Equivalence of space and time-bins in DPS-QKD

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Abstract—Key generation efficiency, and security, in DPS-QKD improve with an increase in the number of path delays or time-bin superpositions. We demonstrate the implementation of superposition states using time-bins, and establish an equivalence with path-based superposition, thus yielding a simpler implementation of higher-order superposition states for differential phase-shift quantum key distribution (DPS-QKD). We set up DPS-QKD, over 105 km of single mode optical fiber, with a quantum bit error rate of less than 15% at a secure key rate of 2 kbps. With temporal guard bands, the QBER reduced to less than 10%, but with a 20% reduction in the key rate.

Index Terms—Quantum key distribution, differential phase, secure key, spatial superposition, time-bin superposition.

I. INTRODUCTION

Quantum key distribution (QKD) enables secure key exchange between authenticated users, Alice and Bob, by relying on two aspects of quantum mechanics, Heisenberg’s uncertainty principle and the no-cloning theorem [1]. When an adversary, Eve, attempts to steal information from the quantum channel, she also inevitably introduces disturbances in the channel and reveals herself. Since the first proposal by Bennett and Brassard in 1984 [2], there have been a variety of QKD protocols, both proposed and implemented [3–6]. Long distance field demonstrations of QKD mostly use discrete variables, some with active stabilization to mitigate environmental fluctuations [7]. In Appendix A, we provide the reader with a quick summary of key rates and channel lengths for a few recent implementations of QKD.

This article aims to establish the equivalence between a spatial and temporal generation of a superposition state for use in a differential phase-shift quantum key distribution (DPS-QKD) system. DPS-QKD as proposed by Inoue et al., is simple to implement and robust against slowly varying environmental fluctuations [6,8]. DPS-QKD uses a pair of phases $\Phi = \{0, \pi\}$ to generate non-orthogonal states that cannot be distinguished with absolute certainty using a single measurement [9]. A theoretical security proof of the DPS protocol, with single photons and weak coherent sources, was established under the assumption that Eve is restricted to individual attacks and also it was concluded that individual attacks are more powerful than sequential attacks [10,11]. An efficient phase encoding quantum key generation scheme, with narrow band heralded photons, was proposed by Yan et al., where key information is carried by the phase modulation directly on the single-photon temporal waveform [12,13]. Time-bin qubits, composed of temporal modes with weak coherent sources, are effective constituents to build a robust and simple QKD system with a high secure key rate [14]. To increase the secure key rate, with minimum resources, researchers have used two-dimensional and four-dimensional QKD protocols with time-bin and phase encoding [15]. Dellantonio et al. proposed two equivalent high dimensional MDI-QKD methods: space and time-bin encoding, which uses space to encode information in different paths and time-slots to encode qudits [16]. In high dimensional QKD protocols, multiple bits of information are encoded on a single photon, hence, it increases the channel capacity and is more robust against channel noise.

The recently introduced round-robin differential phase-shift quantum key distribution (RR-DPS-QKD) scheme addresses the effects of environmental disturbances, and gives us an upper bound on our tolerance to error rates with a bit error rate as high as 29% [17]. But such schemes requires the addition of optical switches and delays that make Bob’s set-up more complex [18].

In Sec. IV, we show that the two schemes, of spatial and temporal superposition, yield comparable key rates in kbps, with a QBER < 0.2. However, time-bins are defined electronically, and are significantly easier to generate. The scheme does require more precise timing synchronization, and we have developed the means to characterize the photon arrival time at our detector to within 50 ps. We can implement DPS-QKD with a temporal multiplexed single photon detector. We further demonstrate that temporal filtering can reduce the QBER of our DPS-QKD implementation, but at a reduced secure key rate.

