UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

UK QUANTUM TECHNOLOGY HUB

FOR QUANTUM COMMUNICATIONS TECHNOLOGIES

ANNUAL REPORT

2014 2015

QUANTUM
COMMUNICATIONS
HUB

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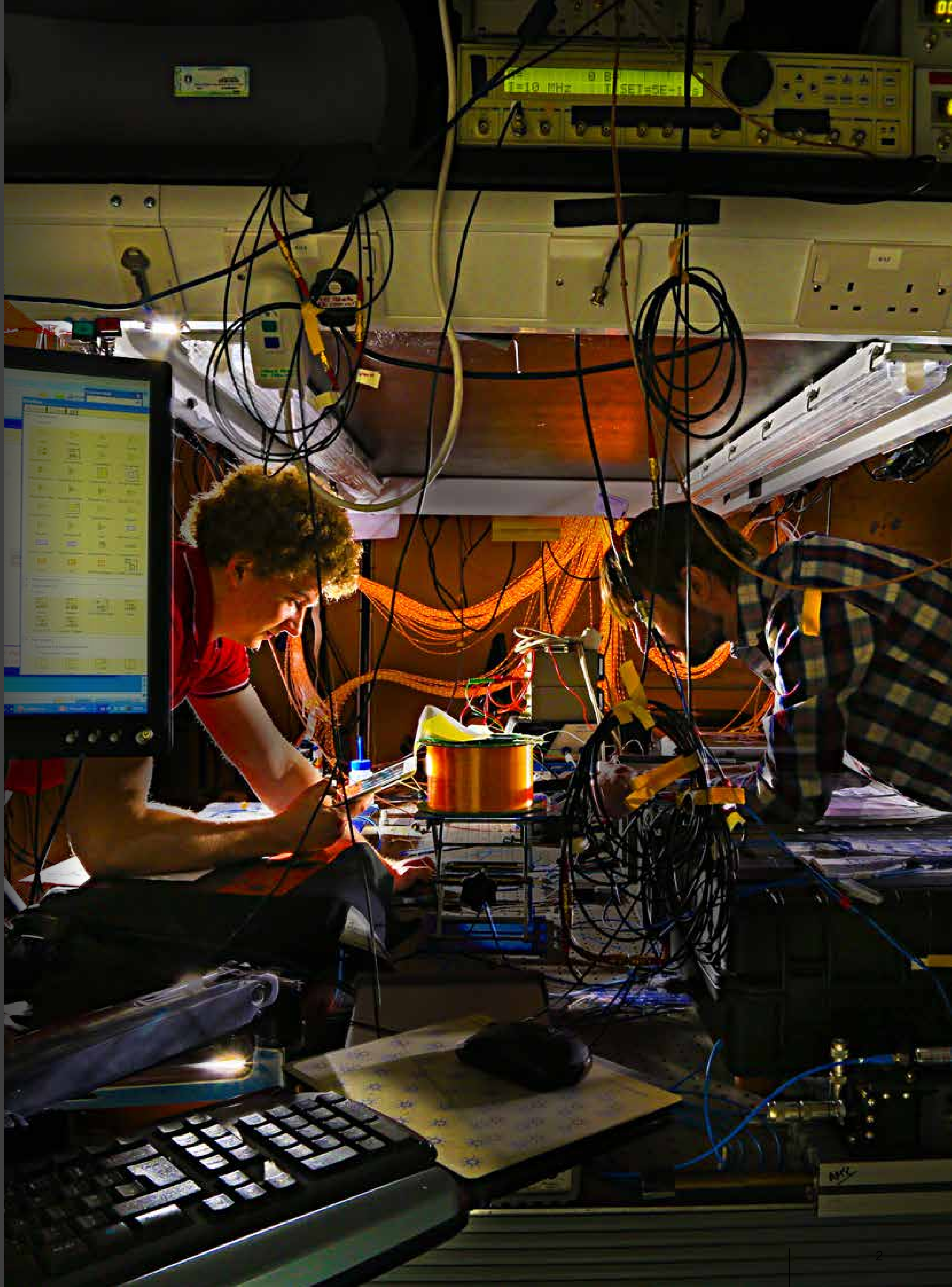

Foreword

The UK National Quantum Technologies Programme has been established to turn the results of world-leading scientific research into actual technologies. In the Quantum Communications Hub, it is our job to do this in the secure communications sector. In this sector some technologies and demonstrators already exist, so the goal of the Hub is to advance these, to overcome current limitations and also to develop new technologies and services – opening up new markets and enabling widespread adoption and use.

Security of information, in transit, in storage and in the future, is of crucial importance for everyone; from individuals and companies through to institutions and government. The Hub is developing technologies for all these end-users, and our work puts the UK in a very strong position in this technology sector – giving us a leading role in future European and international activities.

This report summarises progress during the first year of the Quantum Communications Hub, and outlines ongoing and future directions.

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Professor Timothy P. Spiller, MA PhD CPhys FInstP
Director, UK Quantum Technology Hub for Quantum Communications Technologies
Director, York Centre for Quantum Technologies

Introduction

The UK National Quantum Technologies Programme (UKNQTP) is a UK Government initiative designed to support translation of quantum science into commercial technological applications. The aim is to turn world-leading science into new technologies and services, creating catalysts for new markets, thus boosting the UK economy and resulting in demonstrable effects across all spheres of everyday life. Unlike previous investments in what are perceived as emerging and promising new areas for growth, the focus of this particular programme is on technological development and commercialisation, rather than generation of new science. This approach is based on the strength of the UK's academic leadership in quantum science, coupled with the acknowledgment of the timeliness of technological advances in this area. Progress in quantum research over the last two decades has meant that understanding of the potential implications of quantum theory for technological development is mature enough in many cases to the extent that envisaged applications tend to constitute engineering, rather than theoretical challenges.

Announced in 2013 by the then Chancellor of the Exchequer, the programme was launched as an original investment of £270m over five years. The programme comprised a wide-ranging portfolio of schemes, including further investment into existing Centres for Doctoral Training (CDTs) in quantum science and technologies; numerous research fellowships; a newly launched Quantum Metrology Institute (QMI) hosted at the National Physical Laboratory (NPL) site in Teddington, near London; capital allocations to boost existing projects; and various training and skills hubs to train the next generation of quantum technologists.

The most substantial investment (of £120m) and the centrepiece of the programme has been the creation of a national network of four quantum technology Hubs. Each Hub was a collaboration of industry and research, led by a single university, and directed at the transition from science to technology across four main areas: sensors and metrology (Birmingham); quantum enhanced imaging (Glasgow); quantum computing (Oxford); and quantum communications (York).

The UKNQTP is administered by a partnership of national stakeholders: the Engineering and Physical Sciences Research Council (EPSRC); the Department for Business, Innovation & Skills (BIS); the Defence Science and Technology Laboratory (Dstl); the Government Communications Headquarters (GCHQ); Innovate UK; the Knowledge Transfer Network (KTN); and the National Physical Laboratory. Further information about the UKNQTP is available in the programme website: http://uknqt.epsrc.ac.uk

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UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

UK National Quantum Technology Hub Sensors and Metrology

NQIT Networked Quantum Information Technologies

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QUANTUM COMMUNICATIONS HUB

Vision

The Quantum Communications Hub is a synergistic partnership of eight UK Universities, numerous private sector companies, and public sector bodies that have been brought together in a unique collaboration to exploit fundamental laws of quantum physics for the development of secure communications technologies and services. The main aim of this Hub is to deliver practical secure communications, by exploiting the commercialisation potential of existing prototype quantum technologies beyond their current limitations; to contribute to the establishment of a quantum communications technology industry for the UK; and to feed its future expansion, competitiveness, diversification and sustainability.

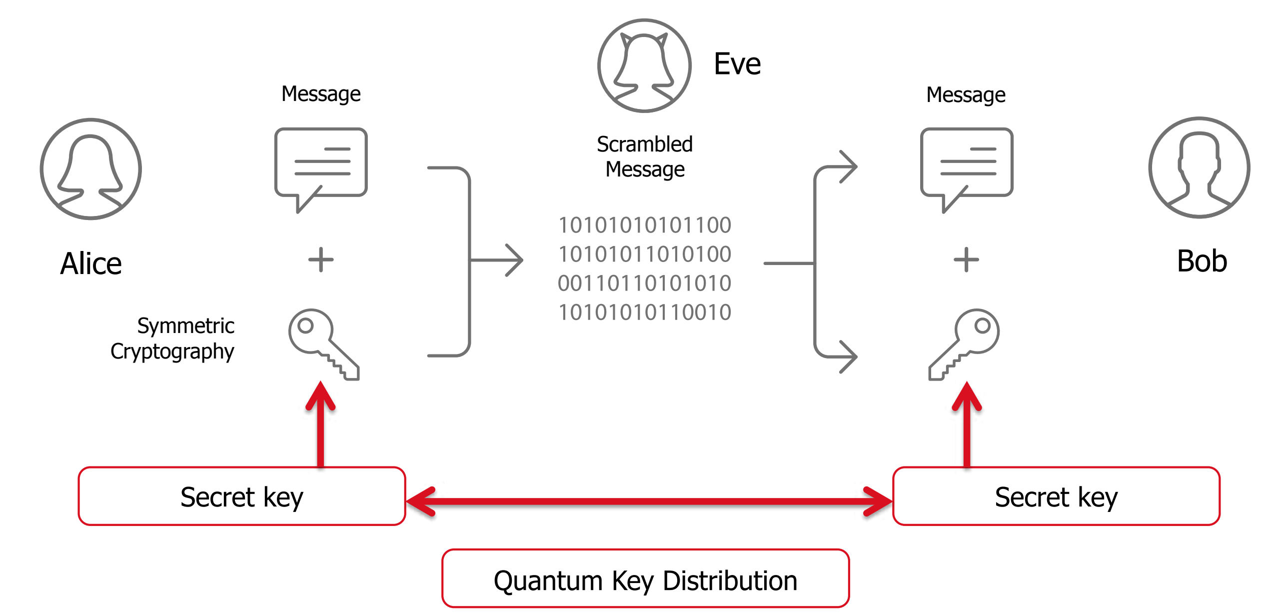
Security in communications and transactions underpin our entire digital economy and applications of the new technologies would span many different sectors. For example, finance and banking, but also Government departments and other organisations involved in the storage and transmission of sensitive data – passwords, biomedical records, social security information, passport and ID card details, employee data, defence intelligence and so on. All would benefit from secure communications that are known to be safe against future developments of other quantum technologies. The project aims to deliver quantum encryption systems that will enable secure transactions and transmissions of data across a range of users in real-world applications: from government and industry to commerce and the wider public.

Quantum Key Distribution

Fundamental to the Hub's objectives is Quantum Key Distribution (QKD), a currently available technology for the secure distribution of secret keys, which can be used for data encryption and other applications. Standard communication scenarios usually involve transmitter and receiver units, traditionally described as "Alice" and "Bob" respectively. Quantum physics dictates that at the scale of individual particles (such as photons which are the particles that comprise light), their quantum properties cannot be measured without being unavoidably and irrevocably disturbed from their original state. This means that no interceptor (or hacker – routinely described as "Eve" in such scenarios) can eavesdrop on quantum transmissions, without their presence becoming known to Alice and Bob. This principle can be described as quantum uncertainty and it underpins all current work in the field of quantum secure communications.

Although immediately detectable, the presence of an eavesdropper can still be disruptive, for example through denial of service attacks. When service is not denied, Alice and Bob need to be sure that only they know this "key". QKD systems generate such shared secret keys which can be used for data encryption and other applications. The uses and applications of these keys are based on conventional communication techniques; however, their generation, distribution and replenishment is underpinned by quantum uncertainty, thus offering to any two communicating parties security based on the laws of quantum physics.

QKD Application in High Data-rate Encrytped Communications



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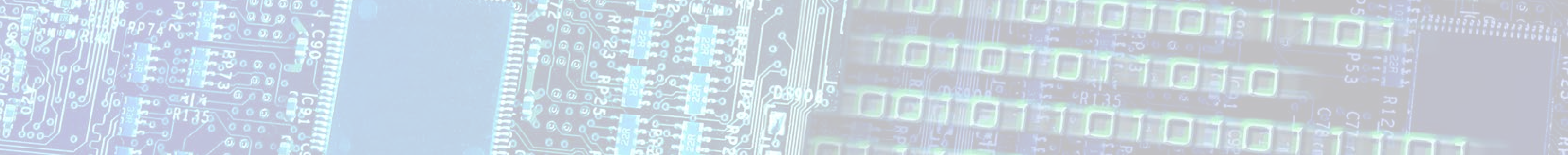


Technology Themes

The Quantum Communications Hub programme of work has been divided across four interlinking themes or work packages (WPs). WPs 1 to 3 aim to advance commercialisation of existing prototype technologies, through the delivery of affordable, practical and compatible products, addressing current technology limitations and opening up new markets. WP4 aims to provide alternatives to existing solutions by testing and investigating the potential of "next generation" quantum communications technologies - beyond basic key distribution.

1. Short-range, Free-space QKD

The central aim in this strand of the Hub's work is the miniaturisation of the Alice (and to some extent, also Bob) units for the easy generation and transmission of secret keys during everyday routine secure transactions. QKD technology is being built into hand-held, credit card-sized "reader" units or pads, or into mobile phones, along the lines of existing PIN generators. Such portable Alice devices will enable many users (consumers) to share quantum keys with a service provider, via a larger, wall mounted Bob - receiver - unit (e.g. incorporated into an ATM unit, for customers sharing keys with a bank or other financial institution). Transmission will take place in free-space, i.e. wirelessly. Such miniaturisation addresses issues of affordability (a current criticism of existing QKD technologies, which can be prohibitive in cost for individual users), and of course practicality – both leading to wide-use consumer applications.

The actual use of the keys isn't quantum, so these keys can be used (once) for subsequent transactions over the internet, or by telephone. Recent research has also demonstrated the potential of standard mobile phone cameras to generate truly quantum random numbers, when operated at the limit of their sensitivity. The Hub is exploring this and other schemes that could allow secure key sharing between a phone and a terminal with minimal modifications to the existing phone hardware.

2. Chip-scale QKD Technology

The use of optical technologies (photonics) has transformed high-speed communications and data transmission. However, much of this technology remains bulky, cumbersome and power-hungry, with barriers to mass manufacture and wide market appeal. The focus of the Hub's work here is incorporation of QKD technologies (the Alice transmitter and the Bob receiver units) onto microchips; delivering compact, lightweight, robust, low-cost, low-energy devices, for mass manufacture and widespread deployment.

