Experimental demonstration of the coexistence of continuous-variable quantum key distribution with an intense DWDM classical channel

Paul Jouguet,[1, 2] Sébastien Kunz-Jacques,[2] Rupesh Kumar,[1] Hao Qin,[1] Renaud Gabet,[1] Eleni Diamanti,[1] and Romain Alléaume[1]

[1]LTCI, CNRS - Telecom ParisTech, 46 rue Barrault, 75013 Paris, France
[2]SeQureNet, 23 avenue d'Italie, 75013 Paris, France

We have demonstrated for the first time the coexistence of a fully functional QKD system with intense classical channels (power of up to 8.5 dBm) over metropolitan distances (25 km in our experiment). This coexistence has moreover been demonstrated with both the quantum and the classical channels in the C-band, wavelength-multiplexed on the DWDM ITU grid. This result has been obtained thanks to new developments with respect to the experimental setup reported on in [3]. They were backed up by experimental measurements of the noise induced on a homodyne detection by WDM classical channels. The demonstrated coexistence, with key rates of a few hundreds of bits/s illustrates an important feature of the Continuous-Variable QKD technology, namely its suitability for the deployment over existing telecommunications network even in conjunction with classical channels of several dBms.

Introduction – Quantum Key Distribution (QKD) is the only technology allowing to distribute a key between two parties with a security proof that does not restrict the power of a potential eavesdropper [1]. It consists in encoding classical information into quantum signals that are exchanged through a quantum channel and monitoring the amount of noise, which is attributed to the eavesdropper, added during the transmission. Then, the two parties of the protocol can extract from their correlated data an amount of secret key that is a function of the noise introduced by the quantum channel. Since quantum signals cannot be regenerated without adding noise, the demonstration of QKD over long distances (i.e. over very noisy channels) is very challenging. So far the most commonly employed discrete-variable protocols exhibit secure distances up to 40 dB losses using superconducting single photon detectors [2] while continuous-variables based QKD has been demonstrated over 80 km of optics fiber and offers the advantage of employing only standard telecommunication components [3].

Another challenge in order to widen QKD deployments is to integrate QKD into classical communication networks. Wavelength Division Multiplexing (WDM) architectures allow to share the use of one single optical fiber to transport several data channels at different wavelengths. This allows to linearly reduce the infrastructure costs linked to fiber deployment. WDM compatibility would thus imply a significant improvement for QKD in terms of cost-effectiveness and compatibility with existing optical infrastructures. Extra noise due to the photon leakage from classical channels into the quantum channel however lowers QKD performance and must be controlled. While optical noise can be efficiently filtered efficiently when its wavelength is sufficiently far from the quantum channel, non-linear processes such as Raman scattering can generate photons at the wavelength of the quantum channel. Coping with Raman noise induced by classical channel is a major problem for QKD systems, especially for discrete variable QKD (DVQKD) that relies on photon counting: Raman spectrum is 200 nm broad and Raman scattering induced by one 0 dBm channel typically higher than 0.1 noise photon per nm per ns, cannot be removed by wavelength filters. The coexistence in DVQKD with classical signals on a DWDM network relying on photon counting has been studied in [8] where no key could be established at 25 km for an input power higher than -3 dBm. Recently several new DVQKD experiments tried to circumvent this limitation. In [5], 4 classical channels where multiplexed with a DVQKD system and 50 km operation was demonstrated. However, the intensity of the classical channels was attenuated to the smallest possible power compatible with the sensitivity limit of the optical receiver (around -20 dBm). This technique was also used in [6], where the temporal filtering technique developed in [4] was applied to obtain an extended range of DVQKD operation in DWDM environment of 90 km. Nevertheless, these two important results have been obtained with strongly attenuated classical channels and cannot realistically be translated to deployed DWDM networks.

