ part. This means that \tilde{S} is restricted to the non-negative integers and unlike S , can occupy all $|x\rangle$ for $0 \leq x \leq T$, where T is the number of time steps in our QW. In fact \tilde{S} is an operator that was introduced earlier in section 2.1.4,

$$\tilde{S} = C \cdot X. \quad (49)$$

2.4 Ancilla-Based Quantum Computing

The quantum walk model of quantum computation is but one of many universal quantum computing models. Another model is known as *ancilla-based quantum computing* (AQC), which, in particular, aims to resolve two conflicting demands when building quantum computers: Qubits must be well isolated to prevent decoherence, yet it must also be possible for them to interact with one another in certain settings, such as implementing the C - X operator. However, a qubit cannot distinguish between unwanted and wanted interactions, resulting in the need for a balancing act that adequately fulfils both of these aims.

AQC aims to resolve this conflict by using additional qubits, known as ancilla qubits, which mediate interactions between the main register qubits. Using this model, it is possible to implement two complementary registers of qubits. The main register can be designed to be strongly isolated from interactions, bar a limited number of interactions with the ancilla registry, whose qubits can be easily manipulated but decohere much faster. Quantum computations can be performed by *delocalising* quantum information from the main register across both the register and the ancilla. After performing a computation on the ancilla qubit, the quantum information is then *relocalised* back into the main register. The ancilla can then be reset to the initial state and used again for other computations. A simple example of a circuit designed for ancilla-based quantum computing is shown in figure 3.

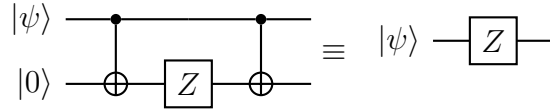


Figure 3: Two circuits that implement a Z gate acting on an arbitrary qubit $|\psi\rangle$. The circuit on the left does so indirectly via interactions with an ancilla qubit.

The circuit on the left hand side of figure 3 does not directly implement any unitary transformations on an arbitrary qubit state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, but instead indirectly acts on $|\psi\rangle$ via the ancilla qubit, to which the quantum information of $|\psi\rangle$ is shared to via a CNOT gate. Acting a Z gate on the ancilla and relocalising the quantum information with another CNOT gate ‘passes on’ the effects of the Z gate. Note however that this would not directly work to implement an X gate on $|\psi\rangle$ if the Z gate were directly switched with an X gate. This is because only amplitudes can be delocalised and relocalised, computational basis states cannot be directly affected by ancilla interactions. If however, $|\psi\rangle$ is mapped to the Hadamard basis, where the basis states differ by their amplitudes, before the Z circuit and mapped back afterwards (see figure 4), then it is possible to effect an X operator in the AQC setting. These two circuits highlight the somewhat counterintuitive nature of AQC. A controlled operation is utilised, where the qudit is the control and the qubit is the target, yet it is the qudit state that is changed and the qubit is left ‘untouched’.

This model of quantum computing does not have to be reserved to qubit computing alone and can be extended to qudits simply by using the general forms of operators, as described in section 2.1.4. An further advantage of AQC is that it is particularly well placed to used registers of qudits with mismatched dimensions. Therefore, it is an extremely suitable model of quantum computation for entanglement transfer as entangled qubits can be used as the

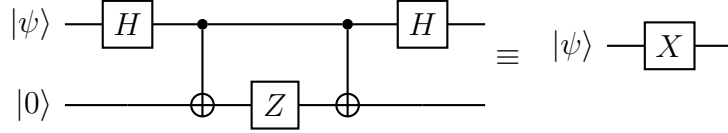


Figure 4: Implementing an X gate on $|\psi\rangle$ in the AQC setting by first mapping $|\psi\rangle$ to the Hadamard basis before and after the Z circuit given in fig 3.

ancilla (to be regularly replaced once the entanglement is transferred), and qudits of arbitrary dimension can be the main register to ensure the entanglement transferred is long-lived.

3 Entanglement Transfer using Quantum Walks

Now the protocol presented in [8] which utilises quantum walk dynamics in order to generate higher dimensional entanglement is summarised.

The imagined setup of this protocol is that there are two labs, A and B , which have a shared source of entangled qubits but are otherwise spatially separated and cannot interact with one another.

In this section we use following notation:

- $|\psi\rangle_J$ is a state belonging to the subspace $\mathcal{H}_J = \mathcal{H}_J^{(A)} \otimes \mathcal{H}_J^{(B)}$, $J \in \{C, W\}$.
- $|\psi\rangle^{(K)}$ is a state belonging to the subspace $\mathcal{H}^{(K)} = \mathcal{H}_C^{(K)} \otimes \mathcal{H}_W^{(K)}$, $K \in \{A, B\}$.
- $|\psi\rangle_J^{(K)}$ is a state belonging to the subspace $\mathcal{H}_J^{(K)}$.

