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## Photonic one-way quantum repeater

### Abstract


A quantum repeater forwards quantum information along with measurement results, enabling a destination endpoint to recover the original quantum information. The quantum repeater receives an input graph state encoding at least one logical qubit from a source endpoint. The quantum repeater generates a first multi-photonic graph state and entangles the input graph state with the first graph state. The quantum repeater forwards the quantum information by providing at least a portion of the first graph state to a subsequent quantum repeater or to the destination endpoint. The quantum repeater also measures the input graph state and provides the measurement results to the destination endpoint, enabling the destination endpoint to recover the at least one logical qubit from the source endpoint.



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## Background/Summary

TECHNICAL FIELD

(1) The present disclosure relates to optical network communication, specifically for quantum communication.

BACKGROUND

(2) Exchanging quantum bits (i.e., qubits) forms the technological basis for quantum communication in a wide-area quantum network, such as a quantum internet. Currently, photonic qubits present the only reliable option to carry qubits across significant distances. Signal attenuation prevents direct transmission of single photons for long distance quantum communication. However, fundamental constraints imposed by quantum physics (e.g., the no-cloning theorem) does not allow the typical classical solutions, such as signal amplification, for

quantum communication.
(3) Quantum repeaters have been proposed that operate on qubits that are encoded in multi-photon states, which accommodate the potential for missing photons through quantum error correction. Each quantum repeater along the path from the source endpoint to the destination endpoint requires quantum storage and processing to recover the multi-photon state at each step.

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## Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1** is simplified block diagram of one-way photonic quantum repeater system between two endpoints, according to an example embodiment.
(2) FIG. **2** is a simplified block diagram of quantum communication encoding a quantum state with quantum error correction, according to an example embodiment.
(3) FIG. **3** is a simplified block diagram of a quantum repeater without quantum storage, according to an example embodiment.
(4) FIG. **4**A illustrates a fusion-based realization of a graph state for quantum communication with quantum error correction, according to an example embodiment.
(5) FIG. **4**B illustrates the graph states used for quantum error correction alongside the corresponding quantum repeater devices, according to an example embodiment.
(6) FIG. **5** is a flowchart illustrating operations performed by a quantum repeater to enable quantum error correction at the destination endpoint for a quantum communication, according to an example embodiment.
(7) FIG. **6** is a block diagram of a computing device that may be configured to perform the techniques presented herein, according to an example embodiment.
DETAILED DESCRIPTION
Overview
(8) A method is provided for forwarding quantum information along with measurement results, enabling a destination endpoint to recover the original quantum information. The method includes receiving an input graph state at a quantum repeater. The input graph state encodes at least one logical qubit from a source endpoint. The method also includes generating a first graph state comprising a plurality of photonic qubits and entangling the input graph state with the first graph state. The method includes providing at least a portion of the first graph state to a subsequent quantum repeater or to the destination endpoint to forward the quantum information. The method further comprises measuring the input graph state to generate measurement results and providing the measurement results to the destination endpoint, enabling the destination endpoint to recover the at least one logical qubit from the source endpoint.
EXAMPLE EMBODIMENTS
(9) The techniques presented herein provide for a one-way, photonic, measurement-based quantum repeater protocol that does not require any quantum memory resources. The quantum communication system encodes logical qubits in multi-photon graph states and runs a measurement-based quantum error correction system. The destination endpoint includes a decoder that determines whether the logical quantum information can be recovered or if the quantum information has been leaked to the environment or an eavesdropper.
(10) Referring now to FIG. **1**, a quantum communication system **100** configured to relay quantum information through a series of quantum repeaters is shown. The quantum communication system **100** transfers quantum information from a source endpoint **110** (e.g., Alice) with encoding logic **112** to a destination endpoint **120** (e.g., Bob) with decoding logic **122**. The encoding logic **112** enables the source endpoint **110** to encode one or more qubits of quantum information into a multi-photon graph state for transmission through the quantum information system **100**. The decoding

logic **122** enables the destination endpoint **120** to recover the qubits from the source endpoint **110** through quantum error correction, as described herein.

(11) The quantum information system **100** includes a first quantum repeater **130** with quantum repeater logic **132**, one or more intermediary quantum repeaters **140** with quantum repeater logic **142**, and a last quantum repeater **150** with quantum repeater logic **152**. The quantum repeaters **130**, **140**, and **150** may be functionally equivalent devices, and their respective positions as first, intermediary, or last quantum repeaters may vary based on the path for exchanging quantum information between the source endpoint **110** and the destination endpoint **120** or any other endpoints attached to the quantum information system.

(12) The source endpoint **110** is connected to the first quantum repeater **130** with an optical link **160**. In addition to the optical link **160**, the optical links **162**, **164**, **166**, and **168** form a path for photons to carry quantum information (e.g., encoded in multi-photonic graph states) from the source endpoint **110** to the destination endpoint **120**. In one example, a reverse path from the destination endpoint **120** to the source endpoint **110** may be provided separately to enable two-way communication. The reverse path may include some or all of the quantum repeaters **130**, **140**, **150**, and/or other quantum repeaters that are not along the forward path from the source endpoint **110** to the destination endpoint **120**.

(13) The quantum communication system **100** also includes a classical network **170** that allows the source endpoint **110**, the quantum repeaters **130**, **140**, **150**, and the destination endpoint **120** to share classical information, such as measurement results that enable quantum error correction. In one example, the classical network **170** may be an optical network or an electrical network that carries classical bits of information.

