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Quantum Key Distribution over a 143 km Heterogeneous SMF-MCF Infrastructure with Co-existing Classical Traffic

J. Argillander[(1),*], C. Lei[(2),*], M. Clason[(1)], M. Ahmadian[(1)], Ming Tang[(3)], R. Lin[(2)], G. B. Xavier[(1)]

[(1)] Linköping University, Department of Electrical Engineering, Linköping, Sweden,
[(2)] Chalmers University of Technology, Electrical Engineering Department, Gothenburg, Sweden,
[(3)] Huazhong University of Science and Technology, Wuhan, China.
* These authors contributed equally

joakim.argillander@liu.se

Abstract *We demonstrate QKD transmission over heterogeneous network infrastructure consisting of a long-distance deployed single-mode fibre link connected to a multicore fibre-based access network, while showing dynamic co-existence with classical traffic within the multicore fibre, enabling one-to-many quantum and classical services. ©2025 The Authors*

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Introduction

Quantum Key Distribution (QKD) is an emerging technology that allows for ultra-secure data transport[1]. It harnesses Heisenberg's uncertainty principle to establish a mutual secret key between parties, and the technology has gained considerable commercial success in recent years. Most discrete-variable QKD protocols like BB84, E91 (and variations of them), as well as continuous-variable QKD are typically only realized as point-to-point links over single-mode fibres[1].

Recently some efforts have been drawn towards the use of spatial-division-multiplexing (SDM) optical fibres[2] for applications in quantum information[3]. More specifically, multi-core fibres (MCFs) have been used for QKD experiments with high-dimensional transverse spatial quantum states[4],[5], boosting the transmission rate of QKD by paralellizing the quantum channel over multiple cores[6], and even for field demonstrations over deployed MCFs by demonstrating high-dimensional QKD with hybrid encoding between time and path[7]. Polarization-based QKD has rarely been demonstrated over long distances, especially beyond 100 km. Most systems employ time-bin encoding due to higher robustness against external disturbances while propagating in optical fibre links. Still, a few stand out: Peng et al. achieved 102 km with decoy states[8], while more recently polarization entanglement has been distributed over a 96 km submarine link[9], and across a 248 km deployed fibre link[10] showing real-world viability. These cases are promising, thus showing the need for more work in this area.

In this work we demonstrate, for the first time to the best of our knowledge, the first successful QKD session over a heterogeneous fibre link, which in our case consists of 110 km single-mode deployed optical fibre connected to a 33 km 7-core spooled fibre representing an access network link with coexisting classical traffic. This scenario is highly relevant in order to connect different metropolitan MCF quantum networks, such as the one in the city of L'Aquila in Italy[7]. We dynamically route the quantum channel and the classical signals over the different cores demonstrating the feasibility of performing classical and quantum routing to different subscribers in the access network. This marks a significant step towards the deployment of realistic QKD infrastructure, while taking advantage of next-generation optical fibres.

Experimental setup

The setup is depicted in Fig. 1 (b). A commercial polarization-encoding QKD transmitter (ThinkQuantum QuKy-TX) is located in a telecommunications exchange node in Nyköping, Sweden, connected to a commercial single-mode optical

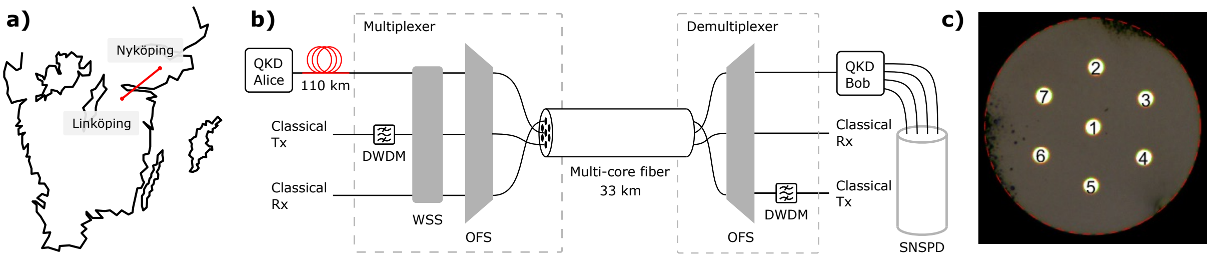

Fig. 1: a) Deployed fibre stretch in eastern Sweden. b) The experimental setup. c) Multicore fibre employed with core assignment.

fibre link (GlobalConnect AB), with a total link loss of 23 dB and a distance of 110 km. The fibre link connects to the Linköping Metro Fibre network before arriving at Linköping University (LiU). This 110 km link is part of the National Quantum Communication Infrastructure in Sweden (NQCIS), a national project that is part of the EuroQCI-framework.

