Atomic Clocks Technologies for Twin-Field QKD in Real World

Cecilia Clivati,[1,*] Alice Meda,[1] Simone Donadello,[1] Filippo Levi,[1] Marco Genovese,[1] Alberto Mura,[1] Salvatore Virzì,[1] Mirko Pittaluga[2], Zhilian Yuan[3] Andrew J. Shields,[4] Marco Lucamarini,[5], Ivo P. Degiovanni,[1] and Davide Calonico,[1]

[1] *Quantum Metrology and Nanotechnology division, Istituto Nazionale di Ricerca Metrologica, strada delle cacce 91, 10135 Torino (IT).*
[2] *School of Electronic and Electrical Engineering, University of Leeds, LS29JT Leeds, U.K.*
[3] *Beijing Academy of Quantum Information Sciences, No. 10 Xi-bei-wang East Road, Haidian District, Beijing 100193, China*
[4] *Toshiba Europe Ltd, Cambridge, U.K.08 Science Park, Milton Rd, CB40GZ Cambridge, U.K.*
[5] *Dept. of Physics and York Centre for Quantum Technologies, University of York, YO105DD York, U.K.*

**c.clivati@inrim.it*

Abstract: Twin-field quantum key distribution on optical fibers, a promising approach to long-distance secure communication, can take advantage from atomic clocks technologies such as narrow linewidth lasers and phase-coherent distribution of optical pulses. We will describe the integration of these technologies in a TF-QKD setup implemented on an extended metropolitan fiber network and report on the expected QKD performances.

1. Introduction

Quantum Key Distribution (QKD) answers the need for sharing secret cryptographic keys with proven security against eavesdropping attacks. Its integration into existing telecom fiber networks and the coverage of regional distances are important challenges today, and are related to overcoming the significant channels attenuation of real world long-distance fibers.

A few years ago, the Twin-Field Quantum Key Distribution (TF-QKD) protocol [1] was proposed as especially suited to this scope, thanks to a higher immunity to fiber loss as compared to traditional QKD protocols, and its capability to fight the so-called PLOB bound [2]. This approach unfolds the traditional Alice-Bob interferometer into a 3-node network, where an intermediate untrusted node, Charlie, acts as a relay, effectively doubling the reach of the link. The conceptual equivalence of this scheme to more traditional QKD topologies relies on two important assumptions, i.e. the distant photon pulses generated in Alice and Bob are phase-coherent, and their coherence is preserved as they are sent to Charlie through uncontrolled fibers. These conditions can be rephrased with the need of realizing space- and time-coherent laser sources and distributing their radiation without degradation over thousands of kilometers. So far, laboratory-based TF-QKD demonstrations achieved record transmission lengths of 830 km [3], but deal only partially with these aspects, which however become of practical relevance in real-world implementation.

A similar challenge was encountered in the optical clocks community as soon as advanced frequency standards (optical clocks) reached unprecedented precision at the 18th decimal digit [4] and the need to distribute their radiation to distant users without degradation arose. This became possible in the last decade thanks to the exploitation of telecom optical networks and the introduction of dedicated technologies, specifically narrow-linewidth lasers featuring coherence lengths of 100'000 km, and laser interferometry techniques that allow to detect and cancel with high precision the fluctuations in the fiber propagation paths [5]. With these tools, phase-coherent laser radiation can be transferred without degradation across thousands-km fibers, allowing regular atomic clocks comparison at the continental scale [6]. Notably, this infrastructure coexists with classical communications and wavelength-division multiplexed networks, which increases the scalability and opens new research opportunities [7].

TF-QKD can take advantage from adopting similar approaches, both in terms of robustness and system performance. The first real-world demonstration of TF-QKD already makes use of narrow-linewidth laser sources [8], and a deeper integration of optical clocks technologies into TF-QKD was recently proposed [9].

Here, we will introduce how atomic clock technologies can support TF-QKD and report on the realization of a TF-QKD setup where they are extensively exploited, enabling us to quantify the reduction in the equivalent quantum bit error rate (QBER) and consequent performance improvement.

2. Integrating optical clocks technologies into TF-QKD

The key components of a TF-QKD apparatus consist in two lasers at the remote Alice and Bob terminals, which produce phase-modulated single-photon pulses that encode the quantum states. Photon pulses are then sent to the intermediate node Charlie via standard telecom networks, and here a pair of single-photon detectors records coincidence counts that are at the basis of a raw key extraction [1].