(14) Referring now to FIG. **2**, an example of transferring quantum information from a source endpoint **110** to a destination endpoint **120** through a quantum repeater **140** is shown. The quantum information in a quantum state **210** is encoded as a logical qubit in a multi-photonic graph state **215**. The multi-photonic graph state **215** includes data qubits (i.e., photons) that collectively encode the quantum information from the quantum state **210** and ancilla qubits that are measured for parity and error correction calculations. The ancilla qubits are measured during or shortly after the logical qubit is encoded in the graph state **215**, and the data qubits carrying the quantum information are transmitted between nodes (e.g., source endpoint, quantum repeaters, and destination endpoint).

(15) In one example, the graph state **215** may be encoded as a Calderbank-Shor-Steane (CSS) stabilizer code. Hereinafter, the multi-photonic graph states (e.g., graph state **215**) will be described as being encoded in a [[7.1.3]] Steane code for simplicity and consistency. As shown in FIG. **2**, the data qubits are shown with circles and the ancillary qubits are shown as squares. However, the techniques described herein are not limited to that CSS stabilizer code and may be applied to other quantum codes, such as a [[48,6,8]] generalized bicycle code.

(16) After the source endpoint **110** encodes the quantum state **210** in the graph state **215**, the graph state **215** is transmitted to the quantum repeater **140**. During the transit from the source endpoint **110** to the quantum repeater **140**, one or more of the photons in the multi-photonic graph state **215** may be lost (e.g., to the environment or to an eavesdropper), and the quantum repeater **140** receives a graph state **220** that may contain one or more errors to be corrected. The errors (e.g., lost photons) are depicted as solid circles in FIG. **2**.

(17) The quantum repeater **140** generates a new graph state **230** and entangles the new graph state **230** with the received graph state **220** to pass the quantum information to the new graph state **230**. The quantum repeater **140** entangles the received graph state **220** with the new graph state **230** through controlled-phase gates **240**, **242**, **244**, **246**, and **248**. The data qubits in the received graph state **220** are coupled with the data qubits in the new graph state **230**.

(18) After entangling the received graph state **220** with the new graph state **230**, the quantum repeater **140** measures the photons of the received graph state **220** with detectors **250**, **252**, **254**, **256**, and **258**. The detectors **250**, **252**, **254**, **256**, and **258** generate measurement results **260**, which

are provided to the destination endpoint **120** to enable the destination endpoint **120** to perform quantum error correction.

(19) Measuring the photons of the received graph state **220** after entangling the received graph state **220** with the new graph state **230** effectively teleports the quantum information from the quantum state **210** to be encoded in the new graph state **230**, which is transmitted to the destination endpoint **120**. The destination endpoint **120** receives a multi-photonic graph state **265**, which may include additional errors to correct. The destination endpoint **120** uses the measurement results **260** from the quantum repeater **140** to perform quantum error correction on the received graph state **265** to recover the quantum information into a quantum state **270**.

(20) In one example, additional quantum repeaters may be included in the path between the source endpoint **110** and the destination endpoint **120**. Each quantum repeater along the path performs similar operations by entangling the photons of the received graph state with a newly generated graph state and measuring the photons of the received graph state. The measurement results from each quantum repeater may be provided to the next quantum repeater or provided directly to the destination endpoint **120**.

(21) If a quantum repeater receives a set of measurement results from a previous quantum receiver along the path from the source endpoint **110** to the destination endpoint **120**, then each quantum receiver may add measurement results that were generated at the quantum repeater before sending the accumulated measurement results to the next quantum repeater or to the destination endpoint. The individual quantum repeaters do not use the measurement results from previous quantum repeaters, but may pass along the measurement results to the destination endpoint **120** to enable the destination endpoint **120** to perform all of the quantum error correction.

(22) In another example, the multi-photon graph states (e.g., graph state **215** and graph state **230**) may be constructed as stabilizers for orthogonal bases (e.g., X stabilizers and Z stabilizers) to alternate stabilizer measurements at each step along the path. For instance, the graph state **215** may be constructed as an X stabilizer graph state and the graph state **230** may be constructed as a Z stabilizer graph state.

(23) Referring now to FIG. **3**, an example of a quantum repeater **300** processing a multi-photonic graph state is shown. When the quantum repeater **300** receives the incoming state **310** (e.g., a multi-photonic graph state), a graph state generator **320** in the quantum repeater **300** generates two stabilizer states **322** and **324**. The stabilizer states **322** and **324** are generated as multi-photonic graph states encoded according to a stabilizer code to correct qubit erasure error through a measurement-based error correction scheme. In one example, the stabilizer states **322** and **324** are stabilizers for orthogonal bases. For instance, the stabilizer state **322** may be a stabilizer code for measurements in the Z-basis and the stabilizer state **324** may be a stabilizer code for measurements in the X-basis.

(24) The quantum repeater **300** entangles the stabilizer state **322** with the stabilizer state **324** through an entangling gate **330**. The quantum repeater **300** then entangles the incoming state **310** with the stabilizer state **322** through an entangling gate **340**. The photons of the incoming state **310** are then measured with detectors **350** and the photons of the stabilizer state **322** are measured with detectors **352** to generate measurement results **360**. In one example, the detectors **350** and **352** measure the photons of the incoming state **310** and the stabilizer state **322** in the X-basis.

(25) The measurement by the detectors **350** and **352** effectively teleports the quantum information from the incoming state to the unmeasured stabilizer state **324**, which is transmitted to the next hop as the outgoing state **370**. The next hop may be another quantum repeater or the destination endpoint. The quantum repeater **300** also provide the measurement results **360** to the destination endpoint through a classical channel in the network. The quantum repeater **300** may provide the measurement results **360** directly to the destination endpoint or the quantum repeater **300** may provide the measurement results **360** to a subsequent quantum repeater, which will forward the measurement results to the destination endpoint.

