

Entanglement Distribution in Quantum Metropolitan Optical Networks

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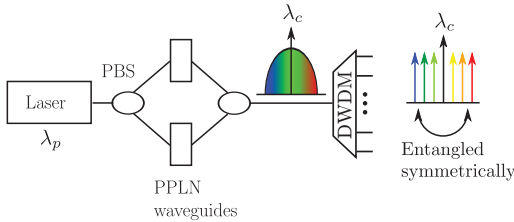
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The ability to generate entangled photon-pairs over a broad wavelength range opens the door to the simultaneous distribution of entanglement to multiple users of a network using a single source and wavelength-division multiplexing technologies. Here we show the design of a metropolitan optical network made of tree-type access networks where entangled photon-pairs are distributed to any pair of users, independently of their location. The resulting network improves the reach, number of users and capabilities of existing proposals. Moreover, it is made up of typical commercial components and uses the existing infrastructure, which allows for moderate deployment costs. Finally, we develop a channel plan and a network design that allow direct optical communications, quantum and classical, between any pair of users. Therefore, multiple quantum information technologies can make use of this network.

Entanglement generation

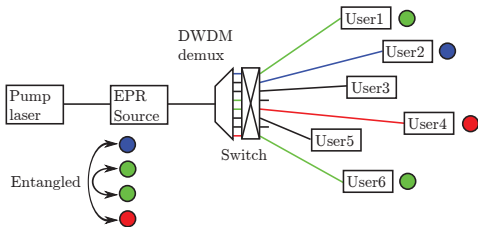
We consider a source based on type-I spontaneous parametric down-conversion (SPDC) and periodically poled Lithium Niobate (PPLN) waveguides. This has the advantage of a relaxed phase-matching condition around 1550nm, producing a signal with a broad spectrum of 70nm [1]. Broader spectra can be generated by shortening the crystals to a few mm.



Photon-pairs are generated symmetrically to the central wavelength given by a degenerate SPDC. At the output, a DWDM demultiplexer slices the broad-spectrum in independent channels that only contain photons entangled with the ones in the corresponding symmetrical channel. Therefore, such a source acts as many independent sources realized by narrowband type-II SPDC processes with the same pump wavelength. Each user would get a private wavelength and would then be connected to a second peer in a fixed way.

Entanglement distribution in a star network

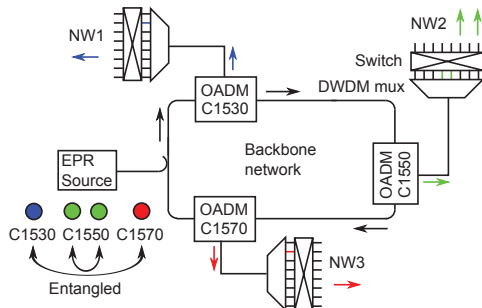
Our task now is to distribute and route these entangled DWDM channels among the network users. For example, we can connect a switch at the output of the DWDM demux, and connect users to the output of the switch. The resulting network is a point-to-multipoint access network where entangled photon-pairs are distributed to any two users [1, 2].



With this simple solution only users attached to a central point of a star network could be connected. More flexible network structures to fit demands of typical telecom networks deployed in the feed are required.

Entanglement distribution in a backbone ring with access trees

A typical MON consists of a ring network with attached, tree-like, access networks supporting fibers to all users waiting to receive entangled photons with any other user in the network. We group the DWDM-sliced spectrum of the sources in CWDM channels and assign access networks to them.



For three access networks, the spectrum of the source, centered at 1550nm, is divided into 3 CWDM channels: C1530 (blue), C1550 (green) and C1570 (red). The signal is inserted into the backbone and each channel is dropped at a different access network (NW1, NW2 and NW3, respectively) using CWDM optical add drop multiplexers (OADM). Hence, by symmetry, entanglement is distributed between NW1 and NW3 (C1530 and C1570) and within NW2 (C1550). By adding more sources with different configurations, we can cover the rest of possible communications. In this case, the CWDM channels have to be shared between all sources trying to reach a particular access network.

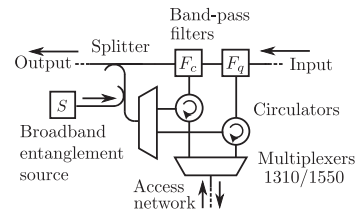
Adding quantum and classical communication

We want to enable also direct communication, quantum and classical, between the users. For this, we arrange the signals in: band O (1260-1360nm) for classical signals, and bands S-C-L (1500-1600nm) for quantum signals (one-way and entangled). As in Ref. [3], each band is divided into CWDM channels and a pair of them is assigned to each access network. In the access network, due to the periodicity of the AWG-based DWDM demux, each output allows to use multiple channels belonging to the same periodical set. In our case, we will use a channel for classical signals and another one for quantum signals.

In this configuration, the entangled photon sources occupy the full CWDM channels. However, they must leave free some of the DWDM channels for one-way quantum signals. For this, we disconnect some outputs at the entangled source. Hence, the ports of the AWG are divided into entanglement and one-way. Users connect to each type using the switch.

Quantum metropolitan optical network

The OADM must be able to: (i) drop two CWDM channels from different spectrum bands, (ii) add signals coming from the access network or the entangled pairs source, and (iii) let pass through the signal that is not dropped. It must avoid interrupting the quantum signal, adding noise or excessive losses.



We propose a design of an OADM using only passive technology and readily available components. Two standard CWDM filters are used to drop the quantum and classical channels that are then multiplexed into one fiber. This fiber also allows for upstream signals, whatever their wavelength, to be incorporated to the ring. The source can also inject its signal into the ring. If a direct optical path is needed between users of the same access network a switch with some extra ports has to be used so that return paths can be configured.

Maximum number of users

The network design is limited by: (i) the loss budget of the source, since it fixes the worst admissible path in terms of losses which in turn dictates the maximum number of access networks; (ii) the bandwidth of the source, since it establishes the maximum number of CWDM channels, which again limits the maximum number of access networks; and (iii) the number of available CWDM channels. In order to estimate it in a realistic configuration in a metropolitan area network, we consider: 4.5 km for the entire access network, 4 km between backbone nodes, 100 GHz DWDM ITU grid for the access networks (0.8 nm at the C band), 13 nm passband for CWDM channels, and $13/0.8 = 16$ DWDM-channels per access network resulting in 16 users free of blocking.

Device	Insertion losses (quantum signal)
AWG-based DWDM mux (32 channels)	3 dB
Optical switch (up to 192x192)	1 dB
OADM (add entangled/one-way)	3.6/6.2 dB
OADM (drop)	1.7 dB
OADM (pass)	4.8 dB

With a symmetric 16x16 switch these available channels are transferred to 16 users. With asymmetric switches $N \times M$ with $M > N$ it is possible to distribute 16 DWDM-channels over a higher number of users reducing the availability of each user depending of the behavior of the others in the same access network.

Conclusions

With a 70 nm bandwidth source and quantum communications able to withstand 30 dB of losses, the network is able to connect 48 users simultaneously (3 access networks). A source with a broader spectrum (100 nm) and at least 40 dB of loss budget would allow the network to grow up to 80 users (5 access networks).

Acknowledgments

UPM acknowledges financial support by project *Quantum Hybrid Networks* (TEC2012-35673), *Ministerio de Economía y Competitividad*, Spain. AIT acknowledges financial support from the *Austrian Research Promotion Agency* (FFG), project *QKD-Tele* (contract No. 835926).

References

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