As analyzed in [7], the coherent detection used in CVQKD to measure the field quadratures acts as a natural and extremely selective filter whose acceptance is equal to the spectral width of the local oscillator (LO). As a consequence, CVQKD, although less suited for very long distance operation, is intrinsically more resilient to WDM-induced noise photons than DVQKD. This comparative advantage allows us to demonstrate for the first time the operation of a fully operational QKD system on a 25 km fiber where intense classical channels (up to 8.5 dBm) are wavelength multiplexed.

DWDM-induced noise on a homodyne detection – The specificity of a homodyne detector is that only photons matching exactly the spatiotemporal and polarization mode of the LO will effectively contribute to the excess noise, while other unmatched photons will generate a negligible excess noise as long as their total intensity is negligible compared to the one of the LO. As a first step of our work and in order to validate the feasibility of a full quantum key distribution deployment test, we have experimentally measured and characterized the noise induced on a homodyne detection by additional wavelength multiplexed channels.

Several processes can contribute to generate spurious photons exactly in the mode of the LO:

– Sideband emission from the classical channel laser can be matched with the LO mode and moreover leak into the quantum channel due to limited cross channel isolation of MUX. However, for non-adjacent channels an isolation of a least 60 dB was measured while sideband intensity was measured to be -64 dBm in a 0.05 nm band around the quantum wavelength. With such figures, the number of matched sideband photons is smaller than 10^{-5} photons/pulse leading to a negligible excess noise.

– Amplifed spontaneous emission: the presence of an Erbium Doped Fiber Amplifier to amplify the classical channels typically also leads to a wideband noise, whose effect is comparable to sidebands from the lasers but potentially higher if the gain of the amplifier is important. However we did not use an EDFA in our experiments.

– Nonlinear effects on the classical channels can lead to the generation of matched photons. As shown in [7], Raman scattering is the dominant source of noise photons as soon as distance is above a few km. This leads to choose preferably experimental configurations minimizing the impact of Raman scattering by setting the classical channels at a higher wavelength than the quantum channel.

We express in Eq.1 the total number N_m of matched noise photons generated by classical channel of power P^{in} in the direction of Bob (forward scattering) and opposite to that (backward scattering) per spatio-temporal mode.

$$N_m = \frac{1}{2}\left[\frac{\lambda^3}{hc^2}\beta\eta_D\eta_B\left(P^{in}_{fwd}Le^{-\alpha L} + P^{in}_{bwd}\frac{1-e^{-2\alpha L}}{2\alpha}\right)\right] \quad (1)$$

Experimental characterization of WDM-induced noise We have assembled a first testbed in which the quantum channel was set at 1543.72 nm (ITU ch 42) while up to 5 classical channels (ITU ch 22, 23, 25, 26, 28) could be multiplexed, each one with a power between 0 and 2 dBm. We have then performed measurements of the total induced excess noise on a homodyne detection (not yet on a full QKD set-up). Such measurements, whose results are displayed on Fig.1 were challenging: the shot noise of the homodyne detection, commonly called N_0 is the noise measured when no light is sent to the homodyne detection via the signal port. For a classical channel of 0 dBm of input power wavelength multiplexed with the quantum channel, we expect an induced excess-noise (dominated by SASRS) not larger than a few times $10^{-4}N_0$. The precision of our measurements (of shot noise and total noise) must therefore be carried out with a very good accuracy. This was achieved by accumulating large data samples (10^8) and by compensating slow hardware drifts by interleaving shot noise and total noise measurements. As can be seen on Fig.1, our results are in very good agreement with eq.1, both in the forward or backward case, indicating that Raman-induced noise is indeed dominant. These results give precious indications for the full CVQKD deployment in coexistence with intense classical channels: in the worst case, one single 0dBm classical channel induces an excess noise around $5.10^{-4}N_0$. Such excess noise can only be detected if the basic excess noise of the experiment (without WDM intense signals) is comparable and/or if very high power (above 10 dBm) are used.

