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(54) **SYSTEM AND METHOD FOR REMOTE PROBABILISTIC SECRET KEY DISTRIBUTION**

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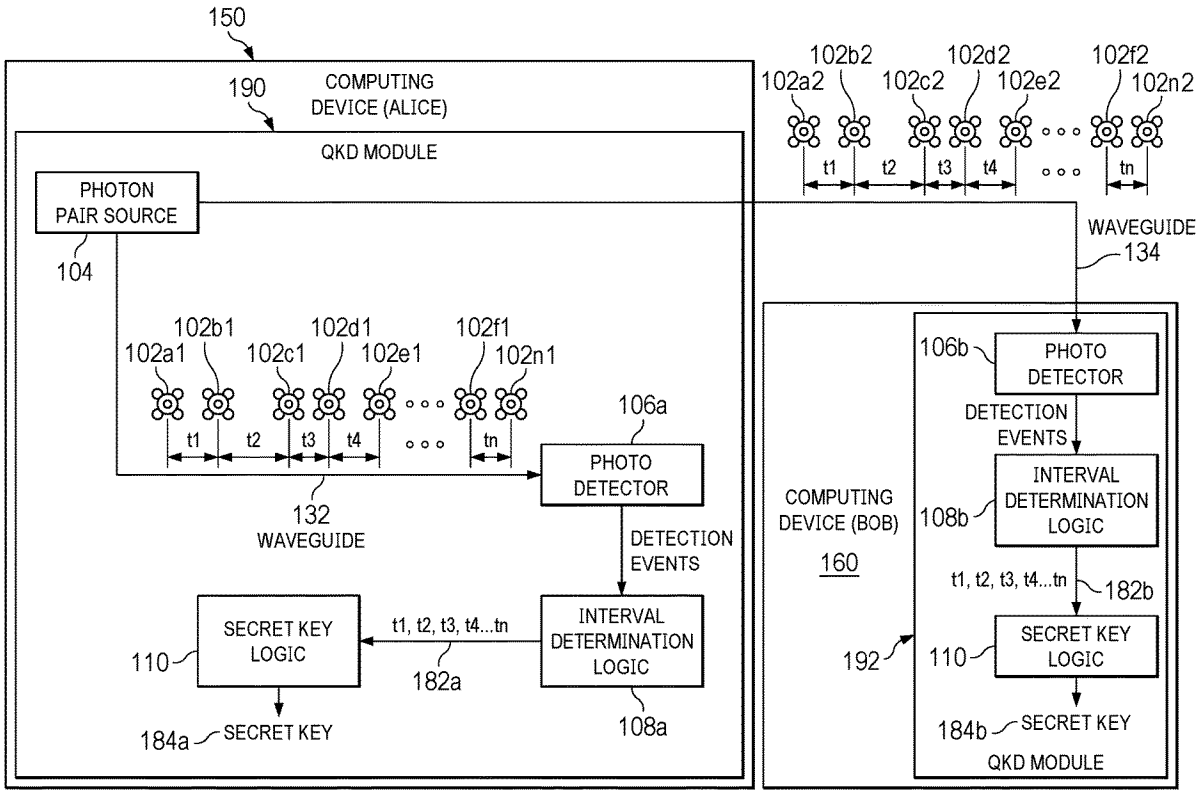
(57) **ABSTRACT**

Embodiments of systems and methods for systems and methods for remote probabilistic secret key distribution that may be utilized for Quantum Key Distribution (QKD) are disclosed. In particular, embodiments of a secret key distribution system as presented herein may utilize an architecture that includes a photonic entropy source. Such a photonic entropy source may be utilized to produce photon sequences at randomly distributed time intervals. Embodiments may utilize this random sequence of time intervals of the production of photons as a source of entropy for provisioning shared secret keys.



