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(54) **Title:** RANDOM NUMBER GENERATION USING UNTRUSTED QUANTUM DEVICES

(57) **Abstract:** A method of generating a sequence of random bits includes receiving a binary input signal from an input signal source and coupling the binary input signal into a plurality of components of the quantum device to initiate a random bit generation cycle. Each of the plurality of components of the quantum device produces a binary output during the random bit generation cycle, and the quantum device is configured to operate according to a non-local game during the random bit generation cycle. The method further includes maintaining isolation of the plurality of components of the quantum device during the random bit generation cycle, obtaining a plurality of binary outputs from the plurality of components of the quantum device, and producing a random bit based on the plurality of binary outputs and the binary input signal. After the random bit generation cycle, communication among the plurality of components of the quantum device is allowed.



RANDOM NUMBER GENERATION USING UNTRUSTED QUANTUM DEVICES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/927,466, filed on January 14, 2014, and titled "RANDOM NUMBER GENERATION USING UNTRUSTED QUANTUM DEVICES," the entire disclosure of which is hereby expressly incorporated by reference herein.

STATEMENT OF GOVERNMENTAL INTEREST

[0002] This invention was made with government support under CCF1216729, CCF1318070 and CCF1017335 awarded by the National Science Foundation. The Government has certain rights in the invention.

BACKGROUND OF THE DISCLOSURE

Field of the Disclosure

[0003] The present disclosure relates to generating random numbers and, more particularly, to methods for generating and expanding random numbers using untrusted quantum devices, the method being translatable to quantum key distribution protocols.

Brief Description of Related Technology

[0004] The background description provided herein is for the purpose of generally presenting the context of the disclosure. Work of the presently named inventor, to the extent it is described in this background section, as well as aspects of the description that may not otherwise qualify as prior art at the time of filing, are neither expressly nor impliedly admitted as prior art against the present disclosure.

[0005] Randomness is an indispensable resource for modern day information processing. Without randomness, randomized algorithms, statistical scientific simulations, and secure cryptography would not exist. However, generating randomness is a fundamental problem that is far from fully solved. In fact, many secret keys currently in use can be broken by exploiting the insufficient randomness used in generating the keys.

[0006] Quantum mechanics is inherently random, therefore offers promising approaches to this problem. Indeed, commercial products and randomness generation, amplification, and expansion protocols to this end have started to emerge (see, e.g., "Robust randomness amplifiers: Upper and lower bounds," M. Coudron, T. Vidick, and H. Yuen, volume 8096 of

Lecture Notes in Computer Science, pages 468–483, Springer, 2013). However, numerous challenges remain. Implementations of quantum operations are, at least in the foreseeable future, far from ideal (e.g., the implementations include unpredictable deviations or errors). These imperfections call for secure protocols that tolerate deviations of quantum devices from ideal specifications. Furthermore, users requiring high levels of security often have to purchase devices from a vendor who is not necessarily trusted. Further still, while some proposed techniques are suggested to have higher levels of security, such techniques require quantum conditions that are not attainable in the real world settings.

SUMMARY OF THE DISCLOSURE

[0007] In accordance with one example, a method of generating a sequence of random bits comprises receiving, at a quantum device, a binary input signal from an input signal source and coupling the binary input signal into a plurality of components of the quantum device to initiate a random bit generation cycle. Each of the plurality of components of the quantum device produces a binary output during the random bit generation cycle, and the quantum device is configured to operate according to a game during the random bit generation cycle. The method further includes maintaining isolation of the plurality of components of the quantum device during the random bit generation cycle, so that each of the plurality of components of the quantum device maintains at least one of superposition or entanglement during the random bit generation cycle, obtaining a plurality of binary outputs from the plurality of components of the quantum device, and producing, at a classical controller coupled to the quantum device, a random bit based on the plurality of binary outputs and the binary input signal. Still further the method includes causing communication among the plurality of components of the quantum device after the random bit generation cycle.

[0008] In accordance with another example, a method of generating a large number of random bits from a small number of input random bits comprises determining parameters including an output length, and retrieving, from a source of random values, a plurality of binary input values. The method further includes, for each of the plurality of binary input values one of: (i) coupling a plurality of random input values from the source of random values into a plurality of components of a quantum device if the binary input value includes a first value, or (ii) coupling a string of null values into the plurality of components of the quantum device if the binary input value includes a second value different from the first value. The coupling of the plurality of random input values and the coupling of the string of null values is independent of values previously coupled into the plurality of components of the quantum devices. The method further includes, for each of the plurality of binary input values, obtaining a plurality of binary

outputs from the plurality of components of the quantum device, and generating a random value based on the plurality of binary outputs and the binary input value.

[0009] In accordance with another example, a system for generating a sequence of random bits comprises a quantum device including a plurality of components. The quantum device is configured to: operate according to a game during a random bit generation cycle, produce a binary output during the random bit generation cycle, maintain isolation of the plurality of components during the random bit generation cycle, so that each of the plurality of components maintains at least one of superposition or entanglement during the random bit generation cycle, and cause communication among the plurality of components after the random bit generation cycle. The system also includes a classical controller coupled to the quantum device and configured to: receive a binary input signal from an input signal source, couple the binary input signal into the plurality of components of the quantum device to initiate the random bit generation cycle, obtain a plurality of binary outputs from the plurality of components of the quantum device, and produce a random bit based on the plurality of binary outputs and the binary input signal.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0010] The figures described below depict various aspects of the system and methods disclosed herein. It should be understood that each figure depicts an embodiment of a particular aspect of the disclosed system and methods, and that each of the figures is intended to accord with a possible embodiment thereof. Further, wherever possible, the following description refers to the reference numerals included in the following figures, in which features depicted in multiple figures are designated with consistent reference numerals.

[0011] Fig. 1 is a block diagram of an example system for generating random numbers, expanding randomness, and/or distributing quantum keys. ;

[0012] Figs. 2A-2D are block diagrams of various example configurations of the system illustrated in Fig. 1;

[0013] Fig. 3 illustrates an example protocol for generating a random output based on a binary input;

[0014] Fig. 4 is a flow diagram of an example method utilizing the protocol illustrated in Fig. 3, where the example method can be implemented in the system illustrated in Fig. 1;

[0015] Fig. 5 illustrates another example protocol for generating a random output based on a binary input;

- [0016] Fig. 6 illustrates a flow of the example protocol illustrated in Fig. 5;
- [0017] Fig. 7 illustrates yet another protocol generalizing the protocols of Figs. 3 and 5;
- [0018] Fig. 8 illustrates an example protocol for exponential randomness expansion;
- [0019] Fig. 9 is a flow diagram of an example method utilizing the protocol illustrated in Fig. 8, where the example method can be implemented in the system illustrated in Fig. 1;
- [0020] Fig. 10 illustrates an example protocol for unbounded randomness expansion;
- [0021] Fig. 11 is a flow diagram of an example method utilizing the protocol illustrated in Fig. 10, where the example method can be implemented in the system illustrated in Fig. 1;
- [0022] Fig. 12 is a flow diagram of an example method for quantum key distribution that can be implemented in the system illustrated in Fig. 1; and
- [0023] Fig. 13 illustrates another example protocol for generating a random output based on a binary input;
- [0024] Fig. 14 illustrates yet another example protocol for generating a random output based on a binary input; and
- [0025] Fig. 15 illustrates an example protocol for simultaneous quantum key distribution and randomness expansion.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0026] The techniques of the present disclosure provide random number generation that is quantum-secure (i.e., secure against quantum adversaries) and randomness that expands at an exponential or unbounded rate. Protocols of the present disclosure tolerate a constant, or uniform, level of imprecision in implementing each quantum operation. This constant may be close to the gap between an near optimal quantum performance and a highest level of quantum performance when devices cease to output randomness.

[0027] Further, the protocols do not require large long term quantum memory, because quantum communication between different components may be allowed, at least in-between consecutive “games” of the protocols (i.e., the components may be “resettable”). Devices implementing the techniques may establish entanglement on-the-fly and may only need to maintain entanglement (e.g., with only a constant level of fidelity) for the duration of a single game. The game may be a non-local game in some implementations. That is, the game may be a cooperative game involving two or more players (e.g., quantum systems), where the players cannot communicate but may share common random bits or a common quantum state.

However, generally, protocols of the present disclosure need not include a non-local game. In particular, the game may be a “contextuality” game, in some implementations. A contextuality game is a game played by a single quantum player (e.g., quantum system), where a compatibility requirement specifies a collection of subsets of the player’s quantum measurements, as discussed further below.

System Overview

[0028] Fig. 1 illustrates an example system 100 for generating random numbers, expanding randomness, and/or distributing quantum keys. The system 100 includes a quantum device 102 operatively and communicatively connected to a classical controller 104. The quantum device 102 and the classical controller 104 may be part of a quantum computing system, in an implementation. For example, the quantum device 102 may operate (e.g., perform computations) based on quantum-mechanical principles, such as entanglement, and the classical controller 104 may control or interact with the quantum device 102 based principles of classical mechanics. In some implementations, the classical controller 104 may prepare quantum systems of the quantum device 102 in one or more initial states so as to perform a computation. The classical controller 104 may also initiate and/or control measurements (e.g., nondestructive measurements) of the quantum systems so as to output results of a computation.

[0029] In some implementations, the quantum device 102 may include a plurality of components 106a-106n (also labeled as $D_1, D_2, \dots, D_n$ in Fig. 1), where each of the plurality of components includes a corresponding input interface 108a-108n, output interface 110a-110n, and quantum system 112a-112n. Generally, the quantum systems 112a-112n may include any suitable systems governed by quantum-mechanical principles and capable of performing operations on data or input based on those quantum-mechanical principles. The quantum systems 112a-112n may represent data or input via quantum-mechanical properties, such as spin, charge, polarization, optical properties, thermal properties, magnetic properties, etc., and, in some cases, each of the quantum systems 112a-112n may include one or more “qubits,” such as two-state quantum-mechanical systems.

[0030] By way of example and without limitation, the quantum systems 112a-112n may include: (i) an Ising spin glass in which data is represented by Ising spins; (ii) non-Abelian topologically ordered phases of matter in which data is represented by braiding of anyonic quasiparticles; (iii) three dimensional (3D) lattice cluster states in which data is represented by topologically protected quantum gates; (iv) superconducting systems in which data is represented by small superconducting circuits (e.g., Josephson junctions); (v) trapped atoms,

ions, or molecules (e.g., trapped by electromagnetic fields or optical lattices) in which data is represented by two or more energy levels, such as hyperfine levels; (vi) one or more quantum dots (or quantum wells) in which data is represented by confined excitations; (vii) linear optical elements in which data is represented by optical modes of photons; or (viii) Bose-Einstein condensates in which data is represented by one or more energetically protected two-level states. It is understood, that any suitable quantum system may represent data or input via quantum-mechanical properties and perform operations on that data based on the quantum-mechanical properties.

[0031] Preparation or manipulation of the quantum systems 112a-112n and extraction of results from the quantum systems 112a-112n may include measurements performed by the corresponding input interfaces 108a-108n and the corresponding output interface 110a-110n, in some implementations. For example, in a case in which the quantum systems 112a-112n include topologically ordered phases of matter (e.g., as in a topological quantum computer), the input interfaces 108a-108n and the output interfaces 110a-110n may include one or more interferometers to perform quasiparticle braiding, topological charge measurement, and/or other topologically transformative manipulations. Alternatively, in the case in which the quantum systems 112a-112n include superconducting systems, the input interfaces 108a-108n and the output interfaces 110a-110n may include various superconducting quantum interference devices (SQUIDs) to measure magnetic properties with high sensitivity. It is understood, however, that the input interfaces 108a-108n and the output interfaces 110a-110n may include any appropriate combination of hardware, classical computer processing, and/or software components configured to measure, manipulate, and/or otherwise interact with the quantum systems 112a-112n.

[0032] Further, some or all of the input interfaces 108a-108n and the output interfaces 110a-110n may be controlled by or communicate with the classical controller 104 in order to measure, manipulate, and/or otherwise interact with the quantum systems 112a-112n, in an implementation. For example, the input interfaces 108a-108n may receive input data values (e.g., input bits) from the classical controller 104 that are subsequently encoded in the quantum systems 112a-112n via operations (e.g., measurements) performed by the input interfaces 108a-108n. Likewise, the output interfaces 110a-110n may communicate results, obtained via measurements performed on the quantum systems 112a-112n, to the classical controller 104 for further processing or utilization. In some cases, the classical controller 104 may implement software applications, via computer-readable instructions, that control all or some of the functionality of the input interfaces 108a-108n and the output interfaces 110a-110n. For

example, the classical controller 104 may control when (e.g., periodically or at pre-defined times) and how (e.g., with what parameters, such as intensity, voltage, etc.) the input interfaces 108a-108n and the output interfaces 110a-110n perform measurements on the quantum systems 112a-112n.

[0033] In some implementations, the plurality of components 106a-106n are configured such that information cannot be exchanged among the plurality of components 106a-106n during certain quantum operations, such as random number generation, randomness expansion, or quantum key distribution. For example, the plurality of components 106a-106n may be disposed in locations far apart from one another so as to ensure that during the period of generating a bit of a random number, the plurality of components 106a-106n cannot exchange information due to a limit imposed by special relativity (i.e., information cannot travel faster than the speed of light). Such a separation of the plurality of components 106a-106n may be referred to as “isolated” or “in isolation” herein. In general, quantum communication or a quantum exchange of information may include any intentional or accidental coupling with an environment (e.g., a coupling that includes a decoherence of quantum states).

[0034] In other implementations, the plurality of components 106a-106n are configured such that information cannot be exchanged among the plurality of components 106a-106n during certain stages or phases of a quantum operation, while information can be exchanged during other stages or phases of the quantum operation. For example, the plurality of components 106a-106n may be disposed in locations such that during one iteration of a protocol, such as the protocols discussed with reference to Figs. 4, 6, and 8, information cannot be exchanged between the plurality of components 106a-106n, while information can be exchanged in between iterations. Such a configuration of the plurality of components 106a-106n may be referred to as “resettable” or “being reset” herein. In this manner, protocols may be implemented with reduced complexity, in some cases. For example, the quantum device 102 may establish entanglement “on-the-fly” and needs only to maintain the entanglement (e.g., with a constant level of fidelity) for the duration of a single protocol iteration.

[0035] Communications between the classical controller 104 and the input interfaces 108a-108n and the output interfaces 110a-110n may include classical communications, in an implementation, facilitated by a control and measurement link 114. The control and measurement link 114 may carry communications from the classical controller to the interfaces 108a-108n and 110a-110n via electromagnetic signals (e.g., current signals) on a current-carrying conductor, such as a ribbon, coaxial, twisted pair, universal serial bus (USB), or other cable. The control and measurement link 114 may, in some implementations, carry encoded

digital signals between the classical controller 104 and the interfaces 108a-108n and 110a-110n, such as signals encoded according to the Hypertext Transfer Protocol (HTTP), Virtual Instrument Software Architecture (VISA) standard, Standard Commands for Programmable Instruments (SCPI), High-Speed LAN Instrument Protocol (HiSLIP), LAN eXtensions for Instrumentation (LXI), PCI eXtensions for Instrumentation (PXI), File Transfer Protocol (FTP), Transmission Control Protocol (TCP), User Datagram Protocol (UDP), etc. In general, the control and measurement link 114 may include any suitable wired and/or wireless components, links, modems, routers, cables, buses, etc. allowing the classical controller 104 to communicate with and/or control the quantum device 102.

[0036] The classical controller 104 may include various interfaces, implemented in any suitable combination of hardware and software, allowing the classical controller 104 to communicate with the quantum device 102 and various other devices or components. In particular, the classical controller 104 may include an instrument control interface 116 configured to send/receive control signals (voltages, currents, digitally encoded messages, etc.) to and from the quantum device 102, respectively. The classical controller 104 may also include a data acquisition (DAQ) interface 118, such as a DAQ PCI card, to receive measurement values from the quantum device 102 (e.g., from the output interfaces 110a-110n) and a network interface 120 allowing the classical controller 104 to communicate with various other network-enabled devices 122.

[0037] Users of the network-enabled devices 122 may interact with the classical controller 104 via a network 124 and network interface 120. The network-enabled devices 122 may include, by way of example, a network-enabled cellular wireless terminal, a phone, a tablet computer, a desktop computer, a server computer, a cluster of server computers, a personal digital assistant (PDA), a smartphone, a laptop computer, a wearable wireless communication device such as a wearable computer, a portable media player, an e-reader, or other similar devices (not shown). Of course, any network-enabled device appropriately configured may interact with the classical controller 104 to, for example, generate a random number, expand a random number, and/or generate or retrieve a quantum key. In some examples, the network-enabled devices 122 represent a network-enabled enterprise in communication with the classical controller 104 of another network-enabled enterprise. Example enterprises, including any two enterprises desiring to establish shared secured communications, such as a design enterprise creating intellectual property (e.g., an integrated circuit designer) and a manufacturing enterprise (fabrication enterprise or foundry).

[0038] The network 124 may be a proprietary network, a secure public Internet, a virtual private network or some other type of network, such as dedicated access lines, plain ordinary telephone lines, satellite links, combinations of these, etc. Where the network 124 comprises the Internet, data communication may take place over the network 124 via an Internet communication protocol. The network 124 may communicate with the network-enabled devices 122 through wireless or wired connections. Further, in some examples, the network 124 is a mobile (or cellular) communication network.

[0039] The network-enabled devices 122 need not necessarily communicate with the network 124 via a wired connection. In some instances, the network-enabled devices 122 may communicate with the network 124 via wireless signals; and, in some instances, the network-enabled devices 122 may communicate with the network 124 via an intervening wireless or wired device, which may be a wireless router, a wireless repeater, a base transceiver station of a mobile telephony provider, etc., or other access point.

