Entanglement Distribution in Quantum Metropolitan Optical Networks

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Introduction

Entanglement is a unique characteristic of quantum mechanics that allows performing operations that have no classical equivalent. In many cases these involve the capability to share entanglement between distant parties, as in QKD protocols.

Bipartite entanglement distribution involves the transmission of one of the particles in an entangled pair to a certain distance. Given that the transmission of single quantum signals is very delicate, it is usual to utilize a dedicated, point to point, fiber in order to limit the noise induced errors as much as possible. However, to lay dedicated fibers connecting many users is prohibitively expensive. To reduce this cost while having a high degree of flexibility, it is essential to use as much as possible the existing network infrastructure and share it with other systems, quantum or classical [1].

In this communication, we show how to generate and distribute entangled photon-pairs to any two users in a *canonical* metropolitan optical network composed of access and core networks. Our approach is based on wavelength-division multiplexing (WDM) which allows distributing the pairs and, at the same time addressing single users by assigning them a dedicated channel. In addition to the capability to distribute entanglement between any two users, the network can also support classical communication. The resulting architecture is flexible, allowing multiple ways of entanglement distribution, while keeping the cost low, and not requiring special devices or hard to do modifications of existing infrastructure.

Entanglement generation

For the generation of entangled photon-pairs, 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 [2]. Broader spectra (~200nm) can be generated by shortening the crystals to a few mm or by using novel ring structures integrated in silicon-on-insulator SOI substrates.

The photon-pairs are generated symmetrically to the central wavelength given by a degenerate SPDC. At the output, we use a DWDM demultiplexer to slice the broad-spectrum signal 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. The goal here is to provide any-to-any connections between all users present in the network.

Entanglement distribution in a star network

From a network point of view, we have a source that is capable of creating entangled DWDM channels, and our task is to distribute those channels among the network users and route the signals accordingly, without disruption and with the minimal losses possible. 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, depicted in Fig. 1, is a point-to-multipoint access network where entangled photon-pairs are distributed to any two users [2-4].

The number of established connections at a given time is limited by the bandwidth of the source. More users can be connected physically to the switch to receive available photons on demand. With this simple solution only users attached to a central point of a star network could be connected. A more flexible network can be obtained by adding a ring connecting several of the networks above.

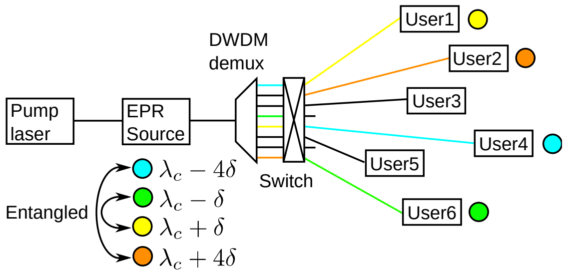

Fig. 1: The pump laser operated at a wavelength λ_p generates entangled photon pairs in the EPR-source symmetrically around a central wavelenght λ_c. The photons of different pairs are separated by the DWDM-demux. A switch is used to supply the connected users with pairs.

Backbone ring with access trees

A typical MAN consists of a ring network with attached, tree-like, access networks. In order to distribute entanglement also between each possible pair of users we propose to group the broad spectrum of the source's signal in CWDM channels. We can then assign a CWDM channel to an access network and within the latter demultiplex the signal into several ones by feeding it into a device-pair that consists of a DWDM demux and a switch as shown in Fig. 2.

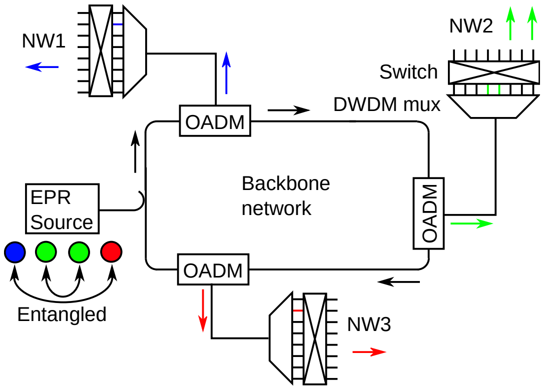

Fig. 2: The source is attached to a ring-shaped backbone network. Photons routed to each access network (NW) are dropped by the CWDM add/drop-mux (OADM) of the corresponding channel. The color indicates the CWDM channel, and symbols are entangled symmetrically (i.e., red with blue, green with green).

