Towards polarisation-encoded quantum key distribution in optical fibre networks

AUTHORS:
Sharmini Pillay[1]
Abdul R. Mirza[1,2]
Francesco Petruccione[1,2,3]

AFFILIATIONS:
[1]Quantum Research Group, School of Chemistry and Physics, University of KwaZulu-Natal, Durban, South Africa
[2]QZN Technology – Innovation Centre, University of KwaZulu-Natal, Durban, South Africa
[3]National Institute for Theoretical Physics, Durban, South Africa

CORRESPONDENCE TO:
Sharmini Pillay

EMAIL:
sharminipillay251@gmail.com

POSTAL ADDRESS:
Quantum Research Group, School of Chemistry and Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa

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Quantum key distribution – a process that encodes digital information – often utilises fibre optic technologies for commercial applications. Fibre provides the benefit of a dark channel as well as the convenience of independence of a line-of-sight connection between the sender and receiver. In order to implement quantum key distribution protocols utilising polarisation encoding, the birefringence effects of fibre must be compensated for. Birefringence is caused by manufacturing impurities in the fibre or a change in environmental conditions and results in a rotation of the state of polarisation of light as it is propagated through the fibre. With dynamic environmental conditions, the birefringence effects should be monitored with a test signal at regular time intervals so that the polarisation of each photon can be appropriately compensated to its original state. Orthogonal states are compensated simultaneously, but most protocols, such as BB84 and B92, require non-orthogonal basis sets. Instead of using a compensator for each basis, the presented scheme fixes the polarisation controller onto the plane on the Poincaré that passes through both bases, compensating both non-orthogonal bases simultaneously.

Introduction

The reliance on information technology for global communication has highlighted the need for data security in recent years. Various applications such as online banking and government communications require a secure transmission between the transmitter and the intended recipient. Physical protection of the data, such as a lock and key transfer, is not feasible in terms of the cost and time implications. Further physical protection also involves an element of human interaction which may compromise the security of the information. It is therefore essential to develop reliable and secure cryptographic systems (cryptosystems) to encrypt sensitive data. Cryptography allows for information to be encrypted into an unintelligible state so that it may be transmitted across public networks without any risk of eavesdropping.

Quantum key distribution (QKD) encodes information into the physical properties of quantum particles, e.g. single photons of light. The Uncertainty Principle[1] and the No Cloning Theorem[2] of quantum physics, rather than the finite complexity of a mathematical algorithm, ensure the security of the key. The information shared between the transmitter (usually referred to as Alice) and the receiver (usually referred to as Bob) is carried by qubits (quantum bits).[3] The qubit is a quantum two-level system used to encode binary data. The state of the qubit, $|\Psi\rangle$, is represented as a linear superposition of two pure states:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle. \qquad \text{Equation 1}$$

The basis set, $\{|0\rangle, |1\rangle\}$, represents the two eigenstates in which a qubit may be measured. The probability of a measurement in these respective states is given by $|\alpha|^2$ and $|\beta|^2$, such that

$$|\alpha|^2 + |\beta|^2 = 1. \qquad \text{Equation 2}$$

Information may also be encoded in any other basis set, in particular:

$$|\pm\rangle = \frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle). \qquad \text{Equation 3}$$

It is noted that $|+\rangle$ and $|-\rangle$ are orthogonal to each other but the set $\{|+\rangle, |-\}$ is non-orthogonal to the set $\{|0\rangle, |1\rangle\}$. For a practical implementation, these two bases can be represented by the rectilinear states of polarisation (SOP) and the diagonal SOPs, as applied to the BB84 and SARG04 protocols.[4,5] Because the bases are non-orthogonal to each other, any measurements carried out with the incorrect measurement basis will yield an ambiguous result.[2] The security of QKD therefore lies in the inability to gain total information from the qubit that Alice has sent to Bob without first knowing which basis to use for the measurement.