In this mathematical framework the overall Hilbert space is comprised of two quantum walk subspaces,

$$\mathcal{H} = \mathcal{H}^{(A)} \otimes \mathcal{H}^{(B)} \quad (50)$$

$$= \mathcal{H}_C^{(A)} \otimes \mathcal{H}_W^{(A)} \otimes \mathcal{H}_C^{(B)} \otimes \mathcal{H}_W^{(B)}. \quad (51)$$

The basic premise of this protocol is this:

1. Entangle the two coin spaces of the walkers $\mathcal{H}_C^{(K)}$. (Fig 5.)
2. Proceed with the quantum walk for some determined number of steps.
3. Use a projective measurement $\mathcal{P}_\gamma = |\gamma\rangle\langle\gamma|$, $|\gamma\rangle \in \mathcal{H}_C^{(A)}$ to then transfer the entanglement so that it solely exists in the subspace $\mathcal{H}_W^{(A)} \otimes \mathcal{H}_C^{(B)} \otimes \mathcal{H}_W^{(B)}$.
4. In similar fashion, find a projection $\mathcal{P}_\delta = |\delta\rangle\langle\delta|$, $|\delta\rangle \in \mathcal{H}_C^{(B)}$ to transfer the entanglement to exist between the two walker subspaces, $\mathcal{H}_W^{(i)}$, only.
5. Accumulate entanglement in the walker subspaces by once more entangling the two coin spaces and repeating the protocol.

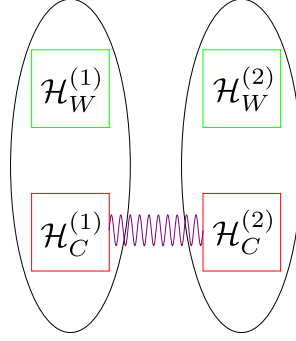


Figure 5: The initial prepared state has entanglement solely between the two coin subspaces. Figure is an edited version of FIG 3 from [8].

In this way, arbitrary amounts of higher dimensional entanglement can be generated. The ordering of steps 3 and 4 is not overly important since the full operators describing the projective measurements are given by

$$|\gamma\rangle \langle \gamma| \otimes I \otimes I \otimes I \quad (52)$$

$$I \otimes I \otimes |\delta\rangle \langle \delta| \otimes I \quad (53)$$

which clearly commute. As is the case with many quantum walk based protocols, particular attention must be paid to the choice of coin used for the quantum walk, as it will have a large impact on the success of the protocol. The shift operator used in this protocol is the \tilde{S} , as outlined in section 2.3.2.

3.1 Transfer using identity coin operator

To illustrate the basic principles of the protocol, consider the case where $C = I$.

1. A state $|\psi(0)\rangle$ is prepared with the coin states entangled and walkers at the origin

$$|\psi(0)\rangle = \underbrace{\frac{1}{\sqrt{2}} \left[|\uparrow\rangle_C^{(A)} |\uparrow\rangle_C^{(B)} + |\downarrow\rangle_C^{(A)} |\downarrow\rangle_C^{(B)} \right]}_{\text{Bell State}} \otimes |0\rangle_W^{(A)} |0\rangle_W^{(B)}. \quad (54)$$

2. The ‘coin’, I , is applied and followed by the shift operator \tilde{S} to advance the quantum walk. Explicitly (dropping the indices and combining some of our kets together) the walk evolves to the state

$$|\psi(1)\rangle = \tilde{S}I|\psi\rangle = \frac{1}{\sqrt{2}} \left[|\uparrow, \uparrow\rangle |0, 0\rangle + |\downarrow, \downarrow\rangle |1, 1\rangle \right]. \quad (55)$$

3. Using the operator $\mathcal{P}_\gamma = |\gamma\rangle \langle \gamma|$ the part of $|\psi(1)\rangle$ residing in the $\mathcal{H}_C^{(A)}$ subspace is projected onto the state $|\gamma\rangle$.

For this example, choose $|\gamma\rangle = \frac{1}{\sqrt{2}} [|\uparrow\rangle + |\downarrow\rangle]$ which then gives

$$\mathcal{P}_\gamma |\psi(1)\rangle = \frac{1}{2} \left[|\gamma\rangle \otimes (|\uparrow, 0, 0\rangle + |\downarrow, 1, 1\rangle) \right]. \quad (56)$$

4. Similarly, project the other coin onto $|\delta\rangle$ which in this instance is taken to be the same state as $|\gamma\rangle = \frac{1}{\sqrt{2}}[|\uparrow\rangle + |\downarrow\rangle]$,

$$\mathcal{P}_\delta \mathcal{P}_\gamma |\psi(1)\rangle = \frac{1}{2\sqrt{2}} \left[|\gamma\rangle \otimes |\delta\rangle \otimes \frac{1}{\sqrt{2}} (|0,0\rangle + |1,1\rangle) \right]. \quad (57)$$

Renormalising gives the final state

$$|\gamma\rangle_C^{(A)} \otimes |\delta\rangle_C^{(B)} \otimes \underbrace{\frac{1}{\sqrt{2}} [|0,0\rangle + |1,1\rangle]}_\text{Bell State}_W, \quad (58)$$

which has a Bell state in the \mathcal{H}_W subspace, and the states in \mathcal{H}_C are separable. Therefore the entanglement that originally resided in the coin subspace has been transferred to the walker one.

3.2 Accumulation

The true motivation behind this protocol is the ability to accumulate the entanglement transferred from the lower dimensional coin subspace to the higher dimensional walker one. This is done by repeating the entire process with some small changes. Again I is used as the coin.

