# Realising Scalable, Commercial Quantum Networks

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**Abstract** We describe work to realise scalable, quantum-secured networks, in which quantum key distribution and other quantum-safe technologies are integrated in a conventional telecom network, accessible by multiple users. ©2023 The Author(s)

## Introduction

Relentless progress in quantum computing threatens to severely weaken much of the cryptography used today. In particular, all widelyused forms of public key cryptography rely on the difficulty of certain mathematically-hard problems, which can be solved efficiently on a large-scale quantum computer. To protect future network communications, it is imperative to develop new "quantum-safe" technologies resistant to attack in the quantum era.

The problem lies not just in the future. Today's data is also susceptible to "harvest now, decrypt later" attacks, where an adversary can store encrypted messages today, to later decrypt when a large-scale quantum processor becomes available. This is particularly problematic for information with a long-term value, such as financial records, medical data, corporate IPR or details of a nation's critical infrastructure.

Quantum cryptography provides a suite of protocols, the security of which can be proven from first principles. In particular, quantum key distribution (QKD) allows secret keys to be shared on optical networks. Unlike algorithmicbased techniques, QKD will be not vulnerable to attack by powerful computers, not even a quantum processor, in the future.

Although QKD protocols can be *Information Theoretic Secure (ITS)*, real-world security requires a careful implementation.[1] There has been considerable effort in recent years to understand attacks and countermeasures on QKD systems and work to create a security certification framework is underway.[2]

There have been several impressive demonstrations of QKD networks to date.[3-7] However, most of these have been conducted using dark fibre or with equipment hosted in a lab. This work will review recent progress to embed quantum security devices, along with quantum resistant algorithms, in operational telecom networks, as well as the technological advances which have made it possible.

## **QKD** Technology

Our QKD systems [8] use laser pulses attenuated to the single photon level as carriers. These inevitably sometimes contain two or more photons, but by sending weaker 'decoy' pulses randomly interspersed with the signals, it is possible to eliminate potential information leakage due to these multi-photon pulses.[9]

The qubits are encoded as a phase difference between two paths in an asymmetric Mach-Zehnder interferometer in the transmitter and read out using a matched interferometer in the receiver.[10] Such fibre interferometers are typically very sensitive to ambient fluctuations in temperature. However, active stabilisation of the path lengths allows to operate the system continuously with minimal fluctuation in key rate.

Secret keys are formed by implementing the BB84 protocol with decoy states, which has a complete security proof under the most general types of attack, and ITS authentication. Its security analysis takes account that a key formation session lasts a finite length of time, with a finite number of measurements, and so results in statistical uncertainty in the measured values. Consequently, keys can be guaranteed secure within a certain confidence bound. The probability of obtaining a compromised key (failure probability,  $\varepsilon$ ) can be set very low, in our case  $\varepsilon < 10^{-10}$ , corresponding a frequency of less than one in tens of thousands of years.[9]

# Long Distance QKD

To achieve the longest possible fibre range, the quantum channel is provisioned on a DWDM channel near 1550nm, where photon loss in the fibre is minimal. Figure 1 plots the key rate measured for the Long Distance (LD) QKD system for different lengths of standard fibre, with an attenuation of 0.2 dB/km at 1550 nm, along with a simulation. Notice the key rate reduces exponentially with fibre length due to fibre loss and drops rapidly to zero when the detected photon rate becomes comparable to the noise rate.



Fig. 1: Secure key rate vs fibre length measured (symbols) on the Toshiba LD QKD system, along with the calculated dependence (solid line).

It can be seen in Fig. 1 that the secure key rate (SKR) is typically ~ 800 kb/s at 50 km fibre length (10 dB loss), sufficient for >3,000 AES-256 keys per second. High key rates are important, especially in the backbone links of the network, which will provide key material simultaneously to thousands of users and applications.

The key rate rolls off around 187 km in Fig.1, corresponding to a maximum loss budget of 37 dB. This value can be extended by cooling the detector to reduce its dark count noise, allowing operation with lower rate quantum signals. In previous work we have demonstrated QKD over 240 km by thermo-electric cooling to -60°C.[11]

The LD system can support a limited number of data channels launched concurrently on vacant DWDM channels in the C-band. The data channels create Raman scattered photons over a broad spectrum. As the launch power, or the number of data channels is increased, the Raman noise increases and eventually swamps the quantum signal, rendering QKD impossible. However, by carefully filtering the Raman noise in the receiver, co-existence of QKD and data channels with a combined launch power of a few dBm is possible for the LD QKD system.

#### **Multiplexed QKD**

Much higher data launch powers can be tolerated if we shift the quantum channel to the O-band (1310 nm), where the Raman noise is much lower. This configuration is used in the Multiplexed (MU) QKD system, to enable operation with a large number of co-propagating DWDM channels. This is highly advantageous in situations where dark fibre is not available, or prohibitively expensive, and the QKD channels must therefore be provisioned on data-carrying fibres.