Two distinct effects destroy the phase coherence of photon pulses as they arrive in Charlie, preventing a key to be extracted: the uncorrelated phase fluctuations of remote photon sources, and the uncorrelated change in the fibers connecting Alice and Bob to Charlie. To mitigate the former issue, a reference laser is usually added to the system, whose radiation, delivered to both Alice and Bob via a separate fiber, represents a common phase-reference to lock photon sources [3]. Still, the intrinsic coherence length of the reference laser has a direct impact on the amount of tolerated unbalance between the Charlie-to-Alice and Charlie-to-Bob arms: for instance, if standard telecom-grade lasers are used, the length of connecting paths must be aligned within a few kilometers. Fluctuations in connecting fibers are dealt with in a post-process approach: the quantum states transmission is interleaved with a deterministic phase pattern, common to Alice and Bob; the phase fluctuations recorded upon interference in Charlie are then ascribed to propagation paths, and cancelled either digitally or by a hardware phase shifter. The effectiveness of this approach is reduced as the link length and noise level increase, because more frequent realignement procedures are needed, which subtracts time to the quantum states transmission and only guarantees a limited link noise suppression, increasing the QBER.

We developed a setup that integrates two important upgrades, based on phase-coherent technologies, and makes the system more robust to the above-mentioned impairments (Fig. 1a).

First, we stabilise the reference laser to an external, high Q-factor resonator, narrowing down its linewidth from a few kilohertz to less than 1 Hz, ensuring coherence lengths of thousands of kilometers. As remote photon sources in Alice and Bob, we use telecom-grade diode lasers tightly phase-locked to the incoming reference radiation, This contributes a lower phase jitter in Charlie, especially in those cases where the two connecting paths are not balanced.

Then, we implemented a system for the continuous, real-time stabilization of connecting fiber paths, exploiting established wavelength-multiplexing technologies. In particular, in Charlie we multiplex the reference signal with an independent "sensing" laser, so that they travel the same fiber towards the remote nodes. There, while the reference laser is extracted to enable phase-lock of the local lasers, the sensing laser is routed back into the QKD fiber, where it propagates together with the quantum signals. The phase fluctuations accumulated by the sensing laser thus fully reflect those acquired by the quantum signal, as they travel the same fiber. In Charlie, the sensing laser is extracted and routed to a separate detector, where its phase is demodulated and used to actively stabilise the fibers. Thanks to a continuous and high-resolution detection of propagation paths fluctuations, this approach ensures better suppression of the fiber noise and avoids the need for interleaving the key transmission with realignment frames, saving time for the actual key distribution and further reducing the QBER contributed by decoherence.

We implemented this system on a 206 km fiber network in northern Italy (Fig, 1b). This fiber is part of the Italian Quantum Backbone, developed by the Italian Metrological Institute, INRIM, to disseminate precise time and frequency references to remote users of the Country [10]. It implements a wavelength-division multiplexing scheme where a pair of channels is dedicated to this experiment, the rest remaining available for standard data traffic and metrological signal dissemination. The Alice/Bob nodes were established in shelters of the telecom network 92 km and 114 km away from INRIM, where the interference was performed. The fiber attenuation is 35 dB and 30 dB for the two arms; while the sensing laser could be amplified using standard Erbium-doped fiber amplifiers, this is not possible in the quantum regime, limiting in practice the size of the setup. Figure 1c shows the interference pattern between QKD lasers, recorded in Charlie once the fiber-stabilization loop is activated. As can be seen, the typical coherence time is as high as few hundreds of milliseconds, over which continuous key streaming can happen before a realignment is required. This represents a thousand-fold improvement as compared to the performances of conventional TF-QKD setups that do not implement fiber stabilization. On the basis of the residual jitter of the interference measurement, the QBER contributed by decoherence was estimated to be $< 1\%$. Notably, these results have been obtained in a highly-unbalanced setup, where the length difference in the two paths amounted to 44 km.

3. Conclusion

We show how metrological techniques such as narrow-linewidth lasers and precise measurement of propagation paths can improve the performances of TF-QKD in real world. Notably, these tools have nowadays a high technology readiness level and are found on the market as compact and turn-key devices.