This novel approach will open up new market opportunities, large volume manufacture, integration with existing optical networks, mobile applications and computing technologies (e.g. through incorporation of the chips onto mobile phones or laptops), and offers the potential for mass market penetration, with the ultimate aim of making quantum secure communications available to the general public. Through the use of state-of-the-art photonic engineering tools and techniques, and a focus on materials such as Indium Phosphide (InP) and Silicon (Si), the Hub is developing QKD optics approximately 103 smaller than those available today. These are being fabricated through commercial foundry services, compatible with low-cost, high-yield, mass manufacturing – enabling rapid prototyping and reduced time-to-market.

3. Quantum Communications Networking

The migration of QKD technology onto microchip-scale products, and their subsequent incorporation into mobile telephony and computing devices will further lead to quantum secure networking. This is the remit of the third strand of the Hub's programme of work, which will result in establishment of the UK's first quantum network (the UKQN). The UKQN will incorporate access- (many individual users connected to one node), metro- (city scale, with multiple connections) and backbone (city to city) network structures. Integration of QKD into existing communication networks, essential for widespread commercial application, will be a feature of the UKQN – building upon recent high profile demonstrations of this by Hub partners. Local metro-networks are being built in Bristol and Cambridge and these will be connected in the UKQN utilising the National Dark Fibre Infrastructure Service (NDFIS).

The NDFIS currently links the universities at Bristol, Cambridge, Southampton and UCL via London, with a planned (shared) extension to the National Physical Laboratory in Teddington, as well as to other key sites in the UK in the longer term. The UKQN will be a test-bed for the technologies developed in this and other Hubs, as well as facilitating exploration of new theoretical approaches, applications, protocols, standards and services, and implementation of next generation quantum communications, beyond QKD. Crucially, the UKQN will be a showcase for user engagement and demonstrations – for stakeholders, customers and the wider public.

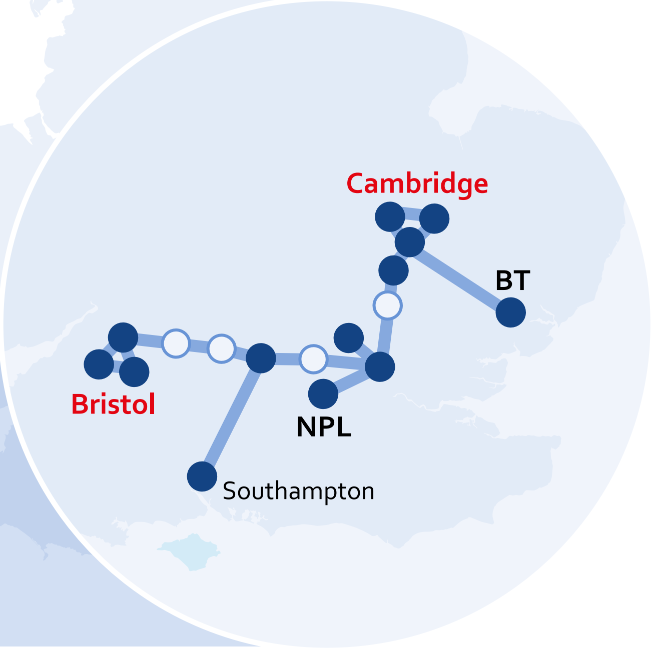
4. Next Generation Quantum Comms

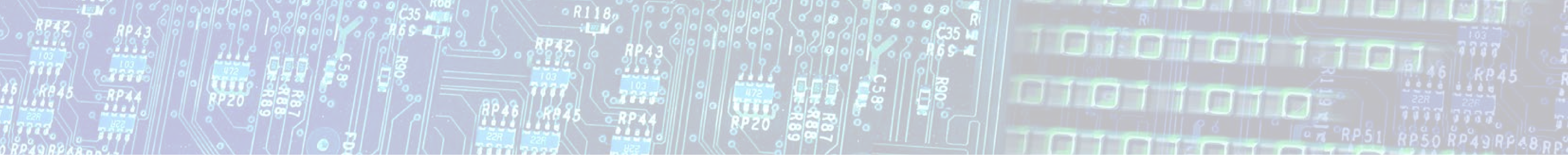
The final strand of the Hub's work focuses on creating technology prototypes from successful laboratory experiments. A number of such options have already been investigated at the scientific level, but few have been tested in real-life scenarios.

Establishment of the UKQN provides an ideal facility for these alternative propositions to be explored and their true potential to be evaluated. Early options include: Quantum Digital Signatures (used to ensure the integrity of messages), quantum repeaters (special "amplifiers", to extend the physical range of QKD); Measurement Device Independent Quantum Key Distribution (a more sophisticated version of QKD, which addresses some of the vulnerabilities arising from current practical limitations). These all complement or extend the capabilities of available qkd technologies, and whose application, development and market potential the Hub is exploring.

NDFIS & The UKQN

- NDFIS key to Hub's UK Quantum Network
- Inter-working with multiple QKD systems
- Connection of Bristol and Cambridge over NDFIS
- Future extensions to NPL and BT Adastral Park





The Partnership

The Hub is led by the University of York, with Professor Tim Spiller as Director. The consortium draws together expertise from a range of partners: academic institutions (the Universities of Bristol, Cambridge, Heriot-Watt, Leeds, Royal Holloway, Sheffield, Strathclyde and York); industrial organisations such as ADVA Optical Networking, Airbus Defence & Space, British Telecom, ID Quantique, L3 TRL Technology, Oclaro, Toshiba Research Europe Ltd. (TREL), and including start-ups such as Cryptographiq and Qumet. The National Physical Laboratory (NPL), the UK's world-leading national measurement institute, is also a Partner. Collaboration on standards and policy is with CESG and ETSI. Engagement with end-users is supported by a number of public bodies, including Bristol City Council and, through their network, the Knowle West Media Centre; Cambridge Network Ltd and Cambridge Science Park. The National Dark Fibre Infrastructure Service (NDFIS) provides access to research partners Bristol, Cambridge and NPL.

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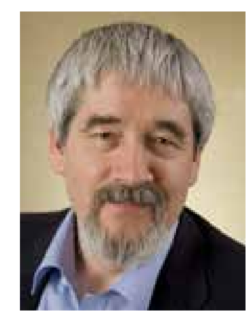
Strategy, Advice, Leadership

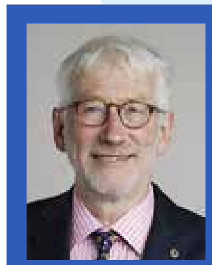


Professor David Delpy, CBE FRS FMedSci FREng. Chair of the UK National Quantum Technologies Programme Strategic Advisory Board.

Dr Martin Sadler, OBE Vice President, Hewlett Packard Labs. Chair of the Quantum Communications Hub Extermal Advisory Board.

Tim Spiller, MA PhD CPhys FInstP, is Professor of Quantum Information Technologies at the University of York, founding Director of the recently launched York Centre for Quantum Technologies, and Director of the Quantum Communications Hub. Prior to this appointment he was at the University of Leeds in the roles of Head of the Quantum Information Group and Director of Research for the School of Physics and Astronomy. Prior to 2009, Spiller was Director of Quantum Information Processing Research at HP Labs Bristol – an activity that he established in 1995 – and a Hewlett-Packard Distinguished Scientist. He has spent 30 years researching quantum theory, superconducting systems and quantum hardware and technologies. He led HP's strategy on the commercialisation of QIP research, and is an inventor on 25 patents linked to quantum technologies and applications.

The Work Packages



Short-range, free-space QKD

Work Package 1

led by Professor John Rarity, MSc PhD FRS, University of Bristol

John Rarity is Professor of Optical Communications Systems and Head of the Photonics Group in Electrical and Electronic Engineering at Bristol. He is a founding father of QT, including the first experiments in path entanglement, QKD, multiphoton interference and quantum metrology, recognised by the 1994 IoP Thomas Young Medal. He has been reviewer/advisor for EU projects and prestigious international projects. He has contributed to the formation of QT research in Europe through various advisory panels (Pathfinder, ACTS), and has led EU consortia, and teams in several large projects. He and colleagues were awarded the Descartes Prize in 2004 for the project QuComm. He has published >120 papers with >9000 citations. He holds an ERC Advanced fellowship, and in 2015, was elected a Fellow of the Royal Society.

Mark Thompson is Professor of Quantum Photonics, Director of the Quantum Engineering Centre for Doctoral Training at Bristol and Deputy Director of the Centre for Quantum Photonics. He holds an EPSRC Early Career Fellowship and is pioneering the emerging field of silicon quantum photonics. He has over five years industrial experience in photonics, working with Corning Cables Ltd, Bookham Technology Ltd and Toshiba, and was awarded the 2009 Toshiba Research Fellowship. He is world-leading in the development of advanced integrated quantum circuits, and was awarded the 2013 IET researcher award for his contribution to this field.

Chip-scale QKD

Work Package 2

led by Professor Mark Thompson, MSc PhD, University of Bristol

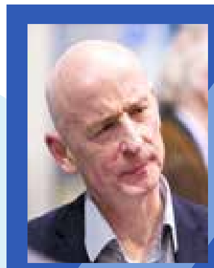
Quantum communications networking

Work Package 3

led by Dr Andrew Shields, PhD FIoP FREng, Toshiba Research Europe Ltd.

Andrew Shields is Assistant Managing Director at TREL Cambridge Research Laboratory. He directs Toshiba's R&D in Quantum Information Technology, heading a world-class team of around 30 scientists and engineers. He has extensive experience of leading large EU programmes in quantum technologies, and in particular QKD network technology development and quantum-device work for long-distance quantum communications.
He is the Chair and co-founder of the Industry Specification Group for Quantum Key Distribution of ETSI (the European Telecommunications Standardisation Institute). In 2013, he was elected a Fellow of the Royal Academy of Engineering and awarded the Mott Medal by the IoP.

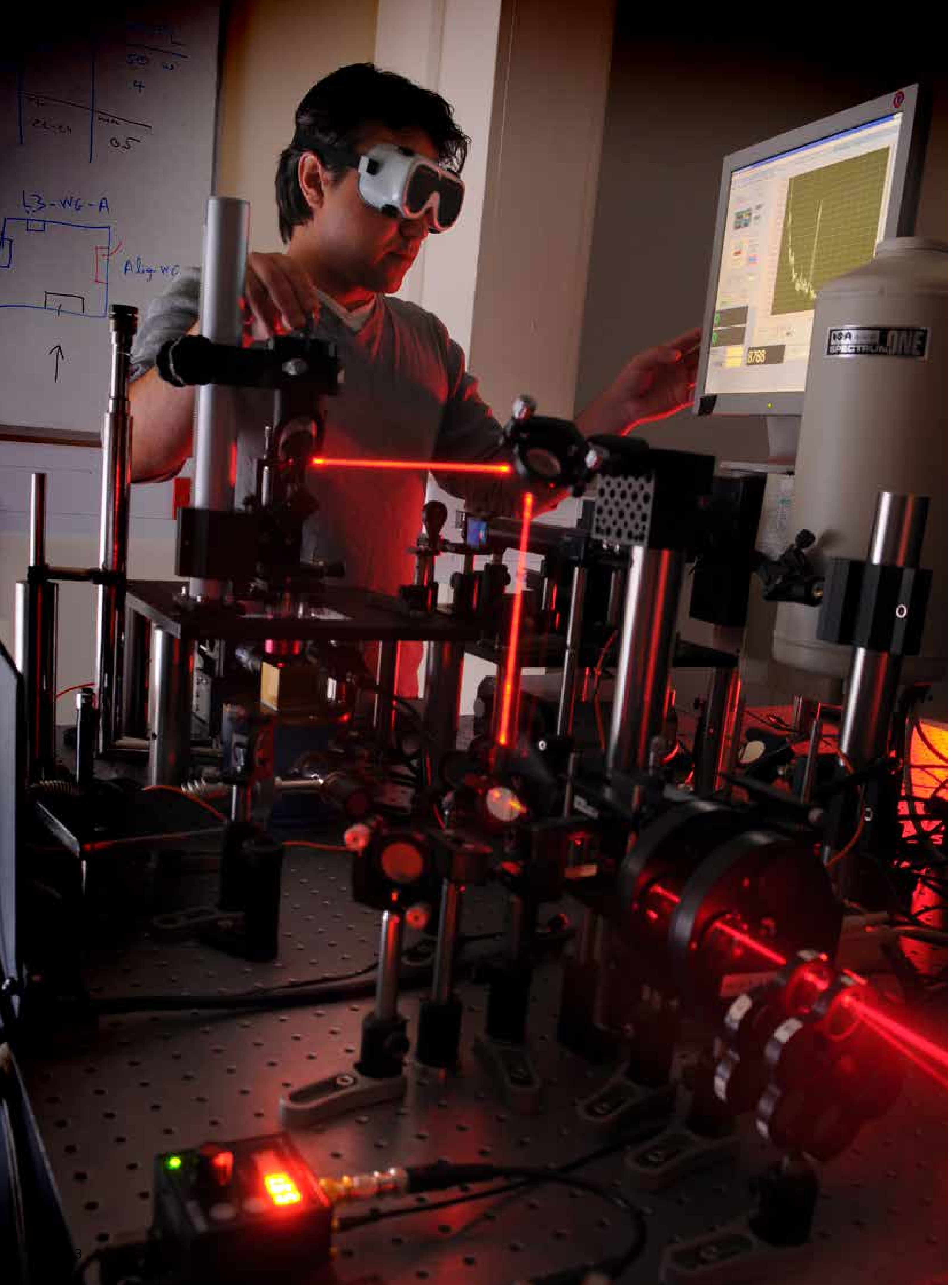
Gerald Buller is Professor of Physics and has served as founding Head of the Photonics and Quantum Sciences Research Institute at Heriot-Watt University. He has worked in single-photon physics for over 20 years and in quantum communication systems for over 15. He has led experimental teams which demonstrated the first fibre-based GHz QKD scheme in 2004 and the first quantum digital signatures scheme in 2012. He has been PI on a range of collaborative research projects funded by the EU, European Space Agency, DSTL, QinetiQ, CERN, etc., including the EQUIS European collaboration. In 2015, he was awarded an EPSRC Established Career Fellowship in Quantum Technology.



Next generation quantum communications

Work Package 4

led by Professor Gerald Buller, PhD FIoP FRSE, Heriot-Watt University



The Project Team

Includes, in addition to the Senior Co-Investigators listed below, 21 Research associates, 16 PhD students, a business development manager, project co-ordinator and support staff at partner institutions.