[0040] The classical controller 104 also includes a program memory 126 and one or more processors 128 (e.g., microcontrollers or microprocessors). The program memory 126 may include an assortment of computer-readable media implemented as semiconductor memories, magnetically readable memories, and/or optically readable memories, for example. Computer-readable media may be any media that may be accessed by the classical controller 104. By way of example, and not limitation, the media may include both volatile and nonvolatile media, removable and non-removable media. Media may also include computer storage media and communication media. Computer storage media may include volatile and nonvolatile, removable and non-removable media that stores information such as computer-readable instructions, program modules, data structures, or other data. Computer-storage media may include RAM, ROM, EEPROM, or other memory technology, optical storage disks, magnetic storage devices, and any other medium which may be used to store computer-accessible information. Communication media may be computer-readable instructions, data structures, program modules, or other data in a modulated data signal or other transport mechanism. Communication media may include wired media such as a wired network or direct-wired connection, and wireless media such as RF, infrared, and other wireless media.

[0041] The program memory 126 may store a basic input/output system (BIOS), containing algorithms to transfer information between components within the classical controller 104. Also, data or program modules that are immediately accessible or are presently in use by the one or more processors 128 may be stored in the program memory 126. Data normally stored in the program memory 126 while the classical controller 104 is in operation may include an operating

system, application programs, program modules, and program data. In particular, the program memory 126 may store a random number generation program 130, a randomness expansion program 132, and a quantum key distribution program 134, as discussed further with reference to Figs. 4, 6, 8, and 9. Programs, such as the programs 130, 132, and 134, may, in some implementations, provide input to or process output from the quantum device 102. That is, some functionality related to random number generation, randomness expansion, and quantum key distribution may be implemented by the classically executed programs 130, 132, and 134, whereas other functionality related to random number generation, randomness expansion, and quantum key distribution may be implemented according to quantum-mechanical principles by the quantum device 102.

[0042] The classical controller 104 may also be communicatively coupled to a database 140. The database 140 may include storage media such as a hard disk drive that may read from or write to non-removable, non-volatile magnetic media, a magnetic disk drive that reads from or writes to a removable, non-volatile magnetic disk, and an optical disk drive that reads from or writes to a removable, nonvolatile optical disk. Other storage media that may be used includes magnetic tape cassettes, flash memory cards, digital versatile disks, digital video tape, solid state RAM, and solid state ROM. The database 140 may store results from computations performed by the quantum device 102, such as random numbers, quantum keys, etc. In addition, the database 140 may store instructions, rules, or other information allowing the classical controller 104 to execute corresponding functionality.

[0043] Figs. 2A-2D are block diagrams of particular example configurations of the system 100 illustrated in Fig. 1. Although particular numbers of network-enabled devices, networks, classical controllers, quantum devices, and components of quantum devices are illustrated in Figs. 2A-2D, it is understood that any suitable number of such devices or components may be implemented in a certain combination. Further, for ease of discussion, components included in classical controllers and quantum device components are not shown in Figs. 2A-2D, but it is understood that the classical controllers and/or quantum devices of Figs. 2A-2D may include some or all the components illustrated in the classical controllers and quantum devices of Fig. 1.

[0044] In particular Fig. 2A is a block diagram of an example system 200 in which a network-enabled device 202a (labeled “A” in Fig. 2A) and a network-enabled device 202b (labeled “B” in Fig. 2A) may interact with a classical controller 204, where the classical controller 204 is communicatively and/or operatively connected to a quantum device 206. Although illustrated as laptop computers in Fig. 2A, it is understood that the network-enabled devices 202a and 202b may include any suitable network-enabled devices, such as those discussed with reference to

Fig. 1. The network-enabled devices 202a and 202b may communicate with the classical controller 204 via the network 208

[0045] Each of the network-enabled devices 202a and 202b may have access to (e.g., be able to interact with via the classical controller 204) one or more quantum components 210a and 210b, respectively. In particular the network-enabled device 202a may interact with, through communications with the classical controller 204, the quantum components 210a, which are j in number. Likewise, the network-enabled device 202b may interact with, through the communications with the classical controller 204, the quantum components 210b, which are $n-j$ in number. That is, the total number, n , of components of the quantum device 206 are split between the network-enabled devices 202a and 202b, in an implementation. In general, the number j may be any suitable number, such as one, two, three, etc. up to $n-1$. Further, in some cases, the quantum components 210a and the quantum components 210b may be isolated from one another, and, in other cases, the quantum components 210a and the quantum components 210b may be resettable allowing quantum communication between protocol iterations. In general, the quantum components 210a and the quantum components 210b may be in the same or different physical locations. In fact, the quantum components 210a may be disposed in a different physical location that is far removed from the physical location of the quantum components 210b.

[0046] Access of the multiple network-enabled devices 202a and 202b to the corresponding quantum components 210a and 210b may allow multiple network-enabled device to carry out quantum computations simultaneously or cooperatively, in an implementation. For example, the network-enabled devices 202a and 202b may initiate a quantum key generation scheme, as further discussed with reference to Fig. 12, where each of the network-enabled devices 202a and 202b are able to initiate respective random number generation protocols via the corresponding quantum components 210a and 210b. In general, however, the network-enabled devices 202a and 202b may perform quantum operations via the corresponding quantum components 210a and 210b independently and for any suitable purpose.

[0047] The network-enabled devices 202a and 202b may also communicate with each other, in some implementations, via the network 208. For example, the network-enabled devices 202a and 202b may communicate as part of a quantum key distribution protocol and may communicate securely after sharing a generated quantum key.

[0048] Fig. 2B is a block diagram of another example system 220 in which a network-enabled device 222a (labeled "A" in Fig. 2A) and a network-enabled device 222b (labeled "B" in Fig. 2A) may interact with a classical controller 224, where the classical controller 224 is

communicatively and/or operatively connected to a quantum device 226. Similar to the system 200, each of the network-enabled devices 222a and 222b may have access to (e.g., be able to interact with via the classical controller 204) one or more quantum components 230a and 230b, respectively. Yet, in the system 220, each of the network-enabled devices 222a and 222b may communicate with the classical controller 224 via a different network. The network-enabled device 222a may communicate with the classical controller 224 via a network 232a, and the network-enabled device 222b may communicate with the classical controller 224 via a network 232b.

[0049] The networks 232a and 232b may be different types of networks, in an implementation. For example, the network 232a may include a wired network, and the network 232b may include a wireless network. Alternatively, the network 232a may include a private network, and the network 232b may include a public network. In general, the networks 232a and 232b may differ based on any parameters or properties, such as privacy, network type, network carrier or provider, etc. Further, communication via the networks 232a and 232b may differ based on required types of security. As such, the network-enabled devices 222a and 222b may communicate with the classical controller 224 such that a common level of security may be established (e.g., via the generation of a quantum key on the quantum device 226), and subsequent communications between the network-enabled devices 222a and 222b may adhere to security requirements of both of the networks 232a and 232b, in an implementation.

[0050] In addition to interacting with the classical controller via separate or different networks, network-enabled devices may interact with a quantum device via separate or different classical controllers, in an implementation. As in an example system 240 illustrated in Fig. 2C, network-enabled devices 242a and 242b may interact with the quantum device 244 via a classical controller 246a and a classical controller 246b, respectively. The network-enabled devices 242a and 242b may be communicatively coupled to the classical controllers 246a and 246b via the networks 248a and 248b, and the network-enabled devices 242a and 242b may only interact with corresponding quantum components 250a and 250b of the quantum device 244, in an implementation. In this manner, interactions or communication with the quantum device 244 from the network-enabled devices 242a and 242b are shielded from one another. That is, the network-enabled devices 242a and 242b may perform quantum computations via the quantum device 244 independent of one another (e.g., via separate or different classical controllers and networks).

[0051] Fig. 2D illustrates still another example system 260 in which one or more network-enabled devices 262 are communicatively coupled to a classical controller 264, via the network

266, allowing interaction between the network-enabled device 262 and a plurality of quantum devices 268. The plurality of quantum devices 268 (Quantum Device 1, Quantum Device 2, . . . , Quantum Device P) may each include a plurality of quantum components ($\{D_1, D_2, \dots, D_{n1}\}$, $\{D_1, D_2, \dots, D_{n2}\}, \dots, \{D_1, D_2, \dots, D_{nP}\}$), and each of the quantum devices 268 may include the same or a different number of quantum components 270 ($n1, n2, \dots, nP$), in an implementation. The multiple quantum devices 268 may simultaneously, or otherwise, execute different algorithms, data manipulations, or protocols, or the quantum devices 268 may cooperatively execute one or more algorithms, manipulations, or protocols. For example, two or more of the quantum devices 268 may execute a protocol for unbounded randomness expansion, as further discussed with reference to Fig. 11. In some implementations, the plurality of quantum devices 268 and corresponding quantum components are isolated from one another and, in other cases, the plurality of quantum devices 268 and corresponding quantum components may be resettable allowing quantum communication between protocol iterations.

Random Number Generation

[0052] Fig. 3 illustrates an example protocol 300 for generating a random number or one bit/value of a random number. The protocol includes a “game,” G , played by a single quantum device with n quantum components. In the particular implementation illustrated in Fig. 3, the game G is played by a quantum device, such as the quantum device 102, with two components 302 and 304 (or “ D_1 ” and “ D_2 ”). In some implementations, the components 302 and 304 are configured to be resettable allowing quantum communication between iterations of the protocol 300, while keeping the components 302 isolated during each iteration.

[0053] In some implementations the game G is a “non-local” game. Generally, non-local games may differ in scenarios in which the games are “played” by, or implemented in, systems operating according to classical mechanics as compared to scenarios in which the games are “played” by, or implemented in, systems operating according to quantum mechanics. An example non-local game is a cooperative game involving two or more players (e.g., quantum systems). The players cannot communicate but may share common random bits or a common quantum state. A controller, or other suitable device, may send an input to one of the players who then responds with an answer. Winning, in the non-local game, may include satisfying a condition dependent on the inputs from the controller (e.g., inputs from a known probability distribution).

[0054] During each iteration of the protocol 300, which iteration produces a random value or bit, the quantum device plays the game G . That is, the quantum device receives an input, g , for a single round of the game and operates such that a result is produced. G may include any

binary Exclusive Or (XOR) game (e.g., a game where inputs and outputs are binary), such as a game with a scoring function depending on the inputs and the XOR of the outputs, where the binary XOR game is strongly self-testing, in an implementation. The game G may be strongly self-testing, or non-local, in that any strategy that is close (within an value ϵ , or ϵ -close) to optimal in its winning probability must be $O(\sqrt{\epsilon})$ -close to a unique optimal strategy in both its state and its measurements, in an implementation. In this case, the term “strongly” refers to the $O(\sqrt{\epsilon})$ term, which is the best possible asymptotic bound for a non-local game. By way of example, strong self-testing games may include the Clauser-Horne-Shimony-Holt (CHSH) game and the Greenberger-Horne-Zeilinger (GHZ) game, but it is understood that the protocol 300 may utilize any such binary XOR game. Although, strong self-testing, or non-local games are discussed above and below by way of example and for clarity, some implementations of protocols for generating random numbers may utilize other contextuality games along with or as an alternative to non-local games, as further discussed with reference to Figs. 5 and 6.

[0055] The protocol 300 may include the following parameters, in an implementation: (i) N , a positive integer representing the output length; (ii) η , a real $\in (0, 1]$ representing the abort threshold; (iii) q , a real $\in (0, 1/2]$ representing the test frequency; (iv) G , an n -player non-local game that is a strong self-test; and (v) D , an untrusted quantum device (e.g., a device provided by or operated by an untrusted party) that can play G repeatedly and cannot receive any additional information. In a single iteration (i.e., use of the protocol) the components 302 and 304 may not communicate, but, in between iterations, the components 302 may communicate. For any real $\omega \in (0, 1)$, the protocol 300, with appropriate parameters, converts any k uniform bits to $\exp(\Omega(k^{1-\omega}))$ extractable bits with $\exp(-\Omega(k^\omega))$ error under a constant level of noise, in an implementation.

[0056] In some implementations, quantum-proof randomness extractors are applied to the outputs of the protocol 300 to produce near perfect random output from the protocol 300. The quantum-proof randomness extractors may be deterministic functions $\text{Ext}(X, S)$ on two arguments: (i) X being the source, which in this case may be the output of the protocol 300; and (ii) S being a perfectly random seed. The extractors $\text{Ext}(X, S)$ may, in an implementation convert any N bits X that have min-entropy $\Omega(N)$ to a near perfect output randomness of length $\Theta(N)$.

[0057] Fig. 4 illustrates an example method 400 for generating random numbers using a protocol, such as the example protocol 300. The method 400 may be implemented in the quantum device 102, for example.

[0058] To begin, a bit $g \in \{0, 1\}$ is determined (block 402). In an implementation, the bit input g may be determined according to a biased $(1-q, q)$ distribution. It is understood, however, that the input bit g may be received from a random, or quasi-random (e.g., based at least partially on a deterministic function), source or determined according to any suitable distribution, as further discussed with reference to Fig. 9.

[0059] Next, it is determined if $g = 1$ (block 404). If $g = 1$, the iteration of the method 400 is determined to be a “game round,” and an input string is determined at random (block 406). In some cases, the input string may be determined from $\{0, 1\}^n$, according to a probability distribution specified by the game G , and given to a quantum device executing the method 400. On the other hand, if $g = 0$, an input string $\{00 \dots 0\}$ is input (e.g., from the classical controller 104) to components of the quantum device implementing the method 400 (block 408).

[0060] Note, a choice of $\{00 \dots 0\}$ for cases in which $g=0$ may assume that $\{00 \dots 0\}$ is among those inputs on which the optimal quantum strategy wins with the largest probability, in an implementation. In general, $\{00 \dots 0\}$ may be replaced by any string on which the optimal quantum strategy wins the game G with the largest probability.

[0061] After inputting or coupling the binary input g into the components of the quantum device, the outputs of the quantum device components are measured (block 410). Depending on (i.e., based on) the measured output of the quantum device components and the rules of game G , a result value is determined and recorded (block 412). For example, in the case of a “game round,” a “P” (pass) or an “F” (fail) may be recorded according to the rules of the game G . In the case of $g = 0$, a “H” (heads) may be recorded when the output from the first component is zero; otherwise, a “T” (tails) may be recorded. In general, any type of binary, numeric, alphabetic, or symbolic result values may be determined based on the output of the quantum device components.

[0062] It is then determined if N result values have been calculated based on the procedure of blocks 402-412 (block 414). If the number of result values that have been generated is less than N , the flow continues to block 415 where the quantum components may be reset (e.g., causing quantum communication between quantum device components), in an implementation, and subsequently reverts back to block 402 where the process of generating another result value is initiated. If the number of result values equals N , the resulting sequence of values (e.g., N -length sequence from the alphabet $\{P, F, H, T\}$) is output for subsequent storage or utilization. For example, the resulting sequence may be stored by a classical controller, such as the classical controller 104, for use as a random number or key. Alternatively, a classical controller

may communicate the result sequence to a network-enabled device, such as one or more of the network-enabled devices 122.

[0063] In some implementations, a quantum device implementing the example method 400 may also determine if the “failure” rate (e.g., out of all the game rounds) exceeds $(1 - w_G + \eta)$, where w_G is the highest probability with which a quantum strategy can win the game G . If the failure rate exceeds $(1 - w_G + \eta)$, the example method 400 may abort, restart, output an error, etc. Also, if more than a certain number of game rounds, such as $2q/N$ or $\eta q/N$ game rounds, have occurred, the example method 400 may abort, in an implementation.

[0064] Although the above protocol is described with reference to non-local games, the game G need not be non-local game or strong self-testing game defined in the manner described above. Generally, the game G may be a “contextuality” game, such as the game further described in “Simple test for hidden variables in spin-1 systems,” A. Klyachko, M. Can, S. Binicioglu, and A. Shumovsky, *Physical Review Letters*, 101(020403), 2008. A contextuality game may be a game played by a single quantum player (e.g., quantum system), where a compatibility requirement specifies a collection of subsets of the player’s quantum measurements. Those subsets of measurements must be mutually commutative, in some cases. A contextuality game G with m measurement setting includes a multilinear polynomial, f , encoding rules for the game. For example, a multilinear function:

$$f(X_1, \dots, X_m) = \sum_{T \subseteq \{1, 2, \dots, m\}} f_T \prod_{i \in T} X_i$$

satisfying $\sum_T |f_T| = 1$ may encode rules for a games as follows. Let D be a contextual measurement device whose set of contexts includes $\text{Supp } f$ (that is, includes every element $T \subseteq \{1, 2, \dots, m\}$ for which $f_T \neq 0$). To play this example game, a subset T is chosen at random under the probability distribution $\{|f_T|\}$, and given as input to the device D . If $(b_1, \dots, b_k)$ are output bits, the score of the game may be given by:

$$\frac{f_T}{|f_T|} \cdot (-1)^{b_1 \oplus b_2 \oplus \dots \oplus b_k}.$$

[0065] In fact, some protocols utilized to generate random numbers may utilize a contextuality game “played” or implemented by a single quantum system. Fig. 5 illustrates such an example protocol 450 including a contextuality game played by a single quantum system. Fig. 6 illustrates a flow of such a protocol (e.g., referred to as “Protocol K”).

[0066] Generally, protocols utilized in systems, such as the example system 100, to generate random numbers may be implemented by any suitable number of quantum devices or systems

and may utilize non-local games, contextuality games, or suitable combinations of these games. The above described protocols 300 and 450 are examples of such protocols. For further clarity, a general or abstract protocol describing both of these example protocols 300 and 500 is illustrated in Fig. 7. When the protocol illustrated in Fig. 7 utilizes a non-local game (e.g., a binary XOR game), the protocol may reduce to the example protocol 300, and, when the protocol illustrated in Fig. 7 utilizes a contextuality game, the protocol may reduce to the example protocol 450. In any event, protocols 300 and 450 may have security guarantees for all noise levels that are within a maximum noise level (e.g., when the devices implementing the protocols 300 and 450 cease to output randomness).

[0067] Further, devices (e.g., including quantum systems) implementing methods, such as the method 400, need not be “trusted” devices. That is, components of a system utilizing method 400, or other example methods described herein, for random number generation are “self-authenticating.” In other words, users of such a system (e.g., the system 100) may test the “quantumness” of the hardware. The only way to pass such a test may be to behave quantum mechanically and honestly, which behaviors automatically imply that the outputs of the system are truly random. Thus, at least in some implementations, a system implementing a method substantially similar to method 400 may not be susceptible to malicious attacks from routines such as embedded backdoor, hardware Trojan, etc.

