Quantum communication without the necessity of quantum memories

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Quantum physics is known to allow for completely new ways to create, manipulate and store information. Quantum communication - the ability to transmit quantum information - is a primitive necessary for any quantum internet. At its core, quantum communication generally requires the formation of entangled links between remote locations. The performance of these links is limited by the classical signaling time between such locations - necessitating the need for long lived quantum memories. Here we present the design of a communications network which neither requires the establishment of entanglement between remote locations nor the use of long-lived quantum memories. The rate at which quantum data can be transmitted along the network is only limited by the time required to perform efficient local gate operations. Our scheme thus potentially provides higher communications rates than previously thought possible.

Quantum communication is a primitive necessary for any future quantum internet\textsuperscript{4,5} - irrespective of whether such communication is over distances of centimeters or thousands of kilometers. It is more than just using a quantum channel to establish shared classical key material\textsuperscript{2} between remote locations. Instead, for instance, it can also be used to transfer information between remote quantum computers\textsuperscript{6,7}. There are a number of ways to reliably distribute quantum information between remote locations (nodes)\textsuperscript{[1]}. The most familiar and de facto approach is to establish entanglement between the nodes and then use quantum teleportation to transfer the information from one node to the other\textsuperscript{[7]}. Depending on the distance between the nodes one may need quantum repeaters\textsuperscript{[8,9]} at intermediate locations, whose role is to mediate entanglement between the endmost nodes. After establishing entanglement between adjacent nodes, one can use entanglement swapping\textsuperscript{[10]} to extend the range of entanglement across the entire network of quantum repeaters\textsuperscript{[20]}. Then standard quantum teleportation\textsuperscript{[6]} allows the information to be moved between the endmost nodes. However the performance of such an approach is ultimately limited by the time it takes to establish the intermediary entangled links\textsuperscript{[21]}. At best this is the signaling time between adjacent nodes, but with most schemes it scales as the multiples of the round-trip time across the entire network\textsuperscript{[20,22]}. This necessitates quantum memories capable of storing information for milliseconds or longer\textsuperscript{[20,23]}.

In this paper we present an alternative approach to quantum communication based on directly transmitting quantum information, in encoded form, across a network\textsuperscript{[24]}. As our scheme does not involve teleportation, it does not require the establishment of entangled links between nodes or long-lived quantum memories. Furthermore, as our scheme utilizes an error-correction code\textsuperscript{[25,28]} that can tolerate photon loss in excess of 50\% in the quantum channels between nodes, it allows for nodes to be spaced further apart than conventionally thought. Our scheme, in principle, allows for communication rates that significantly exceed those of existing entanglement-based schemes, yet is modest in its use of resources and is simple enough to be viable in the medium term.

It is important to begin with a discussion of the fundamental building blocks of our scheme. We are going to consider a transmitter-receiver model\textsuperscript{[21]} [depicted and described in Fig. 1]. Both the transmitter and receiver units comprise a matter qubit (an electron spin for example) located in a cavity. The matter qubits do not require a coherence time anywhere near the time required for photons to propagate between nodes. Hence our matter qubits will not be thought of as quantum memories, instead as information processing qubits. The transmitter unit contains a single photon source while the receiver unit contains a single photon detector. Coupling the transmitter unit in one node to a receiver in another node via an optical fiber then allows a quantum state to be directly transmitted between those nodes.