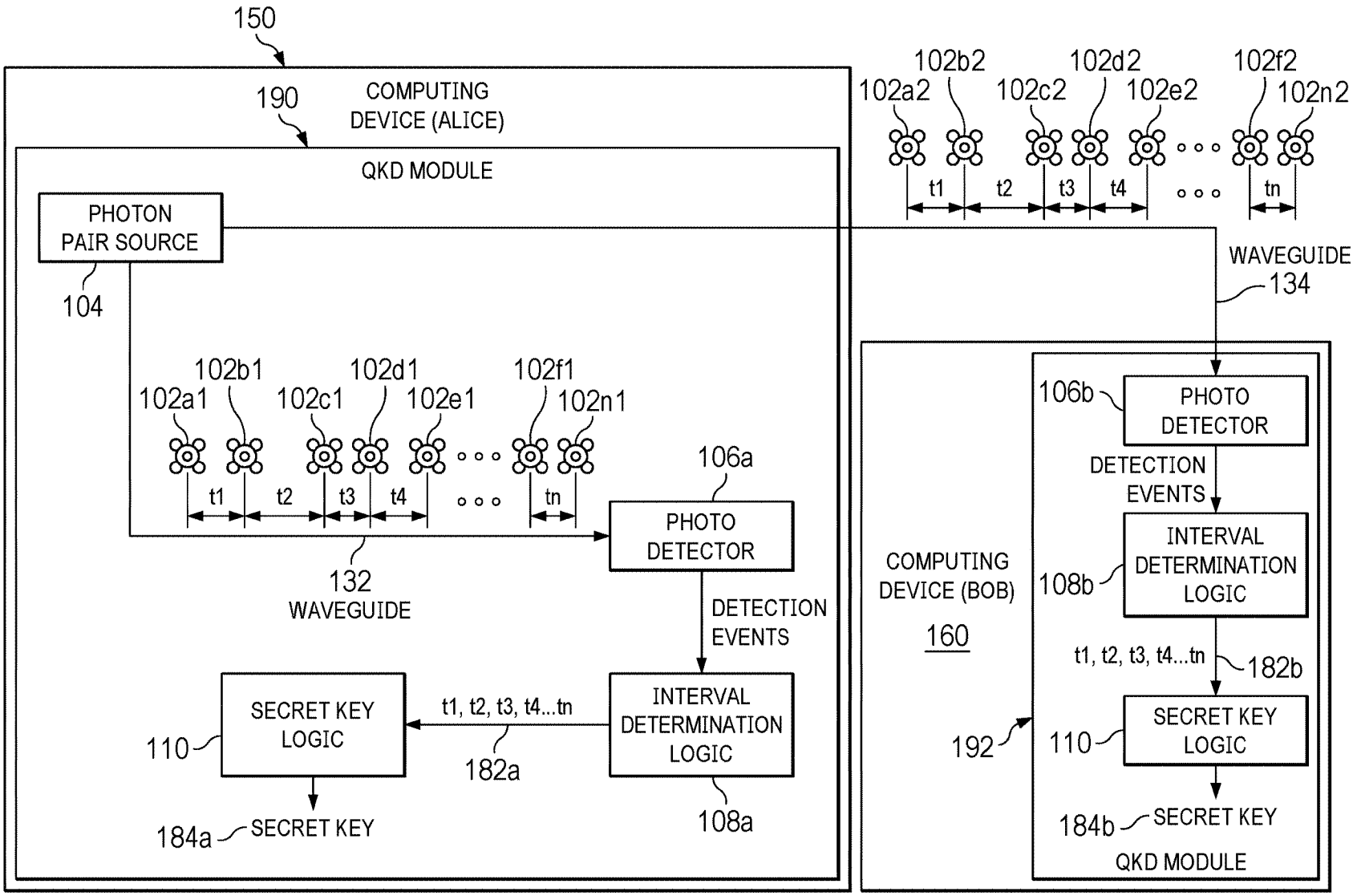

150
190
COMPUTING DEVICE (ALICE)
QKD MODULE
PHOTON PAIR SOURCE
104
102a1
102b1
102c1
102d1
102e1
102f1
102n1
t1
t2
t3
t4
tn
106a
PHOTO DETECTOR
132
WAVEGUIDE
DETECTION EVENTS
INTERVAL DETERMINATION LOGIC
t1, t2, t3, t4...tn
182a
SECRET KEY LOGIC
110
184a
SECRET KEY
108a
102a2
102b2
102c2
102d2
102e2
102f2
102n2
WAVEGUIDE
134
COMPUTING DEVICE (BOB)
160
106b
PHOTO DETECTOR
DETECTION EVENTS
108b
INTERVAL DETERMINATION LOGIC
t1, t2, t3, t4...tn
182b
192
110
SECRET KEY LOGIC
184b
SECRET KEY
QKD MODULE

FIG. 1

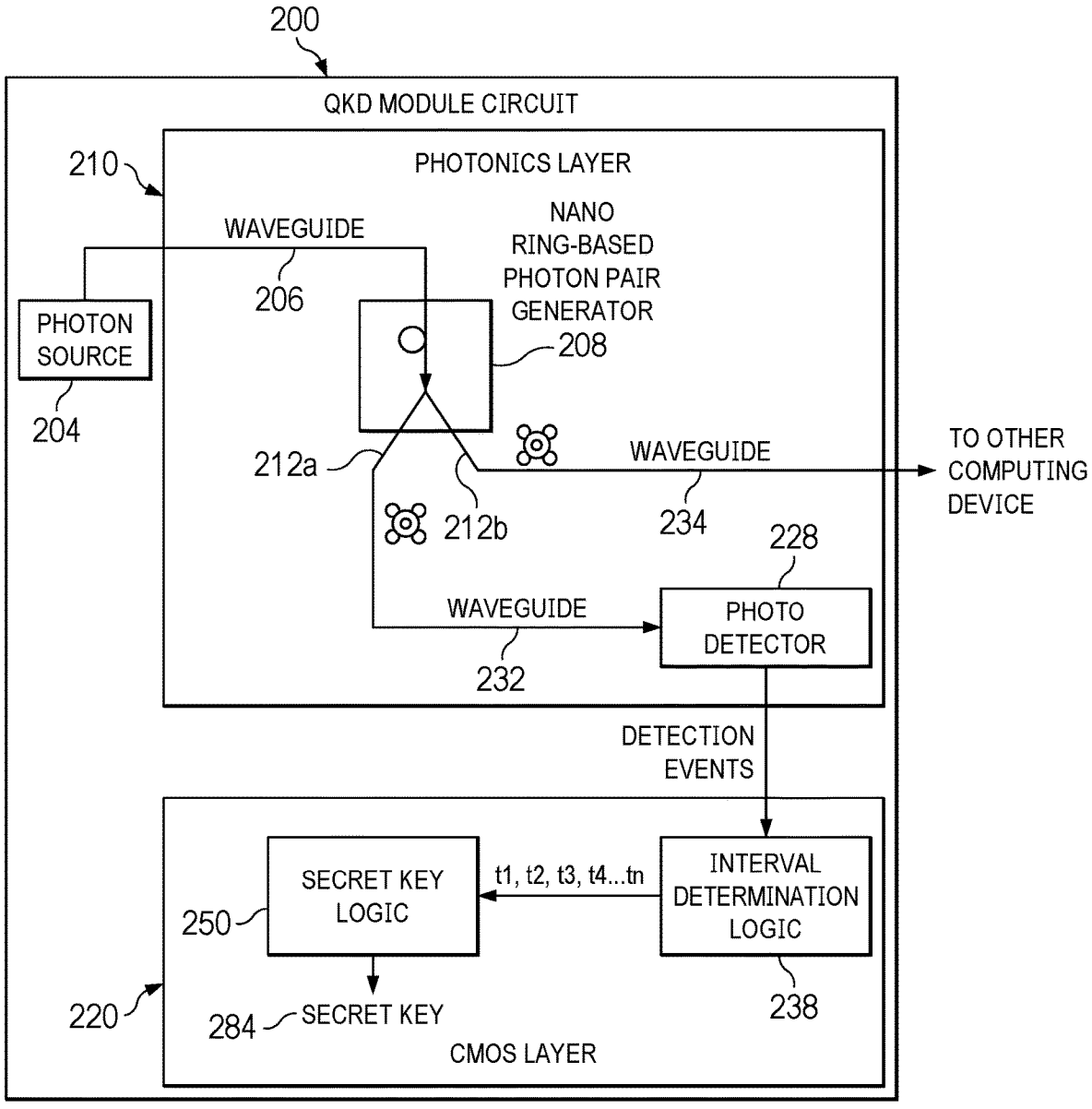

200
QKD MODULE CIRCUIT
210
PHOTONICS LAYER
WAVEGUIDE
206
NANO
RING-BASED
PHOTON PAIR
GENERATOR
208
PHOTON
SOURCE
204
212a
212b
WAVEGUIDE
234
TO OTHER
COMPUTING
DEVICE
228
WAVEGUIDE
232
PHOTO
DETECTOR
DETECTION
EVENTS
SECRET KEY
LOGIC
250
t1, t2, t3, t4...tn
INTERVAL
DETERMINATION
LOGIC
238
220
284
SECRET KEY
CMOS LAYER