Randomness Expansion

[0068] For clarity, certain quantities that may describe properties of the current randomness expansion protocols are discussed briefly below before discusses example methods for randomness expansion.

[0069] A Classical-Quantum (C-Q) state may be considered ideal with y (a positive integer) extractable bits if the first bit of the classical part indicates “Success” or “Failure”, and conditioned on Success, the C-Q state has conditional min-entropy $\geq y$. A randomness expansion protocol may have a yield y with soundness error ε_s if, for any device D , the output is always within trace distance ε_s of an ideal state with y extractable bits. The protocol may tolerate a noise level λ with completeness error ε_c if any device that plays each game independently (e.g., with an expected score no less than $w_G - \lambda$) will abort with probability at most ε_c . If both the soundness and the completeness errors are $\leq \varepsilon$, the “error” of the protocol may be referred to simply as ε . Note, that, in an implementation, ε_s , ε_c , λ may be reals in $(0, 1)$.

[0070] For any strong self-test G , and any $\delta > 0$, there may exist positive constants q_0, η_0, N_0, b, c , such that the following holds when a randomness expansion protocol of the current disclosure is executed with parameters $q \leq q_0, \eta \leq \eta_0$, and $N \geq N_0$:

[0071] 1. (Soundness.) The yield may be at least $(1 - \delta)N$ extractable bits with a soundness error $\varepsilon_s = \exp(-bqN)$.

[0072] 2. (Completeness.) For any constant $\lambda, 0 < \lambda < \eta$, the protocol may tolerate a noise level of λ with a completeness error $\varepsilon_c = \exp(-c(\eta - \lambda)2qN)$.

[0073] Note, input bits $g_1, \dots, g_n$ may be generated either by another random process, or the input bits may be generated deterministically from an initial random input s drawn from a different probability distribution. For example, s may be $O(Nh(q))$ uniformly random distributed bits. The bits $g_1, \dots, g_n$ need only to be independent of the bias q with respect to the quantum device, and can be known completely to another other party, including an adversary. Similarly, any initial random input s , however known to other parties, need only to ensure a limited knowledge of the quantum devices on the generated input bits. In particular, in a case where s is uniform, s needs only to be uniform with respect to the quantum device. That is, even in a scenario in which an adversary knows the input, a protocol utilized in the method 400 or further described with reference to Fig. 8 may be as secure as in the case that the input is globally uniform. Operationally, these properties of the input seed may increase options for the obtaining the input seed. For example, some implementations of the method 400, or example methods further discussed with reference to Fig. 9, may utilize broadcast randomness (e.g., from a government agency or other organization). If a manufacturer of the devices implementing the methods cannot predict the bits broadcast, those random bits may be safe to use in the methods (e.g., the output is secure against anyone including the provider of the random bits).

[0074] For any real $\omega \in (0, \mu)$, a randomness expansion protocol with appropriate parameters may convert any k uniform bits to $\exp(\Omega(k^{1-\omega}))$ near uniform bits with $\exp(-\Omega(\omega))$ error under a constant level of noise. Once a near perfect random output is generated, the output may be utilized as the input to another instance of the protocol, thus expanding further with an accumulating error parameter. As the error parameters decrease at an exponential rate, they may be dominated by the first set of errors.

[0075] Fig. 8 illustrates an example randomness expansion protocol 500. The protocol 500 may receive as input a source X of random bits; which are provided by a trusted party and part of which may be preprocessed to be compatible with certain chosen parameters. By way of example, the chosen parameters may include desired output length, output randomness quality,

failure probability, and the noise level tolerated. A user of a classical controller or network-enabled device may choose these parameters, in an implementation.

[0076] An input extractor 502 of the protocol 500 may obtain an input bit g from a portion of $\mathbf{X}$. The portion of $\mathbf{X}$ from which g is obtained may include a preprocessed portion of $\mathbf{X}$, in an implementation. Then, the input extractor 502 may obtain m bits $\mathbf{x}$ either from the source $\mathbf{X}$ when g is one, or m bits of 0 otherwise. These m bits may then be passed from the input extractor 502 to m quantum components of a quantum device, such as the quantum device 102, to play the game G , as illustrated in the box 504. The protocol 500 may also include an output determination and randomness extraction 506 which outputs result values, from the game G , based on the output of the quantum components playing the game G and the input $\mathbf{x}$. Note, although the box 504 is illustrated as a protocol utilizing a non-local game, the box 504 may be replaced with a protocol utilizing a contextuality game, as described further with reference to Figs. 5 and 6.

[0077] Fig. 9 is a flow diagram of an example method 600 for randomness expansion. The method 600 may utilize the protocol illustrated in Fig. 8 and may be implemented by the classical controller 104 and quantum device 102, for example.

[0078] To begin, parameters for the randomness expansion are received and/or set (block 602). The parameters for the randomness expansion may include desired output length (N), output randomness quality, failure probability, and the noise level tolerated, as discussed above. In some implementations, these parameters are programmed into or determined by executing computer-readable instructions stored in the memory of a classical controller, such as the classical controller 104. Alternatively, a user or operator may set the parameters via manual interaction with a user interface (keyboard, touchscreen, mouse, etc.) operatively connected to a classical controller or network-enabled device. By way of example, the parameters may be selected, chosen, or set according to security requirements for the generation of random numbers, and/or the parameters may be selected to provide an appropriate balance between realistic tolerances or failure rates and desired output properties. In some cases, the received or set parameters allow the rate of randomness expansion and/or the number of output bits as a function of the number of input bits to range between a linear function and an exponential function.

[0079] Next, random values are received from a source $\mathbf{X}$ (block 604), and an input extractor extracts one or more input values g from $\mathbf{X}$. In some cases, the input extractor extracts g from a preprocessed portion of $\mathbf{X}$. If the input value $g = 1$ (as determined at block 608), m values $\{x_1, x_2, \dots, x_m\}$ from $\mathbf{X}$ are coupled into the m components of the quantum device executing the

method 600 (block 610). However, if the input value $g = 0$, m zero values are coupled to the m components of the quantum device (block 612).

[0080] After the m values are coupled to the quantum device and the device plays the game G , such as the game 504, an output is measured from the m quantum device components (block 614). For example, an output may be measured via the output interfaces 110a-110n controlled via the classical controller 104. The measurements of the output may include measurements of any suitable quantum-mechanical properties representing data within the method 600, such as charge, spin, etc.

[0081] One or more result values are then determined based on the measured output from the quantum device components (block 616). For example, a raw output bit z may be determined and recorded (e.g., by a classical controller) as the result of the game. In some implementations, the raw output bit may equal one for winning and zero for losing, according to the scoring rule of the game G , the observed output of the quantum device, and the input x .

[0082] Subsequent to the determination and recording of the output bit or result value, it is determined if the number of result value generated thus far is equal to the desired output length, N (block 618). If less than N result values have been generated, the flow continues to block 619, where quantum device components may be reset by causing communication among the components, and then reverts to block 606 where the generation of further result values is initiated.

[0083] Otherwise, if N result values have been generated, the flow continues to block 620, where it is determined if a number of failures of the method is greater than a threshold. In some implementations, this determination includes determining if the number of failed game plays among those with g equal to one (e.g., game rounds) exceeds the threshold parameter received or set in block 602. In some cases, the quantum device executing the method 600 satisfies an uncertainty principle that ensures that the quantum devices either fails the game G or has high quality output randomness. If the number of failures is greater than the threshold, the flow may continue to block 622, where the method aborts. However, if the number of failures is less than the threshold, the flow continues to block 624, where result values are output.

[0084] In some implementations, the result values generated via the above procedure are output to a known quantum-secure strong randomness extractor and back to the source X to supply the required random seed for the extractor. In such a case, the output of the extractor may be the final output y of the example method 600.

Unbounded Randomness Expansion

[0085] Fig. 10 illustrates an example protocol 700 for unbounded randomness expansion. According to the protocol 700, for all integers N and k and any real $\omega \in (0, \mu)$, k uniformly random bits can be expanded to N output bits with $\exp(-\Omega(k^\omega))$ error under a constant level of noise. The protocol 700 may use $O(\log^* N)$ iterations of randomness expansion protocols 702 and 704, such as the example protocol 500, executed on two or more multi-component quantum devices, such as the plurality of quantum devices 268.

[0086] The $O(\log^* N)$ iterations of the randomness expansion protocol 702 require only two quantum devices, in some implementations. This utilization of only two quantum devices may be based on the fact that when the input to a randomness expansion protocol is independent of the device but not necessary the adversary. The output of the randomness expansion protocol may still be as good as it would be had the input been perfectly random to both the device and the adversary.

[0087] Fig. 11 is a flow diagram of an example method 800 for unbounded randomness expansion. The method 800 may utilize the example protocol 700 and may be implemented by the classical controller 264 and two or more of the plurality of quantum devices 268, for example.

[0088] A fixed number of random values $\mathbf{X}$ is received (block 802). The fixed number of random values may be obtained from a trusted source of random values, in an implementation, as discussed further with respect to Figs. 5 and 6. The fixed number of random values $\mathbf{X}$ may contain any number of random values, such as one, two, three, four, etc. In some cases, a first of the quantum devices implementing the method 800 may receive the random values $\mathbf{X}$ from a classical controller, such as the classical controller 104.

[0089] Subsequently, the first of the quantum devices implementing the method 800 generates a number of random values $\mathbf{Y}$ (block 804), where the number of random values corresponding to $\mathbf{Y}$ is greater than the number of random values corresponding to $\mathbf{X}$. The number of random values $\mathbf{Y}$ may be exponentially greater than the number of random values $\mathbf{X}$, depending on parameters of the randomness expansion protocol utilized by the method. However, it is understood that the random values $\mathbf{Y}$ may be greater in number than the random values $\mathbf{X}$ in any suitable manner, such as greater in number by a fixed number, linearly greater in number, etc.

[0090] Next, the random values $\mathbf{Y}$ are input into a second of the quantum devices implementing the method 800 such that the second of the quantum devices generated random values $\mathbf{Y}'$, where the number of random values corresponding to $\mathbf{Y}'$ is greater than the number

of random values corresponding to Y . As above Y' may be greater in number than the random values Y in any suitable manner. Further, the first and second of the quantum device may implement the same or different randomness expansion protocols and generate increasing random number values at different expansion rates. In some cases, however, the first and second of the quantum devices may implement similar protocols and expand randomness at similar rates.

[0091] It is then determined if the number of random values Y' is greater than or equal to N (block 808), the desired output length of desired number of output/result values. If the output is of the desired length, the result values Y' are output for utilization or further manipulation (block 812). For example, the output values may be communicated to the classical controller 264 and/or the network-enabled device 262.

[0092] If the number of random values Y' is less than N , the flow continues to block 810, where Y' is relabeled as X . Then the flow reverts to block 804, where the new input X (or Y') is utilized as input to the first of the quantum devices. As illustrated in Fig. 10, such a protocol may iterate $2N$ times (each Y labeled as $\{Y_1, Y_3, \dots, Y_{2N-1}\}$ and each Y' labeled as $\{Y_2, Y_4, \dots, Y_{2N-2}\}$), where the output of a first randomness extraction protocol 702 is input to a second randomness extraction protocol 704 and the output of the second randomness extraction protocol 704 is input to the first randomness extraction protocol 702.

[0093] In some cases, a first and second quantum device implementing the method 800 may be isolated from one another, even if corresponding components of each of the devices may be internally resettable. For example, a quantum device executing the first randomness extraction protocol 702 may be isolated from a quantum device executing the second randomness extraction protocol 704.

[0094] In the illustrated example, N is determined for the method 800. In other examples, N may be determined during operation of the method 800, for example, to allow for unbounded expansion until an external decisional control (such as from a classical controller 264), concludes the expansion process.

Quantum Key Distribution

[0095] The above-discussed protocols for random number generation and randomness expansion may be applied to untrusted-device quantum key distribution (QKD) between two example parties *Alice* and *Bob* (e.g., the network-enabled devices 202a and 202b, respectively), in an implementation. *Alice* may interact with a first component of a quantum device, while *Bob* may interact with all the other components of the quantum device. *Alice* and *Bob* may share

randomness for executing a protocol, as well as randomness for later stages of information reconciliation and randomness extraction.

[0096] In some cases, *Alice* and *Bob* may initially have access to randomness of a much shorter than the desired output length. A simplistic QKD implementation of the randomness expansion protocols discussed above includes an initial expansion of randomness by *Alice*, then a use of the expanded secure randomness to execute an existing untrusted device QKD protocol. Such an implementation may produce an end result including an exponentially expanding key distribution protocol.

[0097] However, in other implementations, the randomness expansion protocols of the current disclosure may be adapted to achieve simultaneously randomness expansion and key distribution. Implementations may benefit from such an adaptation in a variety of ways. First, such an adaptation may reduce the number of untrusted devices (e.g., from two to one). When such devices are valuable, a reduction in the number of devices may provide a significant cost savings. Additionally, such an adaptation may rely on any strong self-test. That is, the QKD adaptation may not be restricted to any particular game.

[0098] In some implementations, *Alice* and *Bob* use a public channel to compare their device outputs (e.g., the network 208) for those game rounds, or protocol iterations, in which an input bit g is one. Once a QKD protocol succeeds, *Alice* and *Bob* may apply a standard post-processing method to obtain a shared near uniformly random key.

[0099] Fig. 12 illustrates an example method 900 for quantum key distribution based on the random number generation and/or randomness expansion discussed above. The method may be implemented in the example system 100 or one of the example systems 200, 220, or 240, for example. *Alice* and *Bob*, as described above, will be referred to as party *A* and party *B* below. It is understood, that party *A* and party *B* may include any suitable network-enabled devices, such as those discussed with reference to Fig. 1.

[0100] To begin, a party *A* and a party *B* retrieve or receive random values $\mathbf{X}$ (block 902). The party *A* and the party *B* may retrieve $\mathbf{X}$ from a trusted source of random numbers, and in some cases only one of the parties *A* and *B* retrieve $\mathbf{X}$. For example, a one of the parties *A* and *B* initiating communication with the other of the parties *A* and *B* may retrieve the random values $\mathbf{X}$, or vice versa.

[0101] The random values $\mathbf{X}$ are then shared between the parties *A* and *B* (block 904). In some implementations, this sharing may involve a message from party *A* to party *B*, or vise

versa, and, in other example cases, the source of the random values X may simply send the same random values to both of the parties A and B .

[0102] After sharing the random values X the parties A and B each generate a random number, based on X , using the quantum device components corresponding to party A and the party B , respectively (blocks 906 and 908). In an implementation, the parties A and B may utilize one of the example protocols 300, 500, or 700 to generate the random number. However, each of the parties A and B may utilize any suitable combination of protocols similar to the protocols 300, 500, and 700 to generate a random value or sequence of random values.

[0103] The output (e.g., measure output) of the quantum components corresponding to party B is then communicated with party A . In some implementations, only the output corresponding to “game rounds” (e.g., $g = 1$) is communicated from party B to party A . The communication may be a classical communication and may include electronic communication via one or more private or public networks.

[0104] Next, it is determined if the output from the quantum components is to be accepted (block 912). In some implementations, only one of the parties A and B , such as party A , determines if the output from the quantum components is to be accepted. The determination may be based on any type of pre- or otherwise determined parameters, such as failure rates, thresholds, etc., as discussed further with respect to Figs. 5 and 6. If the output is determined to not be acceptable, the flow may revert to block 902 to restart the method 900, or the method 900 may abort (not shown).

[0105] If the output from the quantum components is accepted, the flow continues to block 914 where information is reconciled between the parties A and B . The reconciliation may include a known method for information reconciliation, in an implementation. Next, a final shared key is output based on the output of the quantum components corresponding to both party A and party B (block 916). The final shared key may be output to the devices corresponding to the parties A and B and/or to other computing devices or network components storing security information or granting access or communications permissions.

[0106] Fig. 12 illustrates an example method by which two entities communicating over a public network may work together, each offering a different quantum system, to construct a random quantum number that is unbounded in comparison to the input number, and which is not discernible to an eavesdropper on that public network. The size of that quantum number can be predetermined by the entities prior to expansion or may be determined, during operation, as the entities exchange input information.

[0107] In some implementations, QKD protocols of the current disclosure may: (i) include any strong self-testing games or contextuality games, as opposed to only one particular game; (ii) achieve exponential expansion with one (multi-component) quantum device simultaneously with QKD; and (iii) achieve simultaneous expansion and QKD with multiple untrusted devices implementing a concatenation strategy.

Further Descriptions Related to Example Protocols

[0108] Further proofs, theorems, corollaries, definitions, protocols etc. relevant to the protocols, techniques, systems, and methods described above are presented below. These proofs, theorems, corollaries, and definitions are provided by way of example and clarification. Some or all of the quantum systems, protocols, etc. discussed above in the example methods and systems may utilize and/or adhere to some or all of the proofs, theorems, corollaries, and definitions. However, any suitable quantum systems as described above may implement the methods, described herein, for generating random numbers, expanding randomness, and/or distributing quantum keys.

[0109] Some of the proofs and theorems depend on the quantum Renyi entropies. For any $\alpha > 1$, and any density matrix ρ and any positive semi-definite operator σ , let:

$$d_{\alpha}(\rho \parallel \sigma) = \text{Tr} \left[\left(\sigma^{\frac{1-\alpha}{2\alpha}} \rho \sigma^{\frac{1-\alpha}{2\alpha}} \right)^{\alpha} \right]^{\frac{1}{\alpha-1}}$$

and let $D_{\alpha}(\rho \parallel \sigma) = \log_2 d_{\alpha}(\rho \parallel \sigma)$. (The quantity $D_{\alpha}(\rho \parallel \sigma)$ is called the Renyi divergence.). The α -Renyi entropy $H_{\alpha}(A|E)$ of a bipartite quantum system (A, E) is computed by the maximum of the value $[-D_{\alpha}(\rho \parallel \sigma)]$ over all operators σ that are of the form $\sigma = I_A \otimes \sigma'$, where $\text{Tr}(\sigma') = 1$. The quantum Renyi entropies have a number of interesting properties. For the purposes presented here, they are interesting because if (A, E) is a classical quantum system, any lower bound on the Renyi entropy of (A, E) provides a lower bound on the number of random bits than can be extracted from A .