1. Starting with the final state obtained from the first iteration of the protocol (equation 58) the coin subspaces are re-entangled, obtaining a new initial state $|\psi(0)\rangle$,

$$|\gamma\rangle_C^{(A)} \otimes |\delta\rangle_C^{(B)} \otimes \frac{1}{\sqrt{2}} [|0,0\rangle + |1,1\rangle]_W \quad (59)$$

$$\xrightarrow{\text{Entangle } \mathcal{H}_C} \frac{1}{\sqrt{2}} [|\uparrow, \uparrow\rangle + |\downarrow, \downarrow\rangle]_C \otimes \frac{1}{\sqrt{2}} [|0,0\rangle + |1,1\rangle]_W \quad (60)$$

$$:= |\psi(0)\rangle. \quad (61)$$

2. Now take two steps instead of one in the walk.

$$|\psi(2)\rangle = (\tilde{S}I)^2 |\psi(0)\rangle \quad (62)$$

$$= \frac{1}{2} \left[|\uparrow, \uparrow\rangle (|0,0\rangle + |1,1\rangle) + |\downarrow, \downarrow\rangle (|2,2\rangle + |3,3\rangle) \right]. \quad (63)$$

- 3–4. Using the same projection operators in the two coin subspaces, $\mathcal{P}_\gamma \in \mathcal{H}_C^{(A)}$, $\mathcal{P}_\delta \in \mathcal{H}_C^{(B)}$, and renormalising gives the final state

$$|\gamma\rangle \otimes |\delta\rangle \otimes \frac{1}{2} [|0,0\rangle + |1,1\rangle + |2,2\rangle + |3,3\rangle]. \quad (64)$$

Using claim 2.2, the log negativity of

$$\frac{1}{2} [|0,0\rangle + |1,1\rangle + |2,2\rangle + |3,3\rangle] \quad (65)$$

is 2, setting $d = 4$ (since both of the qudits only have 4 states of non-zero amplitude they can be simulated by ququarts even if their true dimension is greater than 4). Therefore, 2 units of log negativity have been transferred from the Bell states (each of log negativity 1) to the qudit pair and optimal transfer has been achieved. The process can be repeated to accumulate arbitrarily large amounts of entanglement into our walker subspace. The number of steps needed in the quantum walk for each iteration is as follows.

Claim 3.1. *The n^{th} iteration (counting from 1) of the protocol requires at least 2^{n-1} steps in the quantum walk.*

Proof. Each step in a quantum walk with shift operator \tilde{S} increases the number of basis states with non-zero amplitude by 1, provided that the amplitude $|\downarrow\rangle$ coin basis state is non-zero. Therefore the dimension of each walker can be taken to be $s + 1$, where s is the total number of steps taken in the walk, since the walker space can be reduced to the subspace spanned by the $s + 1$ non-zero amplitude basis states. Using Claim 2.2, the upper bound on the entanglement that can be held between the two walker states is given by $\log_2(s + 1)$ ebits. This implies the following condition on the total number of steps

$$\log_2(s + 1) \geq n \implies s \geq 2^n - 1. \quad (66)$$

Assuming that this inequality is satisfied at equality for the $n - 1^{\text{th}}$ iteration of the protocol gives a total step number of $2^{n-1} - 1$. Therefore, the minimum number of steps for the n^{th} iteration is given by

$$2^n - 1 - (2^{n-1} - 1) = 2^n - 2^{n-1} \quad (67)$$

$$= 2 \times 2^{n-1} - 2^{n-1} \quad (68)$$

$$= 2^{n-1}. \quad (69)$$

□

Whilst this is effective for the identity coin, for the general coin optimal transfer is not nearly as effective. For example, when using the Hadamard coin, it is not possible to transfer all the entanglement to the qudits and instead they only become non-maximally entangled.

3.3 Retrieval

Although accumulating the entanglement in higher dimensions is of significant use, it is also possible to imagine that retrieving the entanglement back into the qubits would also be of use. For example, consider the case where the method of generating entangled qubits is not deterministic but an algorithm requiring large numbers of Bell states is to be executed. If the accumulation of entanglement can be reversed to get Bell pairs back, then the entangled Bell pairs can be stored in the qudits when they are successfully generated and then retrieved all at once to ensure the algorithm can be performed. In the identity coin example, it is rather simple to use a near identical setup, where the qudits play the role of the coins and the qubits are the walkers, to retrieve entangled Bell pairs out of the qudits. For a general coin, it is also possible in principle to retrieve some entanglement back out of the entangled

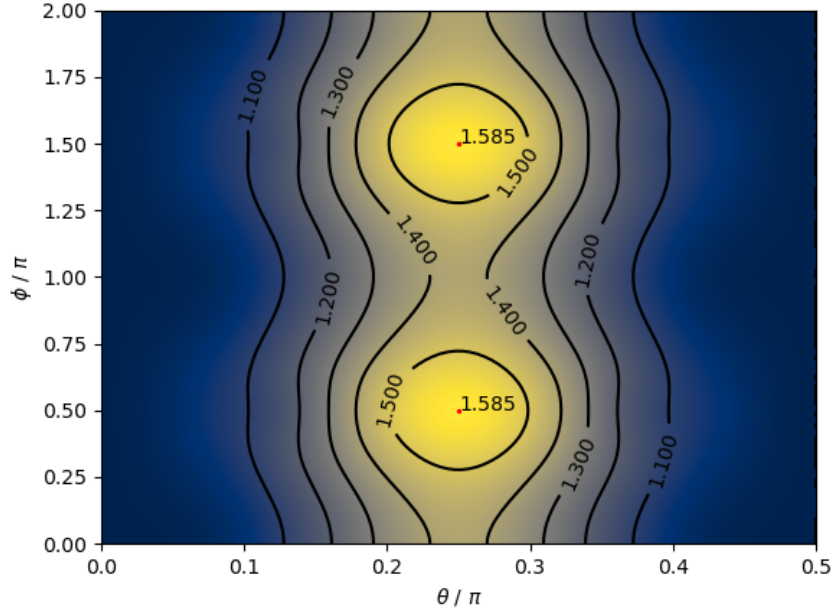


Figure 6: Transferring two ebits using the quantum walk protocol proposed by [8]. θ, ϕ are the parameters describing $|\gamma\rangle$ that defines the projection operator \mathcal{P}_γ .

qudits. However, retrieval after more than 1 ebit has been transferred for the non-identity coin is not simple within the framework of a quantum walk based protocol, due to the non maximal nature of the entanglement present in the qudits.