FIG. 2

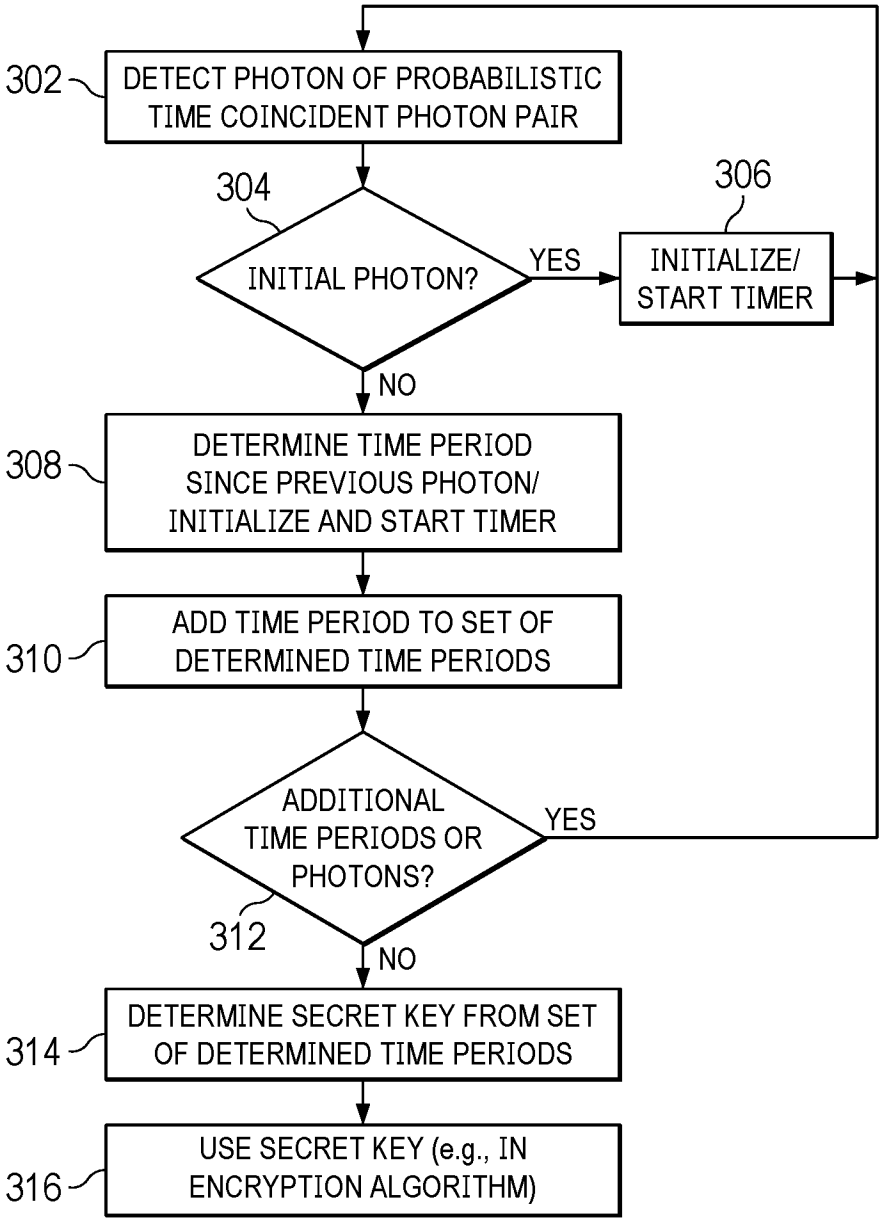

302
DETECT PHOTON OF PROBABILISTIC TIME COINCIDENT PHOTON PAIR
304
INITIAL PHOTON?
YES
306
INITIALIZE/ START TIMER
NO
308
DETERMINE TIME PERIOD SINCE PREVIOUS PHOTON/ INITIALIZE AND START TIMER
310
ADD TIME PERIOD TO SET OF DETERMINED TIME PERIODS
ADDITIONAL TIME PERIODS OR PHOTONS?
YES
312
NO
314
DETERMINE SECRET KEY FROM SET OF DETERMINED TIME PERIODS
316
USE SECRET KEY (e.g., IN ENCRYPTION ALGORITHM)

FIG. 3

SYSTEM AND METHOD FOR REMOTE PROBABILISTIC SECRET KEY DISTRIBUTION

RELATED APPLICATIONS

[0001] This application claims a benefit of priority under 35 U.S.C. § 119 to U.S. Provisional Patent Application No. 63/489,617 filed Mar. 10, 2023, entitled "System and Method For Remote Probabilistic Secret Key Distribution", by Mitchell A. Thornton and William V. Oxford, which is hereby fully incorporated by reference in its entirety.

TECHNICAL FIELD

[0002] This disclosure relates generally to provisioning secret keys shared between devices. In particular, this disclosure relates to quantum photonic key distribution. Even more specifically, this disclosure related to embodiments of multi-source, extractor based, provisioning of shared secret keys between devices.

BACKGROUND

[0003] Quantum Key Distribution (QKD) is a revolutionary cryptographic technique that uses principles of quantum mechanics to securely distribute a value that can be utilized as the basis of a shared secret (also referred to interchangeably as a shared key, secret key or shared secret key) between computing devices (or applications executing thereon). The most common application of QKD is in the generation and distribution of cryptographic keys for secure communication between such computing devices. For example, QKD can be utilized for secure communication in scenarios where the confidentiality of information is critical, such as in secure government communications or financial transactions.

[0004] QKD relies on the principles of quantum mechanics, particularly the behavior of quantum particles like photons. In QKD the quantum particles (e.g., individual photons) are typically used as quantum bits to carry information. To illustrate in more detail, a QKD process involves the exchange or measurement of quantum states between two parties, often referred to as Alice and Bob. In a typical QKD process, Alice sends a series of encoded photons to Bob, and they both measure the polarization states of these photons in order to accomplish the transfer of confidential data between Alice & Bob.

[0005] Bob randomly measures the polarization states of the received photons and communicates the basis used for each measurement to Alice. Alice then informs Bob of the correct basis to use for each measurement. Both parties discard measurements made with the wrong basis, keeping only the measurements made with the correct basis. These measurements of the polarization states can then be used as a basis for a secret key that is shared between Alice and Bob. This secret key can then be used with an encryption algorithm to encrypt and decrypt data between Alice and Bob.

[0006] By leveraging the principles of quantum mechanics to enable the secure exchange of cryptographic keys, QKD offers a level of security that is theoretically impossible to achieve using classical cryptographic methods. Namely, QKD provides information-theoretic security, meaning the security is based on fundamental principles of physics, not on the computational difficulty of solving a mathematical problem. Moreover, detection of eavesdropping attempts is possible due to the principles of quantum mechanics. For example, any attempt by an eavesdropper (Eve) to intercept the quantum states of the photons passing between Alice and Bob (and thus deriving the secret key) will be detectable, as the very act of measuring the quantum states of the photons passing between Alice and Bod would disturb the quantum states of those photons.

[0007] While QKD is thus useful and powerful, there are certain problems with QKD. Many of these have to do with the complexity of implementation. In particular, most QKD is dependent on measurement of the quantum state of a quantum information carrier (e.g., in a preparation and measurement based protocol or an entanglement based protocol). Thus, the implementation of such QKD systems may be quite hardware or processor intensive, among other drawbacks.

[0008] What is desired are simpler systems and methods for implementing QKD.