University of Bristol
- Dr Christopher Erven
- Dr Anthony Laing
- Dr Reza Nejabati
- Professor Dimitra Simeonidou

Royal Holloway University of London
- Professor Kenny Paterson

University of Cambridge
- Professor Richard Penty
- Professor Ian White
- Dr Adrian Wonfor

The University of Sheffield
- Dr Pieter Kok

Heriot Watt University
- Professor Erika Andersson
- Professor Brian Gerardot

University of Strathclyde Glasgow
- Professor John Jeffers

University of Leeds
- Dr Mohsen Razavi
- Professor Ben Varcoe

University of York
- Professor Samuel Braunstein
- Dr Roger Colbeck
- Dr Stefano Pirandola

BT
- Dr Andrew Lord

Toshiba Research Europe Ltd.
- Dr Andrew Shields

NPL National Physical Laboratory
- Dr Christopher Chunnilall
- Dr Alastair Sinclair

Governance

Management

The Hub is led by the Director, supported by the four senior Work Package leads through a Hub Management Team (HMT). The Hub's Business Development Manager and Project Coordinator, both reporting to the Director, are also part of the HMT as non-voting members. The HMT normally has monthly minuted meetings, which monitor progress, request/receive reports and discuss/address arising issues. Standing items on the agenda include new developments, and monitoring of progress against formal targets.

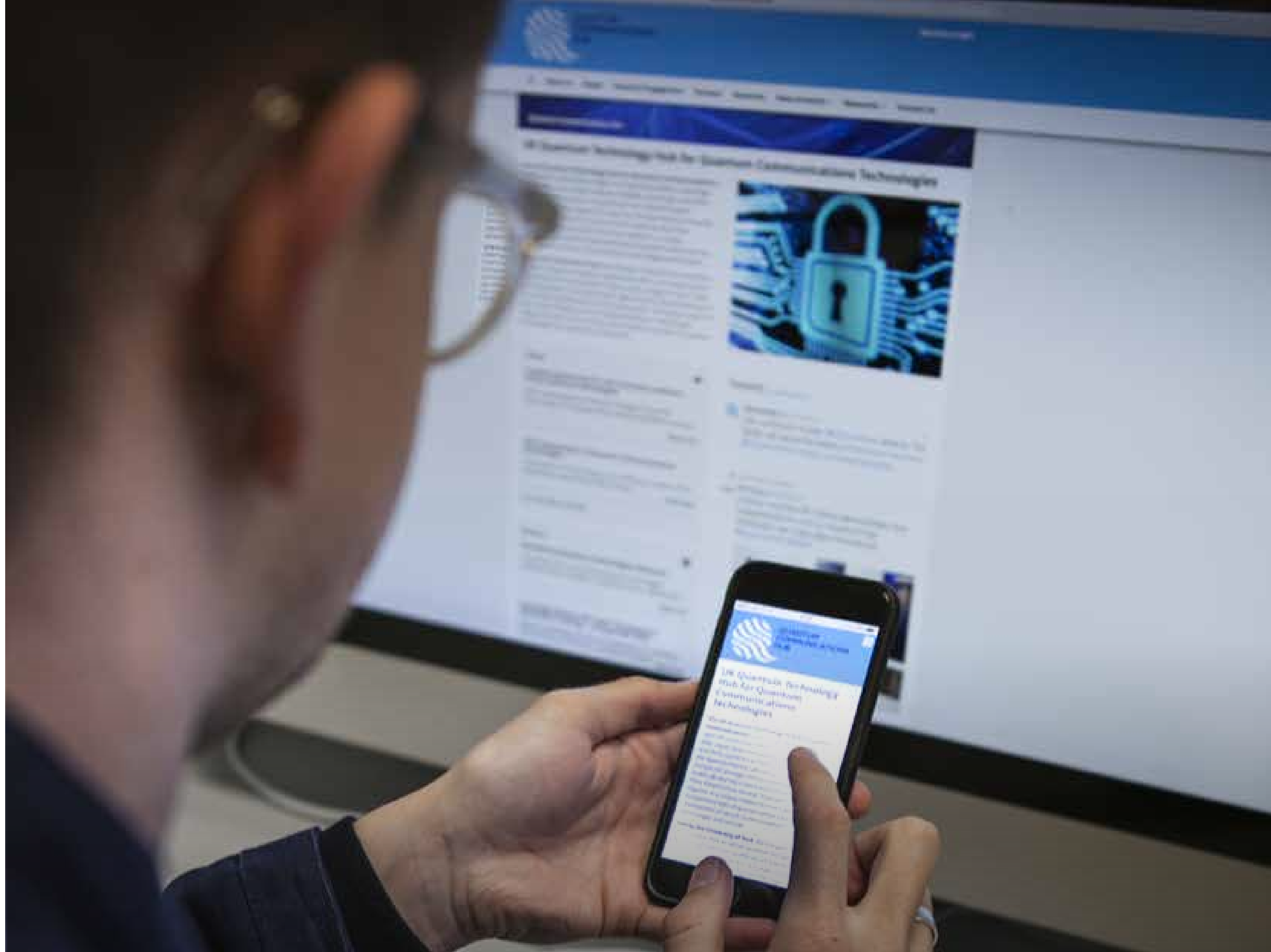
External Advisory Board

The HMT is supported by an External Advisory Board (EAB), made up of senior figures in research and industry with knowledge and experience relevant to the nature and purpose of the Hub. The EAB is chaired by a senior industrialist (Dr Martin Sadler OBE), and advises the HMT on overall strategy and direction, as well as progress against established targets and deliverables. The EAB has a particular focus on the evolution of Hub strategy, longer-term priorities and effective external stakeholder engagement. The Board meets formally every 6 months, normally at one of the Hub's partner institutions, which facilitates a 'deep-dive' into the work-package associated with the partner host.

In addition to the regular team meetings held within individual work packages, and across them as required, Hub Project Meetings are held every 6 months. The purpose of these is to ensure there are opportunities for the Hub as a whole to share progress, issues, practices and directions, as well as networking. These sessions are attended by the HMT, and are open to all members of the Hub. The meetings are considered especially valuable for PhD students and early career scientists. Meetings are hosted in rotation by partners, with the agendas set on the basis of progress reports submitted in advance by all Co-Investigators.

The External Advisory Board members:

- Dr Martin Sadler, Vice President and Director, Security and Cloud Lab, HP Labs (Chair)
- Dr Wendy Carr, EPSRC Portfolio Manager, Quantum Technologies
- Mr Tim Edwards, Technical Sales Director UK & Ireland, ADVA
- Ms Gaby Lenhart, Senior Research Officer and Co-Founder of the QKD Industry Specification Group, ETSI
- Professor Norbert Lütkenhaus, Institute for Quantum Computing, Waterloo, Canada
- Professor Bill Munro, Senior Research Scientist and Group Leader, Theoretical Quantum Physics Research Group, NTT Labs, Japan
- Professor Alwyn Seeds, Professor of Opto-Electronics, Head of Department of Electronic & Electrical Engineering, UCL; Director, UCL-Cambridge CDT in Integrated Photonic and Electronic Systems (IPES); Director, National Dark Fibre Infrastructure Service
- Dr Dan Shepherd, GCHQ
- Professor Will Stewart, Chair of the Communications Policy Panel, The Institution of Engineering and Technology, Visiting Professor at UCL and Southampton (ORC)
- Professor Paul Townsend, Head of Centre and Director of the Irish Photonic Integration Centre (IPIC), Tyndall National Institute, Ireland
- Professor Mike Wale, Director of Active Products Research, Oclaro; Professor of Industrial Aspects, Eindhoven University of Technology, The Netherlands; Hon. Professor of Photonic Communications, University of Nottingham
- Dr Tim Whitley, Managing Director, Research & Innovation, BT



Project Website

The project website - www.quantumcommshub.net - is the main source of information and news about the Hub. It contains background information, and provides updates on relevant upcoming events of interest, news, and Hub vacancies. The site serves as an online depository for all project outputs: from peer-reviewed scientific publications to conference presentations, and from downloadable reports to links for relevant multi-media materials.

The website also serves as the main portal for enquiries from outside the partnership: enquiries@quantumcommshub.net

www.quantumcommshub.net

The Quantum Communications Hub

The First 12 Months

Overview

The first year was predictably hectic, due in part to the concentration of effort required to put in place the essential administrative, contractual and operational machinery of the Hub as a major multi-partner project. Procurement, along with staff recruitment and training, were essential early priorities. In addition to laying such foundations, work began on engagement - with both industry and the public - raising the profile of the Hub and the National Programme.

In the first year we have:

- Recruited and trained the majority of research staff and students responsible for carrying out the main body of the Hub work programme
- Established the main governance (management team, external advisory board) and reporting structures to facilitate effective project management
- Signed agreements with all founding partners, creating a regulatory framework for delivering agreed objectives
- Made significant progress with procurement of capital equipment for the project, following formal tender processes
- Created a project website to serve as an online depository and resource relating to the Hub and its work
- Organised, and participated in, a number of major industry engagement events
- Brought together multiple Hubs QT programme stake-holders for an industry-led analysis of technology requirements for timing and synchronisation
- Agreed the process of allocating partnership resource funding
- Initiated exploratory discussions with a number of potential international collaborators
- Engaged with the public through diverse activities such as public talks, school visits, popular science demonstrations, participation in science festivals
- Took part in the development of industry standards for the regulation of the new quantum communications technologies in association with the relevant regulatory bodies and industry specification groups
- Built demonstrators for use in a range of different engagement scenarios
- Published 23 peer-reviewed scientific papers on the work of the Hub
- Raised a further £1.23m in parallel grants
- Secured a capital equipment grant of £2m to lay the infrastructure of an extension to the UK Quantum Network, linking Cambridge with BT's Adastral Park facility near Ipswich
- Presented our research at 52 conferences/workshops in the UK and abroad

Technology Development - Short-range, Free-space QKD Technologies

Aim: To advance existing "consumer" QKD demonstrations at the University of Bristol and HP Labs, progressing to integrated, practical and affordable Alice and Bob units with their supporting hardware and software. For lower frequency microwave systems, we will produce practically secure Alice and Bob units with their supporting hardware and software.

Developments in WP1 are primarily focused on the miniature electronics required to drive a hand held transmitter. The four LED Alice units can now be driven directly from a credit card scale circuit (USB programmable). A single mode filter based on optical fibre was developed, with work on optimisation to minimise any errors induced by birefringence. A credit card scale unit has been 3D-printed for use in demonstrations. Work on optimisation of the receiver unit and key exchange software continued, with a view to being ready to integrate this with the new miniaturised transmitter.

Proof of principle optical arrangement for credit card Alice device has shown feasibility (alignment, throughput, degree of polarisation), and work begun to create the necessary processes to assemble a first prototype rugged optical device. The credit card electronics became operable as a single USB device (power, data and control) on a small circuit board. An early prototype for a "Flexi Bob" electronics module was assembled. Further, a number of significant weaknesses and side channel attacks on specific instances of CV QKD were identified, together with solutions to overcome them in order to maintain security.

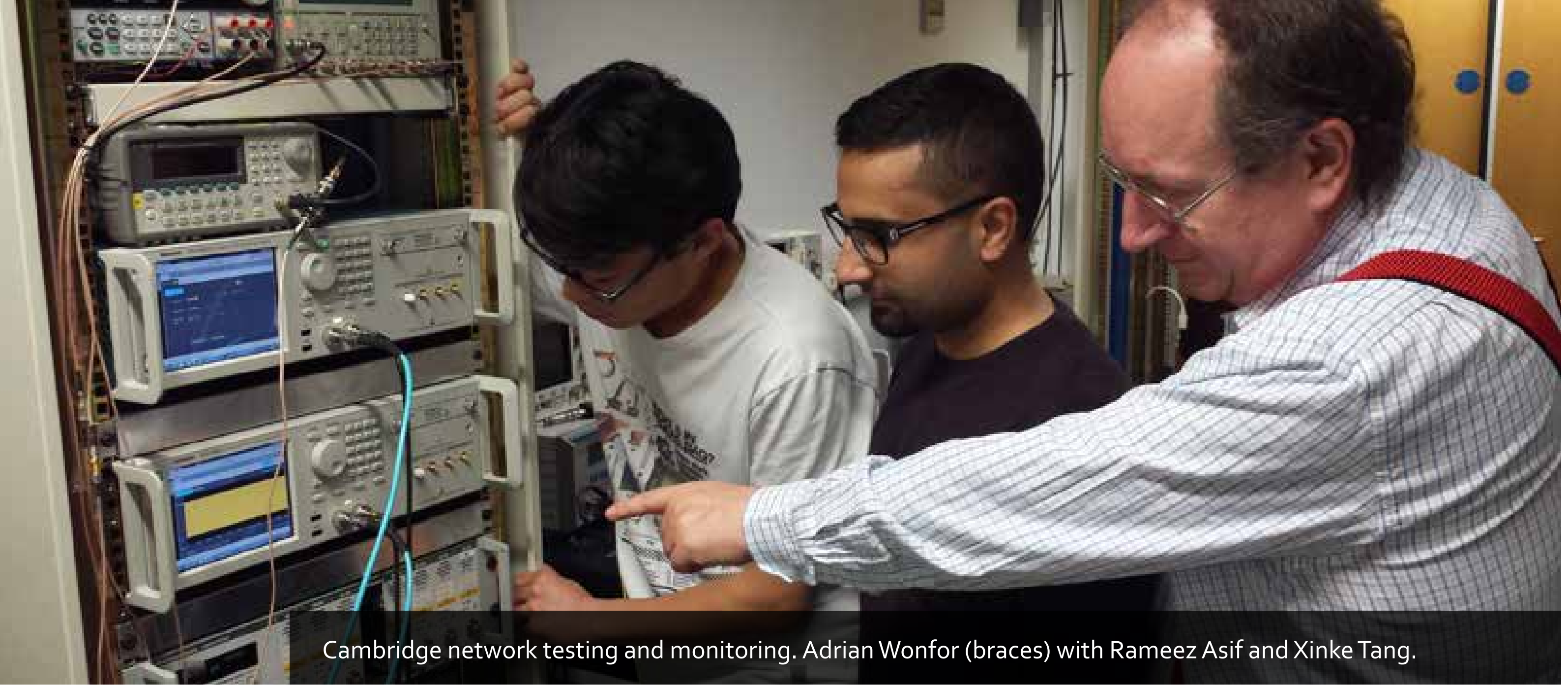
Work on the small, portable Alice transmitter unit for "consumer QKD" advanced both the optics and the electronics of this device. The Alice optics, to generate the quantum signals that are sent to Bob, comprise a small array of four LEDs and an optical fibre filter, all this fitting in a 3D printed, credit-card-sized holder. In parallel with this development and to drive the optical transmission, a purpose-built printed circuit board (PCB) also roughly the size of a credit card was designed and manufactured.