3.4 Results

Despite their simple setup, the state of a quantum walk becomes extremely complex after even just a few steps in most cases due to increase in effective size of the Hilbert space. This is doubly true for two quantum walks running in conjunction. Hence to analyse the protocol in settings that are not as trivial as the identity coin example, numerical simulations were run using Python and some associated packages [CITE SCIPY, NUMPY, MATH]. Figure 6 shows that the protocol, when using a Hadamard coin, can generate a state with log negativity up to approximately 1.585 when the protocol is done twice, assuming both quantum coins are projected onto the same state $|\gamma\rangle = \cos\theta |0\rangle + e^{i\phi} \sin\theta |1\rangle$. Hence a maximally entangled state cannot be generated with the Hadamard coin. *****Simulations using different projective operators $\mathcal{P}_\gamma, \mathcal{P}_\delta$ show 1.585 is still the maximum possible.***** Compare this to the case $C = I$, where optimal transfer is possible.

Clearly whilst this would be a suitable method for a quantum walk based model of quantum computing, there are alternative settings that would be better suited to achieve the aims of entanglement transfer. One possible candidate is presented in section 4.

4 Entanglement Transfer using Ancilla-Based Quantum Computing

In this section an alternative entanglement transfer scheme is outlined. It is designed to operate in the same setting at the QW based protocol, where there are two labs, again called A and B , which share a common source of entangled qubits and each have their own qudits. Analogously to the QW protocol, the qudit can be thought of as a walker driven by the ancilla qubit ‘coin’.

The protocol can be succinctly summarised by the circuit schematic given in figure 7, and essentially is two copies of the same circuit.

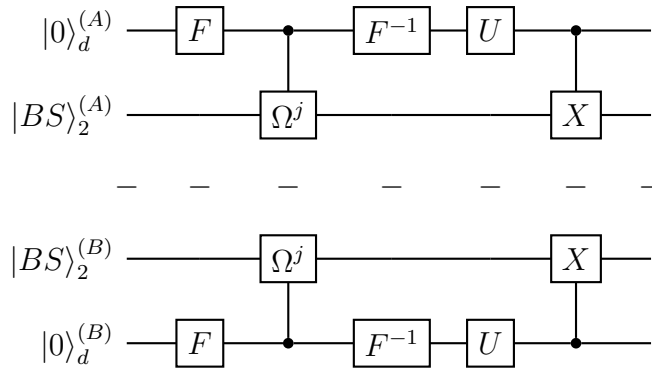


Figure 7: The AQC circuit for entanglement transfer. The schematic shows two separated circuits imagined to exist in spatially separated labs, A and B . The qudits and qubits belonging to each individual lab are labelled by their superscripts. The qubits form an entangled Bell state.

The majority of the gates shown in the schematic are discussed in section 2.1.5, with the exception of the gate Ω^j . The action of Ω in the computational basis is given by the matrix

$$\Omega = \begin{pmatrix} 1 & 0 \\ 0 & \omega \end{pmatrix} \quad (70)$$

$$\implies \Omega^j = \begin{pmatrix} 1 & 0 \\ 0 & \omega^j \end{pmatrix}. \quad (71)$$

Essentially Ω is similar to the Z operator in that it applies relative phase difference, but instead of a phase of -1, a phase corresponding to the d^{th} root of unity is introduced on the $|1\rangle_2$ states, with d corresponding to the dimension of the control qudits. (Indeed, when $d = 2$, $\Omega = Z$.) Therefore the $C\text{-}\Omega^j$ operator is one that acts as

$$C\text{-}\Omega^j(|x\rangle_d |y\rangle_2) = |x\rangle_d \otimes \Omega^{xj} |y\rangle_2 \quad (72)$$

$$= |x\rangle_d \otimes \omega^{xyj} |y\rangle_2 \quad (73)$$

where $|x\rangle_d$ is the control qudit and $|y\rangle_2$ the target qubit.

Claim 4.1. *In the Fourier basis, the $C\text{-}\Omega^j$ operator acts on the product state $|+k\rangle_d \otimes |1\rangle_2$ to give $|+_{k+j}\rangle_d \otimes |1\rangle_2$*

Proof. The Fourier basis state $|+k\rangle_d$ is given by

$$|+k\rangle_d = \frac{1}{\sqrt{d}} \sum_{m=0}^{d-1} \omega^{km} |m\rangle. \quad (74)$$

Therefore

$$C\text{-}\Omega^j (|+k\rangle_d |1\rangle_2) = \frac{1}{\sqrt{d}} \sum_{m=0}^{d-1} C\text{-}\Omega^j (\omega^{km} |m\rangle_d \otimes |1\rangle_2) \quad (75)$$

$$= \frac{1}{\sqrt{d}} \sum_{m=0}^{d-1} \omega^{mj} (\omega^{km} |m\rangle_d \otimes |1\rangle_2) \quad (76)$$

$$= \frac{1}{\sqrt{d}} \sum_{m=0}^{d-1} \omega^{(k+j)m} |m\rangle_d \otimes |1\rangle_2 \quad (77)$$

$$= \left(\frac{1}{\sqrt{d}} \sum_{m=0}^{d-1} \omega^{(k+j)m} |m\rangle_d \right) \otimes |1\rangle_2 \quad (78)$$

$$= |+_{k+j}\rangle_d \otimes |1\rangle_2. \quad (79)$$

□

This exhibits again the counter-intuitive nature of AQC discussed in section 2.4. Despite the qudit being the control and the qubit being the target, the only change effected is on the qudit, shifting the Fourier basis states. Claim 4.1 also demonstrates the role of the index j , which essentially dictates by how many states each Fourier basis state is shifted.

