Impact on traffic and transmission performance of all-optical wavelength converters placed at the network interface or in OXCNs

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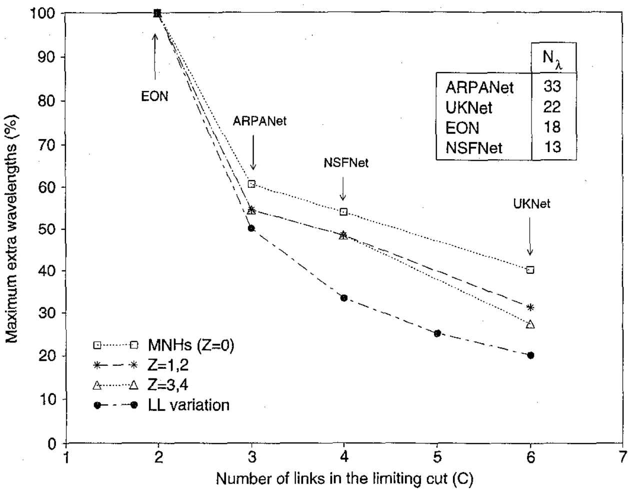
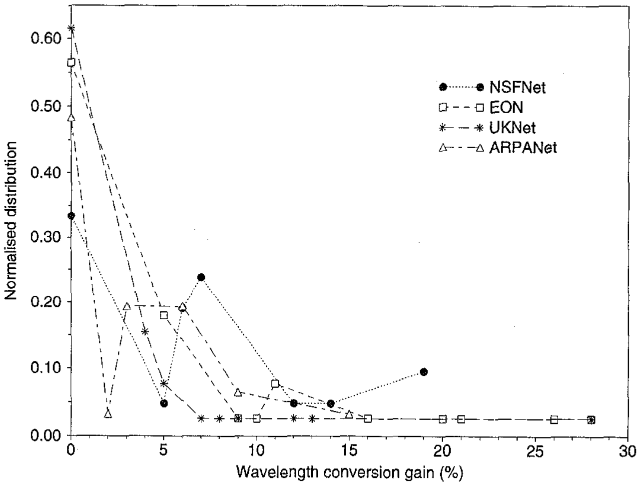


WD5 **Fig. 1.** Maximum extra wavelengths vs. number of links in the limiting cut *C*.



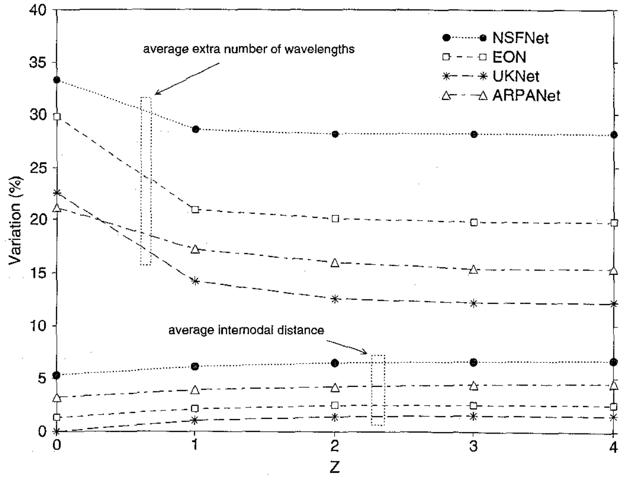
WD5 **Fig. 3.** Normalized distribution of the wavelength conversion gain (in %).

further increases of *Z* did not lead to further reduction in the wavelength requirement [the small difference between the results and the LL curve is a consequence of the imposed condition (1)]. A clear trade-off between the maximum increment of the wavelength requirement and *C* can be seen, indicating that the design of fault-tolerant networks must maximize the number of links in the network limiting cut(s).

Figure 2 shows the average increment in the wavelength requirement versus *Z*. With respect to MNH paths, a reduction was achieved with $Z = 1$ and further increase of *Z* did not lead to any improvement. Hence restoration lightpaths slightly longer than the MNHs ones can be used to reduce the wavelength requirement. On average no more than 20–30% extra wavelengths are necessary to fully restore the logical connectivity, with the actual value dependent on the initial network link loading. Figure 2 also shows that the increment in the average internodal distance for $Z \geq 1$ was always negligible.

The benefit of wavelength conversion in case of link failure restoration is given by the ratio of the new wavelength requirement and the number of channels in the new most loaded link(s). Figure 3 shows the results using only MNHs restoration paths. It should be noted that for all the analyzed topologies, in more than 80% of the link failures, wavelength conversion determines a reduction in the number of wavelengths of 10% or less. Similar results were obtained for many randomly generated network topologies. These results, in agreement with Ref. 4, quantify the benefit of wavelength conversion, and underline the importance of optimizing the restoration algorithm.

The influence of wavelength conversion in the case of nonuniform traffic is also presented. This can be particularly important for optimizing the transport network design.



WD5 **Fig. 2.** Average percentage variation in the number of wavelengths and mean internodal distance vs. the number of additional hops *Z*.