Another advantage that QKD has over conventional cryptography is the ability for the authenticated parties to detect an eavesdropper. The eavesdropper, usually referred to as Eve, may attempt to copy or measure the quantum state of the qubits. However, both these attacks violate the laws of quantum mechanics that fortify QKD. Any measurements done on the qubits during transmission will cause disturbances to the quantum states which can be observed by Alice and Bob. Therefore, if Alice and Bob observe an error rate above the accepted threshold in their transmission, they may infer the presence of Eve. As QKD exploits the physical quantum nature of particles, the principle is not vulnerable to technological advances but bound only by the laws of physics.[6]

As a consequence of the intrinsic attenuation of optical fibre, a fibre optic link is impractical for single photon transmission over 200 km.[7] However, a free space channel can support transmission over longer distances than fibre, because of a lower attenuation and a weaker dispersion property.[8] Additionally, a free space channel does not require the information and communication technology infrastructure required for a fibre network and is therefore suitable for remote locations. These advantages allow the possibility of a satellite QKD network which opens the door for a *global* QKD network. Creating an interface between a fibre channel and a free space channel will allow for fibre-based municipal networks to connect to a local free space node. The free space nodes can transmit to a satellite network and thereby connect to another metropolitan network at another location, shown in Figure 1.

Such a methodology will bring together the advantages of a fibre network, such as a higher signal-to-noise ratio, and the larger transmission distance of a free space network and would facilitate various media of communication in a combined network. Ideally, such free-space–fibre gateways within the global network must remain untrusted. This proves difficult because a fibre network is better suited for phase-encoded QKD and a free space network to polarisation-encoded QKD. A relay device that can convert the quantum systems between various encoding schemes without actually measuring the systems would require the development of quantum repeaters and quantum memories. However, these devices are still under research.[9]

It is therefore necessary to create a passive interface between the fibre channel and the free space channel. In order to achieve this interface, only one type of encoding can be used throughout the entire network. Phase encoding can be used efficiently in a fibre, plug-and-play system but in a free space system, the relative stability between the interferometers can be difficult to implement. Research is currently being done to allow for QKD to be implemented over free space using Laguerre–Gauss modes. These modes carry orbital angular momentum (OAM) which is used as the bit encoding for QKD.[10] The advantage of using OAM states is their infinite dimensional Hillbert space which can be used for encoding instead of the two-dimensional Hillbert space used in other QKD implementations. However, coupling such a system to a fibre network would pose a problem because OAM states would require multimode fibre. Because of the negative effects of modal dispersion, only single-mode fibre is used for QKD purposes. Alternatively, polarisation encoding can be used over both channels. As the atmosphere is non-birefringent, it is more suitable for polarisation encoding. However, the birefringence of a standard single-mode fibre optic cable renders it unable to maintain the SOP of the light it transmits. By cancelling birefringent effects in fibre, an untrusted interface can be developed between a fibre channel and a free space channel.

Birefringence in a fibre optic cable

Birefringence refers to the double refraction of light when transmitted through an anisotropic medium. Orthogonal components of the state of polarisation of light are transmitted through the medium at different speeds, referred to as the differential group delay.[11] The component that is perpendicular to the optical axis of the medium is the ordinary ray and the component that is parallel to the optical axis of the medium is the extraordinary ray.[12] The refractive differences between the ordinary ray and the extraordinary ray cause a decoupling of the components, resulting in the rotation of the state of polarisation as the light is transmitted through the material, as shown in Figure 2.

