

A Beam Steering Platform Enabling Handheld Low-Cost Quantum Key Distribution

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Abstract *In this paper we present the integration of a low-cost QKD system into a low-loss, asymmetrical beam steering platform including a polarisation calibration unit. Initial results are presented demonstrating a secret key rate of 400 bit/s for the overall system. ©2023 The Author(s)*

Introduction

Quantum Key distribution (QKD) allows for the exchange of symmetrical keys with the unique ability to detect eavesdropper thanks to the laws of physics. QKD has been intensively studied for long range links and in fibre networks [1,2]. Recent publication tend to focus on the integration of QKD into lower network layers bringing QKD closer to the user [3-6]. Minimised QKD systems have been reported and first handheld systems have been demonstrated [7-9]. Handheld QKD systems inherently rely on the optical alignment of Alice and Bob. Thus, it is necessary to provide low latency to compensate for hand movements and large coverage area allowing for the user to move freely within. However, the trade-off between pointing accuracy, latency and coverage area is a challenging field. In this paper we present a low-cost QKD system [9] integrated into an asymmetrical beam steering unit. It is desirable to undertake all the tracking and beam steering in a fixed terminal, to reduce the complexity of the handheld device and maintain the size, weight and power (SWaP) requirements of the handheld. Initial results prove the system compensating for hand movements over a time span of 15 s whilst exchanging quantum keys at an average secret key rate of 400 bit/s.

Low-cost QKD system

The low cost QKD system previously reported in [9] uses 4 short pulsed light emitting diodes (LEDs) each linearly polarized to produce the polarization states required for BB84 QKD. The wide spectral bandwidth of the LEDs means no matching of devices is required and a simple bandpass filter can be used to remove spectral side channel information. To combine the spatial modes of the four LEDs, a single mode optical

fibre is used, positioned such that equal coupling is achieved from all LEDs.

The LEDs are driven by commercial off-the-shelf laser driver chips and the device control is provided by a Xilinx Spartan 6. The entire control electronics is approximately the size of a credit card and is powered and controlled by a single micro USB link to a host device. Figure 1 shows the assembled QKD transmitted electronics.

The QKD receiver is a relatively conventional beam splitter arrangement [10] using two non-polarizing beam splitters to allow for random choice of 3 measurement bases (H/V, D/A, R/L) which allows for the correction of arbitrary polarization rotations in the transmission optics. Detections are made using off-the-shelf SPAD modules and a proprietary multi-channel time tagger.

The philosophy of this system is to make the transmitter as low SWaP as possible even if that leads to compromises in the SWaP of the receiver system. An example of a compromise has already been given in the additional hardware to correct polarization rotations. Another example is that there is no external clock synchronization between transmitter and receiver, since this would add additional hardware to the transmitter. Instead using a more



Fig. 1: The QKD transmitter electronics, the micro USB is on the left and the 5 pins for driving the LEDs is on the right. A comparison in size is given by a credit card.

