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Quantum and classical communications on shared infrastructure

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ABSTRACT

Future communications networks not only should enable massive exchange of classical bits, but also the transmission of quantum bits on which many quantum applications rely. This will be the key to offering quantum technologies in a cost-efficient way, and it should encompass the integration of quantum and classical networks at the core of existing optical communications networks, as well as at the access end of such networks. In this work, we cover a range of proposals that enable such an integration for one of the imminent applications of quantum technologies, i.e., quantum key distribution (QKD), by which users can securely exchange a secret key for their cryptographic needs. This will include using wavelength division multiplexing techniques to send quantum and classical data on the same fiber as well as wireless access for QKD users to passive optical networks. In each case, we explore optimal arrangements to find the best way forward for an amicable coexistence.

Keywords: Quantum key distribution; wireless quantum access networks; quantum-classical communications networks.

Quantum information science is at its crucial phase of becoming a technology. The early steps have already been taken with quantum computers of modest size have now been built and are almost ready for commercialization [1], [2]. Secure communication based on quantum key distribution (QKD) techniques have also been in the market for nearly two decades [3], and scientists and R&D companies alike are now exploring ways to provide such services to a larger number of users. This often is achieved via a network of nodes connected by optical fibers, whereas, recently, satellite-based QKD has also become a contender with the ability to connect remote nodes across the globe [4], [5]. Examples of such networks include the China Beijing-Shanghai QKD link [6], the UK quantum communications network [7], and multi-nation projects in Tokyo [8] and the SECOQC project [9]. Communications needs of customers are not, however, limited to QKD based secure communications, and, it is anticipated that, as it stands now, majority of available resources in current and future networks would be allocated to conventional communications applications. A *hybrid* quantum-classical network would therefore need to be developed to address both challenges of secure data transfer as well as high rate communication applications. This paper explores a number of arrangements that needs to be considered at the physical layer to make this integration effective.

For a wide-scale QKD network to be cost-efficient and commercially feasible, certain provisions needs to be made. Given that QKD technology would rely on the transfer of photons as carriers of quantum information, it would make sense to use the existing infrastructure for optical communications, such as the installed fibers all over the world, for quantum communications purposes as well. That would require a certain level of co-existence for classical and quantum signals on possibly the same optical fiber. The challenge is that QKD signals are often very weak, of the single photon nature, whereas classical communications relies on sending rather strong pulses of light on the order of 1 mW. This huge discrepancy would imply that even a faint crosstalk noise, generated by classical signals, could be strong enough to bury the quantum information signal. Any practical solution to integrated quantum-classical functionality should address this issue.

There are certain conventional solutions that have been used in practice [10] or proposed in the literature [11] to alleviate the effect of crosstalk noise. This is often discussed in the context of a wavelength division multiplexing (WDM) system, where some of the channels/bands have been allocated to QKD signals, and some others are used for data communications. There might also be some empty channels to help with the crosstalk noise reduction. The fundamental solutions to mitigate the noise levels are based on temporal and spectral filtering. This requires QKD channels to apply narrow-band filtering and time-gating to reduce the extent of noise that gets to their detectors. Another clever solution is the control of launch power for classical signals. Most sources of crosstalk noise, e.g., Raman scattering and four-wave mixing in fiber, are intensified by the increase in the launched power. Minimizing the launch power is an effective, and sometime inevitable, technique to reduce such noises. That would, however, set a limit on the performance of classical channels. In the case of binary optical communications links, the link budget is often sufficiently large to allow for the reduction of the launch power from its nominal value without much effect on the quality of service in data channels. This will, however, become more stringent when M-ary encoding techniques are in use, which require higher launch power for the same bit error rate.

In addition to the above conventional techniques to reducing the crosstalk noise, there are other methods, which can enhance our ability to use our spectral resources efficiently. One of the proposed techniques relies on optimal or near-optimal wavelength assignment [11]–[13]. In this technique, we take advantage of asymmetric form of the Raman spectrum to place our QKD channels in positions where the total collected crosstalk noise is minimum. Such a wavelength allocation technique can free up a few more channels for QKD or classical communications, which would otherwise must be left unused. The other solution relies on optimal time-frequency filtering enabled by orthogonal frequency division multiplexing (OFDM) techniques [14]. By extending the conventional OFDM systems to all-optical structures suitable for QKD applications [15], not only can we include more channels in the fiber spectrum but also a better isolation between QKD and classical signals can be obtained.

In this work, we provide a summary of effectiveness of each of the above schemes in wireless QKD access networks [16], [17] as well as the optical fiber settings used at backbone networks. Our analytical and numerical analysis suggests that, in WDM access networks with a decent number of users, the only way to cater all users is to reduce the launch power to a few micro Watts regime. This is well below the nominal figure of 1 mW, but, if we want to provide wireless access to QKD users, we have to trade the background noise level with coupling efficiency and mobility features. If the number of users is low, we can then perhaps use higher launch powers but then the four-wave mixing effect would become important and sets some new limitations. In the backbone network, we present optimal configurations for wavelength assignment, which typically takes the form of a multi-band structure where quantum channels are interspersed in between classical ones. We also present low-complexity near-optimal wavelength allocation techniques that can be used in a dynamic setting. In all cases, the finite-key effects will also be considered [13], [18].

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