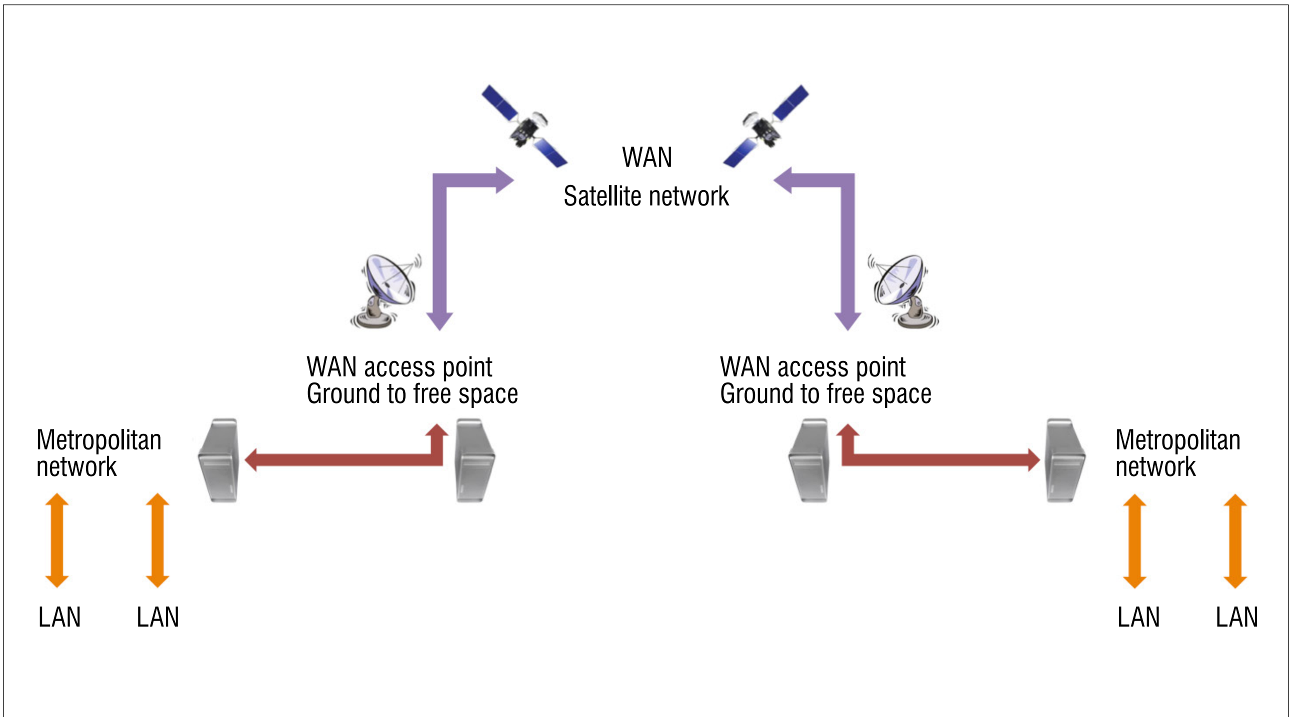
Birefringence occurs in fibre optic cables as a result of asymmetries caused by impurities in the fibre or manufacturing errors.[13] These irregularities cause a fixed rotation, A, of any state of polarisation, E_i, that is transmitted through the fibre. This rotation can be corrected with the use of a passive polarisation controller, represented by the inverse of A, such that

$$E_i = A\ A^{-1}\ E_i. \qquad \text{Equation 4}$$

The polarisation controller therefore applies the inverse of the rotation caused by the birefringence effects, returning the state of polarisation to its original form.

If the fibre is bent or subject to changing environmental stresses, such as heating or vibrations, the birefringent effects will vary randomly with time.[14] Therefore, an active polarisation controller must be used to correct for the changes in the state of polarisation of photons in real time.[15] The effects of the fibre's birefringence must be regularly tested and the polarisation controller must be adjusted each time in order to compensate for these changes. The state of polarisation of each qubit must be accurately transmitted between Alice and Bob in order for them to obtain a cryptographic key; therefore, without this active polarisation control, it would not be possible to implement polarisation-encoded QKD protocols over a fibre channel.

One method of solving the problem of birefringence in fibre would be to use polarisation-maintaining (PM) fibre in the QKD set-up. PM fibre induces a forced and fixed birefringence of any transmitted light.[14] This effect prevents the SOP from rotating as a result of any natural effects such as bends and temperature gradients. However, PM fibre is only



WAN, wide area network; LAN, local area network.

Figure 1: A diagram depicting a potential set-up for a global quantum key distribution network.

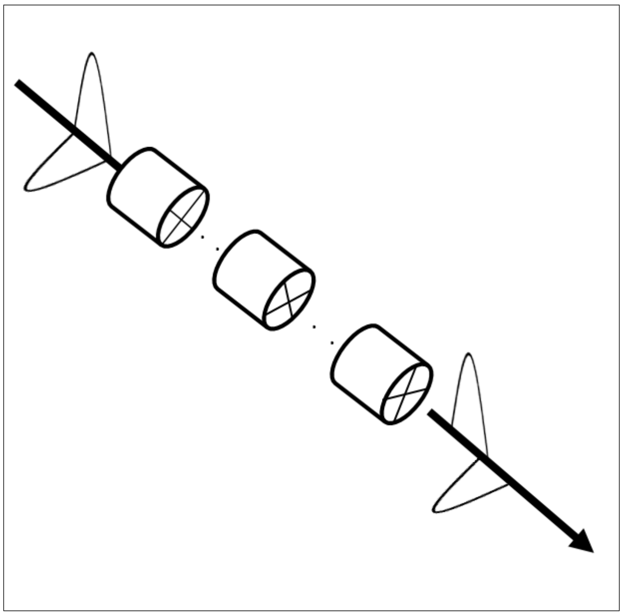


Figure 2: Diagram depicting how a state of polarisation is rotated as it is transmitted through a fibre optic cable. The cross sections of the fibre show that the orthogonal components of the state of polarisation are rotated during transmission as a result of their differing speeds. For illustrative purposes, this figure demonstrates a linear rotation, but practically, the fibre can introduce an elliptical element into the state of polarisation as well.

effective for orthogonal states because the SOPs must be aligned with the fast axis and slow axis of the PM fibre. The necessary use of non-orthogonal states in QKD means the use of PM fibre in the channel is obsolete.