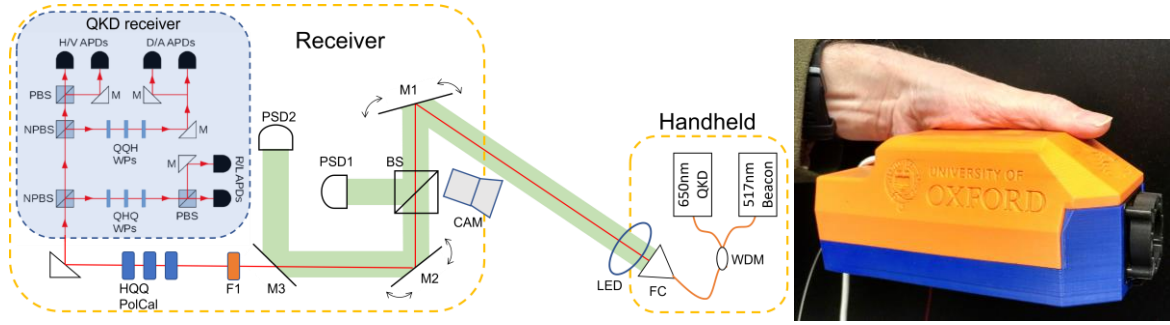


Fig. 1: Encompassing from left to right (a) Schematic of the proposed setup. WDM: wavelength division multiplexer, FC: fibre collimator, LED: LED beacon ring, CAM: camera for localisation, M1: coarse steering mirror, BS: beam splitter, PSD1: coarse steering position sensor, M2: fine steering mirror, M3: dichroic mirror, PSD2: fine steering position sensor, F1: spectral filter, HQQ: polarisation calibration by motorized wave plates. A detailed description of the QKD receiver is given in reference [Dave], (b) A photo taken of the assembled handheld device (dimensions: 190 mm (L) x 80 mm (W) x 75 mm (H)) with a hand for scale.

precise clock and additional post processing the receiver can reconstruct the clock from the quantum measurements. This purely software approach should be contrasted to an example using similar hardware such as in [11], which is more performant but requires additional systems to provide a second optical channel to carry the timing information.

This QKD system was tested in a lab environment with statically positioned transmitter and receiver where it achieved >20 kbit/s secret key rate in a dark environment. It was also shown to be somewhat resilient to background light.

Beam steering platform

Figure 2a shows the schematic of the proposed handheld setup. It is desirable to undertake all the tracking and beam steering in a fixed receiver to reduce the complexity and therefore costs of a potential handheld device. The handheld combines a 517 nm beacon with the 650 nm QKD signal via a WDM. Both wavelengths co-propagate in a single mode fibre before coupled into free-space with the help of a collimator. The free-space beam has a beam waist of 1.5 mm. The design described, guarantees the co-alignment of the beacon and QKD signal. The assembled handheld is shown in Fig.2b. The design offers potential for further reduction in size along all dimensions.

The light of the LED ring from the handheld is picked up by the receiver's camera allowing for an initial localisation of the handheld. The two subsequent beam steering loops are designed to split tasks: The coarse steering covers wide area ($\pm 25^\circ$ at 1 m distance and steered by the PID loop in 10 ms) and fine steering refines the output of the coarse steering into the QKD receiver. As only small angular changes are required, the PID loop for fine steering is optimised for minimum latency ($\pm 0.5^\circ$ steered in 450 μ s). The latencies

of both beam steering loops are well suited for handheld operation as demonstrated by [7].

Both beam steering loops are linked via a 67/33 beam splitter. However, the beam splitter reduces the overall systems performance as demonstrated in [12].

A dichroic mirror separates the QKD signal from the beacon. An additional 10 nm passband filter is used to attenuate leakage transmissions from the beacon as well as ambient light collected within the field of view of the setup. Ambient light is further suppressed by a 5 mm iris between the coarse steering mirror and the beam splitter (not shown in Fig.2). Moreover, the beacon signal has been intensity modulated duty-cycling at 20%, achieving a further reduction of leakage transmissions into the QKD receiver. The modulated beacon offers potential to be used as an optional clock channel of the QKD system as proposed by [11].

A set of motorized wave plates enables the calibration needed to align the polarisation states between the handheld device and the fixed receiver. Mismatches of the polarisation states are induced by imperfections of the components used, birefringence of the single mode fibre in the handheld and hand movements of the user. A real-time calibration and compensation scheme has been proposed for this application [13]. A simple one-time calibration at the beginning of each key exchange session proved sufficient for 15 s of operation if the handheld does not roll. Pitch and yaw rotations are compensated by the beam steering loops. Furthermore, the initial polarisation calibration offers the potential to be used as a finger print of the handheld device and therefore as user authentication.