II. EXPERIMENTAL SETUP

In the first DPS-QKD proposal, a single photon was allowed to pass through a beam splitter, travel through different path delays and then recombined to create a superposition state of the photon [6]. However, this scheme would encounter beam splitter losses and reduces the secure key rate. The more common version of DPS-QKD is one that uses weak coherent pulses (WCPs) [19]. With a path superposition of $N$-paths, and a relative phase of $\{0, \pi\}$ between paths, the photon can be in a superposition of $2^{N-1}$ states. Similar states can also be achieved with time-bin superposition by adding a relative phase at $N-1$ locations within a single pulse. In this article, we define $2^{N-1}$ as $M$, and hence, refer to the 3-pulse DPS-QKD
as a 4-state system. This notation will allow us to describe the creation of superposition states by temporal phase modulation.

We describe our experiments with 4-state DPS-QKD, using space and time-bin superposition of a weak coherent source, as shown in Fig. 1. The time-bin superposition scheme is easier to implement and control, and can be extended to an $M$-state DPS-QKD scheme without any additional hardware complexity. When we use a superposition of 4 states, an intercept and resend (IR) attack by Eve introduces a 33\% error on the sifted key. We had previously reported that the 4-state DPS scheme is more secure against both IR and beamsplitter attacks [20]. This percentage error increases to 50\% when 4-state DPS is extended to $M$-state DPS, but with ideal detectors [20]. The methodology used to implement a weak coherent source (WCS) is described along with the rest of our experimental setup in Sec. IV-A.

III. KEY GENERATION IN DPS-QKD

In our 4-state DPS-QKD implementation, Alice sends a single photon in a superposition of 3 spatial paths to Bob. The probability of a photon traveling through one of the 3 paths in Alice’s set-up is 1/3. The superposition state generated from Alice is represented as:

$$|\Psi\rangle = \frac{1}{\sqrt{3}} \left[ |0\rangle_a |0\rangle_b |1\rangle_c + |0\rangle_a |1\rangle_b |0\rangle_c + |1\rangle_a |0\rangle_b |0\rangle_c \right]$$  \hspace{1cm} (1)$$

$$= \frac{1}{\sqrt{3}} \left[ |100\rangle_{abc} + |010\rangle_{abc} + |001\rangle_{abc} \right]$$  \hspace{1cm} (2)$$

where the paths $a$, $b$, $c$ also represent time-bins. $|\Psi\rangle$ is passed through a delay line interferometer (DLI) at Bob’s site. As a result, the photon is now in a superposition of 4 time-bins. The first and last time-bins do not contain encoded phase difference information, whereas the 2 central time-bins contribute to the key generation. The 4 time-bins can also be observed classically, but at higher photon numbers, as shown in Fig. 2. Alice now encodes her random key bit as a random phase $\phi = \{0, \pi\}$ between successive time-bins. Bob extracts the key information using a DLI and two single-photon detectors.

Eve’s intercept and resend attack introduces an error of 33\% in the sifted key in the 4-state DPS compared to the 25\% error when using a train of WCPs in conventional DPS-QKD.

$$R_{\text{sec}} = R_{\text{sifted}} \left[ \tau - f(\epsilon) h(\epsilon) \right],$$  \hspace{1cm} (3)$$

where $\tau$ is the shrinking factor, $f(\epsilon)$ captures the inefficiency of the error correcting code, and $h(\epsilon)$ is the binary Shannon entropy. The error rate, $\epsilon$, depends upon dark counts and other system imperfections and $\tau$ captures Eve’s knowledge of the key. If we assume Eve’s attack to be limited to the IR and beamsplitter attacks, increasing $N$ changes the efficacy of the attacks, thus making $\tau$ a function of $N$ [20]. Hence, a secure key rate that depends on both $R_{\text{sifted}}$ and $\tau$, varies with $N$ as shown in Fig. 3.