(26) The teleportation process appears similar to teleportation-based error correction schemes, but the usage of CSS error correction codes across the network results in significantly greater loss tolerance. The decoder in the destination endpoint uses all the classical information obtained by measuring qubits across all the repeaters instead of breaking it down to two qubit measurements per quantum repeater.
(27) In one example, the incoming state **310** may be a multi-photonic graph state encoding a logical qubit with data qubits connected by ancilla qubits, as described in the example of FIG. **2**. In this example, the entangling gates **330** and **340** may be controlled-phase gates that operate on the photons of the incoming state **310**, the stabilizer state **322** and the stabilizer state **324**. For instance, the entangling gates **330** and **340** may be constructed from one or more quantum dots that entangle the quantum state of two photons.
(28) In another example, the incoming state **310** may be a fusion-based, multi-photonic graph state encoding a logical qubit with small resource states (e.g., star graphs) that are fused in the multi-photonic graph state, as described with respect to FIG. **4**A. With a fusion-based graph state **310**, the entangling gates **330** and **340** may be fusion measurements of previously unmeasured photons from the small resource states.
(29) Referring now to FIG. **4**A, a representation of a fusion-based graph state **400** corresponding to a [[7,1,3]] Steane code. The graph state **400** includes resource states **410**, **411**, **412**, **413**, **414**, **415**, **416**, **420**, **421**, and **422**. The resource state **410** is a star graph with a central qubit **410**A, two unmeasured qubits **410**B and **410**C, and a fusion qubit **410**D. The fusion qubit **410**D stitches the resource state **410** to the adjacent resource state **420** through a fusion measurement **430** of the fusion qubit **410**D and a corresponding fusion qubit from the resource state **420**. The resource states **411**, **412**, **413**, **414**, **415**, and **416** are also star graphs with a central qubit shown as a solid circle, two unmeasured qubits shown as shaded circles, and 3-5 fusion qubits shown as open circles in a fusion measurement shown as a dashed oval. The resource states **420**, **421**, and **422** are star graphs with a central qubit and 4 fusion qubits, but no unmeasured qubits.
(30) Each resource state **410**, **411**, **412**, **413**, **414**, **415**, **416**, **420**, **421**, and **422** may be generated deterministically based on quantum emitters or probabilistically using a nonlinear material. The two unmeasured qubits in each of the resource states **410**, **411**, **412**, **413**, **414**, **415**, **416**, **420**, **421**, and **422** may be used to entangle two graph states (e.g., incoming state **310** and stabilizer state **322** as shown in FIG. **3**) with a fusion gate.
(31) In one example, the graph state **400** may encode the resource states **410**, **411**, **412**, **413**, **414**, **415**, and **416** as data qubits and the resource states **420**, **421**, and **422** as ancilla qubits to measure stabilizers according to the [[7,1,3]] Steane code. As used by the techniques presented herein, the ancilla qubits of resource states **420**, **421**, and **422** may be measured at each quantum repeater as part of the stabilizer measurements to produce the measurement results used by a destination endpoint to perform the quantum error correction. The graph state **400** may be generated with the ancilla qubits of resource states **420**, **421**, and **422** as X stabilizers or as Z stabilizers.
(32) Referring now to FIG. **4**B, an example of a sequence of quantum repeaters transferring quantum information from a source endpoint **110** to a destination endpoint **120** through [7,1.3] Steane code graph states. The source endpoint **110** encodes a quantum information into a multi-photonic graph state **440** which is generated as a Z stabilizer. The source endpoint **110** sends the graph state **440** to the first quantum repeater **130**, which receives a graph state **450** including any errors that may occur during the encoding or transmission. The first quantum repeater **130** generates a new multi-photonic graph state **452** as an X stabilizer and entangles the new graph state **452** with the received graph state **450**. The first quantum repeater **130** measures the received graph state **450** to generate measurement results **454**, which are provided along a classical network **170** to the destination endpoint **120**. The first quantum repeater **130** also transmits the new graph state **452** to the next quantum repeater **140**.
(33) The next quantum repeater **140** receives a multi-photonic graph state **460**, which includes the

X stabilizer graph state **452** generated at the first quantum repeater **130** and any errors from the transmission to the quantum repeater **140**. The quantum repeater **140** generates a new multi-photonic graph state **462** as a Z stabilizer and entangles the new graph state **462** with the received graph state **460**. The quantum repeater **140** measures the received graph state **460** to generate measurement results **464**, which are provided along a classical network **170** to the destination endpoint **120**. The quantum repeater **140** also transmits the new graph state **462** to a series of quantum repeaters that ends with the last quantum repeater **150**. The series of quantum repeaters alternates between generating a new X stabilizer graph state and generating a new Z stabilizer graph state.

(34) The last quantum repeater **150** receives a multi-photonic graph state **470**, which is a Z stabilizer graph state that includes any errors from the transmission from the previous quantum repeater to the last quantum repeater **150**. The last quantum repeater **150** generates a new multi-photonic graph state **472** as an X stabilizer and entangles the new graph state **472** with the received graph state **470**. The last quantum repeater **150** measures the received graph state **470** to generate measurement results **474**, which are provided along a classical network **170** to the destination endpoint **120**. The last quantum repeater **150** also transmits the new graph state **472** to the destination endpoint **120**.