At LiU, the QKD fibre is connected to a waveshaper (WSS, Coherent 16000A), working as a fixed DWDM multiplexer for the QKD and the classical channels, and a 32x32 optical fibre switch (OFS, Polatis 6000-series). The total insertion loss of both the WSS and OFS is around 6.5 dB. The OFS is used to selectively switch the quantum stream to different cores of the MCF through an integrated fan-in device (not drawn for simplicity), and also to multiplex a classical data stream in coexistence with the quantum traffic on other available cores. The outputs of the MCF fan-out (also not drawn) are connected to other available ports in the same OFS to allow routing of both the inputs and outputs of the MCF. The quantum channel is routed to the QKD receiver (ThinkQuantum QuKy-RX) to generate the raw key, which is post-processed to generate the shared secret key[1]. The QKD receiver has been modified by ThinkQuantum to have the capability of connecting it to four external superconducting nanowire single-photon detectors (idQuantique ID281) with total system detection efficiencies of $\eta_1, \eta_2 \geq 90\%$ and $\eta_3, \eta_4 \geq 80\%$. This increases the loss tolerance of the QKD system to a total of 51 dB.

We first measure the insertion loss through the MCF (including fan-in and fan-out) for each core in order to determine suitable allocation of quantum cores, with the results displayed in Table 1. The insertion loss is measured from the raw count rate in the QKD system when connecting to the different cores, with a reference measurement taken by connecting the QKD link back-to-back, effectively bypassing the MCF. The insertion loss for each core is computed by comparing it to the reference back-to-back configuration. This method measures the attenuation as-seen by the QKD system, which yields the effective attenuation that impacts the QKD performance. As the secret key rate (SKR) is mainly limited by link attenuation, our choice of cores indeed represents the best and worst scenarios from the QKD point of view. We thus choose cores 1 and 2 for the QKD channel as the best and worst case scenarios in terms of attenuation.

In order to show co-existence with classical traffic, we generate a 10 Gbps UDP data stream using two full-duplex SFP+ modules and two 10 Gbps network interface cards. The SFP+ modules have a center wavelength of 1546.12 nm (DWDM channel 39), and a total loss budget of 23 dB (80 km). The SFP+ transmitter is spectrally filtered by passing it through channel 39 in a DWDM-multiplexer to suppress any out-of-band photons that otherwise might couple to the quantum signal through crosstalk in the MCF. This filtering is performed before connecting to the OFS and spatially multiplexed with the QKD channel arriving from the long-distance link from Nyköping. The QKD transmitter's wavelength is 1550.12 nm (DWDM channel 34) which is also connected to the OFS.

Core	Insertion loss (dB)
1	9.9
2	13.6
3	13.0
4	13.5
5	13.0
6	10.6
7	10.8

Tab. 1: Insertion loss for each core of the 7-core MCF.

Traffic	Cores
Quantum	1, 2
Data TX/RX	3, 4, 5

Tab. 2: Core assignment for quantum and classical RX/TX channels

Coexistence in a heterogeneous network

We opt to allocate the cores to quantum/classical data according to Table 2. For all possible assignment triplets of one quantum core and two classical (data) cores (RX and TX respectively) we run a QKD session consisting of 5 blocks of 50 kilobytes of secret key each, while we simultaneously generate realistic IP traffic over the classical cores. In order to assess possible effects on the secret key rate (SKR) caused by any crosstalk in the MCF we consider the core assignment $(\mathsf{TX}_A, \mathsf{RX}_A) = (\mathsf{C}_x, \mathsf{C}_y)$ to be identical to the reversal $(\mathsf{TX}_A, \mathsf{RX}_A) = (\mathsf{C}_y, \mathsf{C}_x)$. The joint effect of backscattering and cross-coupling (and forward-scattering followed by cross-coupling) is believed to be negligible. We monitor the raw and secret key rate, as well as the classical bitrate, packet loss and jitter.

The experiment is then run automatically for all assigned core combinations of QKD and classical data channels. After five blocks of secret key have been acquired for a core combination, the OFS is changed to a new core combination and is repeated for all combinations. Between each five-block key distribution run, the QKD system needs approximately 2 minutes to realign the polarization reference between Alice and Bob. This alignment is required since switching the core combination using the OFS rotates the state of polarization.

Results and Analysis

First we plot the raw key rate (RKR) for both cores for the different classical core placement in Fig. 2. The raw key rate is simply all the detected events recorded by Bob, with no post-processing applied. As expected the RKR is higher for core 1 because of the lower attenuation.