The following sections demonstrate explicitly how the circuit operates.

4.1 Transfer

Assume that there are two qudits in the state $|0\rangle_d$ in labs A and B, and each lab shares a qubit each from an entangled Bell pair. The composite state is therefore given by

$$|00\rangle_d^{(A,B)} \otimes \frac{1}{\sqrt{2}} \left(|00\rangle_2^{(A,B)} + |11\rangle_2^{(A,B)} \right). \quad (80)$$

Note that in the above expression, the qudits and qubits in both labs, A and B , are in fact in the same states. This is true for the entire running of the circuit and as such there is no need to explicitly differentiate the qudits or ancilla qubits in either lab so the superscript labelling is dropped for the rest of this section.

The qudits are first Fourier transformed into the Fourier basis to give

$$|+0+0\rangle_d \otimes \frac{1}{\sqrt{2}} (|00\rangle_2 + |11\rangle_2) \quad (81)$$

$$= \frac{1}{\sqrt{2}} \left(|+0+0\rangle_d \otimes |00\rangle_2 + |+0+0\rangle_d \otimes |11\rangle_2 \right). \quad (82)$$

The change of basis is necessary because to have entanglement in the qudits, they must be in superposition of at least two states of non-zero amplitude. Since only amplitudes can be delocalised across the qudits and ancilla qubits, in order to give other qudit states a non-zero amplitude, it is necessary to be in a basis where the basis states are related to one another by differences in their amplitudes. The Fourier basis is one such basis where the basis states are in equal superposition of all the computational basis states but differ by the relative phases in the superposition. Hence the need to be in the Fourier basis when using the delocalised amplitudes to effect changes in the qudit basis states. The index j on the Ω has an analogy to the QW protocol where the iteration number dictates how many steps need to be taken in the QW. Using the same line of reasoning as outlined in Claim 3.1, on the n^{th} iteration of the protocol, $j = 2^{n-1}$ so in this instance ($n = 1$) $j = 1$. Using claim 4.1, acting $C-\Omega$ in both A and B gives the state

$$\frac{1}{\sqrt{2}} (|+0+0\rangle_d \otimes |00\rangle_2 + |+1+1\rangle_d \otimes |11\rangle_2). \quad (83)$$

The qudits are then transformed back into the computational basis,

$$\frac{1}{\sqrt{2}} (|00\rangle_d \otimes |00\rangle_2 + |11\rangle_d \otimes |11\rangle_2). \quad (84)$$

The operator U is a correctional gate that essentially pairs all the even numbered computational qudit basis states with $|0\rangle_2$ and the odd numbered computational basis states with $|1\rangle_2$. (A more complete description is given in section 4.2.) In this instance, U can be ignored since no corrections are needed, so $C-X$ is directly applied, giving

$$\frac{1}{\sqrt{2}} (|00\rangle_d \otimes |00\rangle_2 + |11\rangle_d \otimes |00\rangle_2). \quad (85)$$

$$= \underbrace{\frac{1}{\sqrt{2}} (|00\rangle_d + |11\rangle_d)}_{\text{Bell state}} \otimes |00\rangle_2. \quad (86)$$

As shown in equation 86, the qudits now effectively form a Bell pair and the qubits are no longer entangled - the entanglement has been transferred to the qudits.

4.2 Accumulation

Assume that one Bell pair has been transferred to our qudits and a second Bell pair is to be transferred. Taking the final state given by equation 86 and replacing the ancilla qubits with another entangled Bell pair gives

$$\frac{1}{2} (|00\rangle_d + |11\rangle_d) \otimes (|00\rangle_2 + |11\rangle_2). \quad (87)$$

Again, the qudits are transformed to the Fourier basis before the $C\text{-}\Omega^j$ gate. As noted in the discussion on $C\text{-}\Omega^j$ above, for this iteration ($n = 2$) $j = 2$, giving the state

$$\frac{1}{2} \left[(|+0+0\rangle_d + |+1+1\rangle_d) \otimes |00\rangle_2 + (|+2+2\rangle_d + |+3+3\rangle_d) \otimes |11\rangle_2 \right]. \quad (88)$$

After doing transforming back to the computational basis, the total state becomes

$$\frac{1}{2} \left[(|00\rangle_d + |11\rangle_d) \otimes |00\rangle_2 + (|22\rangle_d + |33\rangle_d) \otimes |11\rangle_2 \right]. \quad (89)$$