SUMMARY

[0009] To address these needs, among others, attention is directed to embodiments of systems and methods for remote probabilistic secret key distribution that may be utilized for Quantum Key Distribution (QKD). In particular, embodiments of a secret key distribution system as presented herein may utilize an architecture that includes a photonic entropy source where a source of physical entropy may be derived from the quantum photonic source. Such a quantum photonic source may be utilized to produce photon sequences at randomly distributed time intervals (e.g., as well as random superimposed quantum states in some cases). Thus, a random sequence of time intervals of the production of photons, and the randomness present in measurements of a superimposed quantum state based on those photons, may be utilized as simultaneous, but independent, sources of entropy for provisioning shared secret keys. Such a superimposed quantum state may be created, for example, by passing the photon or some other quantum information carrier through a quantum logic gate such as a Hadamard gate or Chrestenson gate.

[0010] Another possible source of entropy can be generated by pairs of photons created in the photon pair generator and generated via the Four Wave Mixing (FWM) or a Spontaneous Parametric Down Conversion (SPDC) process. In one embodiment, for example, a photon pair generator may include a laser adapted to excite a spontaneous parametric down conversion (SPDC) device to generate a heralded single photon source in the form of a signal and idler (also referred to as a trigger) photon pair.

[0011] A photon pair generator (e.g., a single photon source used to provide a signal and idler photon pair) may thus be used to produce pairs of photons that are time coincident (e.g., are produced, or emitted, at the same time). These photons may also be produced in a probabilistic manner (e.g., non-consistent). In embodiments, for each pair of photons produced by the photon pair generator, one photon (e.g., the signal or idler) of the photon pair may be provided to a first location (e.g., in one embodiment kept locally on the system including the photon pair source, such as on a chip, circuit or device), while the other photon of the photon pair (e.g., the signal or idler photon) generated by the photon pair generator may be sent to a remote channel or location (e.g., to another system or device, or another portion of the chip, circuit or device, etc.).

[0012] According to one embodiment then, each production of a photon pair from a photon pair source may result in a (e.g., random) duration that can be determined from measuring the time interval between the production of a detected photon and the detection of a previously detected photon. After some number of (e.g., N) photons are produced by the photon pair source, a set of (e.g., N) time intervals determined from measuring the time intervals between the production of these photons may be determined at both locations. This set of time intervals may thus be a set of (e.g., N) random values that may be the same at both locations that may be used as the basis for determining a secret that can be shared by these locations.

[0013] To illustrate in more detail, at each location the successive time intervals between each of the respective photons may be measured. Such a determination may be made, for example, by providing a waveguide for conducting such a photon from the photon pair source to a photodetector at each location that is coupled to a clock circuit or counter, etc. For example, the idler photon of the photon pair produced by a photon pair generator may be kept locally such that time intervals between successive idler photons produced by the photon pair generator may be measured locally to produce a local series of time intervals based on the idler photons produced by the photon pair generator. Similarly, the signal photon of the photon pair produced by a photon pair generator may be sent to the remote location such that time intervals between successive signal photons produced by the photon pair generator may be measured at the remote location to produce a remote series of time intervals based on the signal photons produced by the photon pair generator.

[0014] As each pair of photons produced by the photon pair generator may be produced at substantially the same time, the local series of time intervals and remote series of time intervals based on measuring the time intervals between successive photons of different ones of the pairs of photons produced by the same photon pair generator should be substantially equivalent. Thus, the local series of time intervals or remote series of time intervals can be utilized as a shared secret or key (again, used interchangeably) between the local and remote location, or utilized as a basis to derive a shared secret or key at the local and remote location. This shared secret can then be used in cryptographic algorithms or the like to secure data passing between the two locations.

[0015] Accordingly, embodiments may provide a remote shared secret or key provisioning mechanism based on generation and distribution of time synchronized photon pairs and specifically, for using photon pair production intervals as a basis for establishing a series of time periods (e.g., intervals) for secret key provisioning on different devices (or different areas of the same device, etc.). These shared secrets or keys can be verified in a variety of ways such as checking portions of the time periods, checking a hash created with the set of time periods or a hash created with the secret key, etc.

[0016] Embodiments of such key distribution systems may be implemented, for example, on a hybrid integrated circuit containing both photonic and digital processing where the key determination functions are implemented either within an on-chip circuitry such as in digital logic or in or embedded electronic processor core or by some other combination of hardware and software.

[0017] Embodiments as presented herein thus may allow the sharing of a secret key using simpler methodologies based on the detection of photons and the time intervals between such photons, allowing the distribution of a key based on quantum properties without actual measurement of the quantum state of a quantum information carrier.

[0018] These, and other, aspects of the disclosure will be better appreciated and understood when considered in conjunction with the following description and the accompanying drawings. It should be understood, however, that the following description, while indicating various embodiments of the disclosure and numerous specific details thereof, is given by way of illustration and not of limitation. Many substitutions, modifications, additions and/or rearrangements may be made within the scope of the disclosure without departing from the spirit thereof, and the disclosure includes all such substitutions, modifications, additions and/or rearrangements.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The drawings accompanying and forming part of this specification are included to depict certain aspects of the disclosure. It should be noted that the features illustrated in the drawings are not necessarily drawn to scale. A more complete understanding of the disclosure and the advantages thereof may be acquired by referring to the following description, taken in conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

[0020] FIG. **1** is a block diagram of an architecture for a Quantum Key Distribution (QKD) system according to embodiments.

[0021] FIG. **2** is a block diagram of a specific implementation of an embodiment of a QKD computing device.

[0022] FIG. **3** is a flow diagram of one embodiment of a method for QKD.

DETAILED DESCRIPTION

[0023] The disclosure and the various features and advantageous details thereof are explained more fully with reference to the non-limiting embodiments that are illustrated in the accompanying drawings and detailed in the following description. Descriptions of well-known starting materials, processing techniques, components and equipment are omitted so as not to unnecessarily obscure the invention in detail. It should be understood, however, that the detailed description and the specific examples, while indicating some embodiments of the invention, are given by way of illustration only and not by way of limitation. Various substitutions, modifications, additions and/or rearrangements within the spirit and/or scope of the underlying inventive concept will become apparent to those skilled in the art from this disclosure.

[0024] Before discussing embodiments in more detail, it may be helpful to give a general overview of certain aspects pertaining to embodiments. As discussed, Quantum Key Distribution (QKD) is a mechanism that uses principles of quantum mechanics to securely distribute a value (such as a set of bit values) that can be utilized as a shared secret between computing devices (or applications executing thereon). This shared key can then be used as the basis for the implementation of cryptographic security measures (e.g., encryption of data passing between the devices). QKD is

therefore extremely useful in a high security environment. Namely, by leveraging quantum mechanics to securely exchange cryptographic keys, QKD offers a level of security that is theoretically impossible to achieve using classical cryptographic methods. Moreover, detection of eavesdropping attempts is possible due to these same quantum principles. The implementation of QKD can, however, be complex. It is thus desired to simplify the implementation of QKD systems and methods.