The QKD receiver splits the incoming light according to its polarisation. Fibre ports are used

to couple each of the 6 outputs into 100 μm fibres, respectively. Those fibres are guiding the photons to their corresponding SPAD. The use of 100 μm fibres allows for the configuration of the fibre ports so that fine steering angles in the range of -0.02° to 0.02° are received uniformly in terms of loss. The field of view for each of the fibre ports is set to have a smaller footprint than the LED ring of the handheld at 1 m distance. The overall loss was measured from handheld output to the output of the fibres feeding the SPADs to be 3.4 dB.

Results

Pointing accuracy allowing for low loss fibre coupling and steering latency allowing for hand movement compensation are essential to provide a handheld QKD system. Reference [7] has demonstrated that the fine steering loop is the key to the success. Figure 3 shows a statistical evaluation of measured steering accuracies at varying integration times of the fine steering PID loop. It can be seen that greater integration times lead to a more accurate beam steering angle. This behaviour is largely attributed to temporal averaging over more PSD reading and therefore reducing their thermal noise. All integration times plotted are well suited for handheld operation, however there are implications towards the PID integration time of the coarse steering loop. The separation in bandwidth / integration time between two mechanically coupled PID loops is one way of avoiding ringing of the steering output [14].

Figure 4 shows the beam steering accuracy for both loops running simultaneously. It can be observed, that the steering angles of all samples lie within the range of -0.02° to 0.02° provided by the 100 μm fibre coupling by a factor of ~ 10 . This factor is the safety margin enabling the dynamic operation of the beam steering system and greatly influences the maximum angular velocity at which the handheld can still be tracked.

Initial results demonstrated an average secret key rate of 400 bit/s over a time span of 15 s with the system described. That very promising result

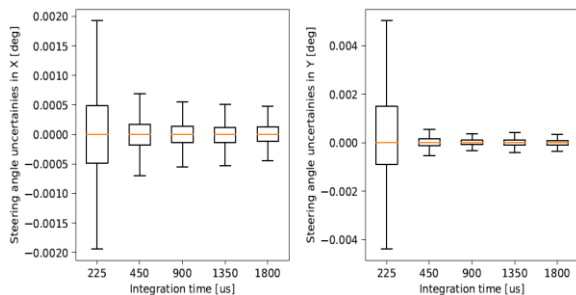


Fig. 3: Steering accuracy as a function of the integration time for the fine steering loop.

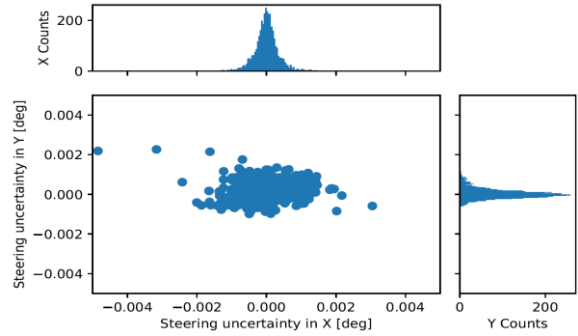


Fig. 4: Steering accuracy of the combined steering output. The integrations of the PID loops for the coarse and fine steering loop have been set to 10 ms and 450 μs , respectively.

was achieved with non-optimal settings of the polarisation calibration, beacon duty cycle and in the presence of 200 lux LED illumination. Further optimisation and characterisation of the system are currently under way.

Conclusion

In this paper we present a beam steering platform enabling the handheld operation of a low-cost QKD system. The platform allows for accurate tracking, latency sufficient for the compensation of hand movements and polarisation calibration for polarisation-based QKD protocols. The system integration caused a reduction of the overall achievable QKD performance, mainly by the introduction of a beam splitter into the quantum channel and the time domain division approach of the beacon. First results of the system demonstrate an average secret key rate of 400 bit/s over a time span of 15 s in non-optimal settings. Current investigations focus on the refinement of the beacon duty cycle, the polarisation calibration and a detailed QKD characterisation especially in the presence of ambient light.

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