An uncertainty principle for Renyi entropy

[0110] Suppose that Q is a qubit, and E is a quantum system that is entangled with Q . Let ρ be a density operator which represents the state of E . Let $\{\rho_0, \rho_1\}$ and $\{\rho_+, \rho_-\}$ represent the states that arise when Q is measured along the $\{0, 1\}$ -basis and the $\{+, -\}$ -basis. We prove the following:

[0111] Theorem. There is a continuous function $\Delta: [0, 1/2] \rightarrow \mathfrak{R}$ satisfying $\Delta(0)=0$ such that the following holds. For any operators $\rho_0, \rho_1, \rho_+, \rho_-$ representing states arising from anti-

commutative measurements, if $\delta = \frac{\text{Tr}(\rho_1^{1+\varepsilon})}{\text{Tr}(\rho^{1+\varepsilon})}$, then

$$\frac{\text{Tr}(\rho_+^{1+\varepsilon} + \rho_-^{1+\varepsilon})}{\text{Tr}(\rho^{1+\varepsilon})} \leq 2^{-\varepsilon(1-\Delta(\delta))}$$

[0112] The above theorem asserts that if the quantity δ determined by the $\{0, 1\}$ measurement is small, then the outcome of the $\{+, -\}$ -measurement must be uncertain (as measured by the $(1 + \varepsilon)$ -Renyi divergence). This parallels other uncertainty principles that have been used in quantum cryptography. The proof of this result is based on a known matrix inequality for the $(2 + 2\varepsilon)$ -Schatten norm.

Certifying randomness from a device with trusted measurements

[0113] Say that a device with trusted measurements D is a single-part input-output device which receives a single bit as an input, and, depending on the value of the bit, performs one of two perfectly anti-commutative binary measurements on a quantum system. The measurements of the device are trusted, but the state is unknown.

[0114] Also, suppose that we make the following modifications to the procedure that defines a protocol similar to the protocol discussed with reference to Fig. 3 (referred to herein as Protocol “R”):

1. Instead of a multi-part binary device, we use a single-part binary device with trusted measurements.
2. Instead of playing a nonlocal game, at each round we simply use the bit g as input to the device and record the output.

This protocol is referred to herein as “Protocol A.” (See Fig. 13)

[0115] Note that Protocols A and R both involve conditioning on a “success” event. One of the central difficulties found in establishing quantum security is in determining the impact that this conditioning has on the randomness of the device D . In the classical security context, one can show that once we condition on the success event, “most” uses of the device D (in an appropriate sense) generate random outputs. By elementary arguments, the outputs therefore accumulate min-entropy linearly over multiple iterations, and randomness expansion is achieved.

[0116] A successful way to interpret the success/abort events in the quantum context may involve two adjustments to the classical approach outlined above. First, the quantum Renyi entropy is used in place of the smooth min-entropy. (The quantum Renyi entropies have elegant arithmetic properties which make them more amenable to induction.) Secondly, rather than directly considering “success” and “abort” as discrete events, a graded measurement of performance interpolates between the two.

[0117] Suppose that E is a quantum system which is initially entangled with D. For the purposes of this discussion, assume that E and D are maximally entangled and the state $\rho = \rho_E$ is totally mixed. Then, the state of E after one iteration can be expressed as

$$\bar{\rho} := (1-q)\rho_+ \oplus (1-q)\rho_- \oplus q\rho_0 \oplus q\rho_1.$$

[0118] Suppose that the randomness of a state is measured with respect to a second party who knows the value of the bit g. Then, an appropriate measure of randomness may be the Renyi divergence $d_\alpha(\rho||\sigma)$ with respect to the operator $\sigma := (1-q)I \oplus (1-q)I \oplus qI \oplus qI$. For the parameter α , it turns out that simply taking $\alpha = 1+q$ is useful.

[0119] Then,

$$d_{1+q}(\bar{\rho} || \sigma) = \text{Tr} \left[(1-q)\rho_+^{1+q} + (1-q)\rho_-^{1+q} + q\rho_0 + q\rho_1 \right]^{1/q}.$$

[0120] One could hope that this quantity is strictly smaller than $d_\alpha(\rho||\sigma)$, but this is not always so (for example, for measurements on a maximally entangled Bell state). But consider instead the modified expression:

$$\text{Tr} \left[(1-q)\rho_+^{1+q} + (1-q)\rho_-^{1+q} + q\rho_0 + \left(\frac{1}{2}\right)q\rho_1 \right]^{1/q}$$

[0121] Theorem 2.1 implies that this quantity is always less than $C^{-1}d_{1+q}(\rho||\sigma)$, where $C > 1$ is a fixed constant. (Essentially, this is because if the quantity δ is large, then the introduction of the $(1/2)$ coefficient lowers the value of the expression significantly, and if δ is small, then the desired bound is implied).

[0122] If,

$$\sigma := (1-q)I \oplus (1-q)I \oplus qI \oplus 2^{(q^{-1})}qI,$$

then $d_{1+q}(\rho||\sigma)$ is equal to:

$$\text{Tr} \left[(1-q)\rho_+^{1+q} + (1-q)\rho_-^{1+q} + q\rho_0 + \left(\frac{1}{2}\right)q\rho \right]^{1/q}$$

[0123] One can think of the function $d_{1+q}(\rho||\sigma)$ as an error-tolerant measure of performance. The presence of the coefficient 2^{q-1} compensates for the loss of randomness when the device-failure quantity $\text{Tr}[\rho_1^{1+q}]$ is large.

[0124] Now let B denote the output register of Protocol R, and let Λ_{BE} denote the joint state of E and B at the conclusion of the protocol. Let Σ be an operator on BE defined by:

$$\Sigma = \sum_{b \in \{H,T,P,F\}^N} (1-q)^{\binom{\# \text{gen.}}{\text{rounds}}} q^{\binom{\# \text{game}}{\text{rounds}}} 2^{\left[\binom{\# \text{of}}{q^{-1} \text{failures}} \right]} |b\rangle\langle b| \otimes I.$$

[0125] An inductive argument proves that $d_{1+q}(\Gamma||\Sigma) \leq C^{-N}$. This inequality is sufficient to deduce that the Renyi entropy of the “success” state Γ grows linearly in N. One can therefore deduce that (for appropriate parameters) the outputs of Protocol A contain a linear number of extractable quantum proof bits.

[0126] It may be further proved that: if Protocol A is executed with a partially trusted measurement device (i.e., a measurement device whose measurements are anticommutative only with a certain positive probability) then it produces a linear amount of randomness. This generalization may be crucial for the carrying over of results into a fully device-independent setting.

Simulation results for partially trusted devices:

[0127] A second insight enabling, at least in some cases, properties of the protocols discussed herein is that nonlocal games simulate partially trusted devices. When certain nonlocal games are played—even with a device that is completely untrusted—their outcomes may match the behavior of a device that is partially trusted.

[0128] To illustrate this, a class of devices is formalized as follows. Definition: Let n be a positive integer. A “binary quantum device” with n components $D = (D_1, \dots, D_n)$ include the following:

1. Quantum system $Q_1, \dots, Q_n$ and a density operator Φ on $Q_1 \otimes \dots \otimes Q_n$ which defines the initial state of the systems.

2. For any $k \geq 0$, and any “transcript” T (representing the collective previous inputs and outputs during previous rounds) a unitary operator $U_T : \otimes_i Q_i \rightarrow \otimes_i Q_i$ and a collection of Hermitian operator $M_{T,j}^{(b)}$ on Q_i satisfying $\|M_{T,j}^{(b)}\| \leq 1$.

[0129] The behavior of the device D is as follows: at round i , the devices first collectively perform the unitary operation U_T , and then, according to their inputs b_i , each performs binary measurements specified by the operators $M_{T,j}^{b_i}$. (This device model allows communication in between rounds, in an implementation)

[0130] Now a somewhat more specific type of device is defined. Suppose that E is a single-part binary quantum device. Say that E is a partially trusted device with parameters (u, v) if the measurement operators $N_T^{(1)}$ that E uses on input 1 decompose as:

$$N_T^{(1)} = (v)P_T + (u - v)Q_T,$$

where P_T is perfectly anti-commutative with the other measurement $N_T^{(0)}$, and Q_T satisfies $\|Q_T\| \leq 1$ (and is otherwise unspecified). Essentially, the device behaves as follows. On input 0, it performs a perfect measurement. On input 1, it does one of the following at random: it performs a perfectly anti-commuting measurement (probability = v), or it performs an unknown measurement (probability = $u - v$), or it ignores its quantum system and merely outputs a perfect coin flip (probability = $1 - u$). (The second possibility is referred to herein as a “dishonest mistake,” and the third is referred to herein as an “honest mistake.”)

[0131] Proving that untrusted devices can be simulated by partially trusted devices is an example of a task that is fairly easy in the classical security context but difficult in the quantum context. For example, if one knows that a quantum device performs at a superclassical level at a particular nonlocal game, then one knows that its outcomes are at least partly random, and thus can be “simulated” by a biased coin flip (or a “partially trusted” coin flip). But to prove quantum security one needs a stronger notion of simulation—one that allows for the possibility quantum side information.

[0132] The basis for a simulation result may be certain known properties of quantum self-testing. Games from the class of strong self-tests are considered (although, as discussed further above, contextuality games may also be implemented in one or more protocols discussed herein):

[0133] Theorem. Let G be a strong self-test, and let D be an (untrusted) binary device with n components. Then, the behavior of D Protocol R can be simulated by a partially trusted device.

[0134] Reducing to the case where $\dim Q_i = 2$, each measurement operator being projective, and after an appropriate choice of basis:

$$M_j^{(0)} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}; \quad M_j^{(1)} = \begin{bmatrix} 0 & \alpha_j \\ \bar{\alpha}_j & 0 \end{bmatrix},$$

with $|\alpha_j| = 1$. The output of D during a generation round is derived from the measurement operator $M_j^{(0)} \otimes I \otimes \dots \otimes I$, which, under an appropriate basis, can be represented as the

block matrix $\begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix}$ on C^{2^n} . The behavior of D during a game round can be given

represented by a reverse diagonal Hermitian matrix $\mathbf{M}$ on C^{2^n} with entries:

$$P_1(\alpha_1, \dots, \alpha_n), P_2(\alpha_1, \dots, \alpha_n), P_3(\alpha_1, \dots, \alpha_n), \dots, \bar{P}_2(\alpha_1, \dots, \alpha_n), \bar{P}_1(\alpha_1, \dots, \alpha_n),$$

where $\{P_i\}$ are rational functions depending on the game. Using the strong self-testing condition, the existence of another reverse diagonal matrix R is shown with entries

$$\beta_1, \dots, \beta_{2^{n-1}}, \bar{\beta}_{2^{n-1}}, \dots, \bar{\beta}_1 \text{ which anti-commute with } M_j^{(0)} \text{ and which satisfies } \|\mathbf{M} - \mathbf{R}\| + \|\mathbf{R}\|$$

$= \|\mathbf{M}\|$. This implies that $\mathbf{M}$ satisfies the decomposition, $N_T^{(1)} = (v)P_T + (u-v)Q_T$, which defines a partially trusted device.

[0135] Proving the existence of the sequence $\beta_1, \dots, \beta_{2^{n-1}}$ is matter of manipulations of complex numbers. One surprising aspect of this proof is that it depends on the fact that G is not only a self-test, but a *strong* self-test.

Protocol A'

[0136] A third protocol, Protocol A' (see further description with reference to Fig. 14), is the same as Protocol A except that a partially trusted measurement device is used. Protocol R can be simulated by Protocol A' for an appropriately chosen partially trusted device. This means not only that the probability distributions of the outputs of the two protocols are exactly the same, but also that there is a simulation of the behavior of any external quantum environment that may be possessed by an adversary. Since the Protocol A' with a partially trusted device produces a linear amount of min-entropy, the same is true of Protocol R. This completes the proof.

Untrusted Quantum Devices

[0137] For further clarity and by way of example, a formalization of some terminology and notation for describing certain example quantum devices is presented below:

[0138] Definition: Let n be a positive integer. Another example "binary quantum device" with n components $D = (D_1, \dots, D_n)$ includes the following:

1. Quantum systems $Q_1, \dots, Q_n$ whose initial state is specified by a density operator, Φ :
 $(Q_1 \otimes \dots \otimes Q_n) \rightarrow (Q_1 \otimes \dots \otimes Q_n)$.
2. For any $k \geq 0$, and any function $T: \{0,1\} \times \{1,2,\dots,k\} \times \{1,2,\dots,n\} \rightarrow \{0,1\}$, a unitary operator U_T :
 $(Q_1 \otimes \dots \otimes Q_n) \rightarrow (Q_1 \otimes \dots \otimes Q_n)$ and a collection of Hermitian operators

$$\left\{ M_{T,j}^{(b)} : Q_j \rightarrow Q_j \right\}_{\substack{b \in \{0,1\} \\ 1 \leq j \leq n}} \text{ satisfying } \|M_{T,j}^{(b)}\| \leq 1.$$

[0139] The device D may behave as follows. Suppose that k iterations of the device have already taken place, and suppose that T is such that $T(0, i, j) \in \{0, 1\}$ and $T(1, i, j) \in \{0, 1\}$ represent the input bit and output bit, respectively, for the j th player on the i th round ($i \leq k$). (T is the transcript function.) Then,

1. The components $(D_1, \dots, D_n)$ collectively perform the unitary operator U_T on $Q_1 \otimes \dots \otimes Q_n$.
2. Each component $(D_1, \dots, D_n)$ receives its input bit b_j , then applies the binary nondestructive measurement on Q_j given by:

$$X \mapsto \left(\sqrt{\frac{I + M_{T,j}^{(b)}}{2}} \right) \times \left(\sqrt{\frac{I + M_{T,j}^{(b)}}{2}} \right)$$

$$X \mapsto \left(\sqrt{\frac{I - M_{T,j}^{(b)}}{2}} \right) \times \left(\sqrt{\frac{I - M_{T,j}^{(b)}}{2}} \right),$$

and then outputs the result.

Simulation – Untrusted Quantum Devices

[0140] Suppose that one binary quantum device D' simulates another binary quantum device D if, for any purifying systems E' and E (for D and D' , respectively), and any input sequence $i_1, \dots, i_k \in \{0, 1\}^n$, the joint state of the outputs of D together with E is isomorphic to the joint state of the outputs of D' together with E' on the same input sequence. Similarly, let us say that a protocol X simulates another protocol Y if, for any purifying systems E and E' for the quantum devices used by X and Y , respectively, the joint state of E together with the outputs of X is isomorphic to the joint state of E' together with the outputs of Y .

[0141] Definition: Say that a binary quantum device D is in “canonical form” if each of its quantum systems Q_i is such that $Q_i = C^{2m_i}$ for some $m_i \geq 1$, and each measurement operator pair

$$(M^{(0)}, M^{(1)}) = (M_{T,j}^{(1)}, M_{T,j}^{(1)}) \text{ has the following } 2 \times 2 \text{ diagonal block form:}$$

$$M^{(0)} = \begin{bmatrix} 0 & 1 & & & \\ 1 & 0 & & & \\ & & 0 & 1 & \\ & & 1 & 0 & \\ & & & \ddots & \\ & & & & 0 & 1 \\ & & & & 1 & 0 \end{bmatrix};$$

$$M^{(1)} = \begin{bmatrix} 0 & \zeta_1 & & & \\ \bar{\zeta}_1 & 0 & & & \\ & & 0 & \zeta_2 & \\ & & \bar{\zeta}_2 & 0 & \\ & & & \ddots & \\ & & & & 0 & \zeta_{m_j} \\ & & & & \bar{\zeta}_{m_j} & 0 \end{bmatrix},$$

Where the complex numbers ζ_i satisfy $|\zeta_i|=1$ and $\text{Im}(\zeta_i) \geq 0$. Note, that the complex numbers ζ_i may be different for each transcript H and each player j . Discussing quantum devices in “canonical form,” the description above and below may make use of the isomorphism $C^{2m} \cong C^2 \otimes C^m$ given by $e_{2k-1} \mapsto e_1 \otimes e_k, e_{2k} \mapsto e_2 \otimes e_k$ ($e_1, \dots, e_r$ denote the standard basis vectors for C). It is proposed that any binary quantum device may be simulated by a device that is in canonical form.

Randomness Expansion with Untrusted Measurements

[0142] Definition: Let $u, v \in (0,1]$ be positive real numbers such that $v \leq u \leq 1$. Then a “partially trusted” device with parameters (u,v) includes the following data:

1. A single quantum system Q in an initial state Φ .
2. For every pair (i,o) of binary strings of equal length, two Hermitian operator $M_{i,o}^{(0)}, M_{i,o}^{(1)}$ on Q (e.g., representing measurements) satisfy the following conditions: (a) there exist perfectly anti-commuting measurement pairs $(T_{i,o}^{(0)}, T_{i,o}^{(1)})$ such that $M_{i,o}^{(0)} = T_{i,o}^{(0)}$ for all i,o ; and (b) the operator $M_{i,o}^{(1)}$ decomposes as $M_{i,o}^{(1)} = (v)T_{i,o}^{(1)} + (u-v)N_{i,o}$, with $\|N_{i,o}\| \leq 1$.

[0143] Intuitively, a partially trusted device is a device D which always performs a trusted measurement $T^{(0)}$ on input 0, and on input 1, selects one of the three operators $(T^{(1)}, N, 0)$ at random according to the probability distribution $(v, u-v, 1-u)$.

[0144] Consider example protocol A with the trusted device replaced by a partially trusted device. The outputs of Protocol A' may be as follows: let g_i denote the bit g from the i th round of the protocol, and let G denote a classical register which consists of the bits $g_1, g_2, \dots, g_N$. Let o_i be equal to 0 if the outcome of the i th round is P or H, and let o_i be equal to 1 if the outcome of the i th round is F or T. Let O be a classical register consisting of the bits $o_1, o_2, \dots, o_N$. Also, *succ* may denote the “success” event in Protocol A'.