The SOP of each photon in the quantum signal is assigned randomly and, therefore, the polarisation controller must adjust each photon uniquely. The SOP of each photon must remain unknown to the polarisation controller so as to maintain the security of the QKD. So as not to violate the security of QKD, no measurements can be made on the SOPs of the photons before the final detection system. The setting for the polarisation controller must be determined before the commencement of the QKD transmission and any adjustments made to the SOPs of photons must be done passively. Test pulses can be propagated through the system, and by compensating the test pulses, the same setting of the polarisation controller will passively compensate the single photon signal.

Polarisation compensation was first addressed by Breguet et al.[15] using two quarter-wave plates to minimise any ellipticity in the SOP introduced by the fibre channel. The orientation axis of the polarisation beam splitter was then adjusted in order to correct for any linear rotations. Automated polarisation compensation in a fibre optic QKD system has been addressed in recent literature. Xavier et al.[16] developed a wavelength division multiplexed (WDM) compensation system using a wavelength separation of 0.8 nm between the reference signal and the quantum channel. The reference signal was counter-propagated through a channel of 8.5 km to reduce the interference to the signal. Two piezoelectric controllers were used to compensate the SOPs in this set-up. A lithium-niobate controller was later used to improve the speed of the system.[17] To test the effectiveness of the system, a polarisation scrambler was introduced into the 16-km quantum channel and the lithium-niobate controller proved effective in controlling fast fluctuations in SOP.

Wu et al.[18] developed a one-way time division multiplexed (TDM) compensation system. In this case, the signal was periodically stopped to allow the polarisation controllers to reset. Two polarisation controllers were used; each controller compensated one of the non-orthogonal bases. The interval time required to reset the controllers varied for the different lengths of the quantum channel, i.e. 50 km, 75 km and 100 km. Chen et al.[19] designed a real-time TDM system which alternated signal pulses and reference pulses using an asymmetric Mach-Zehnder interferometer. A 50-ns time delay was introduced between the signal and the reference and a 50/50 beam splitter was used to separate these signals before reaching the detector. The polarisation compensation was executed using fibre squeezers, controlled by an electronic polarisation controller. The channel length used for this system was 50 km. Ma et al.[20] also developed TDM systems using liquid crystal retarders and piezoelectric controllers. The quantum signal was terminated every 15 min to allow the test signal through the channel. The extinction ratio of the signal was measured and if it was found to be below the accepted threshold, the compensation process was initiated. A step search was utilised to adjust the polarisation controllers and measure the extinction ratio of the signal until the correct settings were obtained. The piezoelectric controllers proved easier to operate because they did not have to be pre-aligned with the polarisation beam splitter. The system presented in this paper improves on the above-mentioned TDM systems by using just one piezoelectric polarisation controller, thereby decreasing both the size and cost of the system.

As mentioned above, a wavelength division multiplexed compensation system can be used to introduce a test signal to the QKD system, but, because of the wavelength-dependence of birefringence effects in fibre, the method of TDM compensation was chosen for this experiment. An SOP stability test was done under laboratory conditions to monitor the change in SOP as a result of standard environmental conditions. The average time for an SOP to change such that the probability of measurement in the correct basis drops by 1% was 332.75 s. Therefore, the test signal must be deployed at least every 333 s in order to ensure an acceptable quantum bit error rate. Of course each environment is different and in order to effectively use the TDM method, an SOP stability test must be done for each new environment in which the system is set up. The duration of the test signal is dependent on the resolution of the compensator used for the system.

Experimental set-up

The experimental set-up is shown in Figure 3. The components for the transmitter in this experiment comprised a pseudo-single photon source and a polarisation state generator. The pseudo-single photon source was provided by a pulsed laser source with a wavelength of 1550 nm, attenuated to simulate the power of a single photon per pulse. The laser pulses were then randomly polarised by a polarisation state generator. The photons were then transmitted through a fixed 1000 m of fibre which served as the quantum channel. The fibres used for the channel and the patchcords were single-mode fibres with a core diameter of 6 μm, unless otherwise stated as PM fibres.

