Building a Quantum Wireless Network

Dominic O'Brien [(1)], Andy Schreier[(1,2)], Vincent Lee[(1)]

[(1)] Department of Engineering Science, University of Oxford, dominic.obrien@eng.ox.ac.uk
[(2)] Now with Fraunhofer Institute for Telecommunications Heinrich Hertz Institute, Berlin, Germany

Abstract *Quantum Key Distribution (QKD) over optical fibres is a well-established area of research. Extending the reach of QKD using optical wireless links is less studied, however. This paper outlines some results from recent experiments, and methods to integrate wireless and wired QKD approaches.*

Introduction

Quantum key distribution is a maturing area of telecommunications research, and there are a number of deployed commercial systems and networks that offer QKD secured data transmission. Work in free-space QKD is less well-developed, although there is significant work on long range links between satellites or between satellites and ground stations and some shorter range examples. There have been relatively few investigations of indoor QKD systems, however. In [1, 2] an analysis of an indoor system is undertaken and in [3-5] short range handheld QKD systems demonstrations are reported. There has also been work on transmitting light from optical fibres through free-space in indoor environments (see for instance [6-8]) and these can be adapted to transport QKD signals. Such systems typically collimate light from a single-mode fibre and steer the resulting collimated beam through free-space to a collimator which then couples light into a destination fibre. Pointing and tracking to with 0.01 degrees or so is required for typical collimators and fibres. In [7] such a system is described.

The broad challenges for free-space QKD are to control path loss, and to mitigate the effects of ambient light. In this paper these challenges are outlined, and several demonstration systems that address these are presented, together with potential future directions.

Challenges for indoor QKD

Ambient light mitigation

In free-space communications ambient light can enter the aperture of the quantum receiver and swamp the desired signal. This effect can be mitigated by (i) minimising the field of view of the receiver, (ii) minimising its optical bandwidth, (iii) minimising the signal detection temporal window by using short transmitting pulses thus minimising the number of ambient light photons detected, and (iv) choosing a wavelength where the interfering radiation has low intensity. Fig. 1 shows the ASTM AM1.5 solar irradiation spectrum for sunlight received at the surface of the earth, converted to the number of photons/second/nm/sq.m vs wavelength. It can be seen that there are particular wavelengths where atmospheric absorption reduces the intensity of sunlight substantially. There are several regions worthy of investigation. Sunlight is completely absorbed by the atmosphere at wavelengths below 280 nm. Also, at ~ 1370 nm there is an absorption band due to water in the atmosphere, and the counts from solar radiation are ~50 dB lower than at visible wavelengths. Operating a QKD system in both these wavelength regimes is possible if the link length is much shorter than the path length that any interfering radiation travels from its source to the QKD receiver (see [9] for more details).

Fig. 2 shows a bench top demonstration of a QKD system operating at 1370 nm. This system deploys a polarisation based BB84 protocol and operation has been demonstrated over a 20 cm path. Currently, there is no steering and tracking unit included as the investigation focused on robustness to ambient light.

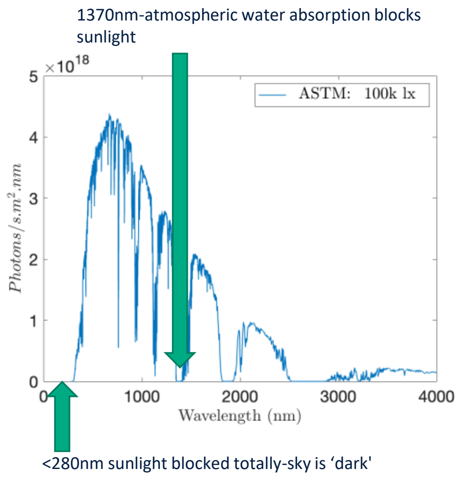

Fig. 1. Spectrum of sunlight

This system uses a 10 nm wide spectral filter centred at 1370 nm, with single-mode fibre coupled detectors to reduce the receiver field of view to ~0.01 degree. Preliminary results indicate that a key rate of 2 kilobits per second can be achieved under an illumination equivalent of direct sunlight (~100000lux).