[0025] Embodiments may therefore provide simplified systems and methods for remote probabilistic secret key distribution that may be utilized for QKD. In particular, embodiments of a secret key distribution system as presented herein may utilize an architecture that includes a photonic entropy source including a photon pair generator to produce pairs of photons that are time coincident (e.g., are produced, or emitted, at the same time), where those pairs of photons are produced in a probabilistic manner (e.g., non-consistently produced) such that the time interval between the production of pairs of photons is random.

[0026] According to embodiments, for each pair of photons produced by the photon pair generator, one photon (e.g., the signal or idler) of the photon pair may be provided to a first location (e.g., in one embodiment kept locally on the system including the photon pair source, such as on a chip, circuit or device), while the other photon of the photon pair (e.g., the signal or idler photon) generated by the photon pair generator may be sent to a remote channel or location (e.g., to another system or device, or another portion of the chip, circuit or device, etc.).

[0027] According to one embodiment then, each production of a photon pair from a photon pair source may result in a (e.g., random) duration that can be determined from measuring the time interval between the production of a detected photon and the detection of a previously detected photon. After some number of (e.g., N) photons are produced by the photon pair source, a set of (e.g., N) time intervals determined from measuring the time intervals between the production of these photons may be determined at both locations. This set of time intervals may thus be a set of (e.g., N) random values that may be the same at both locations that may be used as the basis for determining a secret that can be shared by these locations.

[0028] To illustrate in more detail, at each location the successive time intervals between each of the respective photons may be measured. Such a determination may be made, for example, by providing a waveguide for conducting such a photon from the photon pair source to a photodetector at each location that is coupled to a clock circuit or counter, etc. For example, the idler photon of the photon pair produced by a photon pair generator may be kept locally such that time intervals between successive idler photons produced by the photon pair generator may be measured locally to produce a local series of time intervals based on the idler photons produced by the photon pair generator. Similarly, the signal photon of the photon pair produced by the photon pair generator may be sent to a remote location such that time intervals between successive signal photons produced by the photon pair generator may be measured at the remote location to produce a remote series of time intervals based on the signal photons produced by the photon pair generator.

[0029] As each pair of photons produced by the photon pair generator may be produced at substantially the same time, the local series of time intervals and remote series of time intervals based on measuring the time intervals between successive photons of different ones of the pairs of photons produced by the same photon pair generator should be substantially equivalent. Thus, the local series of time intervals and remote series of time intervals can be utilized as a shared secret between the local and remote location, or utilized as a basis to derive a shared secret at the local and remote location. This shared secret can then be used as the basis for the implementation of cryptographic security measures to, for example, secure data passing between the local and remote locations (e.g., for encryption of data passing between the devices).

[0030] Turning now to FIG. **1**, a block diagram of one embodiment of a QKD system that utilizes time intervals between the production of pairs of photons to distribute a secret key between computing devices is depicted. Each computing device **150**, **160** includes a respective QKD module **190**, **192** for determining a shared secret between the computing devices **150**, **160**. QKD module **190** at one computing device **150** (e.g., referred to herein as Alice's computing device without loss of generality) may include a photon pair source **104**. In one embodiment, a photon pair source **104** may include a laser exciting a spontaneous parametric down conversion (SPDC) device to generate a heralded single photon in the form of a signal and idler photon pair. For example, a photon pair source **104** may be comprised of a pulsed laser source with, for example, wavelength 405 nm serving as a pump and a rotatable half-wave plate (HWP) for adjusting the angle of linear polarization of the pump photon with the optical axis of the SPDC. The down-converted signal and idler photons are at, for example, 810 nm wavelength.

[0031] One output of photon pair source **104** (e.g., the output for the idler photon) is coupled to photodetector **106***a* at Alice's computing device **150** through waveguide **132** (e.g., an optic fiber or the like), while the other output of photon pair source **104** (e.g., the output for the signal photon) is coupled to photodetector **106***b* of QKD module **192** at Bob's computing device **160** through waveguide **134**. These photodetectors **106** can be, for example, single photon avalanche diodes (SPADs). Thus, one photon **102** (e.g., **102***a***1**) of a photon pair **102***a*-**120***n* (e.g., **102***a*) emitted by photon pair source **104** (e.g., the idler photon) is conducted on waveguide **132** to (local) photodetector **106***a* at Alice's computing device **150**, whereas the other photon **102** (e.g., **102***a***2**) of the photon pair **102***a*-**120***n* (e.g., **102***a*) produced by the photon pair source **104** (e.g., the signal photon) is conducted on waveguide **134** to photodetector **106***b* at Bob's computing device **160**.

[0032] Photodetector **106***a* at Alice's computing device **150** is adapted to detect the presence of (e.g., a single) photon **102** on waveguide **132** and output a detection event to interval determination logic **108***a* of QKD module **190**. Similarly, photodetector **106***b* at Bob's computing device **160** is adapted to detect the presence of (e.g., a single) photon **102** on waveguide **134** and output a detection event to interval determination logic **108***b* of QKD module **192**. Interval determination logic **108** (which may be, or include, a clock circuit, counter, or the like) may be adapted to determine a time period (value) reflective of a time interval between reception of detection events from photodetector **106**. The reception of a detection event at interval determination logic **108** may serve to reset or (re)start such interval

determination logic **108**, and to cause an output of any previously determined time period (e.g., a time period determined between reception of a previous detection event and the current detection event) to secret key logic **110**.

[0033] Secret key logic **110** of QKD modules **190**, **192** may thus be adapted to receive (e.g., and store) one or more time periods received from interval determination logic **108** and use this set of received time intervals to generate a secret key (value) **184**. For example, secret key logic **110** may be configured to determine a secret key **184** (e.g., after reset or initialization, etc.) when a certain number of time intervals have been received or when a certain number of photons **102** have been detected by photo detector **106**. This number of time intervals of photons **102** may, for example, be configurable. The secret key **184** may be, for example, the time periods (t**1**-tn) themselves or a value derived from time periods (t**1**-tn).

[0034] In operation then, photon pair source **104** of QKD module **190** at Alice's computing device **150** may be caused to generate a number of photon pairs (**102***a*-**102***n*). The number of photon pairs (**102***a*-**102***n*) generated may be configurable such that both QKD module **190** at Alice's computing device **150** and QKD module **192** at Bob's computing device **160** are aware of the number. As discussed, photons **102** (e.g., **102***a***1**, **102***a***2**) of each photon pair (**102***a*-**102***n*) (e.g., pair **102***a*) are time coincident (e.g., are produced, or emitted, by photon source **104** at the same time), where those pairs (**102***a*-**102***n*) of photons **102** are produced in a probabilistic manner (e.g., non-consistently produced) such that the time interval between the production of pairs (**102***a*-**102***n*) of photons **102** is random. Thus, the time intervals (t**1**-tn) between successive (e.g., idler or signal) photons **102** (of each photon pair **102***a*-**102***n*) may be different and random.