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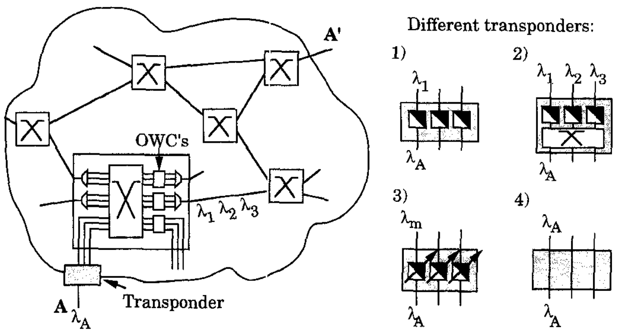
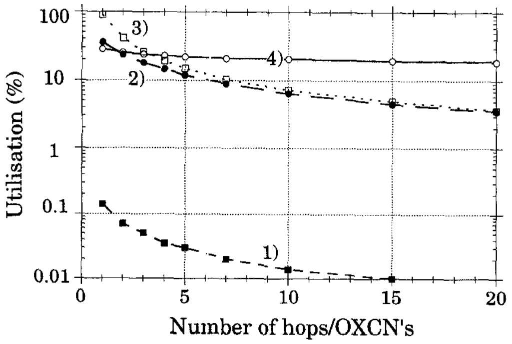
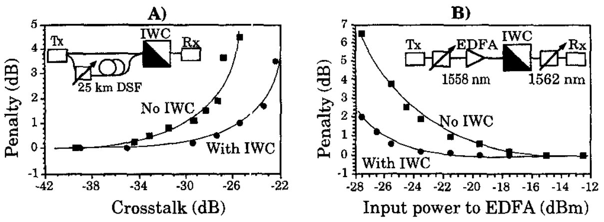
Wavelength-division multiplexing (WDM) networks will need optical wavelength converters (OWCs) in the optical cross-connecting nodes (OXCNs) or in transponders at the network interface to match the



WD6 Fig. 1. Schematic of WDM network and different transponder configurations: the wavelength of user A, λ_A, is matched to a network wavelength (λ_1, λ_2, λ_3 . . . λ_m). OWC: optical wavelength converter.



WD6 Fig. 2. Possible channel utilization as a function of number of hops/OXCs between user A and A'. The different transponder configurations given in Fig. 1 are the parameter; (1 - ■): fixed output wavelength, (2 - ●): OWCs + space switch, (3 - □): tunable OWC's, (4 - ○): OWCs in OXCNs.



WD6 Fig. 3. A) Measured penalty vs. interference cross talk with and without an interferometric wavelength converter (IWC) in the transmission path. B) Measured penalty vs. input power to EDFA with and without an interferometric wavelength converter (IWC) in the transmission path. Bit rate is 20 Gbit/s in both experiments.

incoming wavelengths to those of the network and to reduce blocking probability.[1,2] In this paper we first perform a traffic analysis for different transponder configurations with and without converters in the OXCNs. Second, by experiments at 20 Gbit/s we demonstrate that all-optical interferometric wavelength converters[3–5] placed in the OXCNs can reduce requirements to cross talk and amplified spontaneous emission due to a regenerative capability.

As shown in Fig. 1 we analyze three different transponder configurations for the case without OWCs in the OXCNs: (1) the user wavelength, λ_A, is converted to a fixed network wavelength, or λ_A can be converted to any of the network wavelengths by (2) placing a space switch in front of a converter array or (3) by tuneable converters. Finally, we analyze the situation (4) where the OXCNs deploy converters for which case no conversion is needed in the transponders.

For a fixed blocking probability of 10^{-3} in each of the four cases, Fig. 2 gives the possible channel utilization as a function of the number of OXCNs between two users (A and A'). The calculations are shown for a network constructed by OXCNs with four inlets and eight wavelengths per inlet. The results of Fig. 2 suggest that the converters should be placed in the OXCNs, particularly for large networks, and that case 1 gives unacceptable performance for all network sizes. This tendency is the same for other OXC sizes. The higher utilization in case 3 compared to 2 is because two users of the same transponder can utilize the same wavelengths to access two different outlets when using tunable converters. The higher utilization for cases 2 and 3 compared to 4 for a small number of hops is due to the favorization of the local data compared to remote data (this could also be arranged by a management system for case 4).

Placing interferometric wavelength converters (IWCs) in the OXCNs not only decreases the blocking probability but also improves the transmission performance of the optical network, because a regenerative capability in terms of noise and extinction ratio improvement is possible.[3] This is demonstrated by a 20 Gbit/s experiment, where the penalty from interference cross talk is recorded with and without an IWC[5] in the transmission path. The results shown in Fig. 3A) clearly demonstrate that the cross talk requirements can be relaxed by 4–5 dB by deploying IWCs. The sensitivity for the 20 Gbit/s input signal (1558 nm) and converted signal (1562 nm) without cross talk is −24.8 and −25 dBm, respectively.

Also shown in Fig. 3 is the measured penalty as function of the input power to an erbium-doped fiber amplifier (EDFA) with and without an IWC following the amplifier (bit rate is 20 Gbit/s). Because of a nonlinear transfer function, the IWC improves the EDFA input dynamic range by 4 dB. Consequently, optical networks deploying IWCs in OXCNs are expected to allow more EDFAs to be cascaded.

In summary, placing OWCs in the OXCNs rather than at the network interface not only improves the traffic performance but also enhances the performance of the physical layer, e.g., in terms of relaxed cross talk requirements.

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