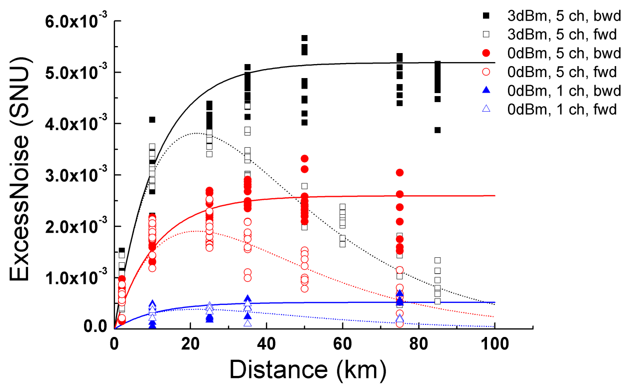

Figure 1: Measured excess-noise, induced by multiplexed classical channels on a homodyne detection. Data are fitted according to eq. 1 with $\lambda = 1543.72$ nm, L the quantum channel length (in km), $\alpha = 0.2$ dB/km, $\eta_D = 0.86$ the transmittance the Add-Drop multiplexer, $\eta_B = 0.3$ the total loss in Bob apparatus. $\beta = 2.7 \times 10^{-9}$/km.nm is the Raman scattering coefficient that we have calibrated independently with a single photon detector. The good agreement confirms that Ramans scattering is the main source of WDM-induced noise but also that the excess noise measured even with up to 10 dBm of input power potentially leave room for secure CVQKD operation for distances up to 50 km.

CVQKD setup in a WDM environment – In our CVQKD setup described in [3], Alice's laser source is divided into two coherent signals: an intense LO and a strongly attenuated quantum signal, which is modulated in both phase and amplitude. These two signals are time- and polarization-multiplexed and propagate through the quantum channel without interfering. At Bob's entrance, a fraction of the LO is used for trigger generation before demultiplexing. A phase modulator on the LO path allows to select a random quadrature which is measured with a shot noise limited homodyne detection. The security of the system relies on the estimation of both the

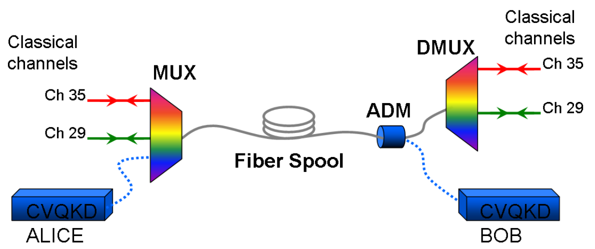

Figure 2: Experimental setup. Each classical channel is used to test noise from forward and backward transmission.

transmittance and the excess noise (i.e. the noise in excess of the shot noise) during a parameters estimation procedure where Alice reveals a fraction of the modulated data. In the presence of one or several classical channels on the quantum channel, the excess noise estimation becomes more challenging.

Indeed, the noise photons induced by the WDM channels affect the shot noise evaluation and therefore the excess noise estimation. To cope with this problem, we introduced an optical switch on Bob's signal path so that we can apply a strong attenuation on this path at some randomly chosen moments. This allows us to compute an estimate of the excess noise from a linear system with a higher precision. This method was suggested in [9] as a real time shot noise measurement method and can also be used to prevent calibration attacks on the LO.

CVQKD operation tests over a 25 km DWDM link– The experimental set-up is depicted in Figure 2.