Experimentally, the generation of a superposition state can be realized spatially using passive beam splitters (or beam combiners). However, passive beam splitters have insertion losses and the sifted key rate is reduced by a factor of $N$, thus making the implementation inefficient. An implementation with $N = 3$ will create $M = 4$ non-orthogonal states that Alice uses to transmit the key. Keeping in mind the ease of implementing time-bin superposition, we advocate temporal bins using phase modulation, over different spatial paths. This would potentially allow us to use $N > 3$ and obtain a higher sifted key rate, as seen in Fig. 3. However, with non-ideal SPDs, the optimal value against all attacks is $N = 3$ [11]. We observe this by the increase in QBER due to afterpulsing, within the same gate pulse, as $N$ increases [21].
IV. Experimental Results

The state at the output port of Bob’s DLI, consists of a single photon in one of 4 time-bins. A correct identification of these time-bins needs an accurate temporal characterization of the single photon detector (SPD), and its associated electronics.

A. Experimental set-up

Alice’s set-up consists of a continuous laser source at 1550.12 nm and a RF pulse generator. A train of electrical pulses, having a pulse width of 500 ps and a time period of 32 ns, is applied to a 10 GHz intensity modulator (IM). The bias voltage to the IM was optimized to get a modulation extinction ratio of more than 14 dB. The resultant optical pulses were then attenuated, using a variable optical attenuator (VOA), to a mean photon number \( \mu \approx 0.1 \), and the photons were sent directly to a gated SPD. We observed 31 K counts/s when the gate window was synchronized with the photon arrival time. This reduced to around 1 K counts/s when the gate was out of sync with the arrival time of the photons.

Two different source configurations for path and time-bin superposition, as shown in Fig. 4 were then used in the DPS-QKD experimental set-up shown in Fig. 5 In Fig. 4(a), weak coherent pulses are passed through a 1×3 and 3×1 beam splitter-coupler combination so that photons coming out from 3×1 coupler are in superposition of three paths before being passed through the phase modulator (PM), shown in Fig. 5 In Fig. 4(b), a 3 ns pulse coming out of the intensity modulator (IM) is attenuated and acts as a source. Phase modulation can be introduced on this pulse, as shown in Fig. 4(c).

![Diagram of weak coherent sources and experimental set-up]

Fig. 4: Weak coherent sources for (a) spatial, and (b) time-bin superposition. LS: laser source, IM: intensity modulator, VOA: variable optical attenuator. (c) Phase modulation pattern

One problem with using two independent detectors to differentiate between 0 and 1 bits is that the detectors are not identical, and will typically have different quantum efficiencies. We mitigate this by using time-multiplexing and capture photon arrival times from both output ports of the DLI. A fiber delay of 10 ns was added at one of the output ports of the DLI. To equalize the loss in both paths from output ports of DLI, an attenuator of 0.5 dB was added in short path. Both ports were then multiplexed using a 2×1 coupler and sent to a SPD. This technique provides a cost-effective configuration since one SPD is enough to extract timing instant information. Unfortunately, half of the photons are lost due to the 2×1 combiner before the SPD. But, since we can generate WCPs at GHz rates, we are limited only by the hold-off time on the SPD and do not perceive any disadvantage to using a time-multiplexed configuration with a single SPD. Instead, using a single detector has the advantage of providing an equal sensitivity on both constructive and destructive interference ports of the DLI. An IM with a high extinction ratio reduces false detections during the 10 ns off time in the time-multiplexed detection scheme.

A field programmable gate array (FPGA) is triggered synchronous to the pulse generator and it is configured to generate control signals for the SPD, TDC and a modulating signal (RF pulses) for the PM. Phase encoding patterns \{0, 0\}, \{π, 0\}, \{0, π\} and \{π, π\} are realized by applying RF pulses to the phase modulator synchronous to the three different time locations within a 3 ns temporal wave packet, as shown in Fig. 4(c). The FPGA also provides a variable gate delay to synchronize the full systems, and to identify the interference slots. We recorded the photon arrival times by varying the RF delay to the PM for a fixed gate delay. Sifted key generation and QBER measurements for both space and time multiplexed schemes were obtained after integrating a TDC and a time-stamp module in the FPGA.