The birefringence effects of the fibre on the SOP of the single photons were then corrected by a polarisation compensator. A half-wave plate was installed after the length of fibre, before the photons were transmitted to a polarisation beam splitter. The half-wave plate served as a means to change the measurement basis of the beam splitter. The fibre between the output of the polarisation compensator and the polarisation beam splitter must be PM fibre to ensure that the state of polarisation is not changed after the compensator makes the necessary corrections. After the polarisation beam splitter, the photons were directed to one of two single photon detectors.

A polarisation locker was used as the automated polarisation controller.[21] This device is a fibre-based controller which includes many internal piezoelectric polarisation controllers driven by varying voltages. Piezoelectric controllers squeeze the fibre optic cables in order to induce a controlled birefringence. An in-line polarimeter and digital signal processor form an internal feedback loop which drives the piezoelectric controllers to produce deterministic SOPs.[21] This device can be pre-programmed so that all output SOPs are adjusted to a constant SOP chosen by the user. The in-line polarimeter monitors the output SOPs and transmits the adjustment commands to the polarisation controller using the feedback loop, enabling the polarisation locker to 'lock' onto a predetermined SOP. The locker can also be operated in manual mode to incrementally adjust the SOP along a grid superimposed onto the Poincaré sphere.

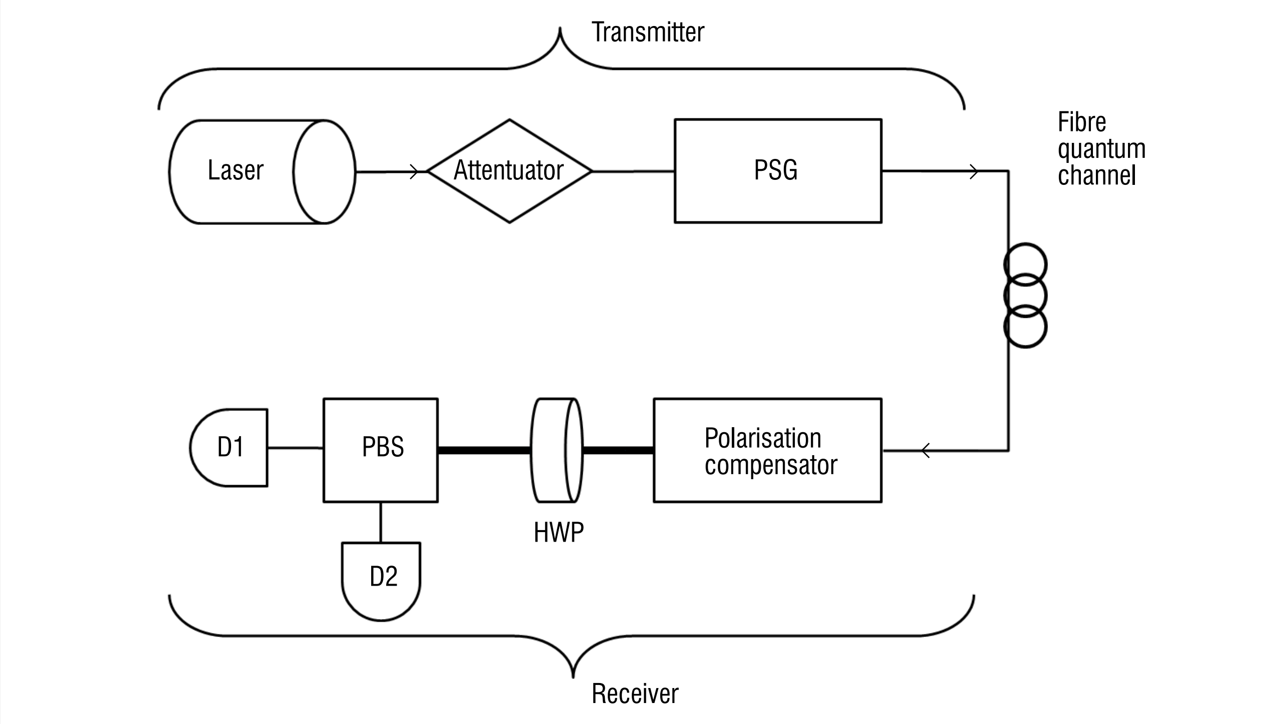


Figure 3: The proposed set-up for a polarisation-encoded quantum key distribution scheme. The laser pulses are first passed through an optical attenuator, which creates pseudo-single photons. Each photon is then assigned a state of polarisation with the polarisation state generator (PSG) and is transmitted through the quantum channel to the receiver. The receiver then uses the polarisation compensator to correct for changes in polarisation. A half-wave plate (HWP) is used to select the basis in which the receiver will measure each photon and, finally, the photons are separated at a polarisation beam splitter (PBS) to be measured at one of two detectors (D1 or D2). The bold lines in the diagram indicate polarisation-maintaining fibre.

Using these functions, the polarisation locker can be employed as an automated compensator for the experimental set-up.

Compensating a single basis

When two orthogonal SOPs undergo the same transformation using a phase retarder, the resulting vectors will also be orthogonal. As an example, a rotation matrix is applied to the Jones vector of a vertical SOP in Equation 5 and its orthogonal state, a horizontal SOP, in Equation 6:

$$\begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \cos\beta \\ \sin\beta \end{bmatrix} \qquad \text{Equation 5}$$

$$\begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} -\sin\beta \\ \cos\beta \end{bmatrix} \qquad \text{Equation 6}$$

The two resulting states are still orthogonal to each other. A similar result can be achieved using the Jones matrix of a quarter-wave plate as well as other sets of orthogonal states.