Two wavelengths have been used for the classical channel, corresponding to ITU channels 29 and ch 35. The classical channel have been multiplexed and demultiplexed to and from 25 Km fiber spool using a 8-port MUX and DMUX of -46dB adjacent and -56dB non-adjacent cross channel isolation. The quantum signal at ITU ch 34 is added to the fiber spool through the MUX and dropped out using an Add Drop Module (ADM). The cross channel isolation of ADM from the adjacent channel is -46dB whereas the non-adjacent channel is -97dB. The advantage of ADM in our setup is that it adds comparatively lower attenuation (0.6dB) to the quantum signal than a typical MUX (2dB). Moreover non-adjacent channel isolation is twofold. Measurements have been taken for four configurations, corresponding to the choice of the classical wavelength (ch 35 or ch 29), and the direction of light (forward or backward). In each of these configurations the power inside the fiber has been varied between 0dBm (1 mW) and 8.5 dBm (7 mW). As can be seen on Fig. 3 (and except in the ch35/forward configuration) the obtained results obtained for the excess noise measurements where almost power-independent. This can be explained by considering that the excess noise of our modified, bare CVQKD system was around $8.10^{-3}N_0$, with fluctuations of the order of $1.10^{-3}N_0$. In this situation, since a classical channel is expected to generate at most $5.10^{-4}N_0$ of excess noise per mW, WDM-induced noise cannot yet be really resolved. Our preliminary results are nevertheless compatible with secure key generation at 25 km for multiplexed power between 0 and 8.5 dBm, i.e power that are 30 dB higher than the one considered in [6]. On the opposite, in the ch35/forward configuration, the excess noise rapidly increases with the input power, reaching $0.04N_0$ at 4 mW and $0.13N_0$ at 7 mW. These results can be explained by the fact that the classical channel is in the forward direction and adjacent to the quantum channel. Since the isolation of the ADM is only -46 dBm, the leakage of classical channel sideband photons generate a non-negligible quantity of matched photons, and thus a noise that increases with the classical channel power, as observed in figure 3.

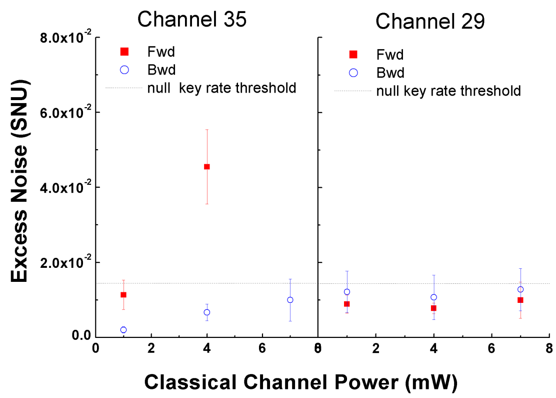

Figure 3: Preliminary measurements of excess noise in forward and backward channel configuration (with error bars indicating one standard deviation). Separate windows correspond to the configuration where the classical channel is adjacent (Ch 35) or non adjacent (Ch 29) to the quantum channel (in Ch 34). Red square and blue circle represents measured excess noise where the classical channel is respective in the forward and backward direction. High excess noise in the adjacent/forward configuration is due to leakage. For theses three other configurations, the measured excess noise are below the null key rate threshold of 0.0144 N_0(assuming collective attacks and 0.95 reconciliation efficiency) and consistent with secure key rates of at least of a few hundreds of bits per second.

Conclusion – After having carefully characterized the excess noise induced by DWDM classical channels on a homodyne detection and realized a dedicated hardware and software update to our CVQKD system, we have carried out the first demonstration of the coexistence of a fully operation QKD setup with intense DWDM signals over 25 km. The reported measurements are still preliminary and not limited by DWDM-induced noise but by system stability, leaving room and hope for improvement. These results nevertheless already constitute an important step forward the deployability of QKD on existing DWDM networks, where intense classical signals are currently used.

[1] V. Scarani *et al.* Rev. Mod. Phys. **81**, 1301 (2009).
[2] H. Takesue *et al.*, *Nature Photon.* **1**, 343–348 (2007).
[3] P. Jouguet *et al.*, *Nature Photon.* (2013).
[4] I. Choi *et al.*, *New J. Phys.* **13**, 063039 (2011).
[5] P. Eraerds *et al.*, *New J. Phys.* **12**, 063027 (2010).
[6] K.A. Patel *et al.*, *Phys. Rev. X* **2**, 041010 (2012).
[7] B. Qi, *et al.* New J. Phys. **12**, 103042 (2010).
[8] N A Peters, *et al.*, *New J. Phys.* **11**, 045012 (2009).
[9] P. Jouguet, *et al.*, *Submitted to QCRYPT 2013*