[0145] Theorem: Let $u, v, \delta > 0$ be real number with $0 < v \leq u \leq 1$. Then, there exists constants $q_0, \eta_0, b, c > 0$ such that the following holds. If Protocol A' is executed with arguments (N, q, η, u, v, D) , where $q < q_0, \eta < \eta_0$, and if the success probability is at least 2^{-cNq} , then

$$[0146] \quad H_{\min}^{\varepsilon}(O \mid EG, succ) \geq (1 - \delta)N,$$

where $\mathcal{E} = \sqrt{2} \cdot 2^{-bNq}$.

Simulation – Expansion with Untrusted Measurements

[0147] Theorem: For any n -player strong self-test G which is positively aligned, there exists $\delta_G > 0$ such that the following holds. For any n -part binary quantum device D , there exists a partially trusted device D' with parameters q_G, δ_G such that Protocol A' (with arguments $N, q, \eta, q_G, \delta_G, D'$) simulates Protocol R (with arguments N, q, η, D, G).

[0148] Consider the behavior of the device D in a first round. It may be assumed that the measurements performed by $D_1, \dots, D_n$ are in canonical form. Write the underlying space as $(C^2 \otimes W_1) \otimes \dots \otimes (C^2 \otimes W_n)$. If $g = 0$, the measurement performed by D_1 is given by the operator:

$$\left[\begin{array}{ccccccc} & & & & & & 1 \\ & & & & & & \\ & & & & & 1 & \\ & & & & \ddots & & \\ & & & & & \ddots & \\ & & & & & & 1 \\ 1 & & & & & & \\ & 1 & & & & & \\ & & \ddots & & & & \\ & & & 1 & & & \end{array} \right] \otimes I_{W_1 \otimes \dots \otimes W_n};$$

(where the matrix on the left is an operator on $(\mathbb{C}^2)^{\otimes n}$, with the basis taken in lexicographic order).

[0149] If $g = 1$ the measurement performed by D is given by the scoring operator $\mathbf{M}$. For some unit-length complex number α , and for any choices of unit-length complex numbers $\alpha_1, \dots, \alpha_{2^{n(n-1)-1}}$, there is a decomposition for $\mathbf{M}$ in the form $\mathbf{M} = \delta_{\mathbf{G}}\mathbf{M}' + (q_{\mathbf{G}} - \delta_{\mathbf{G}})\mathbf{M}''$ with

$$M'' = \begin{bmatrix} & & & & & \alpha \\ & & & & \alpha_1 & \\ & & & \ddots & & \\ & & \alpha_{2^{n-1}-1} & & & \\ & \bar{\alpha}_{2^{n-1}-1} & & & & \\ & \ddots & & & & \\ \bar{\alpha}_1 & & & & & \\ \bar{\alpha} & & & & & \end{bmatrix} \otimes I_{W_1 \otimes \dots \otimes W_n}$$

and $\|M''\| \leq 1$. To simulate the behavior of D with a partially trusted device, we may choose $\alpha_1, \dots, \alpha_{2^{n-1}-1}$ so that M' is perfectly anti-commutative with the operator G . This can be done, for example, by setting $\alpha_1, \alpha_2, \dots, \alpha_{2^{n-2}-1}$ to be equal to α , and $\alpha_{2^{n-2}}, \dots, \alpha_{2^{n-1}-1}$ to be equal to $-\alpha$. Thus the behavior of the device D in the first round of Protocol R can be simulated by a partially trusted device with parameters $(q_G - \delta_G, \delta_G)$. Similar reasoning shows the desired simulation result across all rounds. Further, this theorem holds true without the assumption that G is positively aligned.

[0150] Theorem: Let G be a strong self-test and let $\delta > 0$ be a real number. Then, there exist constants $q_0, \eta_0, b, c > 0$ such that the following holds. If Protocol R is executed with arguments (N, q, η, G, D) , where $q < q_0, \eta < \eta_0$, and if the success probability is at least 2^{-cNq} , then

$$H_{\min}^{\varepsilon}(O | EG, succ) \geq (1 - \delta)N,$$

where $\varepsilon = \sqrt{2} \cdot 2^{-bNq}$.

Untrusted-device Quantum Key Distribution

[0151] To adapt the randomness expansion protocols of the current disclosure to achieve simultaneously randomness expansion and key distribution, the Information Reconciliation (IR) stage is considered below. An implementation may require that the amount of leaked information does not reduce the asymptotic quantity of the smooth min-entropy. Furthermore, an implementation may not include too much randomness. As such, *Alice* and *Bob* may be assumed to have access to a linear (in the output length) amount of shared randomness (which does not need to be secure against the adversary).

[0152] Further, to require that the amount of leaked information does not reduce the asymptotic quantity of the smooth min-entropy, an Azuma-Hoeffding Inequality may be applied to show that, other than a chance of the same order as the expansion soundness error, *Alice* and *Bob*'s strings differ by at most a $1/2 - \lambda$ fraction, for some constant λ . A randomized

protocol may then be constructed through which *Bob* recovers *Alice*'s string without consuming too much randomness and in an efficient manner in terms of time complexity.

[0153] Central results relevant to QKD is included below. The notion of soundness and completeness errors are similarly defined: the soundness error may be the distance of the output distribution to a mixture of aborting and an output randomness of a desired smooth min-entropy, and the completeness error may be the probability of aborting for an honest (possibly noisy) implementation.

[0154] Corollary: For any strong self-test G , there exists a constant s such that for any $\delta > 0$, there exist positive constants q_0, η_0, N_0, b, c such that the following holds when Protocol R_{qkd} (see Fig. 15) is executed with $q \leq q_0, \eta \leq \eta_0$, and $N \geq N_0$.

1. (Soundness) The protocol obtains a key of $(s-\delta)N$ extractible bits with a soundness error $\epsilon_s = \exp(-bqN)$.
2. (Completeness) For any constant $\lambda, 0 < \lambda < \eta$, the protocol tolerates λ noise level with a completeness error $\epsilon_c = \exp(-c(\eta-\lambda)^2)qN$.

The number of initial random bits is $O(Nh(q) + \log N)$. A final key of length $\Omega(N)$ can be obtained by applying a quantum-proof randomness extractor with additional $O(\log^w(N/\epsilon))$ bits as the seed for the extractor, where w can be chosen ≤ 2 , and ϵ is added to the soundness error. The adapted Protocol R_{qkd} may be referred to as the adaption of Protocol R for untrusted-device quantum key distribution. An example Protocol R_{qkd} is illustrated in Fig. 15.

[0155] The proof for the above Corollary may include two steps. The first may show that when Protocol R is run, other than an $\exp(-\Omega(qN))$ probability, A and B differ in at most a $(1/2 - \lambda)$ fraction. The second step may include constructing the efficient IR Protocol for *Bob* to correct the differences with some small failure probability. Note, the protocol R_{qkd} may apply to a broader class of games than the strong self-tests.

Additional Considerations

[0156] Throughout this specification, plural instances may implement components, operations, or structures described as a single instance. Although individual operations of one or more methods are illustrated and described as separate operations, one or more of the individual operations may be performed concurrently, and nothing requires that the operations be performed in the order illustrated. Structures and functionality presented as separate components in example configurations may be implemented as a combined structure or component. Similarly, structures and functionality presented as a single component may be

implemented as separate components. These and other variations, modifications, additions, and improvements fall within the scope of the subject matter herein.

[0157] Additionally, certain embodiments are described herein as including logic or a number of routines, subroutines, applications, or instructions. These may constitute either software (e.g., code embodied on a machine-readable medium or in a transmission signal) or hardware. In hardware, the routines, etc., are tangible units capable of performing certain operations and may be configured or arranged in a certain manner. In example embodiments, one or more computer systems (e.g., a standalone, client or server computer system) or one or more hardware modules of a computer system (e.g., a processor or a group of processors) may be configured by software (e.g., an application or application portion) as a hardware module that operates to perform certain operations as described herein.

[0158] In various embodiments, a hardware module may be implemented mechanically or electronically. For example, a hardware module may comprise dedicated circuitry or logic that is permanently configured (e.g., as a special-purpose processor, such as a field programmable gate array (FPGA) or an application-specific integrated circuit (ASIC)) to perform certain operations. A hardware module may also comprise programmable logic or circuitry (e.g., as encompassed within a general-purpose processor or other programmable processor) that is temporarily configured by software to perform certain operations. It will be appreciated that the decision to implement a hardware module mechanically, in dedicated and permanently configured circuitry, or in temporarily configured circuitry (e.g., configured by software) may be driven by cost and time considerations.

[0159] Accordingly, the term “hardware module” should be understood to encompass a tangible entity, be that an entity that is physically constructed, permanently configured (e.g., hardwired), or temporarily configured (e.g., programmed) to operate in a certain manner or to perform certain operations described herein. Considering embodiments in which hardware modules are temporarily configured (e.g., programmed), each of the hardware modules need not be configured or instantiated at any one instance in time. For example, where the hardware modules comprise a general-purpose processor configured using software, the general-purpose processor may be configured as respective different hardware modules at different times. Software may accordingly configure a processor, for example, to constitute a particular hardware module at one instance of time and to constitute a different hardware module at a different instance of time.

[0160] Hardware modules can provide information to, and receive information from, other hardware modules. Accordingly, the described hardware modules may be regarded as being

communicatively coupled. Where multiple of such hardware modules exist contemporaneously, communications may be achieved through signal transmission (e.g., over appropriate circuits and buses) that connects the hardware modules. In embodiments in which multiple hardware modules are configured or instantiated at different times, communications between such hardware modules may be achieved, for example, through the storage and retrieval of information in memory structures to which the multiple hardware modules have access. For example, one hardware module may perform an operation and store the output of that operation in a memory device to which it is communicatively coupled. A further hardware module may then, at a later time, access the memory device to retrieve and process the stored output. Hardware modules may also initiate communications with input or output devices, and can operate on a resource (e.g., a collection of information).

[0161] The various operations of the example methods described herein may be performed, at least partially, by one or more processors that are temporarily configured (e.g., by software) or permanently configured to perform the relevant operations. Whether temporarily or permanently configured, such processors may constitute processor-implemented modules that operate to perform one or more operations or functions. The modules referred to herein may, in some example embodiments, comprise processor-implemented modules.

[0162] Similarly, the methods or routines described herein may be at least partially processor-implemented. For example, at least some of the operations of a method may be performed by one or more processors or processor-implemented hardware modules. The performance of certain of the operations may be distributed among the one or more processors, not only residing within a single machine, but also deployed across a number of machines. In some example embodiments, the processor or processors may be located in a single location (e.g., within a home environment, an office environment or as a server farm), while in other embodiments the processors may be distributed across a number of locations.

[0163] The performance of certain of the operations may be distributed among the one or more processors, not only residing within a single machine, but also deployed across a number of machines. In some example embodiments, the one or more processors or processor-implemented modules may be located in a single geographic location (e.g., within a home environment, an office environment, or a server farm). In other example embodiments, the one or more processors or processor-implemented modules may be distributed across a number of geographic locations.

[0164] Unless specifically stated otherwise, discussions herein using words such as “processing,” “computing,” “calculating,” “determining,” “presenting,” “displaying,” or the like may

refer to actions or processes of a machine (e.g., a computer) that manipulates or transforms data represented as physical (e.g., electronic, magnetic, or optical) quantities within one or more memories (e.g., volatile memory, non-volatile memory, or a combination thereof), registers, or other machine components that receive, store, transmit, or display information.

[0165] As used herein any reference to “one embodiment” or “an embodiment” means that a particular element, feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. The appearances of the phrase “in one embodiment” in various places in the specification are not necessarily all referring to the same embodiment.

[0166] Some embodiments may be described using the expression “coupled” and “connected” along with their derivatives. For example, some embodiments may be described using the term “coupled” to indicate that two or more elements are in direct physical or electrical contact. The term “coupled,” however, may also mean that two or more elements are not in direct contact with each other, but yet still co-operate or interact with each other. The embodiments are not limited in this context.

[0167] As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, “or” refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

[0168] In addition, use of the “a” or “an” are employed to describe elements and components of the embodiments herein. This is done merely for convenience and to give a general sense of the description. This description, and the claims that follow, should be read to include one or at least one and the singular also includes the plural unless it is obvious that it is meant otherwise.

[0169] This detailed description is to be construed as an example only and does not describe every possible embodiment, as describing every possible embodiment would be impractical, if not impossible. One could implement numerous alternate embodiments, using either current technology or technology developed after the filing date of this application.

What is Claimed:

1. A method of generating a sequence of random bits, the method comprising:
receiving, at a quantum device, a binary input signal from an input signal source;
coupling the binary input signal into a plurality of components of the quantum device to initiate a random bit generation cycle,
wherein each of the plurality of components of the quantum device produces a binary output during the random bit generation cycle, and
wherein the quantum device is configured to operate according to a game during the random bit generation cycle;
maintaining isolation of the plurality of components of the quantum device during the random bit generation cycle, so that each of the plurality of components of the quantum device maintains at least one of superposition or entanglement during the random bit generation cycle;
obtaining a plurality of binary outputs from the plurality of components of the quantum device;
producing, at a classical controller coupled to the quantum device, a random bit based on the plurality of binary outputs and the binary input signal; and
causing communication among the plurality of components of the quantum device after the random bit generation cycle.
2. The method of claim 1, further comprising receiving, at the quantum device, the binary input signal from the input signal source, wherein the input signal source is a trusted source of random bits.
3. The method of claim 2, further comprising receiving, at the quantum device, the binary input signal from the input signal source, wherein the input signal source is a trusted source of random bits compatible with at least one of an output length, an output randomness quality, a failure probability, or a tolerated noise level.

4. The method of claim 1, wherein each of the plurality of components of the quantum device includes:

- (i) a quantum system,
- (ii) an input interface, and
- (iii) an output interface.

5. The method of claim 4, wherein the quantum system includes at least one of a non-Abelian topologically ordered phase of matter, an Ising spin glass, a three dimensional (3D) lattice cluster state, one or more superconducting systems, one or more trapped atoms, ions, or molecules, one or more quantum dots, one or more optical elements, or a Bose-Einstein condensate.

6. The method of claim 1, wherein coupling the binary input signal into the plurality of components of the quantum device includes topologically manipulating non-Abelian topologically ordered phases of matter.

7. The method of claim 1, wherein coupling the binary input signal into the plurality of components of the quantum device includes manipulating magnetic properties via one or more superconducting quantum interference devices (SQUIDs).

8. The method of claim 1, further comprising:

- receiving, at the quantum device, one or more subsequent binary input signals from the input signal source;
- sequentially coupling each of the one or more subsequent binary input signals into the plurality of components of the quantum device to initiate a corresponding one or more subsequent random bit generation cycles;
- maintaining isolation of the plurality of components of the quantum device during each of the one or more subsequent random bit generation cycles;
- obtaining a subsequent plurality of binary outputs from the plurality of components of the quantum device;

producing one or more subsequent random bits based on the subsequent plurality of binary outputs and the one or more subsequent binary input signals; and

causing communication among the plurality of components of the quantum device after each of the one or more subsequent random bit generation cycles.

9. The method of claim 8, further comprising:
storing the random bit and the one or more subsequent random bits; and
creating a random bit word from the stored random bit and the stored one or more subsequent random bits.

10. The method of claim 1, wherein the game is a non-local game.

11. The method of claim 1, wherein the plurality of quantum components are identically configured.

12. The method of claim 1, wherein causing communication among the plurality of components of the quantum device comprises quantum communication of information among the plurality of components.

13. The method of claim 12, wherein the quantum communication of information among the plurality of components causes a loss of the at least one of superposition of entanglement.

14. The method of claim 1, wherein coupling the binary input signal into a plurality of components of the quantum device includes one of:

coupling a random string of values into the plurality of components of the quantum device if the binary input signal includes a first value, or

coupling a string of null values into the plurality of components of the quantum device if the binary input signal includes a second value different from the first value.

15. A method of generating a large number of random bits from a small number of input random bits, the method comprising:

determining parameters including an output length;

retrieving, from a source of random values, a plurality of binary input values; and

for each of the plurality of binary input values one of:

coupling a plurality of random input values from the source of random values into a plurality of components of a quantum device if the binary input value includes a first value, or

coupling a string of null values into the plurality of components of the quantum device if the binary input value includes a second value different from the first value,

the coupling of the plurality of random input values and the coupling of the string of null values being independent of values previously coupled into the plurality of components of the quantum devices,

obtaining a plurality of binary outputs from the plurality of components of the quantum device, and

generating a random value based on the plurality of binary outputs and the binary input value.

16. The method of claim 15, wherein the parameters include the output length and at least one of an output randomness quality, a failure probability, or a tolerated noise level, the method further comprising:

determining if a number of failures is greater than a threshold based on the failure probability and at least one of the plurality of binary input values or the generated random values; and

if the number of failures is less than the threshold, storing the generated random values.

17. The method of claim 15, further comprising:

maintaining isolation of the plurality of components of the quantum device at times between (i) coupling the plurality of random input values from the source of random values into the plurality of components of the quantum device or coupling the string of null values into the plurality of components of the quantum device and (ii) obtaining the plurality of binary outputs from the plurality of components of the quantum device; and

causing communication among the plurality of components of the quantum device after generating the random value based on the plurality of binary outputs and the binary input value.

18. The method of claim 15, further comprising:

sending the generated random value to a quantum-proof randomness extractors; and
storing an output of the quantum-proof randomness extractor.

19. The method of claim 15, wherein the parameters allow a rate of randomness expansion to range between a linear function to an exponential function.