V. Results and Discussion

A sifted key was derived after counting the TDC output, combined with that from a time-stamp module.

A. Key generation

A final key rate of 21 kbps and 10 kbps was achieved in the time-bin superposition and path superposition schemes, with a QBER of 0.17 and 0.21, respectively, over 30 km of optical fiber. By further optimizing the DLI bias voltage and...
the control parameters of the SPD, we were able to observe a QBER of 0.12, shown pictorially in Fig. 6(a), in the time-bin scheme.

![Photon arrival time distribution for (a) path superposition and (b) time-bin superposition](image)

Fig. 6: Photon arrival time distribution for (a) path superposition and (b) time-bin superposition

With reference to Figs. 6 (a) and (b), the QBER is defined as,

\[
\text{QBER} = \frac{C_{00} + C_{10}}{C_{00} + C_{10} + C_{01} + C_{11}} \quad (4)
\]

where

\[
C_{pq} = \sum_{t=T_{\text{start}}}^{T_{\text{stop}}} c_t \quad (5)
\]

represents the counts at the \(p\)th port of the DLI, when Alice’s transmitted raw key is \(q\). \(T_{\text{start}}\) and \(T_{\text{stop}}\) are determined for each case from Table I.

**TABLE I: Classification of photon counts**

| Phase pattern | \(C_{pq}\) | \(T_{\text{start}}\) | \(T_{\text{stop}}\) |
|---------------|---------|----------------|----------------|
| \{0, 0\}      | \(C_{00}\) | \(T_0\)         | \(T_0 + 2\Delta T\) |
|               | \(C_{01}\) | --              | --              |
|               | \(C_{10}\) | \(T_1\)         | \(T_1 + 2\Delta T\) |
|               | \(C_{11}\) | --              | --              |
| \{0, \pi\}    | \(C_{00}\) | \(T_0\)         | \(T_0 + \Delta T\) |
|               | \(C_{01}\) | \(T_0 + \Delta T\) | \(T_0 + 2\Delta T\) |
|               | \(C_{10}\) | \(T_1\)         | \(T_1 + \Delta T\) |
|               | \(C_{11}\) | \(T_1 + \Delta T\) | \(T_1 + 2\Delta T\) |
| \{\pi, 0\}    | \(C_{00}\) | \(T_0\)         | \(T_0 + \Delta T\) |
|               | \(C_{01}\) | \(T_0 + \Delta T\) | \(T_0 + 2\Delta T\) |
|               | \(C_{10}\) | \(T_1\)         | \(T_1 + \Delta T\) |
|               | \(C_{11}\) | \(T_1 + \Delta T\) | \(T_1 + 2\Delta T\) |
| \{\pi, \pi\}  | \(C_{00}\) | --              | --              |
|               | \(C_{01}\) | --              | --              |
|               | \(C_{10}\) | --              | --              |
|               | \(C_{11}\) | \(T_1\)         | \(T_1 + 2\Delta T\) |

We recovered the sifted key and extracted the QBER by directly comparing the sender’s keys with the receiver’s. This approach was used to optimize the RF delay and appropriately insert a phase shift every 1 ns within the 3 ns optical pulse, using a fixed phase pattern of \{0, \pi\}. Although the phase pattern was fixed, with a low mean photon number, channel loss, and a detector efficiency \(\eta \sim 0.1\), we only detect a random bit pattern after the delay line interferometer.

![Optimization of QBER by adjusting the timing of the applied phase (a) with fixed phase modulation pattern (b) with random phase modulation pattern](image)

Fig. 7: Optimization of QBER by adjusting the timing of the applied phase (a) with fixed phase modulation pattern (b) with random phase modulation pattern

The QKD testbed was also used to investigate the effect of excess bias voltage, gate width and hold-off time on the dark count rate (DCR) and afterpulse noises of a gated InGaAs single-photon detector (SPD) [21]. This helped in improving the QBER for all 4 possible phase modulation patterns. We achieved a QBER of 0.12 for a fixed phase pattern \{0, \pi\}, as shown in Fig. 7(a). Other patterns \{0, 0\}, \{\pi, 0\} and \{\pi, \pi\} yielded a QBER of 0.9, 0.14 and 0.27 respectively, while a random pattern yielded a minimum QBER of 0.17 as shown in Fig. 7(b).