This PCB currently takes data over a USB link from a PC (or any other device capable of hosting USB) and converts it into appropriate drive signals to generate short optical pulses. The transmitter operates at 100MHz and generates pulses at 2.1ns with a mean photon number of 0.6 per pulse. This is sufficient for QKD and can be optimised once Alice is integrated into a full QKD system.

Work on the Bob receiver unit focused on a new approach, separating the optics and electronics into distinct modules. This new "Flexi-Bob" has been designed and development of the new component modules initiated. The optical module will feature the option of measuring the incoming signals from Alice in three different polarization bases (Horizontal/Vertical H/V, Diagonal/Anti-diagonal D/A, and Right/Left circular polarisations R/L).

The well-known BB84 QKD approach only requires Bob to measure two different polarisations (H/V and D/A); however, adding the option of a third will allow for a wider range of QKD protocols to be used and it will also increase the utility of the Bob optics, for example to also allow for device characterisation. The separate Bob electronics module will feature all of the relevant hardware to time-tag the detections of the signals from Alice, process these into raw key and then communicate with Alice to establish the final shared secure key.

The advantage of the modular arrangement of "Flexi-Bob" is that it adds important versatility to the Bob receiver terminal. For example, one could replace the bulk optics module, being developed for receiving the signals from the current credit-card or phone "consumer" Alice, with a fibre-based module, without needing to redevelop the other elements of the system. Additionally, as the "Flexi-Bob" electronics module features an FPGA and processing and communications hardware, this can be more widely used in a general laboratory environment as a useful apparatus, for example in time-correlated single photon counting. "Flexi-Bob" thus has wider application than just being a QKD receiver, with correspondingly wider commercialisation potential.



Cambridge network testing and monitoring. Adrian Wonfor (braces) with Rameez Asif and Xinke Tang.

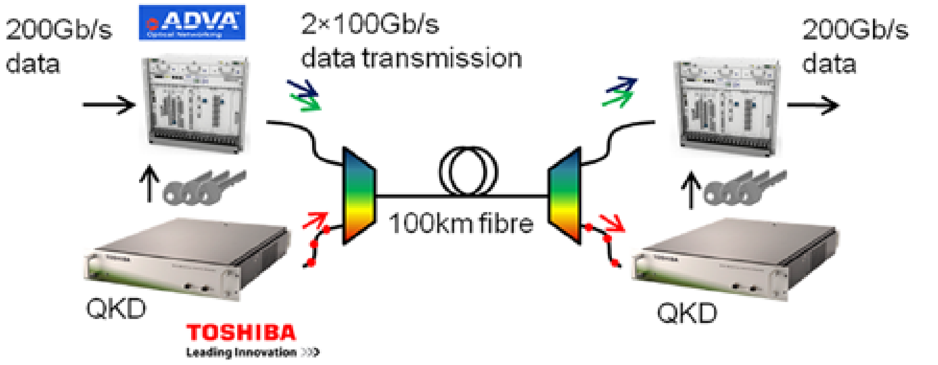
Technology Development - Chip-scale QKD Technology

Aim: To scale down and integrate the QKD component devices to produce robust, miniaturised sender, receiver and switch systems, "QKD-on-a-chip" modules. This advance will address cost, energy-efficiency and manufacturability issues to enable widespread, mass-market deployment and application of QKD.

Integrated waveguide devices have been successfully fabricated, and deployed in the world's first chip-to-chip QKD demonstration. The two chips used to demonstrate this point-to-point link integrate all of the photonics required (except for the single photon detectors) onto monolithic devices. The current Alice unit is an InP transmitter chip, with on-chip lasers, photodiodes and phase modulators. The current Bob unit is a SiON receiver chip, incorporating all the receiver optics except for the actual photon detectors. This technology demonstrated performance comparable to state of the art and commercial devices, with a greatly reduced footprint and therefore ultimately fabrication cost, in a platform conducive to future mass-manufacture. Furthermore, progress was made toward an autonomous QKD system for deployment in the Bristol-is-Open (BiO) local metro-network. More complex designs based on InP chips were also under development. These include demonstrating wavelength-division-multiplexed (WDM) QKD, for increasing key rates, and Measurement Device Independent (MDI) QKD, for addressing some of the limitations of current technologies and thus increasing security.

QKD in silicon-on-insulator waveguide platforms were also demonstrated. The team has developed a method of overcoming the non-ideal characteristics of fast phase modulators in silicon, to implement a number of fast QKD protocols and encodings. Specifically, these include both polarisation- and path-encoded versions of the well-known BB84 approach, in addition to an implementation of the coherent one way (COW) protocol with a secret key rate of 916 kbps over 20km. Furthermore, an integrated quantum random number generator (QRNG) has been developed in silicon, based on quantum homodyne detection of optical vacuum fluctuations. This device includes on-chip photodiodes, generating about 180 MHz of random numbers. Random numbers are required for a vast range of secure communications (not just quantum), other cryptographic applications and beyond. The QRNG has significant commercialisation potential, not limited to QKD systems.

Additionally, we have sought to understand the budgets for loss of and crosstalk between optical signals, and how these influence and limit transmission distances with QKD systems. This understanding informs the aim of designing, and ultimately implementing, a quantum secured router (QSR), which would significantly expand the capability of quantum networking. Substantial progress has been made on the development and characterisation of both the classical and QKD switching elements required for such a router.



Schematic of the 100G Quantum Encrypted Link

Technology Development - Quantum Communication Networking

Aim: To establish a UK Quantum Network (UKQN), which integrates QKD into secure communication infrastructures at access, metropolitan and inter-city scales. Our networks will facilitate device and system trials, integration of quantum and conventional communications, and demonstrations.

High Bandwidth Data Encryption

The real world situation that will face future quantum communication network services is that of optical fibre lit with multiple signals. We have demonstrated a record bandwidth for quantum encryption over such lit optical fibre. This demonstration used a commercial 100G optical data transmission system loaned by ADVA Optical Networking and a new high bit rate QKD prototype loaned by TREL. Two 100G data channels were combined with quantum key distribution onto a single fibre using dense wave divisional multiplexing. Experiments showed it was possible to multiplex QKD and high bandwidth data for fibres up to 100km in length. In addition it was possible to achieve high secure key rates, for example 1.9 Mb/s for a 35 km link, sufficient for >5000 AES-256 keys per second. All this shows that it is possible to send high speed (100G) data down a fibre, encrypted using quantum keys sent down the very same fibre. The system was presented to visitors to the BT Innovation Week in Sept 2015 and reported widely in the press.

Most of the fibre for the Cambridge metro-network section was installed, and the National Dark Fibre Infrastructure network was available for use as part of the wider UKQN. New optical orthogonal frequency division multiplexing (OFDM) techniques for quantum key distribution (QKD) systems were developed. These show that total system throughput, as well as resilience to the background noise from the data channels, can be enhanced with these techniques. Optimal methods for wavelength allocation in hybrid dense-wavelength division multiplexing (DWDM) links were also found, where some channels are used for classical data, and some other for quantum applications (QKD, in particular). These results show patterns for the optimal assignment of wavelength to each application will be useful for future deployment of the UKQN.

Andrew Lord, BT, and Andrew Shields, TREL with a QKD demo at BT Innovation Week, Adastral Park, Sept 2015

Technology Development - Combining QKD with Network Function Virtualisation

The application of QKD in software defined networks (SDN) has been demonstrated for the first time. Network function virtualisation (NFV) is an approach to networking where the network and its capabilities are defined through software deployed to generic hardware. It is therefore crucial that the software deployment and orchestration of the NFV is done in a secure manner. This was demonstrated over an emulated SDN-controlled optical network testbed, through the time-sharing of QKD systems. This work is forming the basis of ongoing discussion and planning for incorporating QKD into the Bristol-is-Open network.

Technology Development - Next Generation Quantum Communications

Aim: To explore new approaches, applications, protocols and services – to open up new markets for quantum communications, beyond key distribution. The themes will be reviewed and revised regularly, based upon progress to implementation, demonstration and technology. The initial themes include quantum digital signatures, multiple-user scenarios, quantum relays/repeaters/amplifiers and device-independent technologies. The hardware developed in WPs1-3 will be fed into this theme, to accelerate progress from the laboratory to the UKQN and eventual commercialisation.

Quantum Digital Signatures

The first year of the Hub saw particularly strong developments in quantum digital signatures (QDS), as the first kilometre-range system was fully demonstrated in the laboratory. This demonstration mainly used QKD components, thereby offering the prospect of using established QKD technologies to implement QDS. With QDS, the Hub has managed a particularly close alignment of theoretical and experimental efforts. Theoretical efforts have shown security analysis on the first quantum signature protocol that incorporates the parameter estimation step, as well as a security proof for measurement device independent (MDI) quantum signatures.

Amplifiers and Repeaters

In March 2015, the first state comparison amplifier (SCAMP) experiment was published, producing amplified coherent states with a nominal intensity gain of 1.8 at a maximum rate of 26k amplified states per second and with fidelity in excess of 98%. More recent advances have clearly demonstrated high gain (in excess of 9), and operation with added noise. Recent work has successfully developed a detailed theoretical model and considered the introduction of feed-forward, illustrating further improvements in success rate and fidelity. The SCAMP aspect of WP4 has shown strong interaction between theoretical and experimental groups, working towards the eventual goal of a high-performance on-chip implementation of the amplifier.

As part of the Hub's theoretical work, we have determined the ultimate rate for quantum communications without the use of quantum repeaters, for lossy channels and discrete-variable channels. These limits set the benchmark for testing the performance of these devices, to quantify when repeaters will outperform the simple point-to-point direct communication between two parties. We have then determined the optimal performance of quantum communications in the presence of quantum repeaters and in general quantum networks.

Measurement Device Independent Quantum Key Distribution (MDI-QKD)

We have performed experimental demonstration of high bit rate MDI-QKD, using a new protocol designed to foil attacks on the detectors used for QKD. This involves performing two-photon interference of light signals generated by the two parties wishing to form a key. By making joint measurements of the pulses from both parties, it is possible to establish correlations between the parties and thereby form a shared key. Previous demonstrations of MDI-QKD have been limited to very low bit rates due to the difficulty of generating indistinguishable laser pulses from distinct sources at high rates. However, the recent work by TREL demonstrated a new laser seeding technique to generate such indistinguishable pulses from ordinary laser diodes at GHz rates. This has enabled a demonstration of MDI-QKD with key rates in excess of 1 Mb/s for the first time - an improvement over previous experiments by between 2 and 6 orders of magnitude.

Single-Photon Sources

We have made significant progress in the task of delivering on-demand indistinguishable single photons for evaluation in quantum communication and cryptography systems. We now have a straightforward way to deliver on-demand, electronically synchronised, indistinguishable single photons to a quantum network. While our current source is among the world's brightest (or most efficient), development is in progress which could ultimately yield a ten-fold improvement in signal. Separately, we are also helping pioneer a new type of single quantum emitter in a layered semiconductor material - such emitters hold immense potential for future integration into chip-based QKD transmitters based on silicon or III-V semiconductor platforms.

Theoretical and Security Analysis

This included development of a protocol for MDI-QKD based on continuous variable systems. The use of less complex quantum resources, such as coherent states, allows this protocol to achieve very high rates at metropolitan distances, potentially several orders of magnitude greater than previous implementations. On-going work includes examination of the device re-use problem in device-independent-QKD. We are investigating ways to close the detection loophole, and highlight the most promising ways to achieve DI-QKD and/or randomness expansion. Other contributions include quantum randomness expansion from a measurement-device independent perspective, including finding the most appropriate practical implementation.

In terms of security analysis, we have been working on developing a deeper understanding of how to build secure channels using classical cryptographic techniques. This has involved analysis of existing protocols, as well as more foundational work developing and exploring security models for secure channels with different security properties. On-going work reflects concern about the role of subversion in conventional cryptographic systems. Such concerns will eventually need to be addressed for quantum cryptographic systems too.

Commercialisation Routes and Partners

The Hub strategy for commercialisation of new secure communications technologies and services is to develop and maintain a range of channels. This is essential as whilst specific technologies may be commercialised via technology companies of varying size, services are delivered through (usually large) service providers - with their own supply chains and customer base.

For example, collaboration with BT, a service provider, gives the Hub access to the company's supply chain, a proportion of which is expected to be early adopters of QT. These companies vary in size, from small businesses that integrate networking technologies into packaged services, to multi-national technology manufacturers, who incorporate premium features at scale for supply to service-providers around the world. Furthermore, BT is a supplier of communications services across public and private sectors, from Government and Health to ICT and Finance. This also provides the Hub with a route for user engagement and trials, including the commercialisation of secure data services. Working with one major UK service provider inevitably creates opportunities for working with others.

The Hub also works closely with the two companies most prominent globally in QKD system development: the large multi-national Toshiba (through TREL), and the SME ID Quantique. Both companies are working with the Hub in establishing the UKQN and so provide routes for the commercialisation of technologies and network services, either directly or through licensing. As the UKQN is being established as a national showcase and facility, the Hub is providing collaboration and commercialisation opportunities not only for our research partners, but for the other Hubs within the wider National QT Programme.

Commercialisation routes also include the use of start-ups and spin-outs. A number of university start-ups were established in advance of the Hub's formation, in preparation for exploitation. These include Qumet Technologies at Bristol, recognising the separate commercial potential of QKD receivers in addition to the complete consumer QKD systems of WP1, and Cryptographiq Ltd at Leeds for microwave technologies. Since the Hub's formal creation, a new start-up at Bristol, KETS, has been created, to exploit the WP2 breakthroughs in secure transmission of shared secret keys between two monolithic integrated devices.

User Engagement

Central to the strategy and vision of the UK National Network of Quantum Technology Hubs is the commercial exploitation of the UK's world-leading quantum research. The Quantum Communications Hub consortium brings together leading researchers and pioneering industrial partners for the development, testing, demonstration and trialling of products and services for a new global market in quantum communications. The Hub embraces a wide range of activities to deliver this strategy – from technical development of hardware and software in some of the most advanced labs in the communications world, to nurturing commercial relationships with multi-national corporates and SMEs.

User-engagement activities in the first year ranged from conference presentations and public talks to raise the profile of the Hub, to more targeted industrial engagement events at the Adastral Park / Innovation Martlesham technology cluster. These culminated in the inaugural National Quantum Technologies Showcase event in November 2015.