20. A system for generating a sequence of random bits, the system comprising:

a quantum device including a plurality of components, the quantum device configured to:

operate according to a game during a random bit generation cycle,

produce a binary output during the random bit generation cycle,

maintain isolation of the plurality of components during the random bit generation cycle, so that each of the plurality of components maintains at least one of superposition or entanglement during the random bit generation cycle, and

cause communication among the plurality of components after the random bit generation cycle; and

a classical controller coupled to the quantum device and configured to:

receive a binary input signal from an input signal source,

couple the binary input signal into the plurality of components of the quantum device to initiate the random bit generation cycle,

obtain a plurality of binary outputs from the plurality of components of the quantum device, and

produce a random bit based on the plurality of binary outputs and the binary input signal.

21. The system of claim 20, wherein each of the plurality of components of the quantum device includes:

- (i) a quantum system,
- (ii) an input interface, and
- (iii) an output interface.

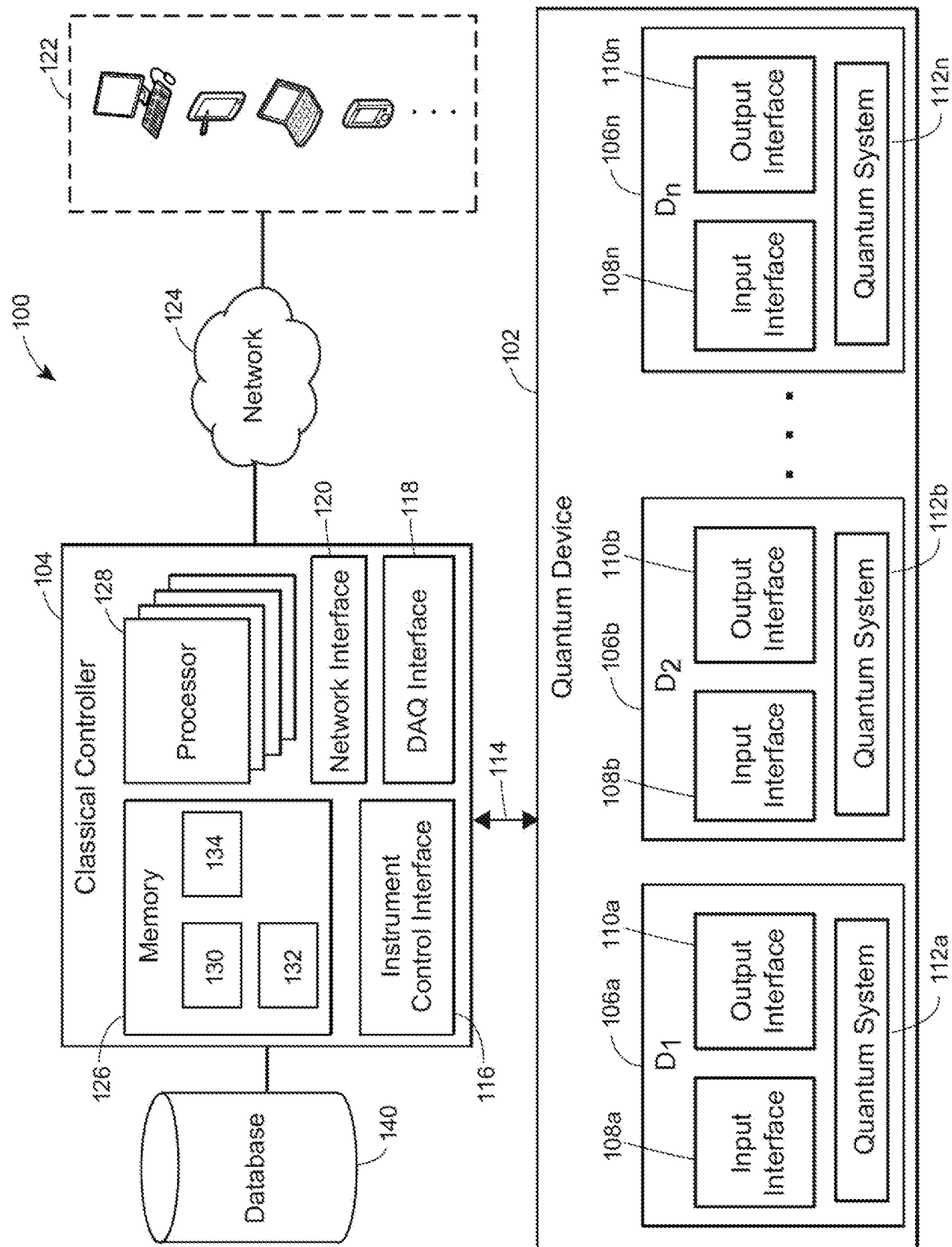


FIG. 1