The sifted key generation rate in our time-bin superposition DPS system can be written as [22]

\[
R_{\text{sifted}} = r_p \mu \eta T_L e^{(-\tau_p \mu \eta T_L \tau_H)} \quad (6)
\]

where the variables used are defined in Table III.

\(T_L\) consists of fiber loss due to attenuation (\(\alpha \approx 0.2\) dB/km) and the net insertion loss (\(L_r\)) of the DLI and coupler. Referring to [8], the values of \(r_p, \eta\) and \(\tau_H\) are 62.5 Mbps, 10% and 10 \(\mu\)s respectively. The exponential term in (6) approaches 1 for a transmitted pulse rate of 62.5 Mbps, with a hold-off time of 10 \(\mu\)s, and \(R_{\text{sifted}}\) decreases linearly with distance. However, the exponent becomes significant for higher transmitted pulse rates, typically \(r_p > 1\) Gbps.
As we observe in Fig. 9, the experimental data fits well to (6), and we estimate $\mu \approx 0.17$. At a fiber length of 30 km, we achieved a sifted key generation rate of 21 kbps with a QBER of 11.5%. We then extended our experiment to 105 km of fiber, and observed the sifted key rate drop to about 2 kbps with a QBER of 14.4%, as shown in Fig. 9.

Fig. 9: Sifted key rate (estimated and experimental) and measured QBER as a function of channel length

We further extended our 4-state DPS experiments to realize 8-state DPS, with a DLI having free spectral range of 2.5 GHz. The phase modulation transition rate was enhanced from 1 GHz to 2.5 GHz within a photon wave packet of width 1.6 ns, where each time-bin size is 0.4 ns. Based on the photon arrival time within 1.2 ns, the QBER was calculated for various phase modulation states, as shown in Fig. 10.

B. Temporal filtering of time-stamps

After identification of the optimized gate and RF delay, we introduce a guard window between time-bins at the output state of Bob’s set-up [23]. In temporal filtering, while we discard the time-stamps collected at the selected guard time, we lose a fraction of bits in sifted keys. However, this method reduces the QBER of a system [24], but at a cost of a reduced sifted key rate, as shown in Fig. 11 (a) and (b). Table III lists the source of errors, contributing in QBER for our QKD test-bed. Error due to DCR, afterpulse probability and timing jitter were estimated from our previous work on gated SPD characterization [25]. The interferometric visibility ($V$) of two DLI with FSR of 1 GHz and 2.5 GHz are 92% and 96% respectively. The QBER introduced into the system due to

| Description                  | Source | $\Delta T = 1$ ns | $\Delta T = 0.4$ ns |
|------------------------------|--------|------------------|-------------------|
| Dark count rate (DCR)        | SPD    | 0.35             | 0.35              |
| Afterpulse effect            | SPD    | 1.5              | 1.5               |
| Extinction ratio             | IM     | 1.6              | 1.6               |
| Timing jitter                | SPD    | 5.0              | 12.5              |
| Imperfect visibility         | DLI    | 4.0              | 2.0               |
| Rise/fall time of PM pattern | PM     | 2.1              | 5.25              |

* From data sheet.
V is (1 − V)/2. Referring to Table III, the major sources of QBER are timing jitter of SPD and phase modulation rise/fall time, which can be reduced by temporal filtering method. For a guard time of 200 ps, 20% key bits are discarded, while the QBER is reduced from 0.12 to 0.09 in a system with a DLI of FSR 1 GHz, as shown in Fig. 11(a). For a DLI with 2.5 GHz FSR, we discard 20% key bits, to reduce QBER from 0.14 to 0.12, as shown in Fig. 11(b). The reduction in QBER for a larger FSR is only marginal. This highlights the challenge of moving to a DLI with a higher FSR. After estimating and optimizing QBER, we followed error correction and privacy amplification to generate secure keys. However, our focus is on QBER measurement and sifted key generation, hence error correction [26] and privacy amplification are not discussed in this paper.

