Publishable Summary for 14IND05 MIQC2
Optical metrology for quantum-enhanced secure telecommunication

Overview

Quantum Key Distribution (QKD) is essentially the generation of perfectly secure random keys between two parties that communicate by an open quantum channel. This enables the parties to establish a secret key from short pre-shared secret and public exchanges, something which has never been shown to be possible with classical, non-quantum means. With increasing amounts of data being transmitted and stored online, there is an increasing need to secure that data. Researchers in the field consider QKD as the only truly secure key distribution technology (except secret courier) since it is secured by the laws of physics. Interestingly, conventional asymmetrical cryptography, which is almost exclusively used for key distribution today, could be rendered insecure by the advent of extremely powerful computers, including quantum computers, or new mathematical insights.

Need

Fibre and free-space QKD systems use real devices, which do not have the ideal characteristics envisaged by the initial QKD concept. This means that those practical systems can be vulnerable to one or more of the many quantum hacking attacks proposed and/or demonstrated. Counter-measures against these attacks have already been identified, but their effectiveness should be ensured by rigorous characterisation of the optical components – this will be addressed by the project.

Another approach against these attacks is represented by entanglement-based QKD techniques e.g. device independent (DI) QKD, measurement-device-independent (MDI) QKD, etc. The development of entanglement characterisation and quantification techniques is essential in order to provide the metrological framework for next-generation (entanglement-based) QKD systems.

Objectives

The aim of this project is to accelerate the development and commercial success of QKD technologies. The main objectives addressed in this project are:

1. The development of efficient measurement techniques for characterisation of counter-measures to side-channel and Trojan-horse attacks in fibre-based QKD systems, and the realisation of pilot measurement comparisons to validate the techniques
2. The development of new high-speed (sine-gated) single-photon detectors for fibre-based QKD and the relative calibration technique
3. The development of measurement techniques for the characterisation of the components of free-space QKD systems for ground-air communication, and the realisation of pilot measurement comparisons to validate techniques developed
4. The development of measurement techniques for characterising the “quantumness” of quantum states
5. To provide two Best-Practice Guides, one on characterisation of counter-measures to side-channel and Trojan-horse attacks, and one on characterisation of components of free-space QKD systems
6. Contribute to impact - via contributions to international guidelines/standards and showcase examples of early uptake by end users

Progress beyond the state of the art

State of the Art prior to 14IND05-MIQC2
EMRP IND06-MIQC developed techniques to characterise specific quantum-layer optical components of fibre-based QKD systems, e.g. pseudo-single-photon sources based on attenuated lasers, and commercial single-photon detectors based on avalanche photodiodes operating in Geiger mode. Two industrial partners (TREL and IDQ) and three NMIs (INRIM, NPL, and PTB) are members of the ETSI Industrial Specification Group on QKD (ETSI ISG-QKD), which TREL currently chairs.

Progress beyond state of the art
Fibre-based commercial QKD systems: traceable methods have been developed to characterise optical components used as counter-measures against hacking attacks.
Free-space QKD systems: techniques to characterise quantum-layer optical components and devices have been developed. The results of the IMERA-Plus qu-Candela can be used to provide traceability to the photon-counting regime.
Next generation (entanglement-based) QKD: accurate measurement techniques for entanglement quantification and/or witnessing, and for estimating the entangling-process efficiency have been developed.

Standards: TREL, IDQ, INRIM, NPL, and PTB, in the context of the ETSI ISG-QKD, provided metrology leadership for the drafting of pre-standards and standards concerned with characterisation, validation, and certification of the quantum-optical layer of QKD systems and networks. Two Group Specification Documents were published: “QKD - Component Characterisation: characterising optical components for QKD systems” and “QKD; Components and Internal Interfaces”, (from results of EMRP IND06-MIQC and EMPIR 14IND05 MIQC2). Two other documents (implementation security, QKD Transmitter Characterisation) are in preparation.

Comparisons at single-photon level: one informal comparison (under CCPR) and three pilot studies towards comparisons have been carried out.

Two project outputs have been exploited – an improved system by MPD for pigtailing their fibre-coupled SPAD and a new measurement service offered by METAS.
Four quantum technologies prototypes developed in this project are considered of possible commercial interest.

The Ccnsortium, after a strategic analysis, agreed on a “go-decision” towards the creation of a European Metrology Virtual Institute for Quantum Photonics (recently dubbed European Metrology Network for Quantum Photonics). In harmony with EURAMET’s decision to develop European Metrology Networks (EMN), MIQC2 Consortium proposed the EMN for Quantum Technologies. Currently the EMN-Q is under construction.