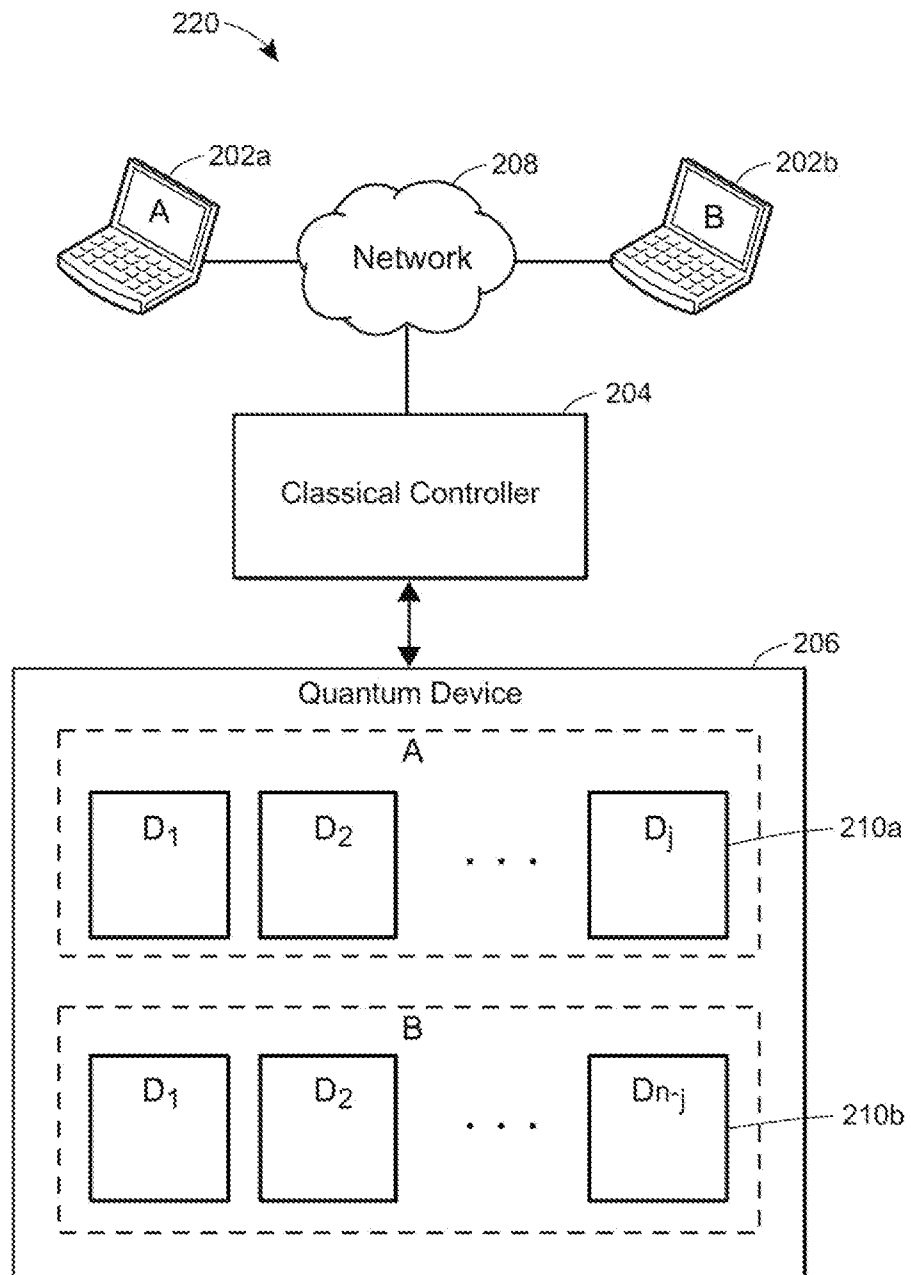


FIG. 2A

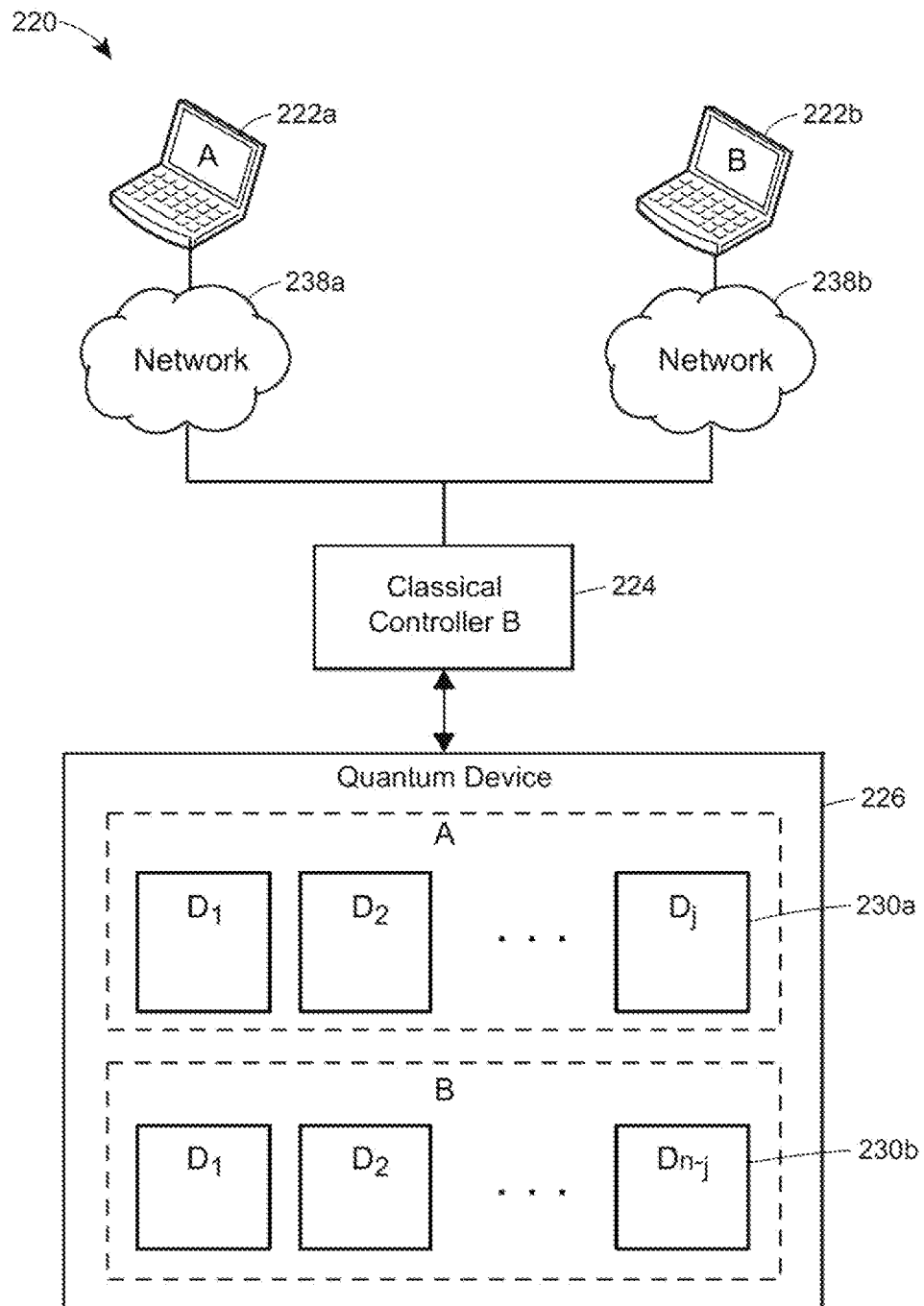


FIG. 2B

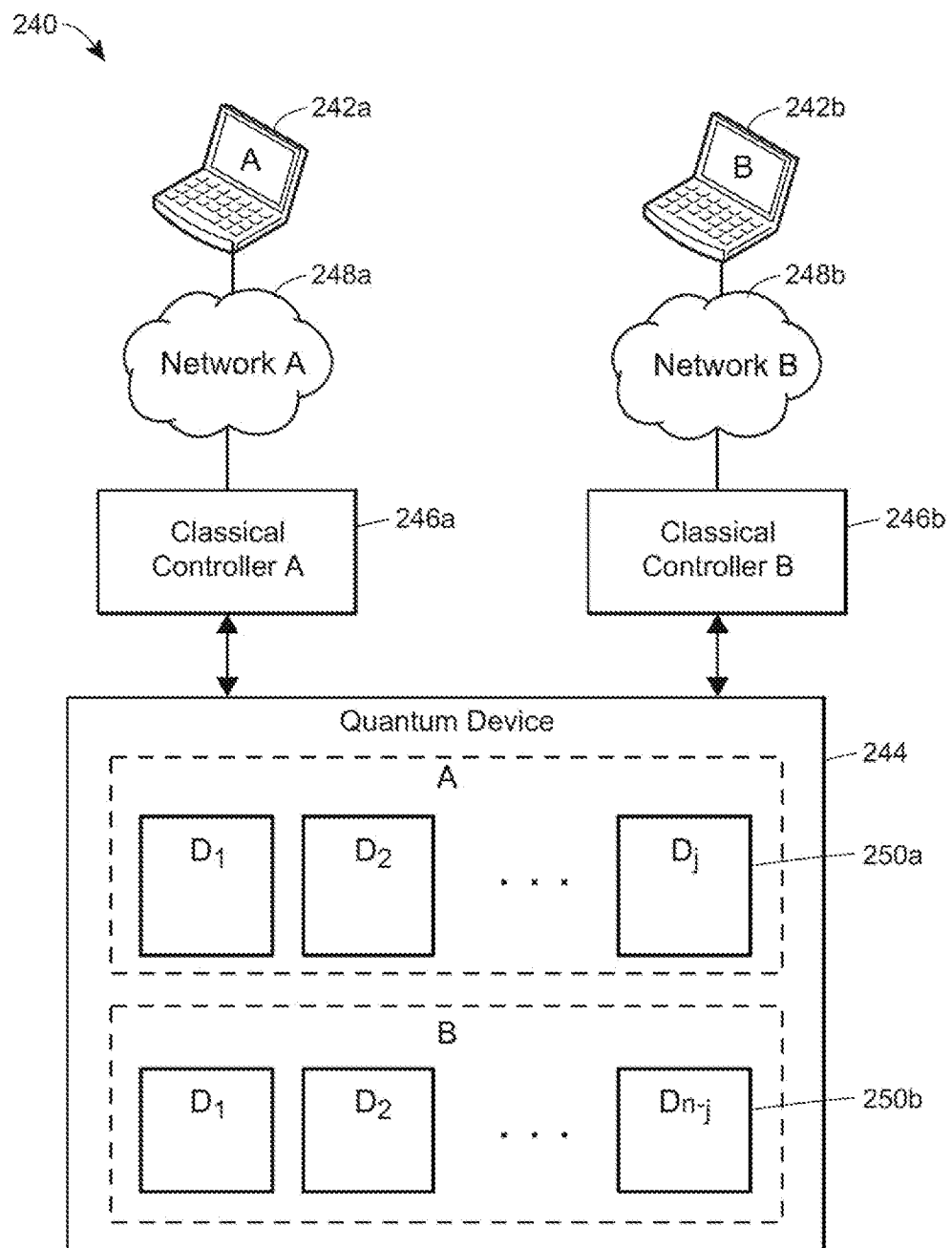


FIG. 2C

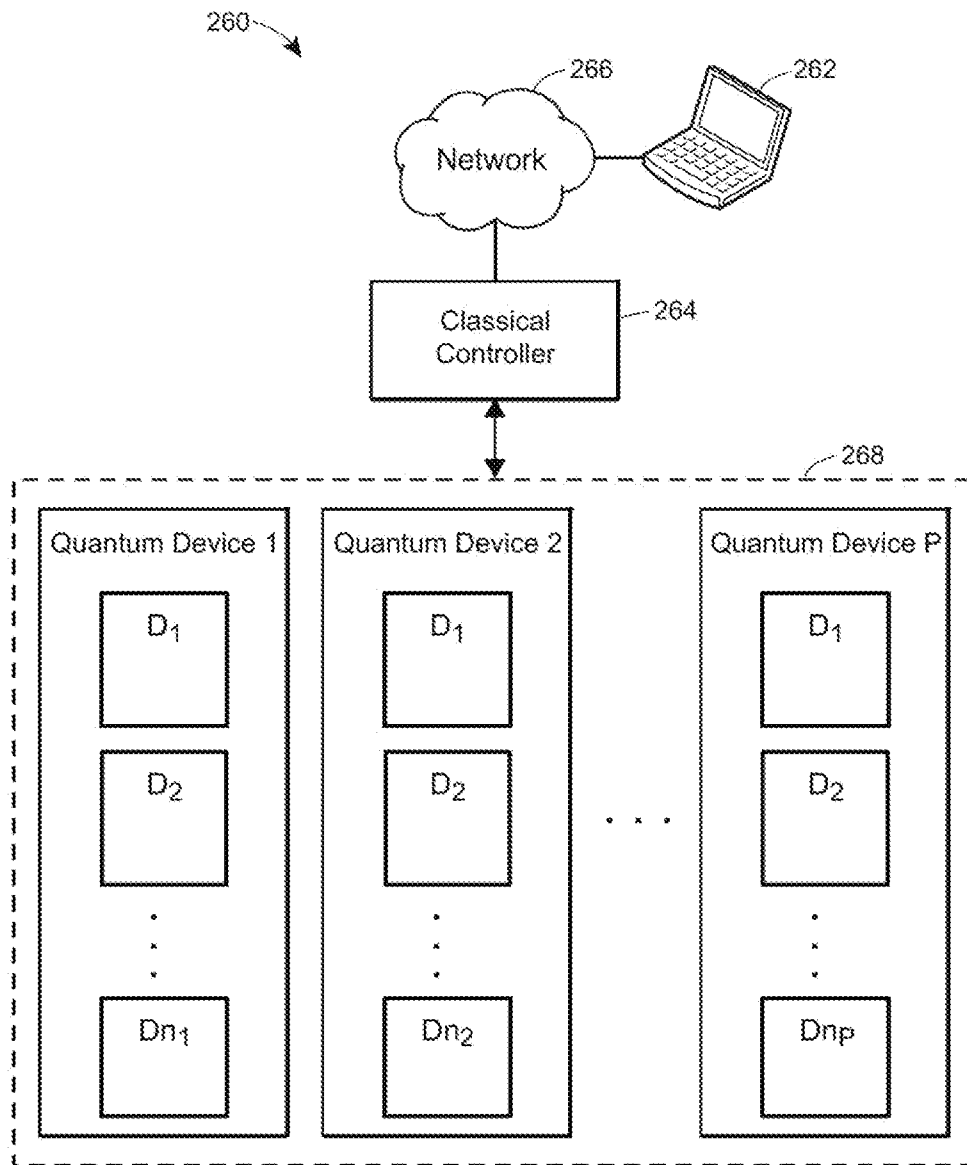


FIG. 2D

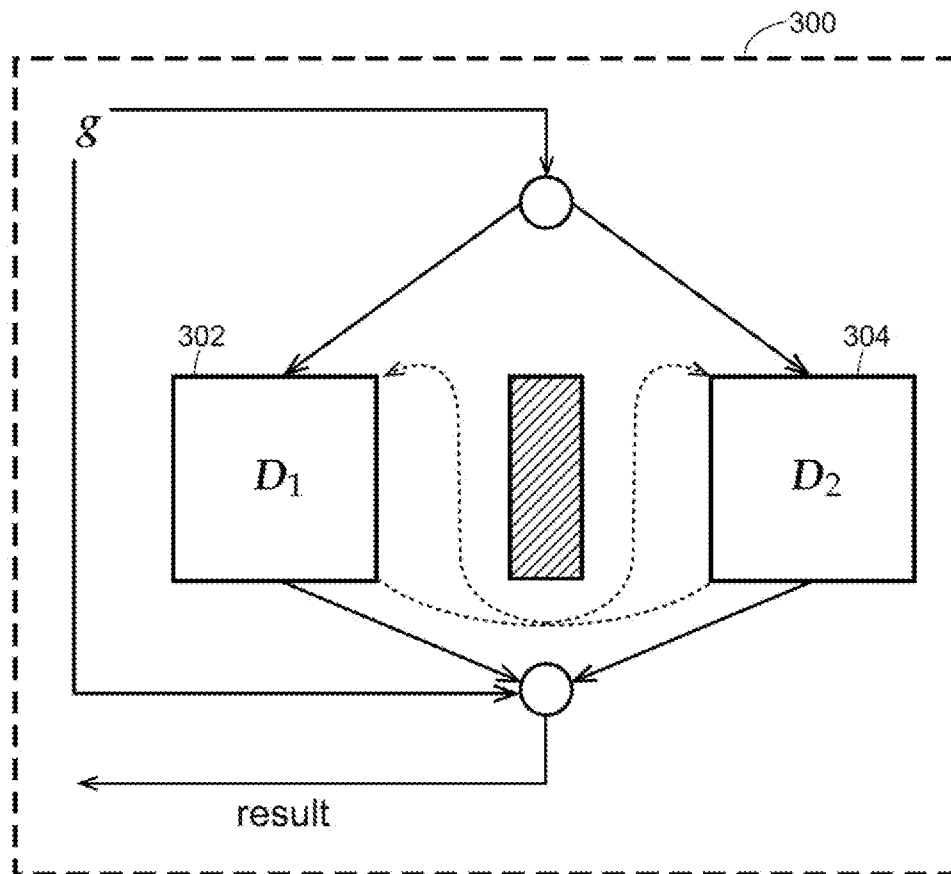
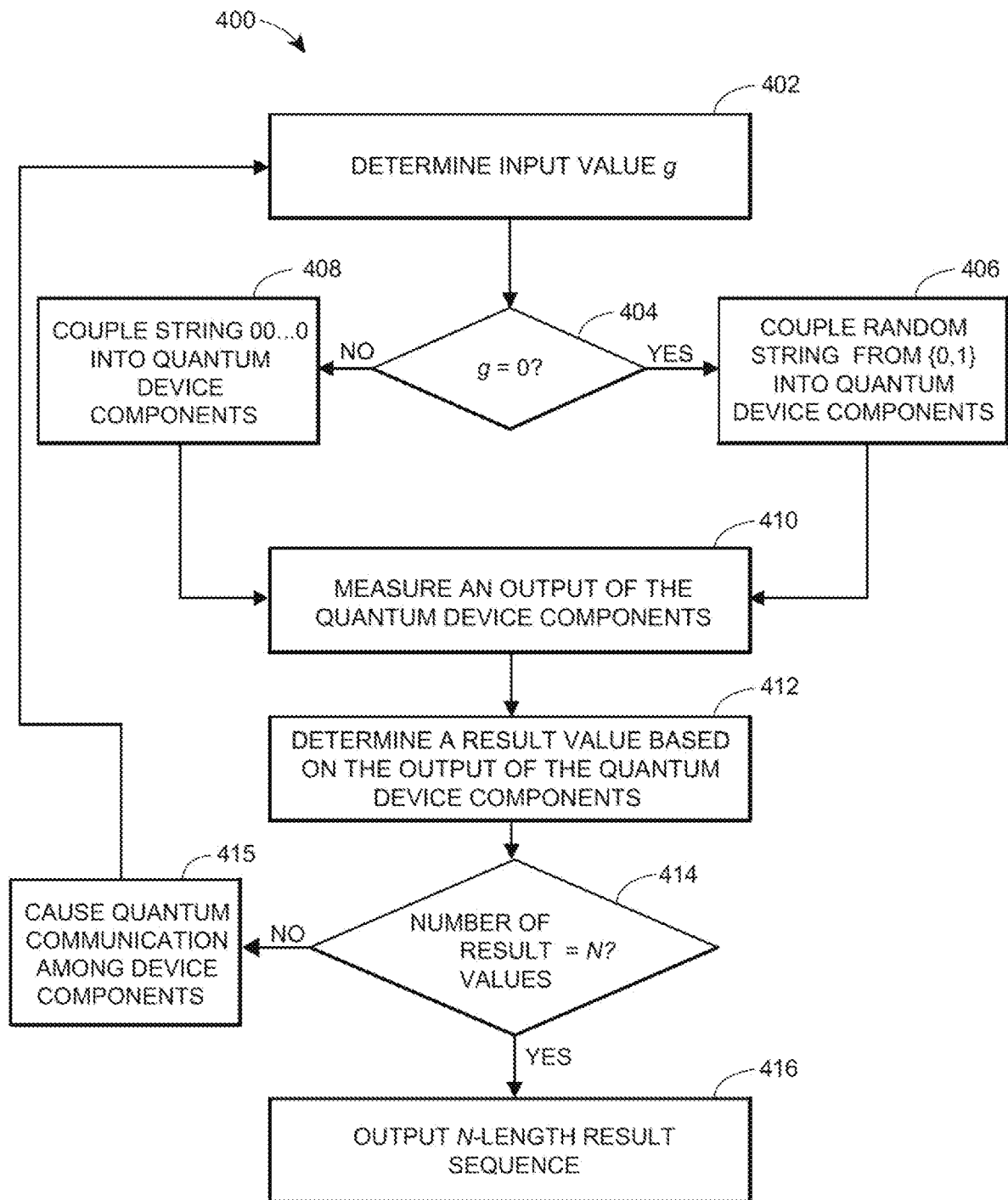
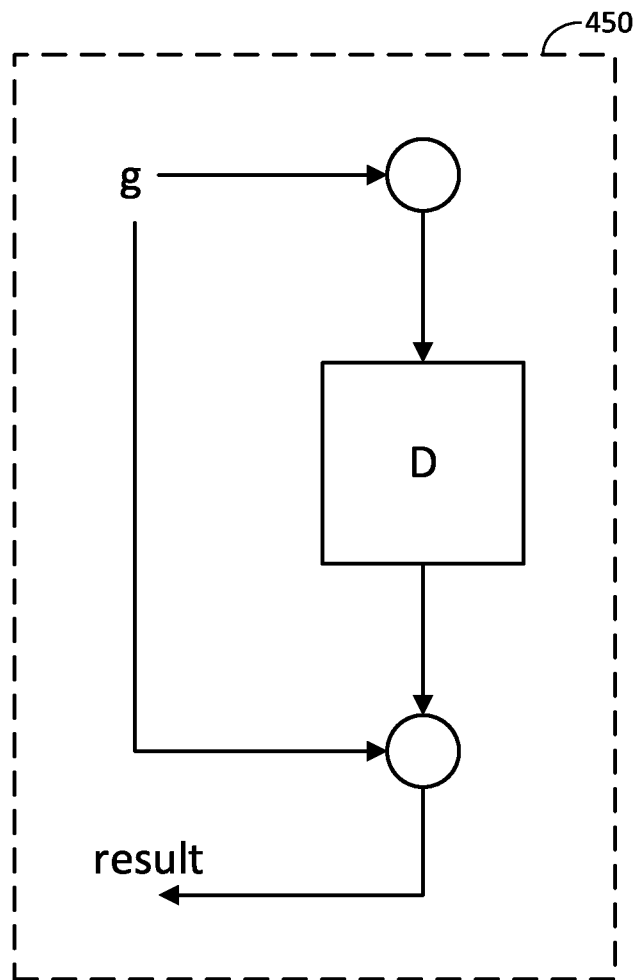


FIG. 3

**FIG. 4**

*FIG. 5*

Arguments:

N : A positive integer (the output length).

m : A positive integer (the number of measurement settings).

χ : A real number from the interval $(0, \frac{1}{2})$. (The failure tolerance.)

q : A real number from the interval $(0, 1)$. (The test probability.)

f : A contextuality game.

D : A contextual measurement device D whose set of contexts contains $\text{Supp } f$.

Protocol K:

1. Choose a bit $g \in \{0, 1\}$ according to the distribution $(1 - q, q)$.
2. If $g = 0$ ("generation round"), then give the context $\{1\}$ to D and record the output bit a .
3. If $g = 1$ ("test round"), then play game f with D . If the score is $+1$, then let $o = 0$. If the score is -1 , then let $o = 1$.
4. Repeat to obtain a sequence of bits $g_1, \dots, g_N$ and $a_1, \dots, a_N$.
5. If

$$\sum_{k=1}^N g_k a_k > \chi q N, \quad (\text{N.2})$$

then the protocol **aborts**. Otherwise, it **succeeds**, and the output is the bit sequence $a_1, \dots, a_N$.