Figure 2 plots the quantum bit error rate (QBER) and SKR measured on a 28.7 km installed fibre (16 dB loss) in BT's network over a 48 day duration. The first 36 days of the trial were performed with only QKD signals propagating on



**Fig. 2:** QBER and SKR recorded on a 28.6 km installed fibre. After day 36, 31 DWDM channels were multiplexed onto the fibre to co-propagate with the quantum channel

the fibre. Remarkably we see no change in the quantum bit error rate or secure key rate when (on day 36) 31 DWDM channels in the C-band (between 1530 and 1560 nm) are multiplexed onto the same fibre. These measurements were limited by the number of wavelengths available, but by increasing the laser power we observed that >20dBm of launch power could be supported in the presence of QKD, equivalent to 100 channels with 0 dBm launch power.

Orange recently reported multiplexing of 60 100G data channels with the MU QKD system over 70 km of fibre.[12]. In other work, JP Morgan Chase and Ciena have demonstrated MU QKD with 800G data channels (total bandwidth 2.4 Tb/s) over a 100 km fibre.[13] These deployments highlight that the MU QKD system can be operated on fibres carrying high data bandwidths, thereby removing the requirement for dark fibre and allowing significantly lower operating costs.

#### **Key Management System**

QKD can be implemented in a networked scenario using our Key Management System (KMS)[14] to facilitate delivery of symmetric keys between any two points connected to the network, as shown in Figure 3. Applications can request key material using a REST-based API, which has been standardised by ETSI.[15]

We abstract the network into a physical QKD link layer, responsible for producing the local keys. These local keys are supplied to a network



Fig. 3: Schematic of a Key Management System supplying keys for AES encryption of data.



Fig. 4: Schematic of the London Quantum Secured Metro Network.

key delivery layer, which is responsible for routing a network key to the desired destination. The network key is protected in transit, using onetime-pad encryption with the corresponding local key, across each hop in the network.

The keys served by the KMS can be used in a variety of ways. For example, for one-time pad encryption of data, with information theoretic security, leveraging QKD's ability to deliver high volumes of key material. More commonly, however, the symmetric keys are used for bulk encryption of data between two sites using AES encryption, which is also quantum safe. Α number of vendors of AES encryption hardware and software, operating in different layers of the OSI stack, have implemented the ETSI QKD-014 interface,[15] allowing compatibility with Toshiba QKD systems. The London network uses optical transport systems, with integrated encryption cards. from ADVA.

### London Quantum-Secured Metro Network

Figure 4 shows a schematic of the London Quantum-Secured Metro Network. It consists of three core nodes located in secure locations in BT exchanges in London. These were chosen to be in central London, East/Docklands financial district and West/M4 Corridor, with the latter providing access to major datacentres to the west of London.

QKD systems were installed on the core links to provide a constant stream of key material between the core nodes, with both Toshiba's LD and MU systems deployed.

Customers connect to the core network via an access tail from their premise to the nearest core nodes provided by OpenReach. The access tails use the Optical Filter Connect (OFC) product[16] which provides use of 8 DWDM wavelengths in the C-band. Three of these channels are used for the quantum, classical and synchronisation channels of the QKD system, while the remaining wavelengths are available for encrypted customer data. OFC is specified to operate over links up to 40 km, although the QKD technology can span a much greater radius around each node. The KMS orchestrates delivery of key material to multiple customers connected to the network simultaneously.



Fig. 5: Schematic of a global Quantum Secured Network, in which large-area fibre QKD networks are linked by Satellite QKD links.

#### **Towards Global Networks**

QKD performance is now sufficient to allow national/continental scale quantum-secured networks based solely on fibre. As discussed above the LD QKD system offers a maximum loss budget of 37 dB, sufficient to directly connect the core nodes of a national network, located in the main population centres. The link loss can be further extended by using lower noise detectors.

Such high loss tolerance is a significant advance, as it eliminates the requirements for trusted nodes in intermediate sites, such as communication huts located between cities, thus reducing the cost of both the hardware in the network and its secure deployment.

The most promising approach for longer distances in the near term is to use low Earth orbit satellites, as shown in Figure 5. These can form a QKD link between the satellite and fibre networks in different regions, thereby forming a global network. A proof-of-principle demonstration has already been made by the Micius satellite.[17] With several other missions planned to launch in the coming few years, rapid progress towards a global quantum-secured network can be expected.

In the longer term, quantum repeaters may become viable for all fibre, global quantum networks. Recently there has been promising progress. Practical techniques for Twin-Field QKD,[18] which has similar scaling to a 1-stage quantum repeater, have been demonstrated [19] and recently extended to allow operation over 1000 km.[20]

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