An alternative approach is to use UV wavelengths, which is likely to be considerably more challenging, due to the availability of suitable sources and detectors. A study to investigate such systems is underway [10].

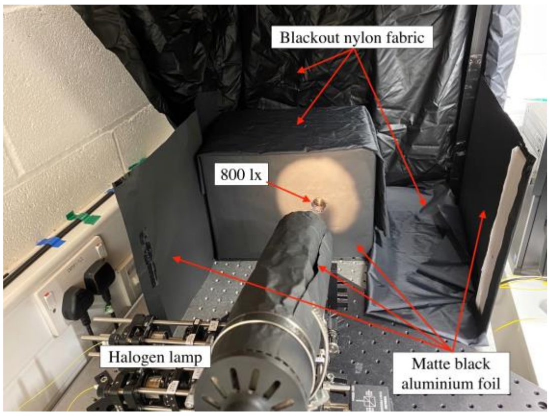

Fig. 2. BB84 bench top system receiver operating at 1370 nm. The halogen lamp illuminates the receiver and creates 1370 nm interference equivalent to 100,000 lux sunlight.

Minimising path loss

Low path loss free-space links are typically achieved using narrow beams of radiation, and together with the requirement to minimise field of view in order to reduce the effect of ambient light, these constraints create challenging tracking requirements. QKD has been implemented over links from 1-10m broadly using two approaches; (1) create custom transmitter and receiver subsystems, incorporating tracking and pointing and (2) using fibre-fed terminals and using commercial QKD systems.

In the following sections a brief outline of these is given.

Handheld QKD systems

Short-range (<1m) links between terminals where either one or both terminals are handheld presents challenging Pointing Acquisition and Tracking (PAT) requirements. The system shown in Fig. 3 meets these requirements and uses a 6 polarisation reference frame independent QKD scheme to provide tolerance to rotational misalignment. (This work was a collaboration between Nokia, Bay Photonics, and the University of Oxford.) Details of its implementation can be found in [3]. The transmitter uses light from 6 resonant cavity LEDs, which is polarized and combined, then spectrally and spatially filtered to ensure indistinguishability. Light from this transmitter is steered by a MEMS mirror and propagates through free space to a receiver. The receiver uses another MEMS mirror to steer the QKD signal to a QKD receiver. This separates the incoming light into 6 polarisations, and the resulting optical signals are then coupled to SPADs via optical fibres light. Both transmitter and receiver have LED-based beacons which are co-aligned with the QKD beam. Position sensitive detectors (PSD) are used to control the steering of the MEMS

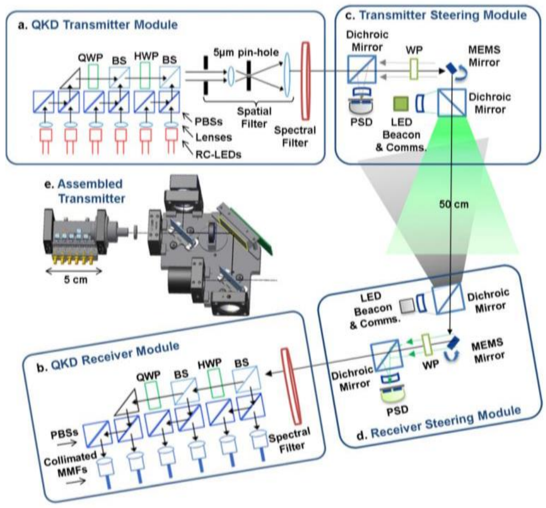

Fig. 3. Diagram of handheld QKD system

mirrors.

This steering system is symmetrical, with tracking and steering implemented at both ends of the link. This is undesirable where a low-cost terminal is required, so work to create a ‘quantum ATM’ that would enable a QKD link to a simple terminal was undertaken. This is a collaboration between the University of Bristol and Oxford. Fig. 4 shows a block diagram of the system. The handheld terminal uses a BB84 protocol, implemented using resonant cavity LED sources operating in the red region of the optical spectrum. The terminal also has a co-aligned green beacon that the user can use as pointing aid, and a ring of infrared LEDs to aid rapid initial setup of the link.

