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Optical network design with mixed line rates

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ABSTRACT

Future telecommunication networks employing optical wavelength-division multiplexing (WDM) are expected to be increasingly heterogeneous and support a wide variety of traffic demands. Based on the nature of the demands, it may be convenient to set up lightpaths on these networks with different bit rates. Then, the network design cost could be reduced because low-bit-rate services will need less grooming (i.e., less multiplexing with other low-bit-rate services onto high-capacity wavelengths) while high-bit-rate services can be accommodated on a wavelength itself. Future optical networks may support mixed line rates (say over 10/40/100 Gbps). Since a lightpath may travel a long distance, for high bit rates, the effect of the physical impairments along a lightpath may become very significant (leading to high bit-error rate (BER)); and the *signal's maximum transmission range*, which depends on the bit rate, will become limited.

In this study, we propose a novel, cost-effective approach to design a mixed-line-rate (MLR) network with transmission-range (TR) constraint. By intelligent assignment of channel rates to lightpaths, based on their TR constraint, the need for signal regeneration can be minimized, and a "transparent" optical network can be designed to support all-optical end-to-end lightpaths. The design problem is formulated as an integer linear program (ILP). A heuristic algorithm is also proposed. Our results show that, with mixed line rates and maximum transmission range constraints, one can design a cost-effective network.

1. Introduction

Traffic flowing through optical backbone networks – which typically employ wavelength-division multiplexing (WDM) – has been increasing steadily, and becoming more heterogeneous as well. As a result, a future-proof optical network needs to be designed which can support mixed line rates (MLR) over different wavelength channels. In such a network, a low-bit-rate service may need minimal or no grooming (i.e., less multiplexing with other low-bit-rate services onto high-capacity wavelengths), while a high-bit-rate service can be set up over a single wavelength [1]. Thus, a MLR network can be a cost-effective heterogeneous optical network design.

In optical WDM backbone networks, MLR can be facilitated by having different sets of wavelengths that can support different rates. Thus, the routing and wavelength-assignment (RWA) problem is modified to the routing, wavelength, and rate assignment (RWRA). In [2], the design of an opaque MLR network is proposed, where each node has electronic regeneration (which can also support wavelength conversion, grooming, etc.). This work also assumed that all wavelengths on a link run at the same rate, but different links have different rates. Based on the distance it needs to travel, a lightpath is routed in such a way that it requires minimum regeneration.

In this work, (1) we consider a more general approach where a single link can have a combination of bit rates, and each physical link in the network may support a combination of bit rates, each on a separate wavelength, and (2) our aim is to design a transparent MLR network that will significantly reduce the amount of electronic signal processing at the nodes.

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Note that the maximum transmission distance of a signal decreases with increasing bit rate based on a threshold bit-error rate (BER) [3]. If we know the network topology (including fiber link lengths) and the traffic demands that need to be carried by it, then we could determine the physical length of each lightpath based on a routing algorithm; then, based on the set of line rates available, we can choose only those paths whose maximum transmission distance is less than the physical length of the route. Hence, it may be beneficial to support different lightpaths at different rates, leading to a MLR network. Such a network is called "transparent" if its end-to-end traffic demands flow over all-optical lightpaths with no electronic regeneration.

In this study, we propose and investigate the characteristics of a method to design a transparent MLR network. We compare our design with single-line-rate (SLR) networks (where all wavelength channels run at the same bit rate), and we study the corresponding cost savings on network design, measured by the cost of line cards. In this context, the maximum transmission range (TR) could make some of the high-bit-rate paths infeasible and we may lose out on the volume discount that a high-bit-rate path provides over several low-bit-rate paths. Thus, placement of signal regenerators at a few nodes may improve the cost scenario as studied in our related work [4].

The rest of the paper is organized as follows. In Section 2,[1] we discuss how the BER is estimated based on the physical layer impairments. Section 3 presents our mathematical formulation of the design problem which turns out to be an integer linear programme (ILP). In Section 4, a heuristic algorithm for the cost-effective MLR network design is presented. Section 5 provides illustrative results. Finally, Section 6 concludes the paper.