[0035] As each (e.g., idler) photon **102***a***1**-**102***n***1** of each produced photon pair (**102***a*-**102***n*) is received (e.g., detected) at the photodetector **106***a* of Alice's computing device **150** over waveguide **132**, detection events are generated by photodetector **106***a* and provided to interval determination logic **108***a*. Interval determination logic **108***a* at Alice's computing device **150** may thus output a set **182***a* of time periods (t**1**-tn) based on the determined time periods between reception of detection events for (e.g., idler) photons **102***a***1**-**102***n***1** of photon pairs (**102***a*-**102***n*) at photodetector **106***a*.

[0036] In the same manner, as each (e.g., signal) photon **10***a***2**-**102***n***2** of each produced photon pair (**102***a*-**102***n*) is received at the photodetector **106***b* of Bob's computing device **160** over waveguide **134**, detection events are generated by photodetector **106***b* and provided to interval determination logic **108***b*. Interval determination logic **108***b* at Bob's computing device **160** may thus output a set **182***b* of time periods (t**1**-tn) based on the determined time periods between reception of (e.g., signal) photons **102***a***2**-**102***n***2** of photon pairs (**102***a*-**102***n*) at photodetector **106***b*.

[0037] Because photons **102** of each photons pair (**102***a*-**102***n*) are time coincident, as discussed, the set **182***a* of time periods (t**1**-tn) determined at Alice's computing device **150** will be the same as the set **182***b* of time periods (t**1**-tn) determined at Bob's computing device **160**. Accordingly, as secret key logic **110** may be the same or similar at Alice's computing device **150** and Bob's computing device **160**, and may determine a secret key based on the same set **182** of time periods (t**1**-tn) (e.g., time periods having the same value), the secret key **184***a* determined at Alice's computing device **150** may be the same as the secret key **184***b* determined at Bob's computing device **160**. This secret key **184** can thus be used as the basis for the implementation of cryptographic security measures implemented on Alice's computing device **150** and Bob's computing device **160** (e.g., encryption of data passing between Alice's computing device **150** and Bob's computing device **160**).

[0038] It will be noted here that for ease of depiction the photon pair source **104** has been depicted as included in Alice's computing device **150**. It will be apparent, however, the embodiments include such a photon pair source that is remote from both Alice's computing device **150** and Bob's computing device **160** and such embodiments are fully contemplated herein. In these embodiments, a first photon of each photon pair produced by this remote photon pair source (e.g., idler or signal photon) may be provided to Alice's computing device while a second photon of each photon pair produced by this remote photon pair source (e.g., idler or signal photon) may be provided to Bob's computing device **160**. The secret key from these photons from the remote photon source can be determined at Alice's computing device **150** and Bob's computing device **160** as discussed.

[0039] As can be seen then, the use of QDK modules **190** at Alice's computing device **150** and QDK module at Bob's computing device **160** may allow a shared secret key **184** to be determined based on simple methodologies that utilize just the detection of photons and the time intervals between such photons, allowing the distribution of a key based on quantum properties without actual measurement of the quantum state of a quantum information carrier. Thus, the shared key **184** may be changed (e.g., redetermined) on a frequent basis with less overhead. According to embodiments, each QDK module **190** (Alice) and QDK module **192** (Bob) may keep a running history of secret keys **184** utilized or determined. This may allow a QDK system to maximize the efficiency of the shared quantum link (e.g., the.

[0040] Moreover, in some embodiments, when the photodetector **106***b* at Bob's computing device **160** reports a photon detection event, then QDK module **192** can add the time difference between the current (single photon detection event) time and the time of a last photon detection event to a list of "candidate" shared secret keys. If QDK module **190** at Alice's computing device **150** also keeps a running count of the time differences between the last several detection events this can be Alice's list of "candidate" shared secret keys. The exact number of detection events that may be kept may be dependent on the quantum efficiency of photodetector **106** detecting photons **102** as well as any impairments in waveguide **134** or a desired quantum key distribution bandwidth.

[0041] In some cases, the reason for keeping a list of time deltas is that there will very likely be lost photons (e.g., single-photon detectors are not 100% efficient and there may also be some photons **102** that are absorbed or scattered in waveguide **134**). This "photonic loss" can be quantified by running the channel (e.g., waveguide **194**) in "classical" communications mode and observing the relative difference in signal strength between the transmitted signal (at Alice's computing device **150**) and the received signals (e.g., at Bob's computing device **160**). Once that "channel efficiency" (e.g., for waveguide **134**) number is known, then it

can be used to determine the number of single photon detection events that must be kept in order to satisfy the desired QKD bandwidth.

[0042] To illustrate in more detail, assume that Alice (e.g., Alice's computing device **150**) sends a series of single photons (P0, P1, P2, P3, etc.) to Bob (e.g., Bob's computing device **160**), where the time intervals (e.g., from which the shared secret may be derived) between the successive transmitted photons are expressed as:

shared_key_1 (SK1)=time_interval_1=[time that *P*1 is received by Bob]−[time that *P*0 is received by Bob]

shared_key_2 (SK2)=time_interval_2=[time that *P*2 is received by Bob]−[time that *P*1 is received by Bob]

shared_key_3 (SK3)=time_interval_3=[time that *P*3 is received by Bob]−[time that *P*2 is received by Bob]

[0043] When Bob (e.g., QKD module **192** at Bob's computing device **160**) detects a single photon event, then the time delta (e.g., equivalent to a shared secret or from which a shared secret may be determined) is reported back to Alice (e.g., QKD module **190** at Alice's computing device **150**) using, for example, a standard classical network link. This reporting may not be done directly, but rather by either encrypting the shared secret or by hashing the shared secret value and then sending that hashed value. For example, a first hash value can be generated using (e.g., from or based on) the first secret and a second hash value can be created using the second secret key. The first hash value and the second hash value can then be compared.

[0044] However, in the case where a photon is dropped (such that the photon is not received or detected at Bob's computing device **160**) (e.g., P2), then the value that Bob (e.g., QKD module **192** at Bob's computing device **160**) reports back to Alice (e.g., QKD module **190** at Alice's computing device **150**) will be the sum of (time_interval_1)+(time_interval_2). In other words, SK1+SK2.

[0045] Alice (e.g., QKD module **190** at Alice's computing device **150**) can then determine that Bob has "missed" P2 by the value that Bob (e.g., QKD module **192** at Bob's computing device **160**) reports, and then Alice (e.g., QKD module **190** at Alice's computing device **150**) replies with a "key agreement" message to Bob (e.g., QKD module **192** at Bob's computing device **160**) with the (encrypted) value of SK1+SK2. If Bob (e.g., QKD module **192** at Bob's computing device **160**) misses both P2 and P3, then Bob (e.g., QKD module **192** at Bob's computing device **160**) will report back to Alice (e.g., QKD module **190** at Alice's computing device **150**) the value of SK1+SK2+SK3, which Alice (e.g., QKD module **190** at Alice's computing device **150**) will then be able to determine is correct (even though Bob may have missed one or more detection events), since Alice (e.g., QKD module **190** at Alice's computing device **150**) has also kept around a running list of candidate shared secrets.