Results

Objective 1
Eleven results from the project have been exploited by manufacturers.

1) The first concerns the security analysis of a typical “Prepare & Measure” (P&M) QKD transmitter, together with the extended security model. Specifically, a quantitative evaluation of fibre-based QKD system security with active and passive counter-measures against Trojan-horse attacks caused by injecting bright laser light into a QKD transmitter and receiver has been carried out.
2) The second is related to the identification and characterisation of the back-flash light emitted by an InGaAs/InP SPAD (single-photon avalanche photodiode). This investigation showed that the back-flashes can be exploited in Trojan-horse attacks, providing a substantial information leakage to an unauthorised party (in the absence of counter-measures).

Furthermore, IDQ contributed to studies which respectively describe

3) the creation of backdoors which can be created for hackers through the use of intense laser pulses
4) the limitations of an earlier counter-measure to an attack to take control of the detectors in QKD systems and
5) (iii) investigation of the same attack on free-running detectors.

These five results listed above are important for the practical security of QKD systems and for this reason they can be considered as early uptakes. On one side QKD manufacturers should take account of these results in designing their new devices, and on the other side the NMIs should develop measurement services necessary for testing the protection strategies implemented.

6) The sixth result consists in the development of techniques for characterising specific “passive” optical components for fibre-based QKD systems (such as a MEMS attenuator, a polarisation-maintaining circulator and interference filters) to test their behaviour and their effectiveness as potential counter-measures against quantum hacking based on Trojan-horse or side-channel attacks. It showed interesting and unexpected results in terms of potential weaknesses QKD manufacturers should be aware of. Based on this perspective, a new service for the calibration of the spectral properties of optical fibre components in the 700 nm to 1800 nm range has been realised by METAS.
7) In connection with the QKD security analysis, an interferometric method and security model for prepare-and-measure QKD to remove side-channel information coming from laser instabilities leading to super-Poissonian statistics.
8) The eighth result is a new secure front-end circuit (developed by MPD and Polimi) for SPADs protecting against quantum hacking attacks. The effectiveness of the implemented counter-measures was demonstrated against the following attacks: i) efficiency-mismatch attacks; ii) after-gate attacks; iii) blinding attacks.
9) Another result, figuring also as an early uptake of the project, was that a Single Photon Detectors manufacturer (MPD), inside MIQC2 consortium, was able to improve the design and implementation of the fibre-coupling in its pigtailed detectors.
10) MPD and INRIM designed a prototype of portable single-photon OTDR system, and MPD is developing this prototype and performing a market analysis regarding its possible commercialisation. The capability developed in the project will be used by INRIM to provide a measurement service for fibre-coupled single-photon detectors at 1550 nm.
11) Furthermore, MIQC2 realised two pilot-studies for measurement comparisons. This is fundamental for validating the metrological calibration techniques at single-photon level at telecom wavelength.

Objective 2

New electronic circuit solutions were developed, and a first prototype of an InGaAs SPAD sine-gated at frequencies greater than 1 GHz has been successfully realised. This device is designed to be tunable over a wide range (900-1400 MHz) for synchronisation with different external laser systems and for selecting the best trade-off between after-pulsing and detection efficiency. The excess bias is adjustable for optimising the main SPAD parameters, like photon detection efficiency, dark count rate, after pulsing, timing jitter. The system can be controlled remotely from a PC and has already demonstrated proved long-term stability.

During the development of this sine-gate module, several unexpected technical issues emerged, due to the demanding specifications of the system in terms of frequency and phase shift. The assembly of the whole SPAD system has been finalised and tested at the end of the project, and it fully satisfies all the target requirements: very low after-pulsing (around few percent), high dynamic range (maximum count rate no more than few hundreds of Mcount/s), high detection efficiency (> 30 % at 1550 nm), low noise (per-gate dark count rate < 1 x 10-4) and low timing jitter (< 100 ps). The realisation of the commercial detector prototype is one of the early uptake of the project.

Due to the unexpected delays occurred in the detector development phase, it has been impossible to develop a protocol for calibrating this kind of detectors during the project lifetime.

Objective 3

One key result for Objective 3 was the establishment of the technical protocol for a pilot study on the detection efficiency measurement of silicon SPADs. This pilot study was performed worldwide (including outside the consortium) and within the Consultative Committee for Photometry and Radiometry (CCPR). 11 NMIs I participated, of which 6 were within this project. CMI, NPL and PTB have already carried out the pilot comparison on Si-SPAD single-photon detection efficiency for the task-Group on Single-Photon Measurements inside the CCPR (CCPR-WG-SP-TG11, CCPR-WG-SP-TG7). INRIM is scheduled to participate in this comparison after the end of the project. INRIM delayed its participation because of technical problems.