2. BER estimation

The static impairments in a lightwave system are: (1) dispersion (chromatic and polarization mode), (2) optical amplifier noise, (3) crosstalk, (4) optical filter concatenation, (5) laser frequency offset, and (6) receiver noises. We have considered all the above impairments in this work in order to estimate the signal quality, i.e., bit-error rate (BER). The dynamic impairments such as four-wave mixing (FWM), cross-phase modulation (XPM), and self-phase modulation (SPM) are not considered in this work. This is because, in a static network design problem, some of these network-state-dependent impairments become intractable to estimate. We have used a fixed margin of 1 dB in the Q-factor to account for the dynamic impairments. This provides some form of practicality in terms of the maximum transparent reach for a given source–destination (s–d) pair. The signal component of the received lightwave is given by:

$$e_s(t) = E_s d_s(t)\cos[2\pi(f_s + \Delta f_s)t + \phi_s(t) + \theta_s] \quad (1)$$

where $E_s = 2\sqrt{P_R}$ is the amplitude of the lightwave, δf_s is the laser frequency misalignment, $\phi_s(t)$ is the laser phase noise term, θ_s is the random epoch, and $d_s(t)$ is the encoded data pulse (NRZ, duobinary, etc.). The autocorrelation of the received lightwave can be expressed as:

$$R_s(\tau) = \mathbf{E}[e_s(t)e_s(t-\tau)]. \quad (2)$$

Bandlimiting due to filter concatenation occurs in the optical switches at the intermediate nodes and in the receiver at the destination node [6]. In order to estimate the bandlimited power, we assume that the optical switches employ grating devices followed by optical filters on each wavelength. The total received power after bandlimiting by $N+1$ filters (including those at the optical switches and at the destination receiver) is given by:

$$P_{RB} = \int_{-\infty}^{\infty}\left(\int_{-\infty}^{\infty} R_s(\tau)\exp(-\mathrm{j}2\pi f\tau)\mathrm{d}\tau\right) \times H_o^m(f+\Delta f_{offset})H_o^n(f-\Delta f_{offset})H_o^r(f)\mathrm{d}f \quad (3)$$

where $H_o(f)$ is the transfer function of the optical filters at the intermediate nodes (we assume that the receiver filter and the intermediate filters have the same transfer function) and we further assume that m filters have positive offset, n filters have negative offset, and r filters are non-offset with respect to the center frequency.

Let us consider a lightpath from node 1 to node $N+1$, traveling N fiber segments on a wavelength. Thus, at node $N+1$, the desired optical signal along with the accumulated receiver crosstalk and ASE noise components is dropped by its space switch operating at the signal wavelength on to the receiver tuned to the same wavelength. The receiver passes the incident signal through a bandlimiting optical filter onto the photodetector. The photodetector output is then passed through a low-pass filter (LPF) followed by a decision circuit. The current at the photodetector output is given by:

$$i_p(t) = R_\lambda\langle e_R^2(t)\rangle + i_{sh}(t) + i_{th}(t) \quad (4)$$

where the first term presents the square-and-average response of the photodetector to the incident lightwave $e_R(t)$ with R_λ as the responsivity of the photodetector, the second term is the shot noise produced by the incident lightwave, and the third term accounts for the receiver thermal noise. The incident lightwave can be expressed as:

$$e_R(t) = e_s(t) + e_x(t) + e_{sp}(t) \quad (5)$$

where $e_s(t)$, $e_x(t)$, and $e_{sp}(t)$ are the signal, crosstalk, and spontaneous lightwaves, respectively. These three terms will produce beating terms with each other at the output of the receiver and contribute to the noise.

Evaluation of BER requires the statistics of the electrical noise at the receiver. The various beat-noise terms at the receiver output are assumed to follow Gaussian statistics whose variances depend on various network parameters.[2]

[1] This section is repeated here from one of our related works [5]. It shows how the BER calculation is performed, a result which is needed for the main contribution of the paper from Section 3 onwards. This section can be condensed or eliminated if the editors feel that way.

[2] Though the signal-spontaneous beat noise has been shown to follow a χ^2 distribution, but the Gaussian approximation works fine up to a certain level of accuracy [7].