[0046] If Alice (e.g., QKD module **190** at Alice's computing device **150**) and Bob (e.g., QKD module **192** at Bob's computing device **160**) had no list of "candidate" shared secrets, then it may be less likely that QKD modules **190**, **192** at Alice's and Bob's computing devices **150**, **160** would ever be able to come to an agreement on a mutually shared secret, especially in the case of a "lossy" link or low-efficiency photodetectors (e.g., on both ends). In some cases, the longer the shared secret list is allowed to grow, the more efficient the shared secret transfer mechanism will be. However, if the list of "candidates" is allowed to be too long, then the security of the system may be decreased, because of the increased number of potential "simultaneously valid" shared secrets.

[0047] In the case of a rapidly-changing link (e.g., waveguide **134**) between Alice's computing device **150** and Bob's computing device **160** (due to, for example, environmental instabilities such as temperature swings, physical movement of the fiber optics, etc.), it may be desirable to have a simultaneous "link health monitor" signal (e.g., that is broadcast over the same transmission channel as the photons sent between QKD modules **190**, **192**, waveguide **134**). This can be accomplished by sending a classical (e.g., not single-photon) signal over the link, but at a slightly different frequency, which can be discriminated at the detector side by a frequency-dependent beam splitter. The difference in frequency between the two signals may be narrow enough that they share the same amount of relative loss through the link, but large enough so that the frequency-splitter can reliably discriminate between the two. In other words, the filters on the receiving end should be of sufficient order that the classical (i.e., multi-photon) signal is attenuated sufficiently that the single-photon detector is not inadvertently triggered by the classical signal.

[0048] FIG. **2** is a block diagram of a specific implementation of an embodiment of a QKD module implemented on a circuit **200** having photonics layer **210** and a CMOS layer **220**. The photonics layer **210** may be coupled to an integrated (e.g., on-chip) or external photon source **204** such that photons emitted from the photon source **204** will be routed to the photonics layer **210** through a waveguide **206**. Waveguide **206** may be coupled to a photon pair generator **208** (e.g., an SPDC device) that may, for example, be a nano ring-based photon pair generator.

[0049] Photon pair generator **208** may produce a signal and idler photon pair on two outputs **212**. One of the outputs **212***a* (e.g., the idler photon output) may be coupled to photodetector **228** through waveguide **232** on photonics layer **210**. The other output **212***b* of the photon pair generator **208** (e.g., the signal photon output) is coupled to waveguide **234** (which may be coupled to another computing device with which it is desired to share a secret key in a QKD system).

[0050] The CMOS layer **220** of the circuit **200** may include RAM or a processor and other processor circuitry as may be desired in various implementations. CMOS layer **220** also includes interval determination logic **238** which may be implemented in hardware, software of some combination of the two and may include a counter or the like. Specifically, photodetector **228** in the photonics layer **210** outputs an electrical signal for a detection event when a photon is detected on waveguide **232**. This electrical signal for the detection event is then received at interval determination logic **238** that can, based on the reception of the electrical signal for the detection event, output a determined time period and reset (and start again). In some cases, then, the reception of a detection event at interval determination logic **238** from photodetector **228** may serve to reset or (re)start interval determination logic **238**, and to cause an output of any previously determined time period (e.g., a time

period determined between reception of a previous detection event and the current detection event) to secret key logic **250** on CMOS layer **220**.

[0051] Secret key logic **250** on CMOS layer **220** QKD is adapted to receive one or more time periods (t**1**-tn) from interval determination logic **238** and use this set of time intervals to generate a secret key (value) **284**. For example, secret key logic **250** may be configured to determine a secret key **284** (e.g., after reset or initialization, etc.) when a certain number of time intervals (t) (e.g., one or more) have been received or when a certain number of photons have been detected. The secret key **284** may be, for example, the (values of) time periods (t**1**-tn) themselves or a value derived from time periods (t**1**-tn).

[0052] Using embodiments of such an architecture then, photonics in the photonics layer may be tightly integrated with a processor (e.g., a CPU), including such integration on a single die. Embodiments may thus have the advantage of providing very small, low power, highly scalable performance that may be updatable (e.g., through software or firmware updates).

[0053] FIG. **3** depicts one embodiment of a method for QKD between two computing devices that may be implemented at one of the computing devices. Initially, a photon of a time coincident photon pair produced by a probabilistic photon pair source may be detected at the computing device (STEP **302**). If this is a detection of an initial photon (e.g., the timer was not previously reset or running) (Y branch of STEP **304**), a timer (e.g., counter) may be initialized (e.g., reset) and started (STEP **306**) and no action may be taken until a detection of a subsequent photon (STEP **302**).

[0054] If, however, the detected photon is not an initially detected photon (N branch of STEP **304**) (e.g., the timer was previously reset and is running), a time period since the previously received photon can be determined and the timer may be initialized (e.g., reset) and started again (STEP **308**). The determined time period may then be added to a set of one more determined time periods between photon detection (STEP **310**). It can then be determined if additional time periods or photon detections are required (STEP **312**). Such a determination may be made based on a configured number of time periods or photon detections for determination of a shared secret (which may be one or more time periods or two or more photon detections, etc.), such that both computing devices participating in QKD may be configured with the same number of time periods or photon detections.

[0055] If additional time periods or photon detections are required (Y branch of STEP **312**) no further action may be taken until a detection of a subsequent photon (STEP **302**). If, however, no additional time periods or photon detections are needed (N branch of STEP **312**), a shared secret may be determined based on the set of determined time periods (STEP **314**). This shared secret may be the values of the determined time periods themselves or a value derived from those time periods. This shared secret can then be used as the basis for the implementation of cryptographic security measures implemented in association with the other computing device (e.g., encryption of data passing between the computing devices) (STEP **316**).

[0056] Finally, it should be noted that the embodiments described above may not provide complete protection against man-in-the-middle attacks. However, by transmitting a pair of cryptographic signatures (one for Alice to send to Bob and one for Bob to send to Alice) for each exchanged secret, then the likelihood of a successful man-in-the-middle attack may be significantly reduced. Such signatures can be calculated using either standard Asymmetric cryptographic methods or by using Symmetric cryptography. For the asymmetric crypto-based embodiments, well-known Public-Key mechanisms such as RSA or ECC-based signatures and other equivalent methods may be used. In addition, newer, Post-Quantum-Cryptography (PQC), signature algorithms may also be utilized. For the symmetric crypto case, signatures based on previously-shared secret keys may be used.