Formal Launch of the Hub

The official Hub launch event took place at the University of York in June 2015 with a delegate list of more than 120 academics, researchers, students, industry representatives and policy makers from the world of quantum technologies. Guests included partners from all eight academic collaborating institutions, as well as UCL and Southampton; partners from industry (ADVA Optical Networking, BT, Oclaro, Toshiba Research Europe Ltd) and closely associated companies (Nokia) and organisations (GCHQ, National Dark Fibre Infrastructure Service, National Physical Laboratory); the funders (EPSRC) and related stake-holders (Innovate UK, the Knowledge Transfer Network); and external advisors from the Tyndall National Institute in Ireland, ETSI, HP Labs, NTT Basic Research Laboratories in Japan, and the Institute for Quantum Computing in Waterloo, Canada.

Keynote addresses on the day included: Professor David Delpy, CBE, Chair of the UK National Quantum Technologies Programme Strategic Advisory Board, who laid out the background to, and vision of, the UK's £270m investment in the field of emerging quantum technologies; Dr Rhys Lewis, Director of the new Quantum Metrology Institute at the National Physical Laboratory; and Dr Tim Whitley, Managing Director of Research at BT and MD of the company's prime research & innovation facility, Adastral Park.

In parallel to the talks, a number of scientific demonstrations took place during the day: ADVA Optical Networking Ltd. showcased secure transmission of data over optical links at high rates; Bristol University's Photonics Group demonstrated prototype personal, hand-held devices for carrying out secure finance transactions using quantum key distribution (QKD) encryption technology; TREL exhibited quantum cryptography technology aimed at detecting tapping of optical fibres, and its potential uses in securing a range of applications. In addition to, to the launch itself, the Hub also hosted on the day the inaugural meeting of the Knowledge Transfer Network's Steering Group for the new Quantum Technologies Special Interest Group.

Right: Official Launch of the Quantum Communications Hub. June 4th, 2015.

1. David Delpy, Chair of UK NQTP SAB
2. Tim Whitley, BT MD of Adastral Park
3. Paul Hogg, Royal Holloway; Brian Fulton, York
4. Koen Lamberts, V-C at York
5. Bob Cockshott, KTN; Trevor Cross, e2v; Richard Murray, Innovate UK
6. Will Stewart, Southampton
7. Rhys Lewis, NPL; John Clark, York
8. Martin Sadler, Chair of Hub EAB; Paul Martin, Plextek
9. Bill Munro, NTT
10. Paul Townsend, Tyndall National Institute; Nigel Walker, BT

Highlight on

The Adastral Park Cluster

British Telecom (BT) is one of the leading providers of global communications and a major industrial partner in the Hub. The company has strategic interests in the development of quantum technologies and applications. Adastral Park, fully owned by BT, is the company's global HQ for R&D. BT's own resources on the site are substantial, ranging from world-class research facilities (basic photonics to the Internet of Things) to unique testing equipment and network reference models. In addition, there are large-scale showcase and demonstration facilities, which can be configured to simulate industrial and commercial environments e.g. in banks, hospitals, retail warehouse operations.

Adastral Park is also the base for over 70 companies working in and around ICT, including multi-nationals (e.g. Cisco, Intel, Huawei, Alcatel-Lucent, Nokia) some of which have their own development labs on site. The site is also the centrepiece of a major BT initiative to better exploit R&D strengths, and to do so through strategic partnerships – with the UK's academic research base, the global telecoms industry, and public stakeholders in the regional ICT economy to which the Park is central. Adastral Park is one of the three major geographic clusters the Hub is working with.

To this end, the Hub organised two events on the site in 2015. The first, in June, was a presentation to, and meetings with representatives of the companies on the site. Presentations from the Park's MD, Dr Tim Whitley, the Hub Director, Tim Spiller, and from Richard Murray of Innovate UK, preceded a networking session to discuss opportunities for collaboration with the companies - ranging from global corporates to SMEs.

The companies located on Adastral Park form the core of Innovation Martlesham – a 'collaborative ecosystem' for technology companies in the region. Innovation Martlesham provides business support, networking, mentoring and incubation space. The cluster offers much and varied potential for collaboration between the Hubs and the companies – from technology development and exploitation to placements.

These were explored further in a larger event ('Opportunities for Industry and Business') later in the same year. This was opened up to the four Hubs as well as NPL/QMI. Hub presentations and dedicated exhibition stands were complemented by both the Knowledge Transfer Network and Innovate UK, promoting and supporting industry collaboration. The industry perspective was provided by targeted presentations from BT, e2v and Id Quantique. Video interviews on the day are available on the project website.

Highlight on

The National Quantum Technologies Showcase

The first year of the project and the programme culminated in a national quantum technologies showcase, jointly organised by the hubs, led by the QuantiC Hub. The primary aim of the event was to celebrate the first anniversary of the four quantum technology hubs by raising awareness of the national quantum technology programme; by increasing industry and government networking opportunities for the hubs; and by highlighting the benefits of quantum technology to industry and beyond. The event took place at the Royal Society in London on 11 November 2015 and was attended by over 300 delegates from industry, business and government.

The day consisted of short talks from all hub directors, introductory talks about the nature and scope of the quantum technologies investment, and industry perspective keynote addresses by Graeme Malcolm (Founder and CEO, M Squared Lasers) and Trevor Cross (Chief Technology Officer, e2v, and member of the UKNQTP Strategic Advisory Board). The talks were interspersed with networking sessions during which delegates were able to interact with a number of demonstrators provided by all the Hubs as well as NPL. These were intended to showcase examples of the novel technology applications and product prototypes that the programme is fostering.

The Hub contributed significantly to the organisation of the event and the demonstrations showcased Hub partner developments. ADVA Optical Networking Ltd. exhibited a system with the ability to secure data transmitted on an optical link and data rates ranging from 10G through 16G, 40G to 100G. Any such application would be of particular relevance to requirements for secure transmission of sensitive data, for example in the finance, government or healthcare sectors. TREL exhibited a system demonstrating how quantum cryptography can be used to secure network communications. TREL also provided a preview of systems designed installation on the UK's first Quantum Network. Finally, Bristol presented a prototype quantum key distribution (QKD) system which comprised a handheld module docking to a fixed terminal and is aimed at mass market applications. This differed from currently commercially available systems (which consist of two expensive, bulky fixed devices), and aims to provide a small and low-cost device suitable for high volume production to compete with devices like RSA SecurID and PINsentry.

Demonstrations at the first National Quantum Technologies Showcase event, Royal Society London, November 2015.
Photo copyright: EPSRC & Dan Tsantilis

Prototype for low-cost, short-range, free-space quantum key distribution device for consumer applications (copyright:University of Bristol).

QKD Demonstration by Toshiba Research Europe Ltd. (copyright TRELL)

Highlight on

KETS Quantum Security Ltd.

KETS Quantum Security Ltd. is a new commercial venture focused on developing the potential of quantum cryptography with integrated quantum photonic platforms. This approach for quantum enhanced cryptography enables the strongest digital communications encryption in a practical and deployable platform. The use of cutting-edge integrated quantum photonics crucially delivers on the demanding size, weight, and power constraints common in many industrial applications, while maintaining state-of-the-art performance in a technology fully compatible with classical micro-electronic integration.

Born out of the research pioneered by Professors Jeremy O'Brien and Mark Thompson at the Centre for Quantum Photonics (CQP) at the University of Bristol and supported by the Quantum Communications Hub, members of KETS demonstrated in 2015 the world's first chip-to-chip quantum secured communication. Using Quantum Key Distribution, they enabled the ultra-secure transmission of shared secret keys between two monolithic integrated devices. In partnership with the Hub, KETS will continue to advance the technology and are developing robust prototypes aimed at addressing a number of market needs.

Through participation in a number of SETSquared (the Global #1 University Business Incubator) programmes, the team has been developing its commercialisation strategy for its integrated QKD technology. Specifically, participation in the ICURe programme facilitated 6 months of extensive market research with over 50+ individuals in 30+ key organisations across a number of market sectors including finance, telecommunications, and defence. This customer engagement has provided key insights for developing a compelling business case and as a result KETS won the 2015 University of Bristol New Enterprise Competition. This included start-up funds, legal services, and space in Bristol's innovative and dynamic high-tech incubator EngineShed.

During the ICURe programme, a number of companies expressed interest in KETS technology, including SMEs and large corporations. These were from different sectors, but with a common interest in a full QKD prototype, and chip-based quantum random number generators. The team are now working to implement the technology for sector-specific deployment. For example: in telecommunications networks, where new developments such as quantum-secured network function virtualisation (NFV) - recently demonstrated by Bristol's High Performance Networks Group and the CQP, together with BT - offer robust network security; in data centres, attracted by the low power consumption and small footprint of the devices; in finance, where the explosion in new fintech solutions has generated demand for the utmost in security; and in defence, with applications including securing soldier radios, commercial aircraft, satellites, and drones.

KETS Founders include:

Dr Jake Kennard

Dr Chris Erven

Prof. Mark Thompson

Dr Philip Sibson

Highlight on

Standards

Industrial standards are essential for ensuring the interoperability of equipment and protocols in complex systems, as well as stimulating a supply chain for components, systems and applications through the definition of common interfaces. Without standards there would be no global networks for fibre optic and mobile communications, or low cost consumer electronics based on reliable and widely available components from multiple suppliers. New standards are required to integrate quantum communications into networks and to stimulate commercialisation.

The Hub is committed to contributing to the generation of a set of standards specifically designed for quantum secure communications. These will be crucial to any nascent industry/market resulting from Hub activities, and contribute to longer-term societal and economic impact of quantum technologies.

The Hub's work on standards is through the European Telecommunications Standards Institute (ETSI), and its Industry Specification Group for QKD, which is chaired by Dr Andrew Shields. Toshiba Research Europe Ltd (TREL) and the National Physical Laboratory (NPL) are both key players in the ETSI group. Although the protocols for QKD can be proven to be theoretically secure, deviation in implementation can create actual vulnerabilities ('side channels'). TREL lead work in the ETSI ISG on the implementation security of QKD systems.

As a leading National Measurement Institute, NPL variously supports quantum-related standardisation, with development and application of measurement standards. This requires accurate metrology of QKD system parts and their components.

The underpinning role of NPL's contribution for the validation of the work of all the quantum technology hubs has been further recognised within the UKNQTP through the investment of £4m towards the creation of a Quantum Metrology Institute, whose role will be to 'test, validate, and ultimately commercialise new quantum research and technologies'.

ETSI World Class Standards

Impact on Policy

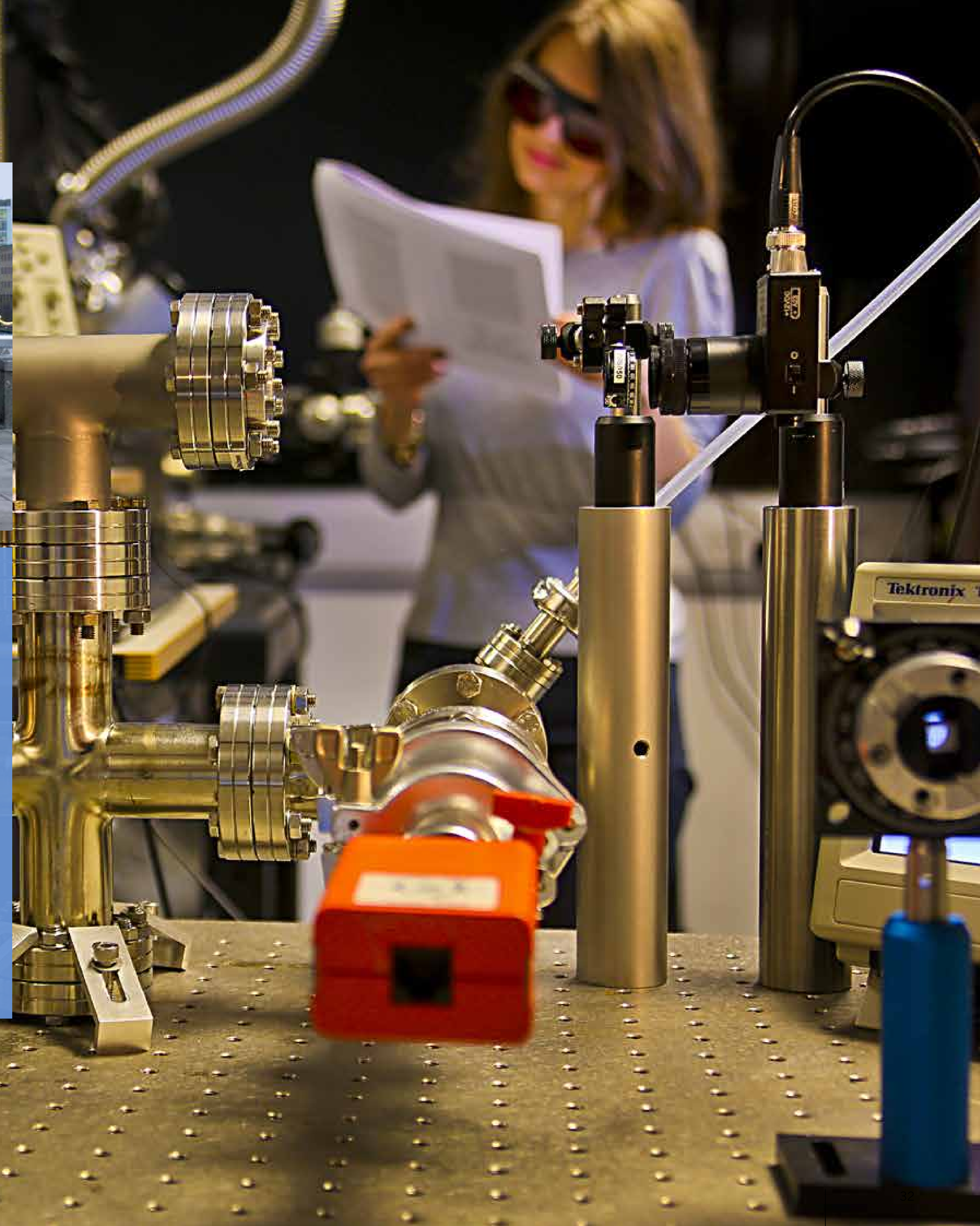
The Hub has contributed to national and international initiatives aimed at shaping long-term policies for the effective commercialisation of quantum technologies.

We participated in a single-day workshop ("Towards a European quantum technology industry") held in Brussels in May 2015, and organised by the European Commission Future and Emerging Technologies (FET) unit of the Directorate General for Communications Networks, Content and Technology (DG CONNECT). The workshop concluded with a key action plan for the development of a quantum technologies industry and market in Europe.

There was further Hub participation to an Expert Round Table on "Future Technologies and Innovations (Quantum)" at Portcullis House, Westminster. The consultation meeting was organised by the Government Office for Science with the aim of discussing emerging quantum technologies and innovation in the context of UK productivity and opportunities for public services.