The ‘ATM’ uses three tracking systems, using the LEDs and a camera to initially align a coarse and fine pointing mirror. Tracking is then undertaken using the green beacon and two PSDs that control coarse and fine pointing systems, respectively [11].

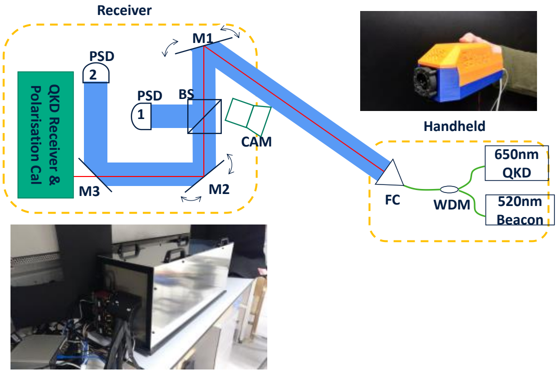

Fig. 4. Block diagram of quantum ATM system

Both systems described above are well suitable for point-to-point approaches but do not offer an easy interface to any other fibre system. Fig. 5 shows a fibre – free-space – fibre terminal system. Each terminal takes light from an optical fibre and converts it to a collimated beam. Mirror based beam steering is used to direct this beam to a distant terminal which couples light from free space into an optical fibre. Such terminals provide bidirectional transparent communication and can support both classical and quantum data transmission. Full details of the terminals can be found in [7]. An experiment was undertaken at the University of Bristol, linking their fibre-based QKD and classical systems with a free-space segment. Full details are reported in [8]. Overall, transmission of 1.6Tbit/s classical data combined with a QKD channel operating with a secret key rate of several kbit/s was demonstrated.

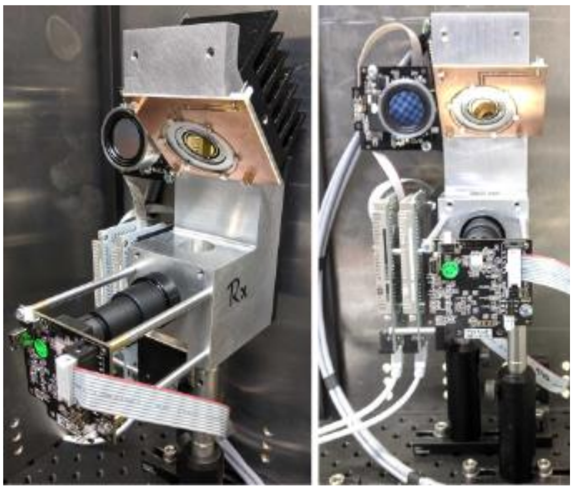

Fig. 5. Beam steering system terminals. The transmitting and receiving apertures can be seen at the top of the system.

Future directions and conclusions

The ultimate QKD network would combine free-space and fibre transmission, for both long and short free-space links. The limited loss allowed in QKD and the trade-off between rate and loss make such networks very challenging to implement. In the short-term combining passive optical networks with short-range optical wireless links is a promising direction. In the longer term, entanglement distribution with quantum repeater nodes may offer a means to secure communications over extended networks. Such work is at an early stage however.

Overall, the work shown here shows that indoor quantum wireless links can be made robust to sunlight and terminal movement, and that fibre QKD systems can support limited free-space propagation and still operate. Securing wireless networks using QKD, and a broader network that can distribute entanglement are long term goals, and enabling work is underway, both at Oxford and elsewhere.

Acknowledgement

This work received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 820474 (project UNIQORN) and agreement No. 761329 (project WORTECS); The UK EPSRC / UKNQTP via The Quantum Communications Hub (EP/M013472/1 and EP/T001011/1) and the UK EPSRC project COALESCE (EP/P003990/1). The authors would also like to acknowledge the numerous contributions of the optical wireless group at Oxford to the various systems shown in this paper.