(35) The destination endpoint **120** receives a multi-photonic graph state **480**, which is an X stabilizer graph state that includes errors from the transmission to the destination endpoint **120**. The destination endpoint **120** uses the measurement results from all of the quantum repeaters (e.g., measurement results **454**, **464**, and **474**) to recover the information from the original graph state **440** in a graph state **482**.

(36) In one example, the quantum error correction process performed by the destination endpoint **120** corrects for loss errors in transmission through optical fibers as well as for errors during the graph state generation process at each quantum repeater. The measurement results **454**, **464**, and **474** capture errors (e.g., photon loss) regardless of the source, and transmission errors may be corrected by the same process as generation errors.

(37) In another example, the quantum repeater system may act on the multi-photonic graph states (e.g., graph states **440**, **450**, **452**, **460**, **462**, **470**, **472**, **480**, and **482**) with controlled phase entanglement of encoded photons, as described with respect to FIG. **2**. Alternatively, the quantum repeater system may act on the multi-photonic graph states (e.g., graph states **440**, **450**, **452**, **460**, **462**, **470**, **472**, **480**, and **482**) with fusion-based entanglement, as described with respect to FIG. **4**A.

(38) Referring now to FIG. **5**, a flowchart illustrates an example process **500** performed by a quantum repeater (e.g., quantum repeater **130**, **140**, or **150**) to extend the range of a quantum transmission from a source endpoint to a destination endpoint. At **510**, the quantum repeater receives an input graph state encoding at least one logical qubit from a source endpoint. In one example, the input graph state may be a graph state corresponding to a CSS code, such as a [[7,1,3]] Steane code or a [[48,6,8]] generalized bicycle code.

(39) At **520**, the quantum repeater generates a first graph state comprising a plurality of photonic qubits. In one example, the first graph state may include a first stabilizer state configured as a stabilizer for a first basis (e.g., an X-basis) and a second stabilizer state configured as a stabilizer for a second basis (e.g., a Z-basis) orthogonal to the first basis. Alternatively, the quantum repeater may determine the form of the first graph state (e.g., an X stabilizer code) based on the form of the input graph state (e.g., a Z stabilizer code).

(40) At **530**, the quantum repeater entangles the input graph state with the newly generated first graph state. In one example, the quantum repeater may entangle the two graph states through a set of controlled-phase gates operating on corresponding photons of the two states. In another example, the quantum repeater may generate two graph states (e.g., an X stabilizer and a Z stabilizer) as the first graph state, entangle the two graph states and then entangle one of the graph

states with the input graph state.

(41) At **540**, the quantum repeater measures the input graph state to generate measurement results. In one example, the quantum repeater may also measure part of the first graph state, such as a stabilizer state that was entangled with the input graph state. In another example, the quantum repeater may measure the photons of the input graph state along the same basis (e.g., the X-basis) that was measured by other quantum repeaters along the path from the source endpoint to the destination endpoint.

(42) At **550**, the quantum repeater provides at least a portion of the first graph state to a subsequent quantum repeater or to destination endpoint. In one example, the quantum repeater provides a portion of the first graph state by transmitting a stabilizer state from the first graph state that was not measured to generate the measurement results.

(43) At **560**, the quantum repeater provides the measurement results to the destination endpoint, enabling the destination endpoint to recover at least the one logical qubit encoded by the source endpoint. In one example, the quantum repeater sends the measurement results directly to the destination endpoint through a classical network. In another example, the quantum repeater provides the measurement results to a subsequent quantum repeater, which will provide the measurement results to the destination endpoint. The quantum repeater may also receive measurement results from a previous quantum repeater and forward the measurement results of the previous quantum repeater toward the destination endpoint.

(44) Referring to FIG. **6**, FIG. **6** illustrates a hardware block diagram of a computing device **600** that may perform functions associated with operations discussed herein in connection with the techniques depicted in FIGS. **1-3**, **4**A, **4**B, and **5**. In various embodiments, a computing device, such as computing device **600** or any combination of computing devices **600**, may be configured as any entity/entities as discussed for the techniques depicted in connection with FIGS. **1-3**, **4**A, **4**B, and **5** in order to perform operations of the various techniques discussed herein.

(45) In at least one embodiment, the computing device **600** may include one or more processor(s) **602**, one or more memory element(s) **604**, storage **606**, a bus **608**, one or more network processor unit(s) **610** interconnected with one or more network input/output (I/O) interface(s) **612**, one or more I/O interface(s) **614**, and control logic **620**. In various embodiments, instructions associated with logic for computing device **600** can overlap in any manner and are not limited to the specific allocation of instructions and/or operations described herein.

(46) In at least one embodiment, processor(s) **602** is/are at least one hardware processor configured to execute various tasks, operations and/or functions for computing device **600** as described herein according to software and/or instructions configured for computing device **600**. Processor(s) **602** (e.g., a hardware processor) can execute any type of instructions associated with data to achieve the operations detailed herein. In one example, processor(s) **602** can transform an element or an article (e.g., data, information, classical bits, qubits) from one state or thing to another state or thing. Any of potential classical processing elements, quantum processing elements, microprocessors, digital signal processor, baseband signal processor, modem, PHY, controllers, systems, managers, logic, and/or machines described herein can be construed as being encompassed within the broad term ‘processor’.

(47) In at least one embodiment, memory element(s) **604** and/or storage **606** is/are configured to store quantum data, classical data, information, software, and/or instructions associated with computing device **600**, and/or logic configured for memory element(s) **604** and/or storage **606**. For example, any logic described herein (e.g., control logic **620**) can, in various embodiments, be stored for computing device **600** using any combination of memory element(s) **604** and/or storage **606**. Note that in some embodiments, storage **606** can be consolidated with memory element(s) **604** (or vice versa), or can overlap/exist in any other suitable manner.