Rory Cellan-Jones of the BBC chairing a panel session on 'The future of cyber-security'. University of York Festival of Ideas, June 20, 2015

The Hub took part in a Quantum Technologies Stakeholder Meeting in Brussels in autumn 2015, organised by the Commissioner Günther Oettinger with the aim of discussing industrial exploitation of quantum technologies by European companies. The event was followed up by a debate meeting on Quantum Technologies: Entangling Europe for Innovation, at the European Parliament in Brussels. The event was part of the 7th European Innovation Summit in the Europe, aimed at engaging European researchers in the field of Quantum Technologies in a debate with European politicians and policy makers. A first outcome has been published in the form of a Pact for Innovation.



Responsible Research and Innovation

Central to the National Quantum Technologies Strategy is creation of the "right social and regulatory context" for quantum technologies. This is particularly relevant for quantum communications, as data security raises issues for individuals, institutions, companies and governments. To promote open discussion on the technologies and services we are delivering, the Hub's strategy incorporates educational, public and user engagement activities, and cross-Hub coordination.

Highlights include: consultation on educational materials and plans for production of public engagement videos and filmed interviews with stakeholders; participation in numerous public engagement events through talks, panel discussions, debates and demos (e.g. York Festival of Ideas, Illuminations); school visits; use of social media (YouTube, Twitter) – all to relate the work of the Hub to a wider audience. High-profile, public technical demonstrations of the technologies developed in the Hub are part of our detailed user engagement strategy. More are planned in the future, using the UK Quantum Network.

The Hub is represented on the Responsible Research and Innovation (RRI) working group, overseen by the EPSRC and chaired by the Oxford-led NQIT Hub. The Hub is also actively participating in the EPSRC-led Communications committee, whose remit is to devise, oversee and implement an effective communications strategy for relating the aims of the National QT Programme to the public.

Future Research Directions

The National Strategy for Quantum Technologies identifies a number of areas for further UK action within the quantum technologies realm, including: enabling a strong foundation of capability in the UK; stimulating applications and market opportunity in the UK; maximising benefit to the UK through international engagement; growing a skilled UK workforce; and creating the right societal and regulatory context. The Hub has been active across all in the first year, with a number of notable developments especially relevant.

1. Stimulating applications and market opportunity

In spring 2015, EPSRC issued a call for additional capital investment in quantum technologies. Proposals were invited that would 'contribute to the expansion of the UK's quantum technology capability' in one or more areas of strategic focus:

- Building technical capability
- Manufacturing tools
- System/ subsystem design
- Acceleration of innovation.

The Hub submitted a proposal for extension of the original UK quantum network (UKQN) to include a link between the UKQN node in Cambridge and Adastral Park, BT's Research & Innovation cluster at Martlesham Heath, near Ipswich. Extension of the UKQN to Adastral Park would stimulate creation of a new networked cluster for quantum technologies innovation by enabling networked interaction between research and industry that would be connected to an extended UKQN. Academic research centres in Bristol and Cambridge that would be connected to each other by the UKQN, would also directly connected to the industrial and commercial resources and facilities on the BT site.

These included R&D Labs, and very large-scale showcase and demonstration facilities. In addition, companies on the site part of the Innovation Martlesham cluster would be provided with access to the quantum network, and as such, to other connected partners and facilities. The showcase and demonstration facilities - with over 50,000 invited visitors a year – provide opportunities for both industry and research to demonstrate technologies, products and services to each other and potential clients. These include major customers for technology – from Government at all levels to Banking and Financial Services and network service providers.

Company access to the UKQN will provide industry and commerce early and first-hand experience of the new technologies and the services that could be built upon them. For example, access to the network would enable user trials of quantum-secured data transmission and storage. Extended access will be provided for early adopters of the technologies wishing to test / evaluate potential for new commercial systems and services.

Acceleration of innovation, and early adoption of new market products are both objectives of the national quantum technologies programme. Access to, and demonstration of QKD across all nodes of the extended UKQN will facilitate early integration with existing technologies.

Demonstration Suite in the Showcase


Adastral Park


BT Lab

2. Maximising benefit to the UK through international engagement

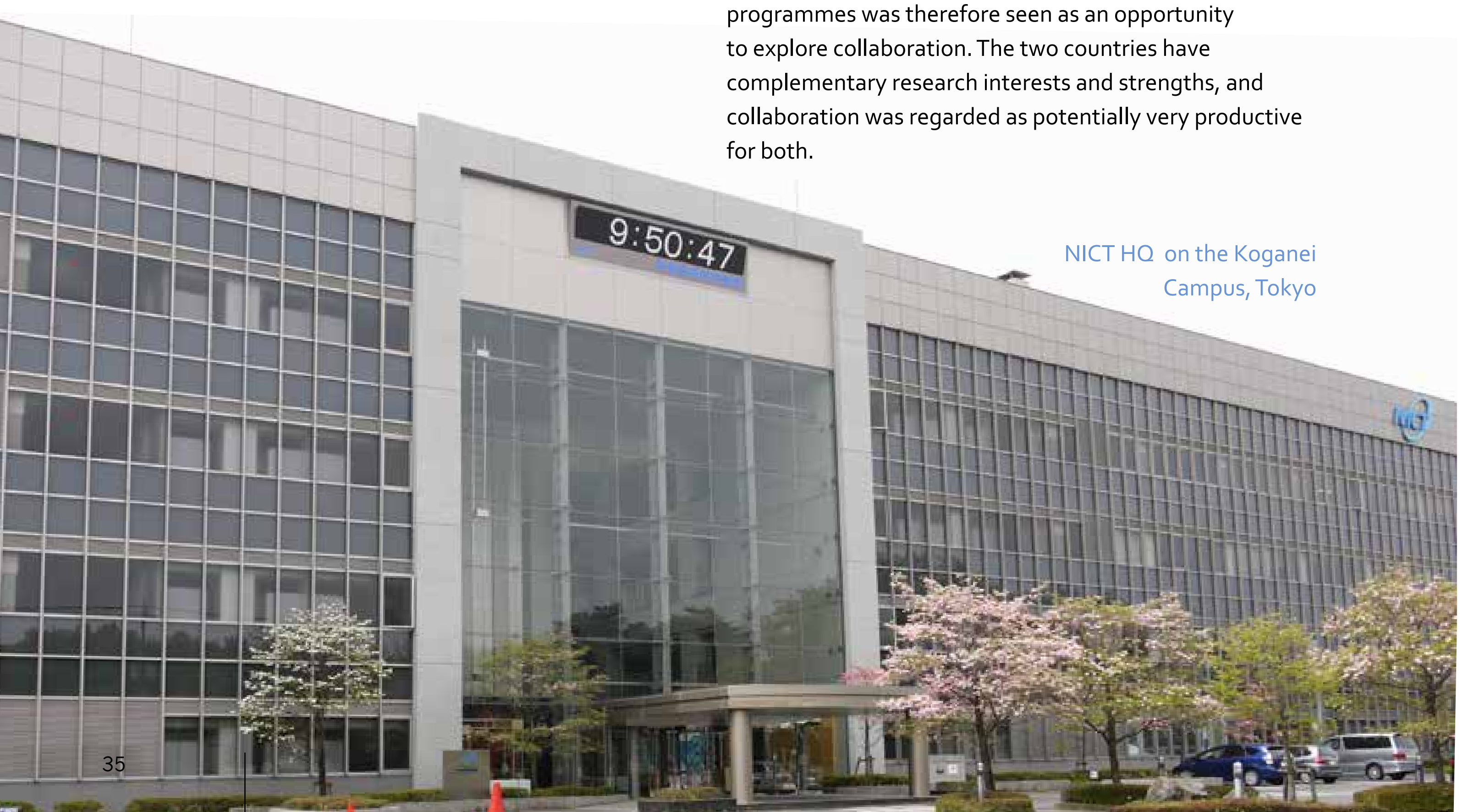
Secure quantum communications are the subject of specific attention in a number of countries. Using the very strong international links of our academic and industry partners, the Hub initiated engagement with individuals, institutions and companies involved in a number of initiatives for both development and exploitation. The breadth of initial engagement is aimed at ensuring that the UK benefits from knowledge of, and where appropriate, collaboration with, international activities that are relevant to our remit for promoting the UK's role in developing and exploiting quantum secure communications.

Some of these significant QKD network initiatives have common or overlapping interests with the Hub. These encompass R&D; engineering and implementation of QKD systems; industrial engagement and partnerships; commercial imperatives; standards, regulation and legal frameworks; the social and political complexities of securing data in the modern world. These matters are of varying weight and priority in the different countries where the QKD networks have been built – by governments, industry, research institutions, or a combination of all.

In 2015 the Hub began an initiative to establish productive relationships with the most significant international QKD activities. We started with the QKD network in Tokyo led by Japan's government-funded National Institute of Information and Communications Technology (NICT). This is a collaboration that includes NTT, Toshiba and Id Quantique, and which utilises technology from the latter two that is being enhanced through the Hub for deployment on the UKQN.

The Hub director, Professor Tim Spiller, was part of a delegation of UK researchers visiting Japan to participate in a UK-Japan Quantum Technologies Workshop organised by the British Embassy in Tokyo, and to present the work of the Quantum Communications Hub. The Japanese government had recently allocated substantial funding for a national premier research and innovation programme in quantum, with a significant focus on quantum cryptography and computing / information processing.

This was the latest in a series of Japanese investments in quantum technologies made in the previous 15 years. The result was particular research strengths in quantum communications, and unusually strong partnerships between academia and major corporate businesses - such as NEC, Toshiba, Fujitsu, Mitsubishi Electric and NTT. The synergy between the Japanese and UK quantum programmes was therefore seen as an opportunity to explore collaboration. The two countries have complementary research interests and strengths, and collaboration was regarded as potentially very productive for both.

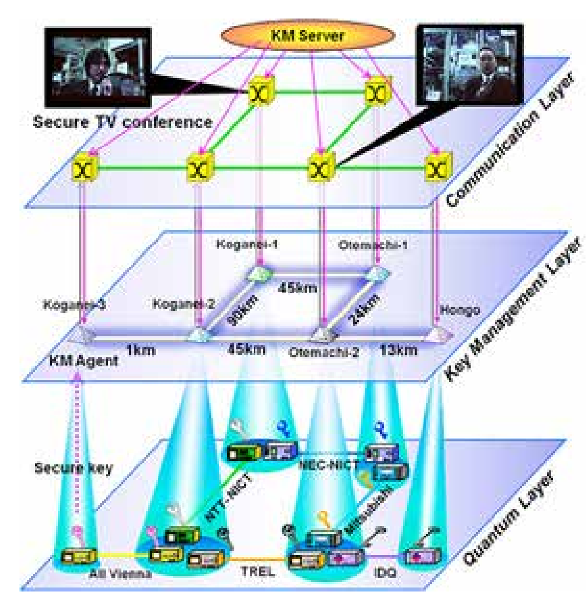


NICT HQ on the Koganei Campus, Tokyo

Layout of the Tokyo QKD Network (JGN2plus = Japan Gigabit Network)

A promising area of common interest was in quantum networks. Through collaboration between NICT and major ICT corporates, Japan had built a fibre-based quantum network in Tokyo. Established in 2011, this provided a national quantum network testbed on a reasonable scale between urban centres.

This was of direct relevance to the equivalent network being built in the UK by the Hub, which will be able to benefit from Japan's pioneering work. This is particularly important in the implementation and testing of network features in the field rather than the lab. Although the Tokyo network had some initial focus on particular applications – for example secure video – it is also addressing major issues relevant to all quantum networks, e.g. key management, which the Hub will also be tackling.



Schematic Layer Structure of the Tokyo QKD Network

The common interests of Japan and the UK in quantum networks that was established by the end of 2015, would prove to be the foundation of productive collaboration in 2016. This would include an annual UK / Japan workshop in quantum communications, and joint development of wider initiatives to support industrial exploitation - particularly in and by the telecommunications industries, in the UK and Japan, but also beyond.

3. Enabling a strong foundation of capability in the UK

Satellite quantum communications had been identified as a UK capability gap by the Hub, and highlighted by high-profile initiatives in mainland Europe and, particularly, Asia. These initiatives were rapidly taking advantage of advances in free-space quantum communications research - much of it based on original work carried out by UK - scientists, notably Professor John Rarity, working with European colleagues. Satellite QKD was therefore becoming strategically significant, but with the UK playing little part.

The Hub therefore began discussions with public and private sector interests to explore options for UK participation in what is an inherently collaborative and international endeavour. Particular synergies were identified with leading exponents in Europe, Canada, Japan and Singapore. Following preliminary discussion, an initiative was established at the end of 2015 to identify collaborative opportunities for the Hub, and the UK space industry. These would lead in the following year to agreements for collaboration on feasibility and development initiatives with UK and non-UK partners in both the public and private sectors.

Opportunities for Industry and Business

Event hosted by BT Research & Innovation

Adastral Park, October 15th, 2015

The Quantum Communications Hub

The laws of quantum physics facilitate advanced communications technologies that will transform the security of networks. The most mature of these technologies, Quantum Key Distribution (QKD), provides the means of sharing secure keys which can be used for a very wide range of functions and applications in which security is vital: from encryption of communications, passwords and ID, to financial transactions and internet shopping.

Vision

New quantum communications technologies that will:

- Reach new markets, enabling widespread use and adoption.
- Benefit sectors and domains, from government, industry, and commerce to consumers and the home.

Approach

Phased development and implementation that will:

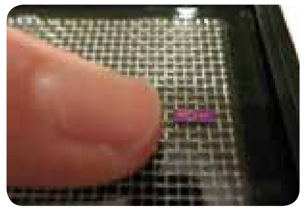
- Advance proven concepts in QKD to commercial-readiness.
- Explore new approaches, applications, protocols and services beyond QKD.

Delivery

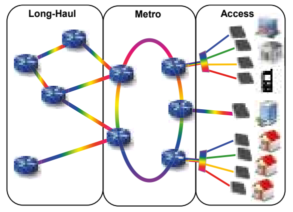
Building, and providing access to:

- Low-cost, short-range QKD for consumer applications.
- Chip-scale QKD modules for integration in computer systems.
- A UK Quantum Network, demonstrating real world communications at access, metro and inter-city scales.

Short Range QKD



Chip scale QKD Modules



Quantum Network Demonstrator

Partnerships – *World-leading researchers in universities and industry:*
York (lead), Bristol, Cambridge, Heriot-Watt, Leeds, Royal Holloway, Sheffield, Strathclyde, BT, the National Physical Laboratory, Toshiba Research Europe Ltd.