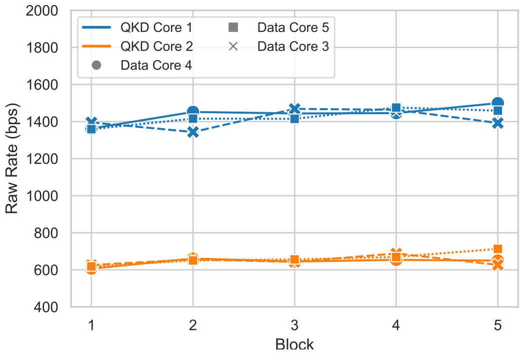

Fig. 2: Raw key rate per block for core 1 and 2, as a function of the quantum core. The lines are a guide to the eye.

The main results are then shown in Fig. 3 for the QKD traffic placed in core 1 and Fig. 4 showing the same measurements from core 2. We show the SKR and the average Quantum Bit Error Rate (QBER) per block for each different core usage. We only show the core allocation for the TX channel, as the RX core placement is not relevant according to our measurements due to having negligible cross-talk from the backward propagation direction.

Irrespectively of the choice of cores for the QKD channel, the QBER for both cores is very similar, owing to the fact that the MCF combined with the DWDM filters employed provide very good isolation and thus no significant crosstalk is taking place. The secret key rate is lower on average on core 2, because of the attenuation difference. The variability in the results between each block stems from the low raw key rate detected, due to the total high attenuation of around 40-43 dB. The average for the SKR and QBER is 221.4 bps $\pm$ 185.5 and 1.07% $\pm$ 0.42 for core 1 and 125.9 bps $\pm$ 126.20 and 1.25% $\pm$ 0.36 for core 2, showing a clear improvement in the QKD performance if core 1 is employed. Nevertheless we achieve successful generation of quantum-secured keys through both measured cores of the MCF while simultaneously maintaining a line speed of 9.47$\pm$0.01 Gbps in all classical cores. As can be seen in Table 3 the classical bitrate is maintained with low packet loss for all core combinations.

Conclusions and Future Work

We have successfully shown coexisting quantum and classical traffic over a heterogeneous fibre network consisting of 110 km of single-mode fibre, followed by 33 km of multi-core-fibre. We demonstrate that multi-core-fibres offer sufficient isolation in the C-band to serve as access network infrastructure for a QKD-service network. Remarkably the MCF and multiplexing setup was added after 110 km of propagation, showing the robustness of modern QKD systems especially when paired with high-efficiency SNSPDs. Further studies include assessing the effects of a fully allocated fibre with multiple simultaneously (high-speed) data streams, in both directions, coexisting with a QKD stream in a dedicated core. Another venue of research is to develop hybrid multiplexing strategies where quantum traffic is wavelength-division-multiplexed onto classical data in the MCF to assess if the core isolation is maintained.

Quantum Core	Classical Core	Bitrate (Gbps)	Packet Loss (%)
1	3	9.50	0.11
1	4	9.48	0.13
1	5	9.51	0.14
2	3	9.43	0.13
2	4	9.46	0.11
2	5	9.46	0.12

Tab. 3: Performance metrics for various quantum-classical core pairs. The mean jitter for all core configurations is less than 0.01 ms. Only the core choice for the TX is shown.

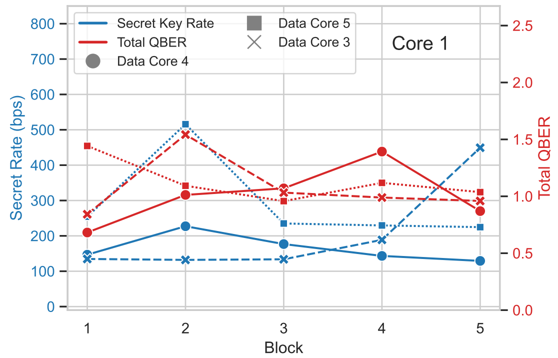

Fig. 3: Secret key rate and quantum bit error rate for quantum core 1. The lines are a guide to the eye.

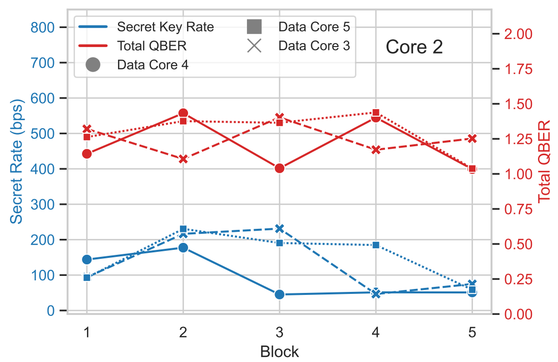

Fig. 4: Secret key rate and quantum bit error rate for quantum core 2. The lines are a guide to the eye.

Acknowledgements

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