(48) In at least one embodiment, bus **608** can be configured as an interface that enables one or more elements of computing device **600** to communicate in order to exchange information and/or data.

Bus **608** can be implemented with any architecture designed for passing control, data and/or information between processors, memory elements/storage, peripheral devices, and/or any other hardware and/or software components that may be configured for computing device **600**. In at least one embodiment, bus **608** may be implemented as a fast kernel-hosted interconnect, potentially using shared memory between processes (e.g., logic), which can enable efficient communication paths between the processes.

(49) In various embodiments, network processor unit(s) **610** may enable communication between computing device **600** and other systems, entities, etc., via network I/O interface(s) **612** (wired and/or wireless) to facilitate operations discussed for various embodiments described herein. In various embodiments, network processor unit(s) **610** can be configured as a combination of hardware and/or software, such as one or more Ethernet driver(s) and/or controller(s) or interface cards, Fibre Channel (e.g., optical) driver(s) and/or controller(s), wireless receivers/transmitters/transceivers, baseband processor(s)/modem(s), and/or other similar network interface driver(s) and/or controller(s) now known or hereafter developed to enable communications between computing device **600** and other systems, entities, etc. to facilitate operations for various embodiments described herein. In various embodiments, network I/O interface(s) **612** can be configured as one or more Ethernet port(s), Fibre Channel ports, any other I/O port(s), and/or antenna(s)/antenna array(s) now known or hereafter developed. Thus, the network processor unit(s) **610** and/or network I/O interface(s) **612** may include suitable interfaces for receiving, transmitting, and/or otherwise communicating data and/or information in a classical network environment.

(50) I/O interface(s) **614** allow for input and output of data and/or information with other entities that may be connected to computing device **600**. For example, I/O interface(s) **614** may provide a connection to external devices such as a keyboard, keypad, a touch screen, and/or any other suitable input and/or output device now known or hereafter developed. In some instances, external devices can also include portable computer readable (non-transitory) storage media such as database systems, thumb drives, portable optical or magnetic disks, and memory cards. In still some instances, external devices can be a mechanism to display data to a user, such as, for example, a computer monitor, a display screen, or the like.

(51) In various embodiments, control logic **620** can include instructions that, when executed, cause processor(s) **602** to perform operations, which can include, but not be limited to, providing overall control operations of computing device; interacting with other entities, systems, etc. described herein; maintaining and/or interacting with stored data, information, parameters, etc. (e.g., memory element(s), storage, data structures, databases, tables, etc.); combinations thereof; and/or the like to facilitate various operations for embodiments described herein.

(52) The programs described herein (e.g., control logic **620**) may be identified based upon application(s) for which they are implemented in a specific embodiment. However, it should be appreciated that any particular program nomenclature herein is used merely for convenience; thus, embodiments herein should not be limited to use(s) solely described in any specific application(s) identified and/or implied by such nomenclature.

(53) In various embodiments, entities as described herein may store classical data/information or quantum data/information in any suitable volatile and/or non-volatile memory item (e.g., magnetic hard disk drive, solid state hard drive, semiconductor storage device, random access memory (RAM), read only memory (ROM), erasable programmable read only memory (EPROM), application specific integrated circuit (ASIC), light quantum memory, solid quantum memory, etc.), software, logic (fixed logic, hardware logic, programmable logic, analog logic, digital logic), hardware, and/or in any other suitable component, device, element, and/or object as may be appropriate. Any of the memory items discussed herein should be construed as being encompassed within the broad term ‘memory element’. Data/information being tracked and/or sent to one or more entities as discussed herein could be provided in any database, table, register, list, cache,

storage, and/or storage structure: all of which can be referenced at any suitable timeframe. Any such storage options may also be included within the broad term ‘memory element’ as used herein.

(54) Note that in certain example implementations, operations as set forth herein may be implemented by logic encoded in one or more tangible media that is capable of storing instructions and/or digital information and may be inclusive of non-transitory tangible media and/or non-transitory computer readable storage media (e.g., embedded logic provided in: an ASIC, digital signal processing (DSP) instructions, software [potentially inclusive of object code and source code], etc.) for execution by one or more processor(s), and/or other similar machine, etc. Generally, memory element(s) **604** and/or storage **606** can store data, software, code, instructions (e.g., processor instructions), logic, parameters, combinations thereof, and/or the like used for operations described herein. This includes memory element(s) **604** and/or storage **606** being able to store classical data, quantum data, software, code, instructions (e.g., processor instructions), logic, parameters, combinations thereof, or the like that are executed to carry out operations in accordance with teachings of the present disclosure.

(55) In some instances, software of the present embodiments may be available via a non-transitory computer useable medium (e.g., magnetic or optical mediums, magneto-optic mediums, CD-ROM, DVD, memory devices, etc.) of a stationary or portable program product apparatus, downloadable file(s), file wrapper(s), object(s), package(s), container(s), and/or the like. In some instances, non-transitory computer readable storage media may also be removable. For example, a removable hard drive may be used for memory/storage in some implementations. Other examples may include optical and magnetic disks, thumb drives, and smart cards that can be inserted and/or otherwise connected to a computing device for transfer onto another computer readable storage medium.