Collaboration – *Across private and public sectors and domains:*

- *Standards:* European Telecommunications Standards Institute (ETSI), GCHQ
- *For the UK Quantum Network:* ADVA, National Dark Fibre Infrastructure Service (NDFIS)
- *For supply/consultancy (optical):* Oclaro, ID Quantique
- *For collaboration/consultancy (microwave):* Airbus, L3-TRL
- *Start-ups (for exploitation):* Qumet (Bristol), Cryptographiq (Leeds/IP Group)
- *User Clusters:* in Bristol, Cambridge and Martlesham, supported by Bristol City Council and the Knowle West Media Centre; Cambridge Network Ltd; BT.

We welcome opportunities to collaborate in exploiting the emerging technologies for new products and services.

For further information or enquiries contact:

Quantum Hub Director:
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Quantum Hub Business Development Manager:
Klitos Andrea (klitos.andrea@york.ac.uk)

QUANTUM COMMUNICATIONS HUB

EPSRC Engineering and Physical Sciences Research Council

Leaflet summarising the Hub programme for potential partners / collaborators

APPENDICES

APPENDICES

Awards and Recognition of Scientific Excellence

- April 2015. Mark Thompson, Professor of Quantum Photonics at the University of Bristol, was awarded the IUPAP C17 Laser Physics and Photonics "Applied Aspects" Young Scientist Prize by the International Union of Pure and Applied Physics (IUPAP). The award was made "for his contributions to the new and emerging field of quantum photonics, and particularly for his pioneering work in integrated quantum photonic circuits."

- May 2015. John Rarity, Professor of Optical Communications Systems at the University of Bristol was elected a Fellow of the Royal Society, recognition of his pioneering work on experimental one-photon and two-photon optics, both in the study of fundamental physical phenomena and also in the development of prototype devices. Rarity has been on the forefront of developments in the field of experimental quantum information for a number of years having spotted early its potential for communications, and is now a world leading figure in this area.

- July 2015. Kenny Paterson, Professor of Information Security at the Royal Holloway, University of London, was awarded the prestigious 2015 PET Award for Outstanding Research in Privacy Enhancing Technologies. The award was made to Kenny and his co-authors Mihir Bellare (UC San Diego) and Phillip Rogaway (UC Davis) for their paper entitled "Security of Symmetric Encryption against Mass Surveillance".

- September 2015. Professor John Rarity, University of Bristol, was awarded an EPSRC Established Career Fellowship to further pursue work on spin-photon systems for scalable quantum processors and applications in repeaters for quantum communications over long distances.

- October 2015. KETS, a start-up company founded by Hub team members, Drs Chris Erven and Jake Kennard, Phil Sibson and Professor Mark Thompson, was awarded top prize at the New Enterprize Competition (NEC) organised annually by the University of Bristol for the best original idea for a self-sustaining business. The main concept behind KETS is the use of quantum cryptography to improve data encryption in all situations, from bank transactions to critical infrastructure to domestic scenarios involving online shopping. The idea came first among 103 entries, all judged by a panel of industry experts.

Peer reviewed publications and conference proceedings

Amiri R & Andersson E. Unconditionally secure quantum signatures. Entropy 2015; 17(8):6535-5659. DOI: 10.3390/e17085635

Bahrani S, Razavi M & Salehi JA. Orthogonal Frequency-Division Multiplexed Quantum Key Distribution. Journal of Lightwave Technology 2015;33(23):4687-4698. DOI: 10.1109/JLT.2015.2476821

Banchi L, Braunstein SL & Pirandola S. Quantum fidelity for arbitrary Gaussian states. Phys. Rev. Lett. 2015;115: 260501. DOI: 10.1103/PhysRevLett.115.260501

Carolan J, Harrold C, Sparrow C, Martin Lopez E, Russ ell N, Silverstone J, Shadbolt P, Matsuda N, Ogama M, Itoh M, Marshall G, Thompson M, Matthews J, Hashimoto T, O'Brien J & Laing A. Universal linear optics. Science 2015;349(6249): 711-716. DOI: 10.1126/science.aab3642

Cheng Q, Ding M, Wonfor A, Penty RV & White IH. The Feasibility of Building a 64x64 Port Count SOA-Based Optical Switch. In: International Conference on Photonics in Switching, Florence, Italy, 22-25 September 2015, pp 199-201. DOI: 10.1109/PS.2015.7328999

Cheng Q, Wonfor A, Penty RV & White IH. Robust Large-Port-Count Hybrid Switches with Relaxed Control Tolerances. In: CLEO: 2015, OSA Technical Digest (online) (Optical Society of America, 2015), San Jose, CA, 10-15 May 2015, paper JTh2A.38. DOI: 10.1364/CLEO_AT.2015.JTh2A.38

Cheng Q, Wonfor A, Wei JL, Penty RV & White IH. Low-energy, high-performance lossless 8×8 SOA switch. In: Optical Fiber Communications Conference and Exhibition (OFC), 2015, Los Angeles, CA, 22-26 March 2015, pp. 1-3. URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7121763&isnumber=7121453

Chunnilall C. (Rapporteur – with also Chapuran T, Degiovanni IP, Gramegna M, Kück S, Lewis A, Lütkenhaus N, Mink A, Peev M, Sinclair AG, Ward M, Yuan ZL. Quantum Key Distribution (QKD); Component characterization: characterizing optical components for QKD systems. ETSI GS QKD 011 V1.1.1 (2016-05)

Ding M, Cheng Q, Wonfor A, Penty RV & White IH. Routing algorithm to optimize loss and IPDR for rearrangeably non-blocking integrated optical switches. In: 2015 Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, 10-15 May 2015, pp. 1-2. DOI: 10.1364/CLEO_AT.2015.JTh2A.60

Donaldson RJ, Collins RJ, Eleftheriadou E, Barnett SM, Jeffers J & Buller GS. Experimental Implementation of a Quantum Optical State Comparison Amplifier. Phys. Rev. Lett. 2015, 114: 120505, DOI: 10.1103/PhysRevLett.114.120505

Fischlin M, Günther F, Azzurra Marson G & Paterson KG. Data Is a Stream: Security of Stream-Based Channels. In: Gennaro R & Robshaw M (eds), Advances in Cryptology - CRYPTO 2015. 35th Annual Cryptology Conference, Santa Barbara, CA, USA, August 16-20, 2015, Proceedings, Part II, Volume 9216 of the series Lecture Notes in Computer Science, pp 545-564. DOI: 10.1007/978-3-662-48000-7_27

Kumar S, Kaczmarczyk A & Gerardot BD. Strain-Induced Spatial and Spectral Isolation of Quantum Emitters in Mono- and Bilayer WSe2. Nano Lett. 2015; 15 (11):7567–7573 DOI: 10.1021/acs.nanolett.5b03312

Ma Y, Ballesteros G, Zajac JM, Sun J & Gerardot BD. Highly directional emission from a quantum emitter embedded in a hemispherical cavity. Opt. Lett. 2015; 40: 2373-2376. DOI:10.1364/OL.40.002373

Ottaviani C, Mancini S, Pirandola S. Two-way Gaussian quantum cryptography against coherent attacks in direct reconciliation. Phys. Rev. 2015; A92:92(6) 062323. DOI: 10.1103/PhysRevA.92.062323

Ottaviani C, Spedalieri G, Braunstein SL & Pirandola S. Continuous-variable quantum cryptography with an untrusted relay: Detailed security analysis of the symmetric configuration. Physical Review 2015, A 91: 022320. DOI: 10.1103/PhysRevA.91.022320

Pearce ME, Mehringer T, von Zanthier J & Kok P. Precision Estimation of Source Dimensions from Higher-Order Intensity Correlations, Physical Review 2015; A 92: 043831. DOI: 10.1103/PhysRevA.92.043831

Penty R, Wonfor R, Cheng Q & White IH. Scalable energy efficient InP space switches. In: International Conference on Photonics in Switching (PS), Florence, Italy, 22-25 September 2015, pp 73-75. DOI: 10.1109/PS.2015.7328957

Pirandola S, Eisert J, Weedbrook C, Furusawa A & Braunstein S. Advances in quantum teleportation. Nature Photonics 2015; 9:641-652. DOI: 10.1038/nphoton.2015.154

Pirandola S, Ottaviani C, Spedalieri G, Weedbrook C, Braunstein SL, Lloyd S, Gehring T, Jacobsen CS & Andersen UL. High-rate measurement-device independent quantum cryptography. Nature Photonics 2015, 9:397-402. DOI: 10.1038/nphoton.2015.83

Pirandola S, Ottaviani C, Spedalieri G, Weedbrook C, Braunstein SL, Lloyd S, Gehring T, Jacobsen CS & Andersen UL. Reply to 'Discrete and continuous variables for measurement-device-independent quantum cryptography'. Nature Photonics 2015; DOI:10.1038/nphoton.2015.207

Spedalieri G, Ottaviani C, Braunstein SL, Gehring T, Jacobsen CS, Andersen UL & Pirandola S. Quantum cryptography with an ideal local relay. In: Proc. SPIE 9648, Electro-Optical and Infrared Systems: Technology and Applications XII; and Quantum Information Science and Technology, 96480Z (October 13, 2015); DOI:10.1117/12.2202662

Spedalieri G & Pirandola S. Restoring broken entanglement by separable correlations. Proc. SPIE 9505, Quantum Optics and Quantum Information Transfer and Processing 2015, 95050B (May 7, 2015); DOI:10.1117/12.2183071

Zhang YC, Li Z, Weedbrook C, Marshall K, Pirandola S, Yu S, Guo H. Noiseless Linear Amplifiers in Entanglement-Based Continuous-Variable Quantum Key Distribution. Entropy 2015, 17: 4547-4562. DOI:10.3390/e17074547

Scientific presentations at conferences and workshops

Amiri, R., Puthoor, I., Wallden, P., Kent, A., Jeffers, J., Andersson, E., Donaldson, R.J., Collins, R.J., Kleczkowska, K. and Buller, G.S. "Unconditionally secure quantum signatures". Poster presentation at the 5th International Conference on Quantum Cryptography (QCRYPT 2015), Tokyo, Japan, 28 September – 2 October 2015

Andersson, E. "Unconditionally secure quantum signatures". Invited talk at the 5th International Conference on Quantum Cryptography (QCRYPT 2015), Tokyo, Japan, 28 September – 2 October 2015

Andersson, E. "Secure quantum signatures". Invited talk at the 3rd ETSI/IQC Workshop on Quantum-Safe Cryptography, Seoul, Korea, 5-7 October 2015.

Buller, G.S. "National Network of Quantum Technologies Hubs – Quantum Communications Hub". Invited talk at the 3rd ETSI/IQC Workshop on Quantum-Safe Cryptography, Seoul, Korea, 5-7 October 2015

Buller, G.S. "Outline of UK QComms Hub activities". Contributed talk at the 3rd ETSI/IQC Workshop on Quantum-Safe Cryptography, Seoul, Korea, 5-7 October 2015

Cheng, Q., Wonfor, A., Wei, J.L., Penty, R.V. and White, I.H. "Low-energy, high-performance lossless 8x8 SOA switch". Contributed talk at the 2015 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, USA, 22-26 March 2015

Cheng, Q., Wonfor, A., Penty, R.V. and White, I.H. "Robust large-port-count hybrid switches with relaxed control tolerances". Contributed talk at Conference on Lasers and Electro-Optics (CLEO) 2015 – European Quantum Electronics, Munich, Germany, 21-25 June 2015

Cheng, Q., Ding, M., Wonfor, A., Wei, J., Penty, R.V. and White, I.H. "The feasibility of building a 64 x 64 port count SOA-based optical switch". Contributed talk at International Conference on Photonics in Switching (PS), Florence, Italy, 22-25 September 2015

Chunnilall C. Invited talk ("Metrology for Quantum Communications") at CLEO 2015, San Jose, United States, 10-15 May 2015.

Chunnilall C. Talk ("Metrology for single-photon technologies") at the Single-Photon Workshop, Geneva, 13-16 July 2015

Chunnilall, C. "Developing standards for quantum technologies. Invited talk at the first Quantum UK International Conference, Oxford, 28-30 September 2015

Colbeck, R. "Device-independence: what it can provide and open challenges". Invited talk at workshop on quantum technologies (QuTe 2015), Sheffield, 31 March 2015

Colbeck, R. "Should we believe in random processes?". Invited talk at the Randomness in Quantum Physics and Beyond conference, Barcelona, Spain, 4-8 May 2015

Colbeck, R. "Quantum circuits for isometries". Invited talk at the VI KCIK Symposium, Sopot, Poland, May 2015

Ding, M., Cheng, Q., Wonfor, A., Penty, R.V. and White, I.H. "Routing Algorithm to Optimize Loss and IPDR for Rearrangeably Non-Blocking Integrated Optical Switches". Contributed talk at CLEO 2015: Laser Science to Photonic Applications, San Jose, USA, 10-15 May 2015

Donaldson, R.J., Collins, R.J., Kleczkowska, K., Amiri, R., Wallden, P., Dunjko, V., Andersson, E., Jeffers, J. & Buller, G.S. "An in–fiber experimental approach to photonic quantum digital signatures operating over kilometer ranges". Contributed talk at the Single Photon Workshop 2015, Geneva, Switzerland, 13 - 17 July 2015

Donaldson, R., Collins, R., Kleczkowska, K., Amiri, R., Wallden, P., Dunjko, V., Andersson, E., Jeffers, J. and Buller, G. "Advances in Experimental Quantum Digital Signatures". Contributed talk at the 5th International Conference on Quantum Cryptography (QCRYPT 2015), Tokyo, Japan, 28 September – 2 October 2015

Elmabrok, O. & Razavi, M. "Feasibility of Wireless Quantum Key Distribution in Indoor Environments". Contributed talk at the IEEE Globecom 2015, San Diego, USA, 6-10 December 2015

Erven, C. (on behalf of Wang, J.). "Chip-to-chip quantum entanglement distribution". Contributed talk at CLEO 2015 – Laser Science to Photonic Applications, San Jose, USA, 10-15 May 2015

Erven, C., Sibson, P. and O'Brien, J. "Integrated Quantum Photonics". Invited talk at Workshop for Quantum Repeaters and Networks, Pacific Grove, USA, 15-17 May 2015

Gerardot, B. "The latest (WSe2 defects) and greatest (InGaAs quantum dots) in solid-state quantum emitters." Invited talk at the International Workshop on Metamaterials and Nanophysics, Cuba, 5-12 April 2015

Gerardot, B. "Screening nuclear field fluctuations in quantum dots for on-demand indistinguishable photons". Invited talk at the 3rd International Workshop on Engineering of Quantum Properties, Austria, 17-18 December 2015

Hu J C-Y & Rarity JG. Presentation ("Saturation nonlinearities of cavity-QED enhanced optical circular birefringence induced by a single quantum-dot spin") at the Topical Research Meeting on Hybrid Quantum Systems, Nottingham, UK, 16-18 December 2015.