This would seem to be an ideal solution but a serious problem exists. Channel and coupling losses (as well as source and detector inefficiencies) will degrade the quantum state that is being transmitted\textsuperscript{[22]}. This may not be an issue for quantum key distribution (QKD) applications based on BB84 as the key material can be post selected on only those that arrive at the end node\textsuperscript{[4,6]} but at a significant expense on the rate. Also for other communication and computational tasks it is not that simple - entanglement could be necessary here. Post selection would require long lived quantum memories at the end nodes\textsuperscript{[21,22]}. This issue can be overcome (to a certain extent) by encoding our state using a general error-correction code\textsuperscript{[24,29,32]}. The error correction code could protect against the loss as quantum signals.
The interaction between the matter qubit and photon is given by \( U = \exp[-i \chi t n_a \otimes |e\rangle\langle e|] \) where \( \chi \) is the coupling strength, \( t \) the interaction time, \( n_a \) the photon field number operator and \( |e\rangle \langle e| \) the excited (ground) state of the matter qubit. Choosing \( \chi t \) appropriately, the photon acquires a \( \pi \) phase shift only if the matter qubit is \( |e\rangle \). The transfer begins by preparing the photon in the dual rail state \( |0\rangle|1\rangle + |1\rangle|0\rangle \). The first mode interacts with the matter qubit initialized as \( \alpha|g\rangle + \beta|e\rangle \) giving \( \alpha|g\rangle(|0\rangle|1\rangle + |1\rangle|0\rangle) + \beta|e\rangle(|0\rangle|1\rangle - |1\rangle|0\rangle) \). Measuring the matter qubit in the \( |g\rangle \pm |e\rangle \) basis projects the photonic state to \( \alpha(|0\rangle|1\rangle + |1\rangle|0\rangle) + \beta(|0\rangle|1\rangle - |1\rangle|0\rangle) \) (up to a known phase correction). This is then sent over the quantum channel temporally multiplexed with a heralding signal to the receiver unit which prepares the matter qubit as \( |g\rangle + |e\rangle \) and then interacts with the first photonic mode. The two modes of the photonic state are recombined on a 50/50 beamsplitter and then measured at one of the two detectors projecting the matter qubit into the state \( \alpha|g\rangle + \beta|e\rangle \) (again up to a known phase correction).

The probability of no photon arriving in the \( m \) photon logical qubit is \( p_f = (1 - p)^m \) where \( p \) is the probability of a single photon arriving at the adjacent node. Second, at least one of the logical qubits must arrive with no loss. With \( n \) logical qubits the probability we do not receive at least one logical qubit without error is \( p_f = 1 - (1 - (1 - p)^m)^n + [1 - p^m - (1 - p)^m]^n \). Once we set our target failure error rates, \( p_f \), and given \( p \), we can determine the minimum \( n \) and \( m \) required. For illustrative purposes Table 1 shows estimates of \( m \) and \( n \) for various \( p \). The resources are quite modest for \( p > 0.60 \) but increase significantly as \( p \) decreases. However, this can be overcome by realizing that a single photon can carry more than one qubit of information (photons have multiple degrees of freedom, such as time bin, polarization, spatial modes)\(^{22, 33} \). This means fewer photons need to be send through the channel and so we have a higher chance of receiving them all.

Encoding more than one qubits on a photon has long being known in the linear optical quantum computation community as a way to reduce the number of photons required to undertake certain tasks. It can be used to the same effect here in quantum communication and networks. Consider a general two matter qubit state \( \alpha_0|gg\rangle + \alpha_1|ge\rangle + \alpha_2|eg\rangle + \alpha_3|ee\rangle \) which we want to transfer on to a single photon prepared into a equal superposition state over four spatial modes \( |10\rangle|00\rangle + |01\rangle|00\rangle + |00\rangle|10\rangle + |00\rangle|01\rangle \). The transfer is achieved by performing a CPhase operation between the first matter qubit and second photonic mode and a CPhase gate between the second matter qubit and fourth photonic mode. Measuring the matter qubits in the \( |g\rangle \pm |e\rangle \) basis gives the