Unlike the previous example for $n = 1$, here the correctional operator U is needed so that the $C\text{-}X$ will ensure all the qubit states are $|0\rangle_2$, allowing our qubit state to be completely separable from its associated qudit. In order for the $C\text{-}X$ to do this, it must act as the identity on $|0\rangle_2$, implement an X operation on $|1\rangle_2$. Since X is self inverse, the control must be in an even labelled basis state (turning X into the identity) when the target is $|0\rangle_2$ and in an odd labelled basis state (leaving X unchanged) when the target is $|1\rangle_2$. Hence in this case, U must implement

$$|1\rangle \mapsto |2\rangle \quad (90)$$

$$|2\rangle \mapsto |1\rangle, \quad (91)$$

which then gives the state

$$\frac{1}{2} \left[(|00\rangle_d + |22\rangle_d) \otimes |00\rangle_2 + (|11\rangle_d + |33\rangle_d) \otimes |11\rangle_2 \right]. \quad (92)$$

As desired, U has paired even numbered qudit basis states with $|00\rangle_2$ and odd numbered qudit basis states with $|11\rangle_2$. Therefore after the $C\text{-}X$ operation the state becomes

$$\frac{1}{2} (|00\rangle_d + |22\rangle_d + |11\rangle_d + |33\rangle_d) \otimes |00\rangle_2. \quad (93)$$

The two qudits are now in an entangled state with a log negativity of 2 (claim 2.2). This protocol can be repeated again and again with the sole change needed being the index j of $C\text{-}\Omega^j$ and the operator U . For $n > 2$ there is no unique choice of U , as long as odd numbered states less than $\frac{d}{2}$ and the even numbered states greater than or equal to $\frac{d}{2}$ are swapped in some way.

4.3 Retrieval

Given that this is a circuit that solely utilises unitary transformations, retrieval of entangled Bell pairs is trivially done by running the circuit backwards. Furthermore, there is no requirement to use the same ancilla qubits to retrieve the entanglement. By the end of the circuit the ancilla qubits are in the $|0\rangle$ state, therefore any pair of ancilla qubits in the $|0\rangle$ state may be used to retrieve the entanglement.

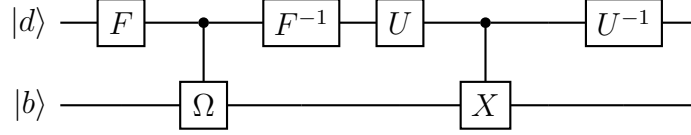


Figure 8: The AQC circuit with one qudit and qubit which can store arbitrary qubit states in the qudit.

5 Further Uses of the AQC Circuit

Although the goal of this research was to design a protocol in a similar setting to the QW based protocol that could optimally generate maximally entangled states, further probing of the AQC circuit shows that it has further uses beyond storage of entanglement. In this section, consider a scenario where the quantum information contained in a collection of qubits is to be stored. By taking one half of the circuit given for the two lab setting and adding a gate U^{-1} that undoes the basis state map seen before, as shown in figure 8, arbitrary qubit states can be stored in the qudit, provided that $d \geq 2^n$, where n is the number of qubit states to be stored. Furthermore, in the case that two or more qubit states are stored via this circuit then it is in fact possible to retrieve the qubit states in a different order to that in which they were stored, as long as the original order they were stored in is known. Therefore, this circuit can be utilised in turning qudits into quantum random access memory.

5.1 Quantum Random Access Memory

The procedure for utilising the circuit as a quantum random access memory is as follows. Assume that there is a qudit in state $|0\rangle_d$ and two qubits, qubit 1 and qubit 2, in states $a|0\rangle_2 + b|1\rangle_2$ and $c|0\rangle_2 + d|1\rangle_2$ respectively. We first run the circuit with the qudit and qubit 1,

$$|0\rangle_d \otimes (a|0\rangle + b|1\rangle) \longrightarrow (a|0\rangle_d + b|1\rangle_d) \otimes |0\rangle_2. \quad (94)$$

We then replace qubit 1 with qubit 2 and run the circuit again,

$$(a|0\rangle_d + b|1\rangle_d) \otimes (c|0\rangle_2 + d|1\rangle_2) \longrightarrow (ac|0\rangle_d + bc|1\rangle_d + ad|2\rangle_d + bd|3\rangle_d) \otimes |0\rangle_2. \quad (95)$$

In order to retrieve qubit 2 back, this can be done simply by running the circuit backwards. However, if we wish to retrieve the qubit 1 state then we first require a specific unitary operator. The form of the unitary transform can be found as follows. Rewrite each of the qudit basis state numbers in binary, i.e.

$$|0\rangle = |00\rangle \quad (96)$$

$$|1\rangle = |01\rangle \quad (97)$$

$$|2\rangle = |10\rangle \quad (98)$$

$$|3\rangle = |11\rangle. \quad (99)$$

Rewriting the final state of equation 95 in this way we obtain the following expression

$$ac|0\rangle + bc|1\rangle + ad|2\rangle + bd|3\rangle = ac|00\rangle + bc|01\rangle + ad|10\rangle + bd|11\rangle, \quad (100)$$

which can be rewritten as the product state

$$\underbrace{(c|0\rangle + d|1\rangle)}_{\text{Qubit 2}} \otimes \underbrace{(a|0\rangle + b|1\rangle)}_{\text{Qubit 1}}. \quad (101)$$

Quite remarkably the qudit has an intuitive alternative expression as the product state of qubit 1 and qubit 2. If the circuit is run backwards, we will retrieve qubit 2. Therefore, to retrieve qubit 1 instead, the qudit state should be expressable as

$$\underbrace{(a|0\rangle + b|1\rangle)}_{\text{Qubit 1}} \otimes \underbrace{(c|0\rangle + d|1\rangle)}_{\text{Qubit 2}}. \quad (102)$$