Synergic development of fields such as optical frequency metrology, quantum communication and fiber transmission systems opens scenarios of higher scalability, interoperability and overall growth, offering important adds-on such as precise synchronization and time-base alignment between remote nodes. In particular, fiber-based atomic clocks networks may represent an important physical layer for further development of TF-QKD in real-field, supporting its transition to a robust and mature technology, ready for today's challenges of secure communication.

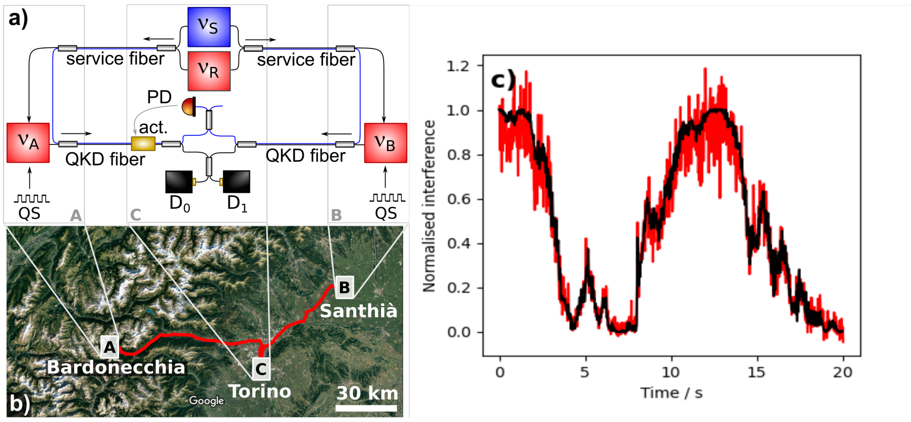

Fig. 1. a) A sketch of the experimental setup. Quantum states (QS) are encoded on the phase of lasers L_A and L_B. Photon pulses, sent via dedicated QKD fibers to the intermediate node are here interfered on single-photon detectors D_0 and D_1. A reference laser (L_R) is sent to the remote nodes using a separate service fiber, for phase stabilization of L_A and L_B. The sensing laser L_S is mutiplexed onto the same fibers, routed forth and back in the two arms and demodulated on a separate photodiode (PD) to detect the fiber noise, which is corrected by a hardware actuator (act). b) Map of the experimental layout, on the Italian Quantum Backbone; the overall fiber length is 206 km. c) The normalised interference pattern recorded in C between incoming radiation from L_A and L_B, when the fiber is stabilised. Traces report the measurement obtained with a classical photodiode (black trace) or with single-photon detectors (red). The phase evolves by 2π in about 10 s, while this would happen in tens of μs without active stabilization, preventing efficient key extraction.

References

1. M. Lucamarini et al., “Overcoming the rate-distance limit of quantum key distribution without quantum repeaters,” Nature **557**, 400 (2018).
2. S. Pirandola, R. Laurenza, C. Ottaviani, and L. Bianchi, “Fundamental limits of repeaterless quantum communications,” Nat. Commun. **8**, 15043 (2017).
3. S. Wang et al., “Twin-field quantum key distribution over 830-km fibre,” Nat. Photon. **16**, 154-161 (2022)
4. S. M. Brewer, J.-S. Chen, A. M. Hankin, E. R. Clements, C. W. Chou, D. J. Wineland, D. B. Hume, and D. R. Leibrandt, ”Al+ quantum-logic clock with a systematic uncertainty below 10^{-18},” Phys. Rev. Lett. **123**, 033201 (2019)
5. C. Lisdat et al., “A clock network for geodesy and fundamental science,” Nat. Comm. **7**, 12443 (2016).
6. C. Clivati et al., “Coherent optical fiber link across Italy and France,” Phys. Rev. Applied, in press.
7. G. Marra et al., “Optical interferometry–based array of seafloor environmental sensors using a transoceanic submarine cable, Science **376**, 874-879 (2022)
8. J. P. Chen et al., “Twin-field quantum key distribution over a 511 km optical fibre linking two distant metropolitan areas,” Nat. Photon. **15**, 570–575 (2021).
9. C. Clivati et al., “Coherent phase transfer for real-world twin-field quantum key distribution,” Nat Commun. **13**, 157 (2022).
10. C. Clivati et al., “Common-clock very long baseline interferometry using a coherent optical fiber link,” Optica **7**, 1031-1037 (2020).