In parallel, PTB, INRIM and NPL have performed a pilot-study on measurement of the $g^2(0)$-values (Glauber second order correlation function) of VIS/NIR (@ 850nm) sources. A paper is already publicly available on MIQC2 web portal and on the arXiv.org portal, and will be disseminated to CCPR.
Furthermore, detectors and amplifiers providing traceability of measurements at single-photon level to conventional radiometric standards have been realised and characterised.

NPL is going to exploit the capabilities developed inside the project to create a measurement service for free-space single-photon detectors in the VIS/NIR. Techniques for characterising components of free-space QKD systems for ground-air communication have been organised and are ready for use. High-quality single-photon sources have been realised and characterised. In particular, a stand-alone quantum dot based single-photon source prototype has been developed by TUB. Furthermore, MIQC2 realised two pilot-studies for measurement comparisons. This is fundamental for validating the metrological calibration techniques at single-photon level in the VIS-NIR.

Objective 4
Optimal estimators have been developed for measuring the amount of entanglement and the geometric discord with the minimum uncertainty level achievable.
Experimental set-ups encoding information in several spatial degrees of freedom (Hilbert space larger than 2) exploiting multi-core fibres have been realised. 2-dimension and 4-dimension entanglement has been generated and analysed by quantum state tomography.
Experimental realisation of weak measurements and weak values estimation has been performed, allowing the properties of quantum systems to be measured, without, to some extent, the wave-function collapse. This has provided some important returns not only in the field of quantum metrology.
Realisation of a first version of a new source (folded-sandwich configuration) of polarisation entangled photon pairs, highly tuneable in frequency. This source is particularly useful as an interface for quantum hybrid systems.
A high rate, long distance detector-device independent (DDI-QKD) scheme has been realised using two degrees of freedom of the same photons; the security analysis has been carried out. This represents a first step towards a more feasible approach to MDI-QKD.

Impact

The project contributed to: 29 peer reviewed publications (20 open access); 125 conference presentations (93 talks [39 invited] and 32 posters); 6 conference paper publications; 2 early uptakes and 12 exploitable results.
The Single Photon Workshop 2015 (SPW2015) was successfully organised at the University of Geneva (CH) in July 2015. There were around 200 attendees. The consortium contributed also to the organisation of the Single Photon Workshop 2017 (SPW2017) at University of Colorado in the USA (approximately 250 attendees). Furthermore, as a side event of SPW2017 the consortium organised a successful Lecture Course entitled “Single-photon metrology and its application to quantum technologies” dedicated mainly to PhD and early Postdoc Researchers (40 attendees). A partner of MIQC2 consortium was designated to host the following Single Photon Workshop 2019 (SPW2019, Italy, summer/fall 2019).
A parallel symposium on the topic of ‘Assurance and Certification for Quantum Communication Technologies’, co-organised by MIQC2 and the ETSI ISG-QKD, was held at QCrypt2017, Cambridge (UK), in September 2017.
A Special Symposium on “Metrology for Quantum Communications” was held at the Quantum Technologies Conference of the SPIE Photonics Europe 2018 Meeting in Strasbourg (FR), in April 2018. 5 presentations were given (approximately 50 attendees).
Web-lectures have been realised and published on the MIQC2 website (http://empir.npl.co.uk/miqc2/), with periodical updates. These lectures cover the topics of single-photon sources and detectors, discrete-variable and measurement-device independent QKD, and an overview of the European metrology effort for quantum cryptography. A Webpage for ‘European single-photon metrology has been created (http://empir.npl.co.uk/quantumphotonics/). This gives the overall perspective on European metrology for single-photons and related technologies, e.g. quantum communications.

Impact on relevant standards

TREL, IDQ, INRIM, NPL, and PTB, in the context of the ETSI ISG-QKD, contributed to the drafting of pre-standards and standards concerned with characterisation, validation, and certification of the optical layer of QKD systems and networks (The Impact report details 18 engagements with the ETSI ISG-QKD). Two Standardisation Documents have been already published. The ETSI Group Specification document “ETSI QKD GS 011 – Component characterisation: characterising optical components for QKD systems”– was published by ETSI in May 2016. This document took about 2 years to compose, and the work on the initial drafts was supported by EMRP projects IND06-MIQC and EXL02-SIQUTE. This document is, to our knowledge, the first measurement (pre-) standard for a quantum 2.0 technology. Since it is focussed on the characterisation of attenuated laser sources and gated single-photon detectors, it is also relevant to all quantum optical technologies utilising these devices.
The ETSI Group Report document “ETSI GR QKD 003 – Quantum Key Distribution (QKD); Components and Internal Interfaces” was published by ETSI in March 2018.
Two other documents currently in draft receive support from this project, in particular:

-ETSI GS QKD 010: Implementation Security - Protection against Trojan horse attacks in one-way QKD systems (Rapporteur TREL)

- ETSI GS QKD 013: Characterisation of QKD transmitter modules (Rapporteur INRIM).