This can be thought of as switching the positions of our two qubits, which leads us to the unitary transformation we need. We need a map, M , which will switch the positions of our two qubits. M is found by mapping each of the binary qudit state representations $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$ to the basis state with the binary digits switched.

$$|00\rangle \mapsto |00\rangle \quad (103)$$

$$|01\rangle \mapsto |10\rangle \quad (104)$$

$$|10\rangle \mapsto |01\rangle \quad (105)$$

$$|11\rangle \mapsto |11\rangle. \quad (106)$$

We can check that this gives us the form that we want taking the RHS of equation 100 and acting M on it to obtain

$$M(ac|00\rangle + ad|01\rangle + bc|10\rangle + bd|11\rangle) = ac|00\rangle + ad|10\rangle + bc|01\rangle + bd|11\rangle \quad (107)$$

$$= \underbrace{(a|0\rangle + b|1\rangle)}_{\text{Qubit 1}} \otimes \underbrace{(c|0\rangle + d|1\rangle)}_{\text{Qubit 2}}, \quad (108)$$

as required. M can be expressed in terms of the original qudit state labelling by converting the binary back

$$|0\rangle \mapsto |0\rangle \quad (109)$$

$$|1\rangle \mapsto |2\rangle \quad (110)$$

$$|2\rangle \mapsto |1\rangle \quad (111)$$

$$|3\rangle \mapsto |3\rangle. \quad (112)$$

The matrix representation of M is given by

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \quad (113)$$

Generalising this to larger numbers of qubits stored is done via the same thought process. Imagine that there is now third qubit to be stored in the qudit, qubit 3, in the state

$$e|0\rangle + f|1\rangle. \quad (114)$$

When qubits 1, 2 and 3 are stored in that same order, it results in the state

$$ace |0\rangle + ade |1\rangle + bce |2\rangle + bde |3\rangle + ace |4\rangle + adf |5\rangle + bcf |6\rangle + bdf |7\rangle, \quad (115)$$

which again, when converted to binary numbers, can be expressed as the product state

$$(e |0\rangle + f |1\rangle) \otimes (c |0\rangle + d |1\rangle) \otimes (a |0\rangle + b |1\rangle). \quad (116)$$

If the state of qubit 1 is needed then M must implement the map

$$|1\rangle = |001\rangle \mapsto |100\rangle = |4\rangle \quad (117)$$

$$|3\rangle = |011\rangle \mapsto |110\rangle = |6\rangle \quad (118)$$

$$|4\rangle = |100\rangle \mapsto |001\rangle = |1\rangle \quad (119)$$

$$|6\rangle = |110\rangle \mapsto |011\rangle = |3\rangle \quad (120)$$

with all other basis states mapped to themselves as they are identical when switching the first and last digits of their binary representations. Having operated M on the qudit state, the circuit can be run backwards in order to retrieve qubit 1. As with retrieving Bell pairs in section 4, any qubit in the state $|0\rangle$ can be used to retrieve qubit 1.

In a practical setting it may be more efficient to build a gate, P , that permutes the order of the qubits instead of swapping two digits. One example of P would be the map that permutes each qubit one place the right,

$$|1\rangle = |001\rangle \mapsto |100\rangle = |4\rangle \quad (121)$$

$$|2\rangle = |010\rangle \mapsto |001\rangle = |1\rangle \quad (122)$$

$$|3\rangle = |011\rangle \mapsto |101\rangle = |5\rangle \quad (123)$$

$$|4\rangle = |100\rangle \mapsto |010\rangle = |2\rangle \quad (124)$$

$$|5\rangle = |101\rangle \mapsto |110\rangle = |6\rangle \quad (125)$$

$$|6\rangle = |110\rangle \mapsto |011\rangle = |3\rangle. \quad (126)$$

Again $|0\rangle, |7\rangle$ are mapped to themselves as the permutation does not affect them. In this way, any of the qubit states can be retrieved by continually applying P until the qubit state to be retrieved is in the right ‘place’. Utilising a single gate would also be more appropriate for the ancilla-based quantum computing setting where a minimal gate set is desired for the control qudits. However, this would require multiple applications of the same gate which, without adequate error correction, would lead to greater decoherence of the quantum information than if just a single switching gate M were applied.

6 Discussion

In the example given in section 3, it is shown that the protocol proposed in the QW setting can optimally transfer all the entanglement to the qudit pair. However, this is with the significant caveat that the example does not use quantum walk dynamics in order to transfer the entanglement, as using the identity as a coin is akin to having no coin at all. In analysing

the protocol with the Hadamard coin, it was only possible to transfer one Bell state’s worth of entanglement optimally and numerical simulations of the protocol for storing two Bell states, found that the resulting state had around 1.585 units of log negativity (figure 6). Furthermore, the projective measurements employed as part of the protocol mean that it is not a unitary protocol, therefore not deterministic and non-trivial to reverse in order to retrieve the entanglement out from the entangled qudits. The experimental implementation suggested in the paper also required the use of post selection, where undesirable states were discarded and the protocol run again. All this in combination results in a protocol which is rather inefficient in achieving its aims, and serves more as a proof of concept in that it is possible to use quantum walk dynamics to transfer entanglement, but falls short in being a suitable implementation for the task.

Adapting the identity coin example to the ancilla-based quantum computing circuit given in section 4 resulted in a circuit that solved these inefficiencies. The entanglement can always be transferred optimally and exclusive utilisation of unitary operators means that the circuit can just be reversed with any ancilla qubit in the $|0\rangle$ state.