VI. CONCLUSION AND PERSPECTIVES

We have presented two different experimental approaches (a) spatial superposition and (b) time-bin superposition, to realize a 4-state DPS-QKD over a 105 km quantum channel. We observe that the time-bin superposition scheme is more efficient and easier to implement and can be extended to an M-state DPS-QKD system. After optimization of various parameters, we achieved a sifted key rate of around 21 kbps with QBER of 0.12 over 30 km of fiber. We then extended our time-bin superposition based DPS-QKD system to 105 km of optical fibre, and achieved a sifted key rate of 2 kbps while maintaining a QBER of 0.14. We also applied temporal filtering method in our DPS-QKD system, and shown that it helps to reduce the QBER, back to 0.12, but at a cost of reduced sifted key rate.

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APPENDIX

TABLE IV: Decoy state implementations [27–29]

| Author, Year | Protocol | Encoding | Channel length | Key rate bits/s |
|--------------|----------|----------|----------------|-----------------|
| Frohlich et al., 2017 | BB84, Simplified | Phase | 240 km | 5.8 |
| Boaron et al., 2018 | BB84, variant | Time-bin | 421 km | 6.5 |
| Yuan et al., 2018 | BB84 | Phase | 10 km | 13.7 M |

TABLE V: Measurement-device-independent (MDI) QKD implementations [30–37]

| Author, Year | Protocol | Encoding | Channel length | Key rate bits/s |
|--------------|----------|----------|----------------|-----------------|
| Yin et al., 2016 | Decoy state MDI | Time-bin | 404 km | 0.00032 |
| Tang et al., 2016 | BB84 | Polarisation | 40 km | 10 |
| Comandar et al., 2016 | BB84 | Polarisation | 102 km | 4.6 K |
| Wang et al., 2016 | RFI | Time-bin | 20 km | 0.0063 |
| Valivarthi et al., 2017 | BB84 | Time-bin | 80 km | 100 |
| Liu et al., 2019 | BB84 | Time-bin | 160 km | 2.6 |
| Wei et al., 2020 | Asymmetric MDI | Polarisation | 180 km | 31 |
| Zhou et al., 2021 | RFI | Time-bin | 200 km | 1 |

TABLE VI: Twin-field (TF) QKD implementations [38–44]

| Author, Year | Protocol | Encoding | Channel length | Key rate bits/s |
|--------------|----------|----------|----------------|-----------------|
| Minder et al., 2019 | TF | Phase | 90.8 dB | 0.045 |
| Wang et al., 2019 | SNS-TF | Time-bin | 300 km | 2.01 K |
| Liu et al., 2019 | TF | Time-bin | 300 km | 39.2 |
| Zhong et al., 2019 | TF | Phase | 55.1 dB | 25.6 |
| Fang et al, 2020 | TF | Phase | 502 km | 0.118 |
| Liu, Hui et al, 2021 | SNS-TF | Time-bin | 428 km | 3.36 |
| Wang, et al, 2021 | TF | Time-bin | 830 km | 0.01 |

Sending-or-not-sending twin-field.

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### TABLE VII: Continuous variable-QKD 

| Author | Year | Protocol | Encoding scheme | Channel length | Key rate bits/s |
|--------|------|----------|-----------------|----------------|-----------------|
| Wang et al., 2017 | | CV | Gaussian modulation | 50 km | 700 |
| Zhang et al., 2019 | | CV | Gaussian modulation | 50 km | 5800 |
| Zhang et al., 2020 | | CV | Gaussian modulation | 202.8 km | 6.2 |

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