Impact on industrial and other user communities

In the project consortium there are two key European QKD manufacturers (IDQ and TREL), as well as single-photon detector manufacturers (MPD and IDQ), and having as collaborators (members of the stakeholder advisory board) an organisation working in the field of information security (CAENqS), and of single photon detector (PicoQuant). These ensured that the work was aligned with the industrial requirements during the lifetime of the project. For example, investigation of backflashes from single-photon detectors have been carried on in collaboration with TREL, and part of the investigation has been performed on detectors by IDQ, and prototypes provided by MPD in collaboration with PoliMi. Moreover, it should be noted that the published security analyses, derived inside this consortium to improve the protection of the QKD apparatus from quantum-hacking attacks, can lead to: (i) exploitation of the results by QKD manufacturers (impact on industry); and (ii) a required measurement standard and service for establishing whether the required optical isolation is achieved (impact on metrology).

Two project outputs have been exploited – an improved system by MPD for pigtailing their fibre-coupled single-photon detectors (based on tests performed with the set-up developed at INRIM to characterise fibre-couple single-photon detectors), and a new measurement service offered by METAS (based on their work to characterise various passive devices used as countermeasures).
In addition, six results on attack vulnerabilities and their countermeasures – on Trojan-horse attacks, back-flash, photon-source emission instabilities and three aspects of bright-pulse attacks – are expected to be exploited by QKD manufacturers to make their systems more secure, and may also lead to the need for measurements by certification laboratories to confirm the effectiveness of counter-measures.
Four prototypes developed in the context of this project (a lab-prototype of single-photon OTDR, a fast gated detector, a new secure front-end circuit for SPADS against quantum hacking and a stand-alone quantum dot based single-photon source) are considered as possible commercial interest.

Finally, two Best Practice Guides have been prepared to be open access: the *"Best practice guide on characterisation of counter-measures to side-channel and Trojan-horse attacks"*, and the *"Best Practice Guide on characterisation of components of free-space QKD systems".* These are downloadable for free from the MIQC2 website

Impact on the metrological and scientific communities

Eight members of the project are also members of the Consulting Committee on Photometry and Radiometry (CCPR), and have been working to incorporate photon-based quantities into its strategic planning. Furthermore, seven members of the project are members of the EURAMET Technical Committee for Photometry and Radiometry ensuring that CCPR and EURAMET are kept informed about the progress of the project and that CCPR & EURAMET roadmaps address the needs of the single-photon and QKD communities. It should be mentioned that this project triggered the establishment of the informal comparison on detection efficiency of single-photon detector in the VIS-NIR under the umbrella of the task group on “Single-Photon

Radiometry" within the working group "Strategic Planning" of the Consultative Committee for Photometry and Radiometry. In a worldwide effort, 11 NMIs (6 are partners of this project), agreed on a technical protocol to carry out the informal comparison on the detection efficiency of Si-SPADs (coordinated by PTB, the comparison started in May 2016).

Moreover, a pilot study on measurement of detection efficiency in the photon counting regime at 1550 nm have been performed, together with two pilot-studies on the measurement of the $g^2(0)$-values (Glauber second order correlation function) for pulsed and CW light sources (emission at single-photon level) in the VIS and at telecom spectral region, respectively. Three papers reporting the results of these comparisons will be publicly available on MIQC2 web portal and on the arXiv.org portal, and will be disseminated to CCPR, EURAMET TC PR (and their relevant working groups), ETSI and IEC meetings.

It is worth noting that the strategic analysis promoted between the European NMI partners of the consortium (INRIM, NPL, PTB, CMI, Aalto, Metrosert and METAS) returned a unanimous and synergetic vision about the creation of a European Metrology Virtual Institute for Quantum Photonics (lately renamed: European Metrological Network for Quantum Photonics). A structure able to coordinate the European metrological effort in the field of quantum photonic technologies, and to exploit in a cooperative and efficient way the resources available.

Beyond the project objectives, and in harmony with the EURAMET decision to develop internal structures called European Metrology Networks (EMN), the Consortium proposed the creation of the EMN for Quantum Technologies that broaden the scope beyond Quantum Photonics. EURAMET approved the proposal and the EMN for Quantum Technologies (EMN-Q) is under construction.

List of publications

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