Variations and Implementations

(56) Embodiments described herein may include one or more networks, which can represent a series of points and/or network elements of interconnected communication paths for receiving and/or transmitting messages (e.g., packets of information) that propagate through the one or more networks. These network elements offer communicative interfaces that facilitate communications between the network elements. A network can include any number of hardware and/or software elements coupled to (and in communication with) each other through a communication medium. Such networks can include, but are not limited to, any local area network (LAN), virtual LAN (VLAN), wide area network (WAN) (e.g., the Internet), software defined WAN (SD-WAN), wireless local area (WLA) access network, wireless wide area (WWA) access network, metropolitan area network (MAN), Intranet, Extranet, virtual private network (VPN), Low Power Network (LPN), Low Power Wide Area Network (LPWAN), Machine to Machine (M2M) network, Internet of Things (IoT) network, Ethernet network/switching system, any other appropriate architecture and/or system that facilitates communications in a network environment, and/or any suitable combination thereof.

(57) Networks through which communications propagate can use any suitable technologies for communications including wireless communications (e.g., 4G/5G/nG, IEEE 802.11 (e.g., Wi-Fi®/Wi-Fi6®), IEEE 802.16 (e.g., Worldwide Interoperability for Microwave Access (WiMAX)), Radio-Frequency Identification (RFID), Near Field Communication (NFC), Bluetooth™, mm.Math.wave, Ultra-Wideband (UWB), etc.), and/or wired communications (e.g., T1 lines, T3 lines, digital subscriber lines (DSL), Ethernet, Fibre Channel, etc.). Generally, any suitable means of communications may be used such as electric, sound, light, infrared, and/or radio to facilitate communications through one or more networks in accordance with embodiments herein. Communications, interactions, operations, etc. as discussed for various embodiments described herein may be performed among entities that may directly or indirectly connected utilizing any algorithms, communication protocols, interfaces, etc. (proprietary and/or non-proprietary) that allow for the exchange of data and/or information.

(58) Communications in a network environment can be referred to herein as ‘messages’,

‘messaging’, ‘signaling’, ‘data’, ‘content’, ‘objects’, ‘requests’, ‘queries’, ‘responses’, ‘replies’, etc. which may be inclusive of packets. As referred to herein and in the claims, the term ‘packet’ may be used in a generic sense to include packets, frames, segments, datagrams, and/or any other generic units that may be used to transmit communications in a network environment. Generally, a packet is a formatted unit of data that can contain control or routing information (e.g., source and destination address, source and destination port, etc.) and data, which is also sometimes referred to as a ‘payload’, ‘data payload’, and variations thereof. In some embodiments, control or routing information, management information, or the like can be included in packet fields, such as within header(s) and/or trailer(s) of packets. Internet Protocol (IP) addresses discussed herein and in the claims can include any IP version 4 (IPv4) and/or IP version 6 (IPv6) addresses.
(59) To the extent that embodiments presented herein relate to the storage of data, the embodiments may employ any number of any conventional or other databases, data stores or storage structures (e.g., files, databases, data structures, data or other repositories, etc.) to store information.
(60) Note that in this Specification, references to various features (e.g., elements, structures, nodes, modules, components, engines, logic, steps, operations, functions, characteristics, etc.) included in ‘one embodiment’, ‘example embodiment’, ‘an embodiment’, ‘another embodiment’, ‘certain embodiments’, ‘some embodiments’, ‘various embodiments’, ‘other embodiments’, ‘alternative embodiment’, and the like are intended to mean that any such features are included in one or more embodiments of the present disclosure, but may or may not necessarily be combined in the same embodiments. Note also that a module, engine, client, controller, function, logic or the like as used herein in this Specification, can be inclusive of an executable file comprising instructions that can be understood and processed on a server, computer, processor, machine, compute node, combinations thereof, or the like and may further include library modules loaded during execution, object files, system files, hardware logic, software logic, or any other executable modules.
(61) It is also noted that the operations and steps described with reference to the preceding figures illustrate only some of the possible scenarios that may be executed by one or more entities discussed herein. Some of these operations may be deleted or removed where appropriate, or these steps may be modified or changed considerably without departing from the scope of the presented concepts. In addition, the timing and sequence of these operations may be altered considerably and still achieve the results taught in this disclosure. The preceding operational flows have been offered for purposes of example and discussion. Substantial flexibility is provided by the embodiments in that any suitable arrangements, chronologies, configurations, and timing mechanisms may be provided without departing from the teachings of the discussed concepts.
(62) As used herein, unless expressly stated to the contrary, use of the phrase ‘at least one of’, ‘one or more of’, ‘and/or’, variations thereof, or the like are open-ended expressions that are both conjunctive and disjunctive in operation for any and all possible combination of the associated listed items. For example, each of the expressions ‘at least one of X, Y and Z’, ‘at least one of X, Y or Z’, ‘one or more of X, Y and Z’, ‘one or more of X, Y or Z’ and ‘X, Y and/or Z’ can mean any of the following: 1) X, but not Y and not Z; 2) Y, but not X and not Z; 3) Z, but not X and not Y; 4) X and Y, but not Z; 5) X and Z, but not Y; 6) Y and Z, but not X; or 7) X, Y, and Z.
(63) Additionally, unless expressly stated to the contrary, the terms ‘first’, ‘second’, ‘third’, etc., are intended to distinguish the particular nouns they modify (e.g., element, condition, node, module, activity, operation, etc.). Unless expressly stated to the contrary, the use of these terms is not intended to indicate any type of order, rank, importance, temporal sequence, or hierarchy of the modified noun. For example, ‘first X’ and ‘second X’ are intended to designate two ‘X’ elements that are not necessarily limited by any order, rank, importance, temporal sequence, or hierarchy of the two elements. Further as referred to herein, ‘at least one of’ and ‘one or more of can be represented using the’ (s)′ nomenclature (e.g., one or more element(s)).
(64) In summary, the techniques presented herein encode logical qubits in a graph state of photons corresponding to a CSS code and perform measurements (e.g., Bell measurements) at each

quantum repeater. The classical information obtained from the measurement outcomes, which also contains measurement of loss events, bit flip errors, or any other type of errors, is not processed until received by the destination endpoint that performs the error correction across the quantum network based on the accumulated measurement results.