For three access trees the source centered at 1550nm needs to produce a spectrum broader than 60nm, which is then divided into 3 CWDM channels: C1530 (blue), C1550 (green) and C1570 (red). The signal is inserted into a ring-shaped 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 to the network with different central wavelengths, we can cover the rest of possible communications: NW1 and NW2, NW2 and NW3, only NW1 or only NW3. In this case, the CWDM channels have to be shared between all sources trying to reach a particular access network. The resulting network corresponds to the *canonical* view of a metro network: multiple tree-type access networks interconnected using a ring-shaped backbone. Therefore, it can be easily integrated in existing optical infrastructure in most metro areas.

Quantum and classical communication

Our goal now is to enable also direct communication, quantum and classical, between the users from the access networks. Here we also consider one-way QKD. For this, we first arrange the following channel plan:

- Band O (1260-1360nm): classical signals.
- Band S-C-L (1500-1600nm): quantum signals (one-way and entangled photon-pairs).

Each band is divided into CWDM channels and a pair of them is assigned to each access network. Therefore, each OADM will now drop two CWDM channels. In the access network, thanks to the periodicity of the AWG-based DWDM demux, each output allows not only for one single wavelength, but for all that belong to the same periodical set. We can choose two well separated wavelengths, typically one in the O-band and other in the C-band, to have two non-interfering channels: one for classical and other for quantum signals.

If we want to allow for quantum channels that do not transport entangled photons, we have to leave part of the spectrum free. The entangled photon sources cannot occupy the full CWDM channels anymore; they must leave free some of the DWDM channels of each CWDM channel in order to permit one-way quantum signals in those channels. This is simple to accomplish by disconnecting the corresponding outputs at the entangled source. Hence, the ports of the AWG are divided into entanglement and one-way quantum signals. Users can connect to each type using the switch.

Quantum metropolitan optical network

The network design presented in Fig. 2 needs little modification in order to use the new channel plan. In fact, at the physical layer, the only change is the OADM, that has to be specifically designed. The new OADM must be able to:

- Drop two CWDM channels separated in different bands of the spectrum.
- Add signals coming from (i) the access network, and (ii) the entangled pairs source. The signal can belong to any CWDM channel since an access network or source can communicate with any access network.
- Pass through: the part of the signal that is not dropped.

Moreover, this has to be done without interrupting the quantum signal, adding noise or excessive losses.

We propose in Fig. 3 a feasible design of an OADM that achieves all these goals using only passive technology and usual components. Two standard CWDM filters (20nm width) 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

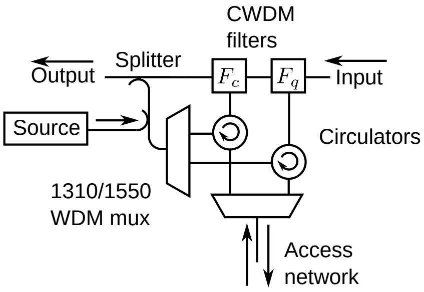

Fig. 3 Backbone node based on passive optical technology. It is a modified OADM, with the addition of the entanglement source. It drops the corresponding quantum and classical signals directed to the access network. In the upstream direction, it adds to the backbone any signal coming from the access network, and from the entanglement source.

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.

Note that, besides the physical layer, the new network requires a management layer that should be capable of satisfying the user requests of different type of communications, allowing their access and configuring the switches accordingly.

Maximum number of users

Regarding the maximum number of users, the network design is limited by:

- The loss budget of the source: it fixes the worst admissible path in terms of losses, which in turn dictates the maximum number of access networks and thus of users.
- The bandwidth of the source: it establishes the maximum number of CWDM channels, which again limits the maximum number of access networks and thus of users.
- Available CWDM channels.

In order to estimate it, we use the following considerations: 4.5km for the entire access network, 4km between backbone nodes, 100GHz DWDM ITU grid for the access networks (0.8nm at the C band), 13nm pass-band for CWDM channels, and 13/0.8=16 users per access network. Now, with a 70nm-bandwidth source and quantum communications able to withstand 30dB of losses, the network is able to connect 48 users simultaneously (3 access networks). A source with a broader spectrum (100nm) and at least 40dB of loss budget would allow the network to grow up to 80 users (5 access networks).

Tab. 1 Losses of the main components of the network.

Component		Losses (dB) (Entangled/direct optical path)
Fiber (1550 nm)		0.2
OADM (Backbone Node)	Add	3.6/6.2
	Drop	1.7
	Pass	4.8
AWG (32 ch, 100GHz)		3
Switch (4x4 – 192x192)		1

Conclusions

This work presents a network that is able to distribute entanglement between any two users. It also allows for a direct optical path that can be used to create a quantum channel to perform, for example, QKD using one way systems. The network is able to support many users and it is designed in a way that reuses existing deployed networks and as much standard telecommunication equipment as possible. The only non-standard device is the OADM/source module, that can be constructed out of readily available components plus the entangled pairs source itself.

Acknowledgements

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