References

[1] O. Elmabrok and M. Razavi, "Feasibility of Wireless Quantum Key Distribution in Indoor Environments," in *2015 IEEE Globecom Workshops (GC Wkshps)*, 6-10 Dec. 2015 2015, pp. 1-2, doi: 10.1109/GLOCOMW.2015.7414112.

[2] O. Elmabrok and M. Razavi, "Quantum-Classical Access Networks with Embedded Optical Wireless Links," in *2016 IEEE Globecom Workshops (GC Wkshps)*, 4-8 Dec. 2016 2016, pp. 1-6, doi: 10.1109/GLOCOMW.2016.7849014.

[3] H. Chun, I. Choi, G. Faulkner, L. Clarke, B. Barber, G. George, C. Capon, A. Niskanen, J. Wabnig, D. O'Brien, and D. Bitauld, "Handheld free space quantum key distribution with dynamic motion compensation," *Opt. Express,* vol. 25, no. 6, pp. 6784-6795, 2017/03/20 2017, doi: 10.1364/OE.25.006784.

[4] D. Lowndes, S. Frick, B. Harrington, and J. Rarity, "Low cost, short range quantum key distribution," in *2017 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, 25-29 June 2017 2017, pp. 1-1, doi: 10.1109/CLEOE-EQEC.2017.8087424.

[5] G. Vest, P. Freiwang, J. Luhn, T. Vogl, M. Rau, L. Knips, W. Rosenfeld, and H. Weinfurter, "Quantum key Distribution with a Hand-Held Sender Unit," *Physical Review Applied,* vol. 18, no. 2, p. 024067, 08/25/ 2022, doi: 10.1103/PhysRevApplied.18.024067.

[6] A. Gomez, K. Shi, C. Quintana, R. Maher, G. Faulkner, P. Bayvel, B. C. Thomsen, and D. O'Brien, "Design and Demonstration of a 400 Gb/s Indoor Optical Wireless Communications Link," *Journal of Lightwave Technology,* vol. 34, no. 22, pp. 5332-5339, 2016, doi: 10.1109/JLT.2016.2616844.

[7] R. Singh, F. Feng, Y. Hong, G. Faulkner, R. Deshmukh, G. Vercasson, O. Bouchet, P. Petropoulos, and D. O'Brien, "Design and Characterisation of Terabit/s Capable Compact Localisation and Beam-Steering Terminals for Fiber-Wireless-Fiber Links," *Journal of Lightwave Technology,* vol. 38, no. 24, pp. 6817-6826, 2020, doi: 10.1109/JLT.2020.3022754.

[8] A. Schreier, O. Alia, R. Wang, R. Singh, G. Faulkner, G. Kanellos, R. Nejabati, D. Simeonidou, J. Rarity, and D. O'Brien, "Coexistence of Quantum and 1.6 Tbit/s Classical Data Over Fibre-Wireless-Fibre Terminals," *Journal of Lightwave Technology,* pp. 1-7, 2023, doi: 10.1109/JLT.2023.3258146.

[9] V. Lee, A. Schreier, and D. O'Brien, "Towards the engineering of a Quantum Key Distribution receiver robust to ambient light," in *SPIE Photonex, 2022*, 2021/10/06/ 2022, vol. 11881: SPIE, doi: 10.1117/12.2603355.

[10] F. Liu, A. Schreier, G. Faulkner, J. Farmer, and D. O'Brien, "Towards Short-Range Wireless Quantum Key Distribution at UVC," in *Submitted to ECOC 2023*, 2023.

[11] A. Schreier, J. Sagar, D. Lowndes, H. Chun, S. K. Joshi, G. Faulkner, J. Rarity, and D. O'Brien, "A Beam Steering Platform Enabling Handheld Low-Cost Quantum Key Distribution," in *Submitted to ECOC 2023*, 2023.