Kleczkowska, K., Jeffers, J., Collins, R.J. and Buller, G.S. "Theoretical model of an experimental quantum digital signature system". Poster presentation at the 5th International Conference on Quantum Cryptography (QCRYPT 2015), Tokyo, Japan, 28 September – 2 October 2015

Kok P. Invited tutorial ("Continuous-variable quantum computing: a tutorial") at the Workshop on parametric effects in the quantum regime, Gothenberg, Sweden, 19 March 2015.

Kok P. Invited talk ("Quantum imaging and metrology") at the QuTe2014 Conference, Sheffield, 31 March 2015.

Kok P. Invited talk ("Quantum imaging and metrology") at the BQIT 2015 Conference, Bristol, 15 April 2015.

Kok P. Invited talk ("Entanglement generation in quantum dots using chiral effects in waveguides") at the "Unifying Physics and Technology in Light of Maxwell's Equations" Royal Society meeting, Chicheley Hall, 18 November 2015.

Laing, A., Carolan, J., Harrold, C., Sparrow, C., Martín-López, E., Rusell, N.J., Silverstone, J.W., Shadbolt, P.J., Matsuda, N., Oguma, M., Itoh, M., Marshall, G.D., Thompson, M.G., Matthews, J.C.F., Hashimoto, T. and O'Brien, J.L. "Universal Linear Optics for Quantum Information Processing". Contributed talk at the CLEO 2015 - European Quantum Electronics Conference, Munich, Germany, 21-25 June 2015

Laing, A., Carolan, J., Harrold, C., Sparrow, C., Martín-López, E., Rusell, N.J., Silverstone, J.W., Shadbolt, P.J., Matsuda, N., Oguma, M., Itoh, M., Marshall, G.D., Thompson, M.G., Matthews, J.C.F., Hashimoto, T. and O'Brien, J.L. "Universal Linear Optics". Contributed talk at the SPIE Optics and Photonics International Conference2015, San Diego, USA, 9-13 August 2015

Lo Piparó, N., Razavi, M. and Munro, W. "Measurement-device-independent quantum key distribution with Nitrogen Vacancies in Diamond". Poster presentation at the 5th International Conference on Quantum Cryptograpy (QCRYPT 2015), Tokyo, Japan, 28 September – 2 October 2015

Lowndes, D., Frick, S., Nock, R., Linares-Vallejo, E. and Rarity, J. "Low cost, short range quantum key distribution". Contributed talk at Conference on Lasers and Electro-Optics (CLEO) 2015 – European Quantum Electronics, Munich, Germany, 21-25 June 2015

Newton E, Everitt M, Wilson F, Varcoe B. Poster presentation ("Hanbury-Brown Twiss correlations in Bose-Einstein condensates of photons at Cold atoms") at the Summer school, Ecole de physique des Heuches, Les Heuches, France, 15 September 2015.

Ottaviani, C. "High rate quantum cryptography with untrusted relay: Theory and experiment". Invited Talk at 1st Trustworthy Quantum Information conference (TyQI2015), University of Michigan, Ann Arbour, MI USA, 27 June – 2 July 2015

Penty, R.V., Wonfor, A., Qixiang, C. and White, I.H. "Scalable energy efficient InP space switches". Invited talk at International Conference on Photonics in Switching (PS), Florence, Italy, 20-22 September 2015

Pirandola, S. "Non-Markovian Reactivation of Quantum Repeaters". Invited Seminar at the Department of Optics, Palacky University, Olomouc, Czech Republic, 13 April 2015

Pirandola, S. "Restoring Broken Entanglement by Separable Correlations". Invited talk at the SPIE Optics + Optoelectronics 2015, Quantum Optics and Quantum Information Transfer and Processing, Prague, Czech Republic, 15-16 April 2015

Pirandola, S. "Non-Markovian reactivation of relay-based quantum protocols". Invited talk at the Workshop on Macroscopic Quantum Coherence, University of St Andrews, 1 - 3 June 2015

Pirandola, S. "Measurement-device-independent quantum key distribution at metropolitan distances: Comparison between discrete variables and continuous variables". Poster presentation at the Trustworthy Quantum Information conference (TyQI) 2015, University of Michigan, Ann Arbor, Michigan, USA, 28 June – 2 July, 2015

Pirandola, S. "Relay-based protocols in correlated-noise Gaussian environments Invited Seminar at the Department of Physics, University of Milan, Italy, 14 July 2015

Pirandola, S. "High-rate measurement-device-independent quantum cryptography: Theory and experiment". Contributed talk at the Quantum Information Processing and Communication (QIPC) 2015, University of Leeds, UK, 13-18 September 2015

Pirandola, S. "Quantum cryptography with an ideal local relay". Invited talk at the SPIE Security + Defence 2015, Quantum Information Science and Technology, Toulouse, France, 21-24 Sept 2015

Pirandola, S. "High-Rate Measurement-Device-Independent Quantum Key Distribution". Invited Talk at the Quantum UK 2015 Conference, Oxford, UK, 28-30 September 2015

Rarity, J.G. "Secrets for Consumers: Handheld QKD" Invited talk at the Quantum UK 2015 Conference, Oxford, UK, 28-30 September 2015

Rarity, J.G. "Secrets for Consumers: Handheld QKD". Invited talk at the 3rd ETSI/IQC Workshop on Quantum-Safe Cryptography, Seoul, Korea, 5-7 October 2015

Rarity JG, Androvitsaneas P, Young A, Schneider C, Höfling S, Oulton R, 'Progress towards a deterministic spin photon interface in a quasi-1D system', CLEO Europe 2015, 21-25 June 2015, Munich, Germany

Rarity, J.G, Androvitsaneas P, Young AB, Schneider C, Höfling S, Kamp M, Harbord E, Oulton R. "Progress towards a deterministic spin photon interface in a quasi-1D system". Contributed talk at Single Photon Workshop, Geneva, Switzerland, 13-17 July 2015

Rarity JG. Invited talk ("Interfering with photons") at the International Conference for Young Quantum Information Scientists (YQIS), Paris, France. 16 – 17 Nov 2015

Sibson, P. "Chip-based Quantum Key Distribution". Contributed talk at CLEO 2015 - Laser Science to Photonic Applications, San Jose, USA, 10-15 May 2015

Sibson, P. "Chip-based Quantum Key Distribution". Contributed talk at Conference on Lasers and Electro-Optics (CLEO) 2015 – European Quantum Electronics, Munich, Germany, 21-25 June 2015

Spiller, T. "National Network of Quantum Technologies Hubs – Quantum Communications Hub". Invited talk at Quantum UK 2015 Conference, Oxford, 28-30 September 2015

Spiller, T. "Quantum Communications Technologies". Invited talk at the Conference of Astronomy & Physics Students (CAPS) 2015, organised by the Institute of Physics, University of Manchester, Manchester, UK, 25-28 June 2015

Spiller, T. "UK National Quantum Technologies Programme. National Network of Quantum Technologies Hubs". Invited talk at the Quantum Information Processing and Communication conference (QIPC 2015), University of Leeds, Leeds, 13-18 September 2015

Spiller, T. "Overview of the EPSRC Quantum Communications Hub". Invited talk at Quantum Symposium organised by the British High Commission in Singapore in collaboration with the Centre for Quantum Technologies and the National University of Singapore, Singapore, 26-27 March 2015

Spiller, T. "Overview of the EPSRC Quantum Communications Hub". Invited talk at UK-Japan Quantum Technology Workshop, British Embassy, Tokyo, Japan, 23-24 March 2015

Thompson, M.G. "Integrated Photonic Technologies for Quantum Communications". Invited talk at the 5th International Conference on Quantum Cryptography (QCRYPT 2015), Tokyo, Japan, 28 September – 2 October 2015

Thompson, M. "Silicon Quantum Photonics". Contributed talk at the IEEE Photonics Society's Annual Meeting, Virginia, USA, 4-8 October 2015

Wilson F, Newton E, Everitt M, Varcoe B. Poster presentation ("Integrating QKD with existing communications systems") at the QIPC 2015- Quantum Information Processing and Communication international conference, Leeds, UK, 13-18 September 2015.

Selected Media Coverage

On the Announcement of funding for the four UK Quantum Technology Hubs:

- Physicsworld.com ("UK unveils £120m quantum-technology hubs", 26 November 2014): http://physicsworld.com/cws/article/news/2014/nov/26/uk-unveils-GBP120m-quantum-technology-hubs
- Engineering and Technology magazine ("Quantum tech commercialisation network launched", 26 November 2014): http://eandt.theiet.org/news/2014/nov/quantum-technology-network.cfm
- The Press newspaper ("York leads national quantum physics network", 26 November 2014); http://www.yorkpress.co.uk/news/11627621.York_leads_national_quantum_physics_network/
- Science ("U.K. bids for a lead in quantum technologies", 26 November 2014); http://www.sciencemag.org/news/2014/11/uk-bids-lead-quantum-technologies
- cambridgenetwork.co.uk ("Cambridge to help UK's quantum leap in secure communications", 27 November 2014); http://www.cambridgenetwork.co.uk/news/cambridge-to-help-uks-quantum-leap-in-secure-communications/
- Nature ("Four UK hubs to make 'spooky' quantum physics useful", 2 December 2014); http://www.nature.com/news/four-uk-hubs-to-make-spooky-quantum-physics-useful-1.16426
- fibre-systems.com ("University of York to head quantum communication hub", 14 January 2015); http://www.fibre-systems.com/news/story/university-york-head-quantum-communication-hub

On our 'High-rate measurement-device independent quantum cryptography' publication:

- University of York website ("Researchers find the 'key' to quantum network solution", 26 May 2015): https://www.york.ac.uk/news-and-events/news/2015/research/quantum-network/
- Phys.org (" Researchers confirm 'realistic' answer to quantum network puzzle", 19 November 2015): http://phys.org/news/2015-11-realistic-quantum-network-puzzle.html

On the Adastral Park industrial engagement events:

- Telecompaper.com ("Adastral Park becomes quantum communications hub", 10 June 2015): http://www.telecompaper.com/news/adastral-park-becomes-quantum-communications-hub--1086623
- Innovationmartlesham.com ("Adastral Park prepares for major role in National Quantum Communications Initiative", 11 June 2015): http://www.innovationmartlesham.com/articles/adastral-park-prepares-for-major-role-in-national-quantum-communications-initiative/
- Btplc.com ("BT ready to 'lead the world' in quantum communications", 18 June 2015): http://www.btplc.com/Innovation/Innovationnews/quantumcommunications/index.htm
- Itpro.co.uk ("UK could lead world in quantum tech, says BT", 15 October 2015): http://www.itpro.co.uk/strategy/25441/uk-could-lead-world-in-quantum-tech-says-bt
- Ipswich Star newspaper website ("BT and Innovation Martlesham to host quantum technology experts", 15 October 2015): http://www.ipswichstar.co.uk/news/bt_and_innovation_martlesham_to_host_quantum_technology_experts_1_4271463
- Innovationmartlesham.com ("Adastral Park welcomed the UK's National Programme for the exploitation of cutting-edge Quantum Technologies", 15 October 2015): http://www.innovationmartlesham.com/articles/adastral-park-welcomed-the-uks-national-programme-for-the-exploitation-of-cutting-edge-quantum-technologies/

On the "Advances in Quantum Teleportation" publication:

- University of York website ("Scientists produce status check in quantum teleportation", 30 September 2015): https://www.york.ac.uk/news-and-events/news/2015/research/quantum-teleportation-communications/
- Futurity.org ("Why 'teleportation' is no longer science fiction", 1 October 2015): http://www.futurity.org/teleportation-reality-1015872/
- Redorbit.com ("Teleportation isn't just stuff of science fiction anymore", 2 October 2015): http://www.redorbit.com/news/science/1113409511/teleportation-isnt-just-stuff-of-science-fiction-anymore/

On the record bandwidth for quantum encryption (200 Gb/s) and up to 100 km fibre by partners ADVA, BT, TREL:

- Theinquirer.net ("UK scientists create quantum cryptology world record with 'unhackable' data", 2 October 2015): http://www.theinquirer.net/inquirer/news/2428789/uk-scientists-create-quantum-cryptology-world-record-with-unhackable-data
- electronicsweekly.com ("Quantum cryptography demoes 200Gbit/s over 100km fibre", 5 October 2015); http://www.electronicsweekly.com/news/research-news/quantum-cryptography-200gbits-100km-fibre-2015-10/
- motherboard.vice.com ("Researchers Say They Have Designed an 'Unhackable' Fiber Network", 2 October 2015); http://motherboard.vice.com/en_uk/read/researchers-say-they-have-designed-an-unhackable-network
- itpro.co.uk ("Unbreakable encryption is closer than ever following quantum breakthrough", 2 October 2015); http://www.itpro.co.uk/security/25379/unbreakable-encryption-is-closer-than-ever-after-quantum-breakthrough
- computing.co.uk ("Toshiba and BT boast 'unhackable' network security with new quantum cryptography tech", 5 October 2015); http://www.computing.co.uk/ctg/news/2428904/toshiba-and-bt-boast-unhackable-network-security-with-new-quantum-cryptography-tech
- business-reporter.co.uk ("Researchers claim to have designed 'unhackable' fibre broadband", 5 October 2015): http://business-reporter.co.uk/2015/10/05/researchers-claim-to-have-designed-unhackable-fibre-broadband/

On the work carried out in the context of the UK National Quantum Technologies Programme:

- newscientist.com ("Quantum technology set to hit the streets within two years", 4 October 2015): https://www.newscientist.com/article/mg22830434-100-quantum-technology-set-to-hit-the-streets-within-two-years/

On the Quantum Technologies Showcase event at the Royal Society:

- newselectronics.co.uk ("Future technology on show at Quantum Technology Showcase", 12 November 2015): http://www.newelectronics.co.uk/electronics-news/future-technology-on-show-at-quantum-technology-showcase/109917/
- epsrc.ac.uk ("UK's Quantum Hubs show future technology", 13 November 2015): https://www.epsrc.ac.uk/newsevents/news/ukquantumhubs/
- theengineer.co.uk ("Quantum research in the spotlight", 18 November 2015): http://processengineering.theengineer.co.uk/oil-and-gas/quantum-research-in-the-spotlight/1021441.article

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