6.1 Further Steps

As discussed in Section 5, the circuit given in figure 7 has potential uses beyond the original scope in which it has been designed. It would be of interest to see if it can also be applied to a scenario where we wish to transfer multipartite entanglement to higher dimensional qudits, for example transferring GHZ states or W states. Such analysis should be relatively straightforward to generalise to the multipartite scenario, although extending computational simulations may not be so trivial without adequate computational power. Furthermore, the analysis of this work could be brought to greater completion if the circuit was generalised to the scenario where we wish to store qudit states, or entanglement associated with qudit pairs, rather than just qubit states.

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References

- [1] Charles H. Bennett and Stephen J. Wiesner. ‘Communication via one- and two-particle operators on Einstein-Podolsky-Rosen states’. In: *Phys. Rev. Lett.* 69 (20 Nov. 1992), pp. 2881–2884. DOI: [10.1103/PhysRevLett.69.2881](https://doi.org/10.1103/PhysRevLett.69.2881). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.69.2881>.
- [2] Charles H. Bennett and Gilles Brassard. ‘Quantum cryptography: Public key distribution and coin tossing’. In: vol. 560. Jan. 1984, pp. 175–179. DOI: [10.1016/j.tcs.2011.08.039](https://doi.org/10.1016/j.tcs.2011.08.039).
- [3] Charles H. Bennett et al. ‘Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels’. In: *Phys. Rev. Lett.* 70 (13 Mar. 1993), pp. 1895–1899. DOI: [10.1103/PhysRevLett.70.1895](https://doi.org/10.1103/PhysRevLett.70.1895). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.70.1895>.

- [4] Neil Shenvi, Julia Kempe, and K. Birgitta Whaley. ‘Quantum random-walk search algorithm’. In: *Phys. Rev. A* 67 (5 May 2003), p. 052307. DOI: [10.1103/PhysRevA.67.052307](https://doi.org/10.1103/PhysRevA.67.052307). URL: <https://link.aps.org/doi/10.1103/PhysRevA.67.052307>.
- [5] Andrew M. Childs. ‘Universal Computation by Quantum Walk’. In: *Physical Review Letters* 102.18 (May 2009). ISSN: 1079-7114. DOI: [10.1103/physrevlett.102.180501](https://doi.org/10.1103/physrevlett.102.180501). URL: <http://dx.doi.org/10.1103/PhysRevLett.102.180501>.
- [6] Viv Kendon. ‘Decoherence in quantum walks – a review’. In: *Mathematical Structures in Computer Science* 17.06 (Nov. 2007). ISSN: 1469-8072. DOI: [10.1017/S0960129507006354](https://doi.org/10.1017/S0960129507006354). URL: <http://dx.doi.org/10.1017/S0960129507006354>.
- [7] Andrew M. Childs et al. ‘Exponential algorithmic speedup by a quantum walk’. In: *Proceedings of the thirty-fifth ACM symposium on Theory of computing - STOC '03* (2003). DOI: [10.1145/780542.780552](https://doi.org/10.1145/780542.780552). URL: <http://dx.doi.org/10.1145/780542.780552>.
- [8] Taira Giordani et al. ‘Entanglement transfer, accumulation and retrieval via quantum-walk-based qubit-qudit dynamics’. In: *arXiv e-prints* (Oct. 2020). arXiv: [2010.07127 \[quant-ph\]](https://arxiv.org/abs/2010.07127). URL: <https://arxiv.org/abs/2010.07127>.
- [9] Martin B. Plenio and Shashank Virmani. ‘An Introduction to entanglement measures’. In: *Quant. Inf. Comput.* 7 (2007), pp. 1–51. arXiv: [quant-ph/0504163](https://arxiv.org/abs/quant-ph/0504163).
- [10] G. Vidal and R. F. Werner. ‘Computable measure of entanglement’. In: *Physical Review A* 65.3 (Feb. 2002). ISSN: 1094-1622. DOI: [10.1103/physreva.65.032314](https://doi.org/10.1103/physreva.65.032314). URL: <http://dx.doi.org/10.1103/PhysRevA.65.032314>.
- [11] Ben Tregenna et al. ‘Controlling discrete quantum walks: coins and initial states’. In: *New Journal of Physics* 5 (July 2003), pp. 83–83. ISSN: 1367-2630. DOI: [10.1088/1367-2630/5/1/383](https://doi.org/10.1088/1367-2630/5/1/383). URL: <http://dx.doi.org/10.1088/1367-2630/5/1/383>.

Appendices

A Equivalence of Maximally Entangled Ququart State to 2 Bell States

First consider a system of two qubits. The Hilbert space of this system is spanned by four states,

$$|00\rangle, |01\rangle, |10\rangle, |11\rangle. \quad (\text{A.1})$$

Hence, this two qubit system can simulate a ququart and the four basis states can be relabelled

$$|00\rangle = |0\rangle \quad (\text{A.2})$$

$$|01\rangle = |1\rangle \quad (\text{A.3})$$

$$|10\rangle = |2\rangle \quad (\text{A.4})$$

$$|11\rangle = |3\rangle \quad (\text{A.5})$$

Consider now four qubits forming two Bell pairs. This can be described by

$$(|00\rangle + |11\rangle) \otimes (|00\rangle + |11\rangle) \quad (\text{A.6})$$

$$= |00\rangle |00\rangle + |00\rangle \quad (\text{A.7})$$