(65) Unlike typical error correction methods, the individual repeaters do not perform any error correction, which offers several advantages in addition to improved error correction. Since each quantum repeater does not need to decode the received graph state into the logical qubit, the quantum repeaters do not need any quantum storage with matter qubits and do not need to make any adaptive measurements. Additionally, the quantum gates and measurements within each quantum repeater is independent of the choice of stabilizer code. These advantages provide a flexible protocol that adapts with advances in hardware technology and new generations of quantum codes.

(66) In some aspects, the techniques described herein relate to a method including: receiving at a quantum repeater, an input graph state encoding at least one logical qubit from a source endpoint; generating a first graph state including a plurality of photonic qubits; entangling the input graph state with the first graph state; measuring the input graph state to generate measurement results; providing at least a portion of the first graph state to a subsequent quantum repeater or to a destination endpoint; and providing the measurement results to the destination endpoint, enabling the destination endpoint to recover the at least one logical qubit from the source endpoint.

(67) In some aspects, the techniques described herein relate to a method, wherein the first graph state includes a first stabilizer state for a first basis and a second stabilizer state for a second basis, the first basis orthogonal to the second basis.

(68) In some aspects, the techniques described herein relate to a method, wherein entangling the input graph state with the first graph state including applying a controlled-phase gate between the input graph state and the first stabilizer state.

(69) In some aspects, the techniques described herein relate to a method, wherein measuring the input graph state includes measuring the input graph state along the first basis.

(70) In some aspects, the techniques described herein relate to a method, further including measuring the first stabilizer state after the first stabilizer state is entangled with the first graph state to generate additional results for the measurement results.

(71) In some aspects, the techniques described herein relate to a method, wherein providing at least the portion of the first graph state to the subsequent quantum repeater or to the destination endpoint includes providing the second stabilizer state to the subsequent quantum repeater or to the destination endpoint.

(72) In some aspects, the techniques described herein relate to a method, wherein the quantum repeater provides at least the portion of the first graph state to the subsequent quantum repeater or to the destination endpoint without storing the input graph state.

(73) In some aspects, the techniques described herein relate to an apparatus including: an optical input configured to receive an input graph state encoding at least one logical qubit from a source endpoint; a graph state generator configured to generate a first graph state including a plurality of photonic qubits; a processor configured to: entangle the input graph state with the first graph state; and measure the input graph state to generate measurement results; an optical output configured to provide at least a portion of the first graph state to a subsequent quantum repeater or to a destination endpoint; and a network interface configured to provide the measurement results to the destination endpoint, enabling the destination endpoint to recover the at least one logical qubit.

(74) In some aspects, the techniques described herein relate to an apparatus, wherein graph state generator is configured to generate the first graph state as a first stabilizer state for a first basis and a second stabilizer state for a second basis, the first basis orthogonal to the second basis.

(75) In some aspects, the techniques described herein relate to an apparatus, wherein the processor is configured to entangle the input graph state with the first graph state by applying a controlled-

phase gate between the input graph state and the first stabilizer state.
(76) In some aspects, the techniques described herein relate to an apparatus, wherein the processor is configured to measure the input graph state by measuring the input graph state along the first basis.
(77) In some aspects, the techniques described herein relate to an apparatus, wherein the processor is further configured to measure the first stabilizer state after the first stabilizer state is entangled with the first graph state to generate additional results for the measurement results.
(78) In some aspects, the techniques described herein relate to an apparatus, wherein the optical output is configured to provide at least the portion of the first graph state to the subsequent quantum repeater or to the destination endpoint by providing the second stabilizer state to the subsequent quantum repeater or to the destination endpoint.
(79) In some aspects, the techniques described herein relate to a system including: a plurality of quantum repeaters, each quantum repeater configured to: receive a corresponding input graph state encoding at least one logical qubit from a source endpoint; generate a corresponding first graph state including a plurality of photonic qubits; entangle the corresponding input graph state with the corresponding first graph state; measure the corresponding input graph state to generate corresponding measurement results; and transmit at least a portion of the corresponding first graph state; and a destination endpoint configured to: receive a last graph state from a last quantum repeater of the plurality of quantum repeaters; receive a plurality of measurement results from the plurality of quantum repeaters; and recover the at least one logical qubit from the source endpoint from the last graph state based on the plurality of measurement results.
(80) In some aspects, the techniques described herein relate to a system, wherein each quantum repeater is configured to generate the corresponding first graph state as a corresponding first stabilizer state for a first basis and a corresponding second stabilizer state for a second basis, the first basis orthogonal to the second basis.
(81) In some aspects, the techniques described herein relate to a system, wherein each quantum repeater is configured to entangle the corresponding input graph state with the corresponding first graph state by applying a controlled-phase gate between the corresponding input graph state and the corresponding first stabilizer state.
(82) In some aspects, the techniques described herein relate to a system, wherein each quantum repeater is configured to measure the corresponding input graph state by measuring the corresponding input graph state along the first basis.
(83) In some aspects, the techniques described herein relate to a system, wherein each quantum repeater is further configured to measure the corresponding first stabilizer state after the corresponding first stabilizer state is entangled with the corresponding first graph state to generate additional results for the corresponding measurement results.
(84) In some aspects, the techniques described herein relate to a system, wherein each quantum repeaters if configured to transmit at least the portion of the corresponding first graph state by transmitting the corresponding second stabilizer state.
(85) In some aspects, the techniques described herein relate to a system, wherein each quantum repeater is configured to receive the corresponding input graph state and transmit at least the portion of the corresponding first graph state without storing the corresponding input graph state.
(86) Each example embodiment disclosed herein has been included to present one or more different features. However, all disclosed example embodiments are designed to work together as part of a single larger system or method. The disclosure explicitly envisions compound embodiments that combine multiple previously-discussed features in different example embodiments into a single system or method.
(87) One or more advantages described herein are not meant to suggest that any one of the embodiments described herein necessarily provides all of the described advantages or that all the embodiments of the present disclosure necessarily provide any one of the described advantages.