It is inferred that if a polarisation controller is used to compensate for changes in the vertical SOP, the horizontal SOP will be simultaneously compensated. A similar result is obtained for the diagonal basis. Figure 4a demonstrates the compensation of a vertically polarised signal. The signal was then rotated using a free space polariser such that all linear SOPs were incident on the fibre channel. These measurements show that both the vertical and horizontal states are conserved but all states that were non-orthogonal to the rectilinear basis were not compensated. Figure 4b shows a similar result for diagonal SOPs.

Compensating non-orthogonal bases

The presented scheme, shown in Figure 3, utilises just one polarisation controller, i.e. the polarisation locker, in a TDM system. The single photon signal is periodically stopped in order to deploy a test signal through the quantum channel and apply the appropriate settings to the locker. The test signal propagates a single SOP through the fibre and the locker is set to return the test signal to its original state after its rotation in a birefringent medium. For a vertically polarised test signal, this initial setting would also compensate the horizontal SOP. The same polarisation locker must be used to compensate the diagonal SOPs as well. The locker must therefore isolate the plane on the Poincaré sphere that passes through all four SOPs used in the QKD transmission.

In order to do this, a step search may be utilised for the locker to find the plane on which all four SOPs exist. This is done by rotating the test signal to simulate all linear SOPs and measuring any ellipticity induced by the fibre channel. The locker must be incrementally adjusted in order to eliminate the ellipticity of the test signal, thus returning all SOPs back to their original linear states on the equatorial plane of the Poincaré sphere. This method has been implemented manually for a four-state protocol and the results are shown in Figure 5. In practice, any number of states that form a plane on the Poincaré sphere may be compensated through this technique.

Analysis

The polarisation locker proved effective in reversing the birefringence effects of the fibre channel. The measurements shown in Figure 5 indicate that the polarisation locker can easily be used to minimise the elliptical component of the SOP of any incoming light as well as rotate the SOP linearly so that it returns to its original state. The locker is therefore able to passively compensate all four SOPs simultaneously. Because the polarisation locker is able to lock onto any plane on the Poincaré sphere, the same method can be used to compensate the rectilinear and circular bases as well. The range of the angle of inclination obtained from the above measurements was between $-0.89°$ and $1.69°$, keeping the error rate as a result of the polarisation locker below 0.1%. The angle of inclination may deviate by 5.74° if an error of 1% is allowed. The maximum deviation of the ellipticity of the SOP may therefore be set according to the expected quantum bit error rate of the entire system.