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**FIG. 1.** Schematic representation of the direct transmission of the information from one communication node to another using a transmitter unit and receiver unit, where each comprises a matter-based contained in a cavity coupled to an optical fiber. The resources are quite modest for \( p > 0.60 \) but increase significantly as \( p \) decreases. However, this can be overcome by realizing that a single photon can carry more than one qubit of information (photons have multiple degrees of freedom, such as time bin, polarization, spatial modes). This means fewer photons need to be send through the channel and so we have a higher chance of receiving them all.
FIG. 2. Schematic representation in a of the transmission of a quantum signal using a redundant quantum parity code. It begins in i with the construction of the redundant quantum parity code on the matter qubits and the encoding of a quantum state with parameters $\alpha, \beta$. This requires highly efficient single- and two-qubit operations. In ii the quantum states of each of the matter qubits are transferred to photonic states, as detailed in Fig. (1). The matter qubits are now free to be used again. In iii the photons are transmitted over the lossy channel to the remote receiver units. In iv the information encoded on the photonic states is transferred to matter qubits. Next in v the photons are measured to herald loss events. The loss-affected parity blocks are then disentangled from the remaining part of the quantum state by measuring one or more of the matter qubits in the Z basis. Parity blocks that have no loss are left untouched and so we have now finished the transfer of information between nodes. We can now if required use the general error correction properties inherent in the code to correct small dephasing errors. Finally in vi the quantum state at the receiver side can be re-encoded back to its original size by using the discarded matter qubits. The receiver can then act as a transmitter to send the signal to the next node and so the state can be sent over long distances as shown in b.

spatial encoded photonic state

$$\begin{align*}
\{\alpha_0 \pm \alpha_1 \pm \alpha_2 + \alpha_3\} |10\rangle|00\rangle \\
+ \{\alpha_0 \pm \alpha_1 \mp \alpha_2 - \alpha_3\} |01\rangle|00\rangle \\
+ \{\alpha_0 \pm \alpha_1 \pm \alpha_2 + \alpha_3\} |00\rangle|10\rangle \\
+ \{\alpha_0 \pm \alpha_1 \mp \alpha_2 - \alpha_3\} |00\rangle|01\rangle
\end{align*}$$

The four spatial photonic modes can then be send temporally multiplexed across the channel to the receiver units where a similar procedure can be used to transfer it back to matter qubits.

Now we encode our redundancy parity code uniformly over all the photons and degrees of freedom such that one photon does not carry more than one qubit from a particular parity block. While this may seem trivial, it significantly reduces the number of physical qubits required within each communication node, as is shown in Table I.

So far we have focussed on loss as our main source of error. However in realistic systems we also have gate errors that occur during the encoding and decoding circuits or during the transferral between matter-based and photons. We also have measurement errors as each logical qubit with photon loss needs to be measured out in the Z basis. Imperfect Z measurements can lead to a logical error on our encoded state, however this can be minimized by using a majority voting tactic. It is likely that more than one qubit will have been successfully transferred
within each loss affected logical qubit and so by measuring them all in the $Z$ basis we can decrease the effect of such errors. While not designed to handle general errors the redundant quantum parity code has some ability to correct these as the code is based on a generalization of the Shor code for $n, m \geq 3$. In the situation where $q$ logical qubits are received in fact we can correct $\frac{m-1}{2}$ bit flip errors within each logical qubit and also $\frac{m+1}{2}$ sign flip errors. Without additional error correction on top of the parity code the local error rate from the gates and measurements sets a limit on how much loss our code can tolerate and thus how far we can transmit our quantum signal.