Numerous other changes, substitutions, variations, alterations, and/or modifications may be ascertained to one skilled in the art and it is intended that the present disclosure encompass all such changes, substitutions, variations, alterations, and/or modifications as falling within the scope of the appended claims.

## Claims

1. A method comprising: receiving at a quantum repeater, an input graph state encoding at least one logical qubit from a source endpoint; generating a first graph state comprising a plurality of photonic qubits; entangling the input graph state with the first graph state; measuring the input graph state to generate measurement results; providing at least a portion of the first graph state to a subsequent quantum repeater or to a destination endpoint; and providing the measurement results to the destination endpoint, enabling the destination endpoint to recover the at least one logical qubit from the source endpoint.
2. The method of claim 1, wherein the first graph state comprises a first stabilizer state for a first basis and a second stabilizer state for a second basis, the first basis orthogonal to the second basis.
3. The method of claim 2, wherein entangling the input graph state with the first graph state comprising applying a controlled-phase gate between the input graph state and the first stabilizer state.
4. The method of claim 3, wherein measuring the input graph state comprises measuring the input graph state along the first basis.
5. The method of claim 3, further comprising measuring the first stabilizer state after the first stabilizer state is entangled with the first graph state to generate additional results for the measurement results.
6. The method of claim 3, wherein providing at least the portion of the first graph state to the subsequent quantum repeater or to the destination endpoint comprises providing the second stabilizer state to the subsequent quantum repeater or to the destination endpoint.
7. The method of claim 1, wherein the quantum repeater provides at least the portion of the first graph state to the subsequent quantum repeater or to the destination endpoint without storing the input graph state.
8. An apparatus comprising: an optical input configured to receive an input graph state encoding at least one logical qubit from a source endpoint; a graph state generator configured to generate a first graph state comprising a plurality of photonic qubits; a processor configured to: entangle the input graph state with the first graph state; and measure the input graph state to generate measurement results; an optical output configured to provide at least a portion of the first graph state to a subsequent quantum repeater or to a destination endpoint; and a network interface configured to provide the measurement results to the destination endpoint, enabling the destination endpoint to recover the at least one logical qubit.
9. The apparatus of claim 8, wherein graph state generator is configured to generate the first graph state as a first stabilizer state for a first basis and a second stabilizer state for a second basis, the first basis orthogonal to the second basis.
10. The apparatus of claim 9, wherein the processor is configured to entangle the input graph state with the first graph state by applying a controlled-phase gate between the input graph state and the first stabilizer state.
11. The apparatus of claim 10, wherein the processor is configured to measure the input graph state by measuring the input graph state along the first basis.
12. The apparatus of claim 10, wherein the processor is further configured to measure the first stabilizer state after the first stabilizer state is entangled with the first graph state to generate additional results for the measurement results.
13. The apparatus of claim 10, wherein the optical output is configured to provide at least the

portion of the first graph state to the subsequent quantum repeater or to the destination endpoint by providing the second stabilizer state to the subsequent quantum repeater or to the destination endpoint.

14. A system comprising: a plurality of quantum repeaters, each quantum repeater configured to: receive a corresponding input graph state encoding at least one logical qubit from a source endpoint; generate a corresponding first graph state comprising a plurality of photonic qubits; entangle the corresponding input graph state with the corresponding first graph state; measure the corresponding input graph state to generate corresponding measurement results; and transmit at least a portion of the corresponding first graph state; and a destination endpoint configured to: receive a last graph state from a last quantum repeater of the plurality of quantum repeaters; receive a plurality of measurement results from the plurality of quantum repeaters; and recover the at least one logical qubit from the source endpoint from the last graph state based on the plurality of measurement results.

15. The system of claim 14, wherein each quantum repeater is configured to generate the corresponding first graph state as a corresponding first stabilizer state for a first basis and a corresponding second stabilizer state for a second basis, the first basis orthogonal to the second basis.

16. The system of claim 15, wherein each quantum repeater is configured to entangle the corresponding input graph state with the corresponding first graph state by applying a controlled-phase gate between the corresponding input graph state and the corresponding first stabilizer state.

17. The system of claim 16, wherein each quantum repeater is configured to measure the corresponding input graph state by measuring the corresponding input graph state along the first basis.

18. The system of claim 16, wherein each quantum repeater is further configured to measure the corresponding first stabilizer state after the corresponding first stabilizer state is entangled with the corresponding first graph state to generate additional results for the corresponding measurement results.

19. The system of claim 16, wherein each quantum repeaters if configured to transmit at least the portion of the corresponding first graph state by transmitting the corresponding second stabilizer state.

20. The system of claim 14, wherein each quantum repeater is configured to receive the corresponding input graph state and transmit at least the portion of the corresponding first graph state without storing the corresponding input graph state.