FIG. 6

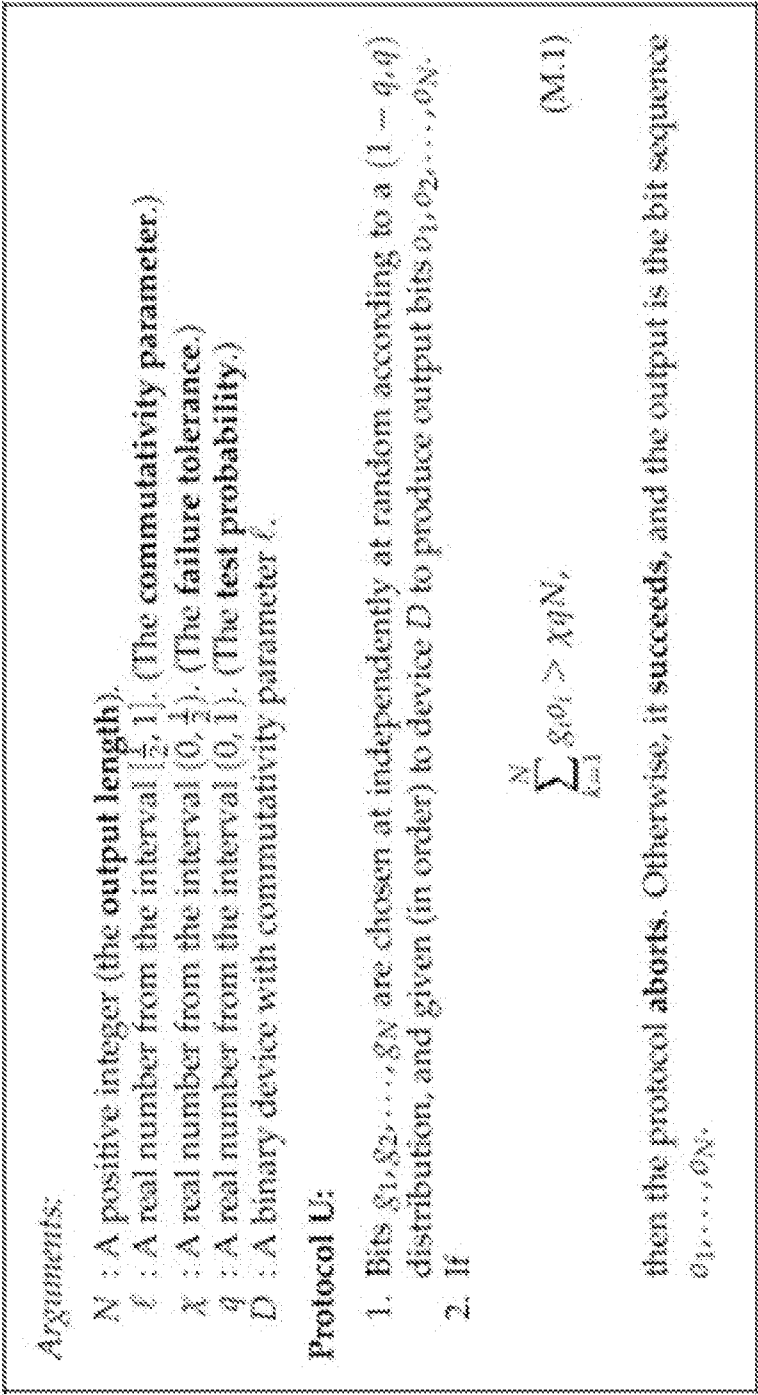


FIG. 7

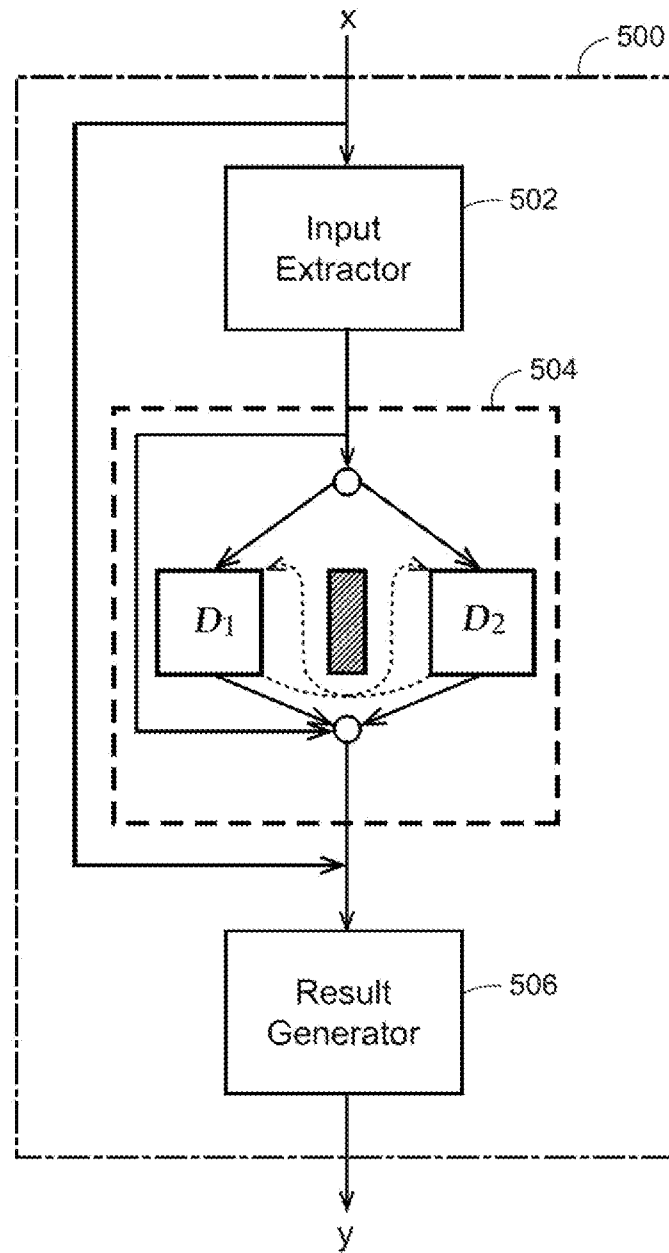


FIG. 8

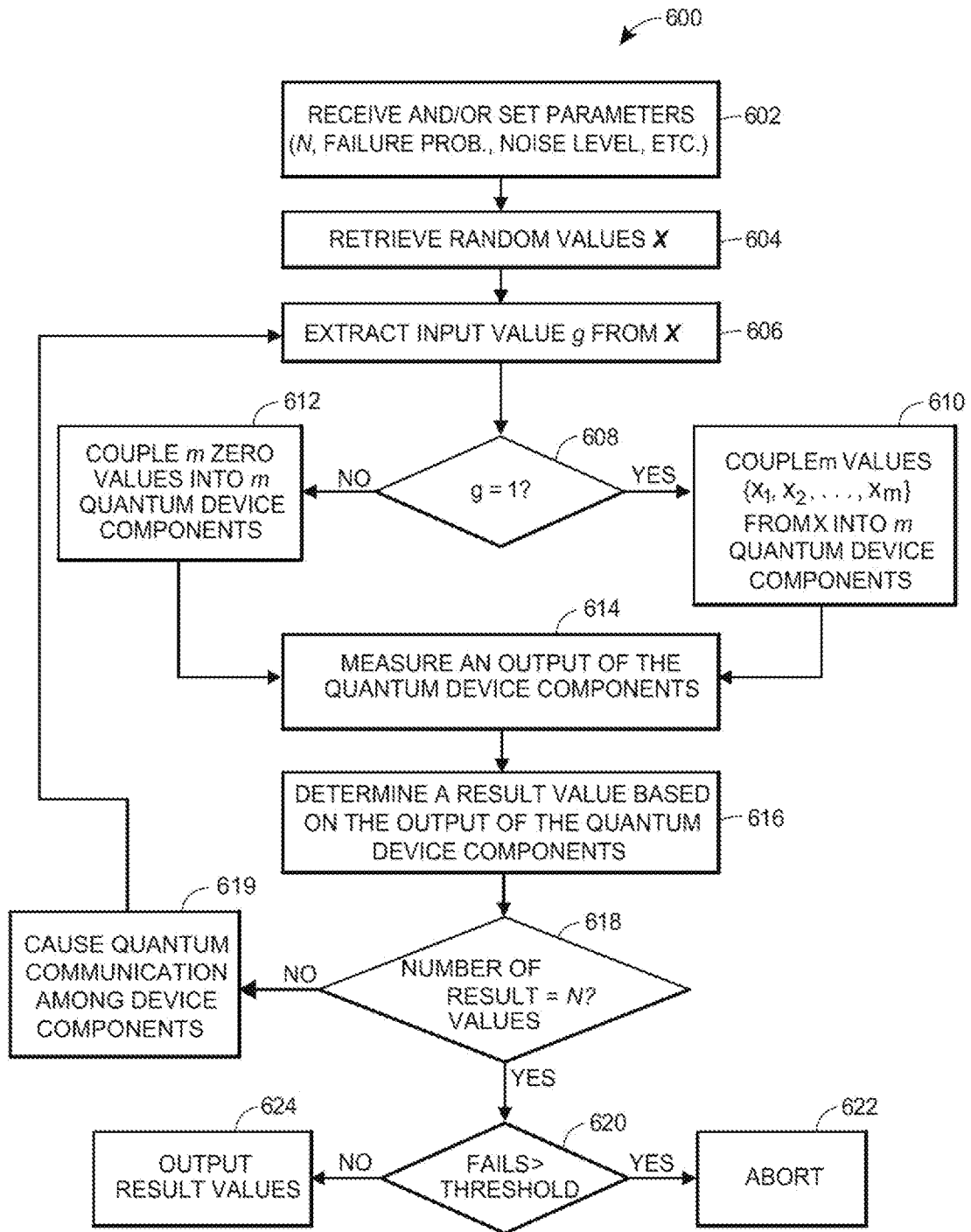


FIG. 9

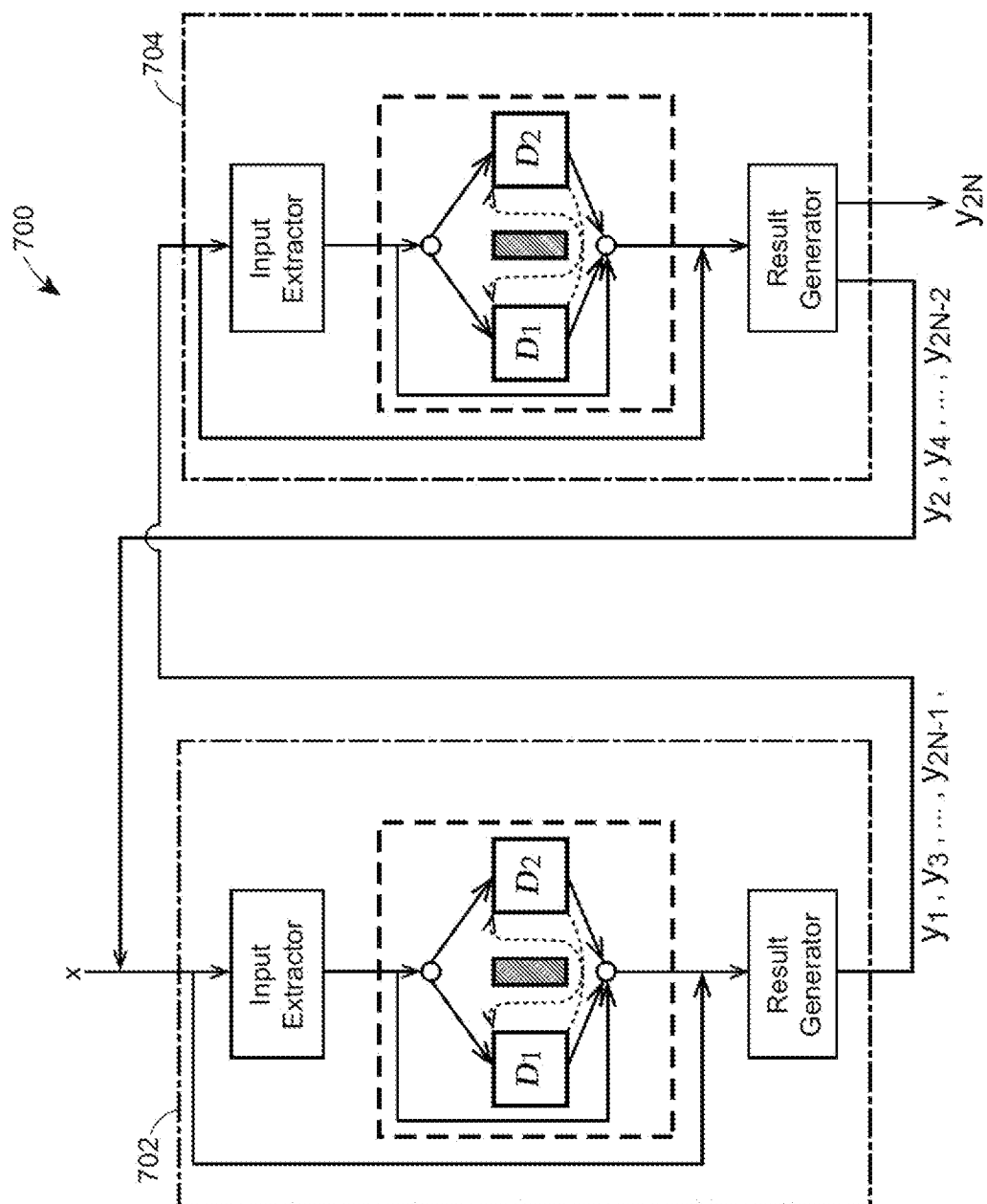


FIG. 10

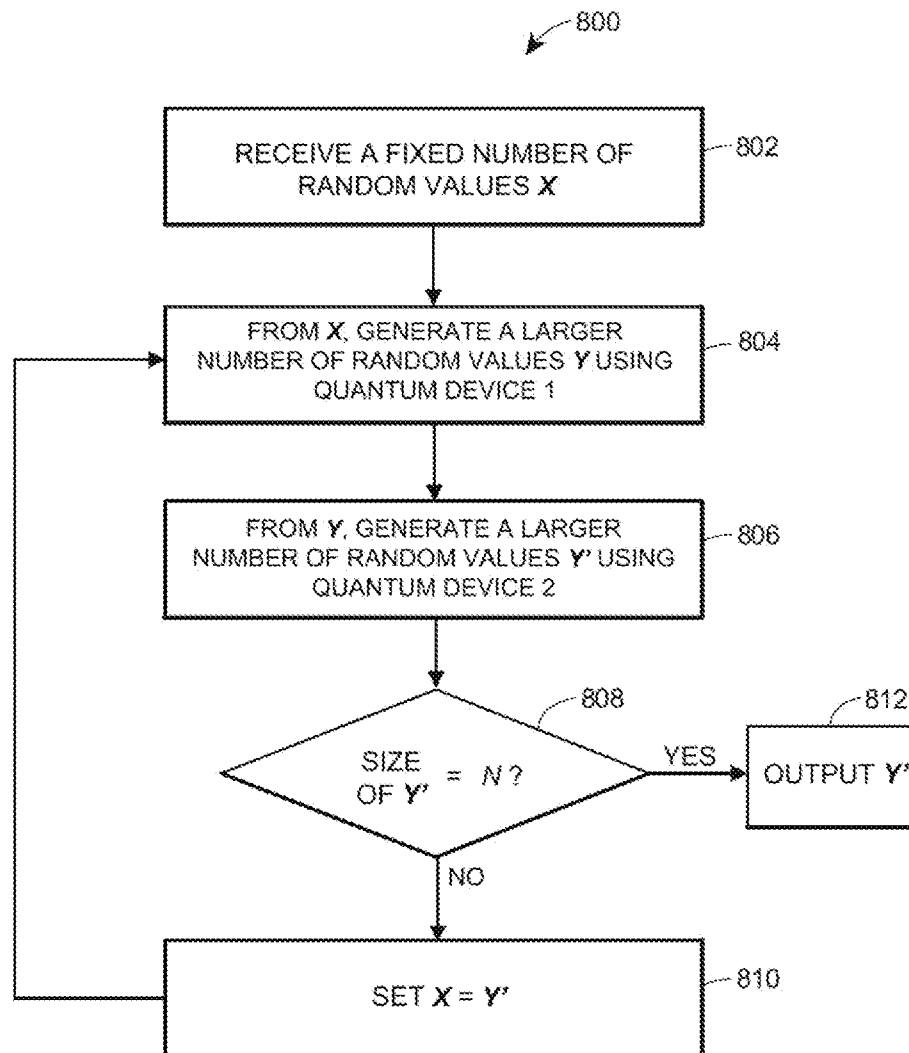


FIG. 11

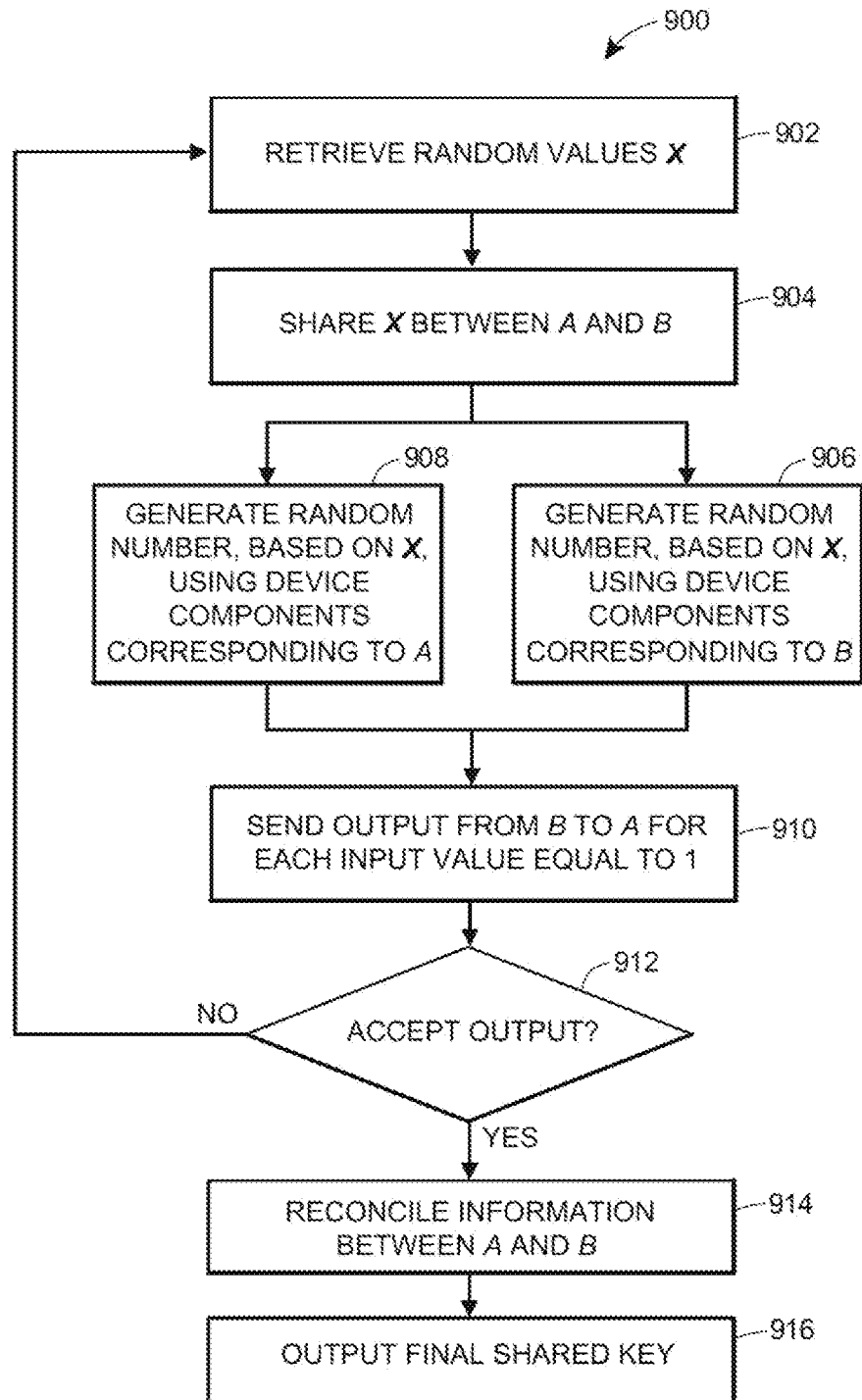


FIG. 12

Protocol A:*Arguments:*

N = positive integer
 $q \in (0, 1)$
 $\eta \in (0, 1/2)$
 D = device with trusted measurements

1. A bit $g \in \{0, 1\}$ is chosen according to a biased $(1 - q, q)$ distribution. The bit g is given to D as input, and an output bit o is recorded.
2. If $g = 1$ and the output given by D is 0, then the event P ("pass") is recorded. If $g = 1$ and the output is 1, the event F ("fail") is recorded.
3. If $g = 0$ and the output given by D is 0, then the event H ("heads") is recorded. If $g = 0$ and the output is 1, the event T ("tails") is recorded.
4. Steps 1 – 3 are repeated $N - 1$ (more) times. Bit sequences $\mathbf{g} = (g_1, \dots, g_N)$ and $\mathbf{o} = (o_1, \dots, o_N)$ are obtained.
5. If the total number of failures is more than $\eta q N$, the protocol **aborts**. Otherwise, the protocol **succeeds**. If the protocol succeeds, it outputs the bit sequences $\mathbf{g}$ and $\mathbf{o}$.

FIG. 13

Protocol A':*Arguments:*

v = real number such that $v \in (0, 1)$,
 h = real number such that $h \in [0, 1 - v]$,
 N = positive integer
 $q \in (0, 1)$
 $\eta \in (0, v/2)$
 D = partially trusted device with parameters (v, h) .

1. A bit $g \in \{0, 1\}$ is chosen according to a biased $(1 - q, q)$ distribution. The bit g is given to D as input, and the output bit o is recorded.
2. If $g = 1$ and the output given by D is 0, then the event P ("pass") is recorded. If $g = 1$ and the output is 1, the event F ("fail") is recorded.
3. If $g = 0$ and the output given by D is 0, then the event H ("heads") is recorded. If $g = 0$ and the output is 1, the event T ("tails") is recorded.
4. Steps 1 – 3 are repeated $N - 1$ (more) times. Bit sequences $\mathbf{g} = (g_1, \dots, g_N)$ and $\mathbf{o} = (o_1, \dots, o_N)$ are obtained.
5. If the total number of failures is greater than $(h/2 + \eta)qN$, then the protocol **aborts**. Otherwise, the protocol **succeeds**. If the protocol succeeds, it outputs the bit sequences $\mathbf{g}$ and $\mathbf{o}$.

FIG. 14

Arguments:

G : An n -player nonlocal game that is a **strong self-test**

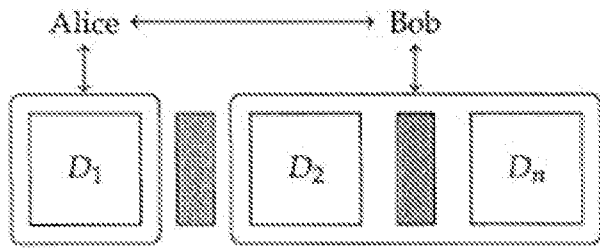
D : An untrusted device (with n components) that can play G repeatedly and cannot receive any additional information. Alice interacts with the first component while Bob interacts the rest of the device. No communication is allowed among the components during Step 1-4 of the protocol. All random bits chosen by Alice and Bob together are assumed to be perfectly random to D .

N : a positive integer (the **output length**.)

λ : A real $\in (0, w_G - 1/2)$. ($1/2 - \lambda$ is the **key error fraction**.)

η : A real $\in (0, \frac{1}{2})$. (The **error tolerance**.)

q : A real $\in (0, 1)$. (The **test probability**.)



A diagram of Protocol $R_{q,d}$.

Protocol:

1. Alice and Bob choose a bit $g \in \{0, 1\}$ according to a biased $(1 - q, q)$ distribution.
2. If $g = 1$ ("game round"), then Alice and Bob choose an input string at random from $\{0, 1\}^n$ according the probability distribution specified by G . They give their part(s) of D the corresponding input bit, exchange their output bits and record a "P" (pass) or an "F" (fail) according to the rules of the game G .
3. If $g = 0$ ("generation round"), then the input string $00 \dots 0$ is given to the device. Alice records the output of her device component in the O register for this round. Bob stores in the B register for this round the unique bit that XOR'ing with the output bit(s) of his device component(s) would constitute a win for the game. That is, their bits are the same if and only if they win the game.
4. Steps 1 – 3 are repeated $N - 1$ (more) times.
5. If the total number of failures is more than $(1 - w_G + \eta)qN$, the protocol **aborts**.
6. If not yet aborted, they run the Efficient Information Reconciliation (EIR) Protocol on the registers O and B with the parameters λ and $\epsilon = \exp(-qN)$. If the EIR Protocol does not abort, the register B is replaced with Bob's guess $\tilde{B}$ of O . The protocol terminates successfully with Alice and Bob's version of the key being their N -length sequence from the alphabet $\{P, F, H, T\}$ representing the outcomes of each round (H and T for 0 and 1, respectively, stored in O and $\tilde{B}$).

FIG. 15