The next question is what is the performance of our system and how does it compare to others in the literature? Initially assuming the local operations are good enough so that we do not require local purification it is straightforward to determine the performance. In Table (I) we show the communication rate for various $p$ where we have assumed that all local gate operations can be done with a total time of 100ns implying a raw communication rate of $10^7$ quantum states being transmitted per second. With $p = 0.60$ we require at least 200 matter qubits per node. However what distance does this correspond to? The probability $p$ is given by $p = p_s p_d R_c^2 \exp[-c/L]$, where $p_s$ is the probability the source emits a single photon, $p_d$ the probability a single photon is detected and $p_c$ the probability of coupling a photon to the cavity. $L$ is the distance between the adjacent nodes and $L_0$ is the attenuation length of the channel (25km for commercial fiber). If we choose $p_s = p_d = p_c = 0.97$ then $p = 0.60$ corresponds to a distance between nodes of $L = 10km$. Having 80 communication nodes would allow the transmission of quantum states over 800km with a success probability exceeding 98% using $80 \times 200$ matter qubits ($R_c = 2400$Hz). If the transfer fidelity between adjacent nodes is of the order of 99.9% then an overall fidelity of 90% could be achieved without the need for further error correction (or purification). This seems to indicate a good potential which could be improved further with faster local operations but this does not give us an indication of whether this performance is good or bad. To do this we need to make a comparison to other known schemes.

There are a number of other schemes we can use as a comparison. The most obvious is the direct transmission of the photon over the entire 800km which occurs with a success probability $p \sim 10^{-15}$ using two qubits (which would correspond to a rate $< 10^{-6}$Hz). The original DLCZ protocol gives a rate of $10^{-3}$Hz using 32 qubits (atomic ensembles) divided between 16 links and achieving a fidelity of 90%. An improved protocol based on photon-pair sources and multimode memories (able to store 100 modes) to implement a temporally multiplexed version of the DLCZ protocol achieves a rate of 0.1Hz using 16 links. Alternatively a spatially multiplexed scheme with the 20 links (with 50 qubits/node) separated by 40km and deterministic local gates can achieve an approximate rate of 2400Hz. To compare these we could look at the rate of data transfer over 800km divided by the total number of qubits used. In such a case our scheme presented here is nearly two orders of magnitude better. These considerations have assumed that the number of links is low enough such that purification is not likely to be required. With purification it was found that a rate of 80Hz could be achieved over the same distance using 32 links each composed of 16 qubits. Using a fully error corrected scheme it was found a rate of 100Hz could be achieved using 80 links each composed of 30 – 150 qubits. So in terms of the rate divided by the total number of qubits over the whole network these schemes can achieve $R/\text{total qubits} \sim 10^{-4} - 1$. Our scheme is between two to four orders of magnitude better.

Finally while our approach has so far been about sending information along the network, it can also be used to generate entanglement between the end nodes as we depict in Fig(3) still without the need for long-lived quantum memories. In this situation a parity encoded Bell state is created at the central node. One half is send to the left and the other half to the right using the redundant parity code on each. This entanglement could be used, for instance, in device-independent QKD and Bell tests over long distances.

To summarize, we have presented a quantum communication scheme based on parity codes, which allows the direct transmission of quantum states between distributed systems. The scheme gives high communication rates with modest resource usage for modestly separated nodes (less than 10 km). More importantly our scheme does not require the use of long-lived quantum memories but does requires accurate local gates. This potentially enables communication rates several orders of
FIG. 3. Schematic representation illustrating how the direct transmission scheme can be used in a butterfly arrangement [21] to distribute entanglement between Alice and Bob without the need for long-lived quantum memories.

magnitude faster than current schemes. This work shows the importance of efficient interfaces between light and matter. While we have focused on sending information directly it is also straightforward to consider a butterfly arrangement [21] to distribute entanglement between the end nodes (still without the need for long-lived memories). Our scheme has important implications for the development of quantum communication technologies in the future. Without special attention to being paid to the system design one will easily become limited by classical signalling costs.

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Note added: The numbers in Table I have changed a little from the published version due to the modification to add an extra term to the probability distribution. This restricts the total loss to less than 50 percent.

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[17] Tittel, W., Afzelius, M., Chanei`ere, T., Cone, R.L., Tittel, W., Afzelius, M., Chaneli`ere, T., Cone, R.L., Sangouard, N., Dubessy, R., & Simon, C. Quantum re-
[23] If the photon carried a logical qubits worth of infor-
[25] Our scheme is not restricted to using simple redundant parity codes. Instead we could use a more general code such that only