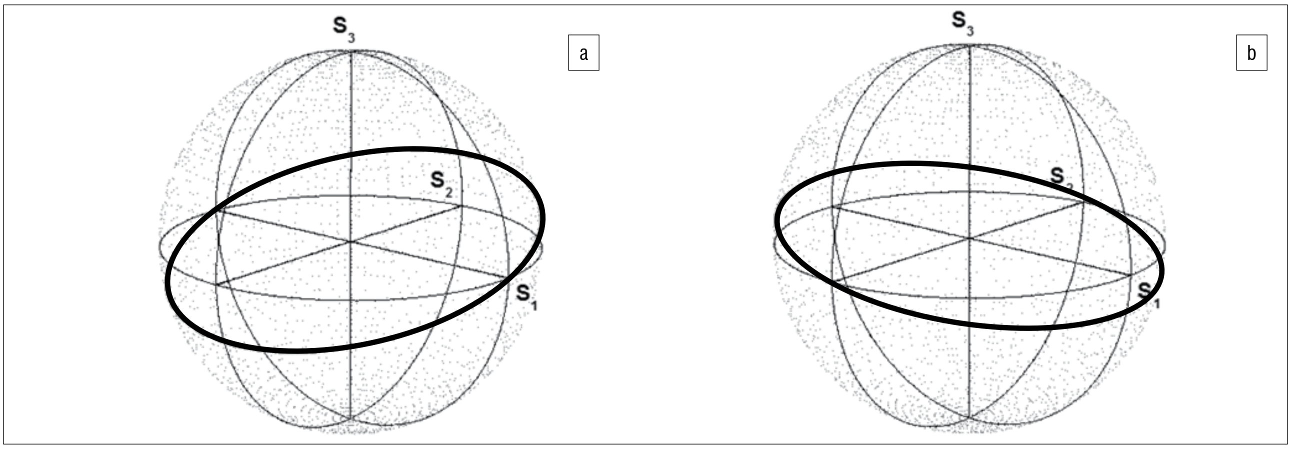


Figure 4: In (a), the bold line shows the measured states of polarisation (SOPs) of the test signal on the Poincaré sphere. The S1 axis represents the rectilinear basis, the S2 axis represents the diagonal basis and the S3 axis represents the circular basis. The measurements show that both the vertical and horizontal SOPs were returned to their original states, even though only the vertical SOP was compensated in this case. Similarly, in (b), both diagonal SOPs were corrected, even though only one of them was compensated for.

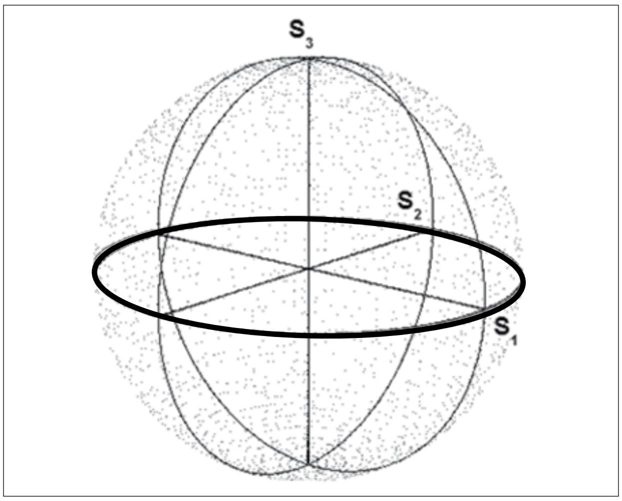


Figure 5: This figure shows the compensation of all four states used in the quantum key distribution protocol using one polarisation controller. The S1 axis represents the rectilinear basis, the S2 axis represents the diagonal basis and the S3 axis represents the circular basis. The bold line in the figure, indicated on the equator of the Poincaré sphere, shows that only linear states of polarisation were measured, thus eliminating any ellipticity induced in the fibre channel.

Conclusion

Birefringence in fibre optic cables creates a bottleneck for polarisation-encoded QKD in metropolitan fibre networks. The negative effects of birefringence were compensated for by monitoring the changes in SOP in real time using a TDM test signal. A polarisation locker was implemented to compensate the states of two non-orthogonal bases simultaneously. A search algorithm can be used to identify the plane on the Poincaré sphere on which both the non-orthogonal bases are located, thereby enabling the compensation of birefringence effects with just one device. Future work will focus on automating the search algorithm and integrating it into the QKD system so that polarisation-encoded QKD can be implemented in fibre.

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Authors' contributions

S.P. was responsible for the experimental conception and design, acquisition of data, analysis and interpretation of data and drafting of the manuscript. A.R.M. was responsible for the experimental conception and design, analysis and interpretation of data and critical review of the manuscript. F.P. was the project leader and was responsible for the study conception and design as well as the critical review of the manuscript.

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