[0057] Although the invention has been described with respect to specific embodiments thereof, these embodiments are merely illustrative, and not restrictive of the invention. The description herein of illustrated embodiments of the invention, including the description in the Summary, is not intended to be exhaustive or to limit the invention to the precise forms disclosed herein (and in particular, the inclusion of any particular embodiment, feature or function within the Summary is not intended to limit the scope of the invention to such embodiment, feature or function). Rather, the description is intended to describe illustrative embodiments, features and functions in order to provide a person of ordinary skill in the art context to understand the invention without limiting the invention to any particularly described embodiment, feature or function, including any such embodiment feature or function described in the Summary. While specific embodiments of, and examples for, the invention are described herein for illustrative purposes only, various equivalent modifications are possible within the spirit and scope of the invention, as those skilled in the relevant art will recognize and appreciate. As indicated, these modifications may be made to the invention in light of the foregoing description of illustrated embodiments of the invention and are to be included within the spirit and scope of the invention. Thus, while the invention has been described herein with reference to particular embodiments thereof, a latitude of modification, various changes and substitutions are intended in the foregoing disclosures, and it will be appreciated that in some instances some features of embodiments of the invention will be employed without a corresponding use of other features without departing from the scope and spirit of the invention as set forth. Therefore, many modifications may be made to adapt a particular situation or material to the essential scope and spirit of the invention.

[0058] Reference throughout this specification to "one embodiment", "an embodiment", or "a specific embodiment" or similar terminology means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment and may not necessarily be present in all embodiments. Thus, respective appearances of the phrases "in one embodiment", "in an embodiment", or "in a specific embodiment" or similar terminology in various places throughout this specification are not necessarily referring to the same embodiment. Furthermore, the particular features, structures, or characteristics of any particular embodiment may be combined in any suitable manner with one or more other embodiments. It is to be understood that other variations and modifications of the embodiments described and illustrated herein are possible in light of the teachings herein and are to be considered as part of the spirit and scope of the invention.

[0059] In the description herein, numerous specific details are provided, such as examples of components and/or meth-

ods, to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that an embodiment may be able to be practiced without one or more of the specific details, or with other apparatus, systems, assemblies, methods, components, materials, parts, and/or the like. In other instances, well-known structures, components, systems, materials, or operations are not specifically shown or described in detail to avoid obscuring aspects of embodiments of the invention. While the invention may be illustrated by using a particular embodiment, this is not and does not limit the invention to any particular embodiment and a person of ordinary skill in the art will recognize that additional embodiments are readily understandable and are a part of this invention.

[0060] It will also be appreciated that one or more of the elements depicted in the drawings/figures can also be implemented in a more separated or integrated manner, or even removed or rendered as inoperable in certain cases, as is useful in accordance with a particular application. Additionally, any signal arrows in the drawings/figures should be considered only as exemplary, and not limiting, unless otherwise specifically noted.

[0061] 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, product, article, or apparatus that comprises a list of elements is not necessarily limited only to those elements but may include other elements not expressly listed or inherent to such process, product, article, or apparatus.

[0062] Furthermore, the term "or" as used herein is generally intended to mean "and/or" unless otherwise indicated. 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). As used herein, a term preceded by "a" or "an" (and "the" when antecedent basis is "a" or "an") includes both singular and plural of such term (i.e., that the reference "a" or "an" clearly indicates only the singular or only the plural). Also, as used in the description herein and throughout the claims that follow, the meaning of "in" includes "in" and "on" unless the context clearly dictates otherwise.

What is claimed is:

1. A system for a Quantum Key Distribution (QKD), comprising:

a first computing device, including:

a first photodetector adapted to detect first photons of a set of photon pairs and generate first detection events for each of the detected first photons, wherein the set of photon pairs were produced by a photon pair source adapted to probabilistically generate the set photon pairs and each photon pair comprises a time coincident first photon and second photon;

first interval determination logic adapted to receive the first detection events from the first photodetector and generate a first set of time periods based on time periods between received first detection events; and

first secret key logic adapted to receive the first set of time periods and generate a first secret key based on the received first set of time periods.

2. The system of claim **1**, wherein the photon pair source is coupled to a second computing device via a waveguide, the second computing device comprising:

a second photodetector adapted to detect the second photons of the set of photon pairs and generate second detection events for each of the detected second photons;

second interval determination logic adapted to receive the second detection events from the second photodetector and generate a second set of time periods based on time periods between received second detection events; and

second secret key logic adapted to receive the second set of time periods and generate a second secret key based on the received set of time periods.

3. The system of claim **2**, wherein the first photodetector is a single photon avalanche diode.

4. The system of claim **1**, wherein the first computing device includes the photon pair source.

5. The system of claim **1**, wherein the photon pair source is remote from both the first computing device and the second computing device.

6. The system of claim **1**, wherein the photon pair source creates the set of photon pairs using spontaneous parametric down conversion or four wave mixing.

7. The system of claim **1**, wherein the photon pair source is a nano ring based photon pair generator.

8. A method for Quantum Key Distribution (QKD), comprising:

at a first computing device:

detecting first photons of a probabilistically generated set of photon pairs, the first photons time coincident with corresponding second photons of the set of photon pairs;

generating a first set of time periods based on time periods between detection of the first photons of the set of photon pairs; and

generating a first secret key based on the received first set of time periods.

9. The method of claim **8**, further comprising:

at a second computing device:

detecting the corresponding second photons of the set of photon pairs;

generating a second set of time periods based on time periods between detection of the second photons of the set of photon pairs; and

generating a second secret key based on the received first set of time periods.

10. The method of claim **9**, wherein the set of photon pairs are generated at the first computing device.

11. The method of claim **10**, further comprising, providing the corresponding second photons from the first computing device to the second computing device.

12. The method of claim **11**, wherein the second photons are provided to the second computing device over a link between the first computing device and the second computing device.

13. The method of claim **12**, further comprising sending a health monitor signal between the first computing device and second computing device.

14. The method of claim **13**, wherein the health monitor signal is a classic signal sent over the link between the first computing device and the second computing device.

15. The method of claim **9**, further comprising encrypting or decrypting data sent between the first computing device and second computing device based on the first secret key or the second secret key.

16. The method of claim **9**, further comprising checking the first secret key against the second secret key.

17. The method of claim **16**, wherein the first secret key is checked against the second secret key by creating a first hash value from the first secret key and a second hash value using the second secret key and comparing the first hash value and the second hash value.

18. The method of claim **16**, further comprising maintaining a first candidate list of secret keys at the first computing device and a second candidate list of secret keys at the second computing device, wherein the first secret key is checked against the second secret key based on the first candidate list or second candidate list.

19. The method of claim **9**, wherein a number of the first photons or second photons, or a number of the first set of time periods or second set of time periods, is configured at the first computing device and the second computing device.

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