Time-Bin Entanglement Distribution on a Wavelength-Division-Multiplexed Network

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Abstract: We describe a scheme for distributing time-bin entangled photons to multiple pairs of clients. With clients linked through the strong spectral correlations between the photons, a single down-conversion source can serve many clients simultaneously.

OCIS codes: (270.5585) Quantum information and processing; (270.5565) Quantum communications.

Quantum key distribution (QKD), a secure means of distributing a shared cryptographic key between two spatially separated parties, has been demonstrated in a number of different configurations: with single photons, entangled photons, and continuous variables; via free-space and fiber links; and at visible and infrared wavelengths. By design, all of these implementations are inherently point-to-point, i.e., one Alice connected to one Bob. This suggests that QKD is not well suited to situations with multiple clients, since each pair of clients would require its own independent QKD link. A few studies have focused on the feasibility of transmitting quantum signals alongside conventional high-powered, classical signals in a fiber network [1,2]. Other efforts have focused on the development of multiuser QKD networks using conventional telecom components [3,4]. In these studies, however, quantum communication is centralized, occurring between a server and one or more clients. While such quantum “networks” represent important advances, they do not provide full network functionality, in that quantum communication cannot be performed between any pair of clients. An alternate approach is to use a single source to serve multiple clients simultaneously. We describe such a system below. The source emits time-bin entangled photons that are also strongly entangled in their spectral degree of freedom. Although it is possible to exploit the spectral entanglement to carry information, we are interested here in using the spectral entanglement only to distribute photon pairs to correlated pairs of network channels using, for example, a wavelength division multiplexing (WDM) scheme. Because of the strong spectral correlations, each client would be “linked” only to the client with the conjugate wavelength. In this way, a single SPDC source can support dozens or perhaps hundreds of users simultaneously. Moreover, the network could be re-configured so that any client could be linked to any other client.

This approach to QKD on a network was investigated using the set-up shown in Fig. 1. A 787 nm pump from a ps Ti:Sapphire laser is incident on a mismatched interferometer and the two beams are spatially overlapped at the beam splitter with a delay between the two pulses. The pump beam coupled into a single waveguide on a periodically- poled potassium titanyl phosphate (PPKTP) waveguide chip to undergo type-0 SPDC and the broadband SPDC emission and residual pump are collected by a microscope objective placed close to the output facet of the waveguide chip. A silicon filter removes residual pump and the photons are coupled into single-mode fiber and sent to the WDM device. Several channels exit the WDM and are sent to individual user stations, each of which consists of a fiber-free space coupler, and an unbalanced interferometer with the mismatch equal to that of the pump. Key features of these components are discussed in more detail below.

Fig. 1. WDM QKD scheme. See text for details.
The key requirement of the SPDC source is a high degree of spectral entanglement. In practical terms, this means that the SPDC bandwidth should be large, and that the correlation between signal and idler energies should be quite strong. The strong energy correlation can be realized by pumping the SPDC process with a narrow-band pump field. Conservation of energy constrains the signal and idler photon energies to sum to the energy of one of the pump photons, so the pump bandwidth is directly related to the strength of the energy correlations. Even with the relatively large bandwidth of the laser used in our experiment (~1 nm), the spectral entanglement can be quite strong, provided the SPDC bandwidth is sufficiently large. With a small pump bandwidth, this is possible only if the phase-matching bandwidth is large. Phase-matching bandwidth is determined by the dispersive properties of the SPDC material and by the crystal length—the bandwidth is typically smaller for type-II interactions and for longer crystals. This is particularly true for visible wavelengths, where large bandwidths are possible only for type-I (or type-0) interactions and only using very short crystals. However, materials tend to be less dispersive at longer wavelengths and so it is possible to achieve large bandwidths, even with relatively long crystals. Such is the case with our source, which is a 25-mm PPKTP waveguide phase-matched for degenerate type-0 SPDC. Even at this length, the predicted phase-matching bandwidth is predicted to be greater than 160 nm (FWHM). The measured spectrum, shown in Fig. 2, is smaller, possibly because of waveguide effects not included in the model. Nevertheless, the bandwidth is still large enough to support multiple WDM channels simultaneously.

After being emitted from the PPKTP waveguide, the photons are coupled into the fiber network. In the configuration shown in Fig. 1, the PPKTP output is sent to a re-configurable WDM router that directs photons to different output ports according to wavelength. However, other configurations are also possible. For example, the photons could be sent along a ring configuration in which each client uses a re-configurable drop filter to select a specific wavelength. In either configuration (or in a combination of the two) ideal energy correlations would ensure that specific signal-idler pairs are delivered to specific pairs of clients. In practice, the correlations are not perfect, primarily because of the finite bandwidth of the pump. As a result, there is not a one-to-one correspondence between spectral bins. That is, photons received by Alice will have conjugates received not only by her partner client, Bob, but also by Bob\_j+1 and by Bob\_j-1 (and perhaps more). However, this less-than-perfect correspondence is mostly harmless. From the perspective of Alice and Bob, the photons in the adjacent bins are treated as loss—they lead to a lower secret key rate, but do not represent a security threat. Of course, the amount of leakage into neighboring wavelength bins can be reduced with larger bins. But this means that fewer clients can be supported. It turns out that the optimal bin size is on the order of the pump bandwidth. Figure 3 shows the joint spectrum calculated for our source and plotted on a 200 GHz grid. With this channel spacing, the source can support about 60 channels with very little leakage between adjacent channels.

References