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Design methodology for WDM backbone networks using FWM-aware heuristic algorithm ☆

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ABSTRACT

The problem of lightpath topology design (LTD) and traffic routing over the lightpaths for wavelength-routed optical backbone networks has been investigated extensively in the past using heuristic as well as linear-programming based approaches. Sensitivity of such long-haul backbones to physical-layer impairments is required to be adequately addressed during LTD phase to improve overall performance. For optical communication using wavelength-division multiplexing (WDM) over a long-haul fiber backbone, four-wave mixing (FWM) may become one of the significant transmission impairments. Intrinsically, for a WDM-based wavelength-routed network with wavelengths assigned using equally-spaced channels, the generated FWM components are found to remain more crowded at the center of the fiber transmission window. Using this observation, we propose an LTD scheme employing a unique wavelength assignment (WA) technique, wherein long lightpaths (traversing through a larger number of fiber links) are allocated wavelengths at the either edges of the fiber transmission window whereas short lightpaths (consisting of fewer fiber links) are placed in the middle of the transmission window, thereby reducing the FWM crosstalk for long lightpaths. Since long lightpaths comprise of large numbers of fiber links and intermediate nodes, they experience large amplified spontaneous emission (ASE) noise and switch crosstalk. Therefore, by using the proposed WA technique, long lightpaths while suffering from more ASE noise and switch crosstalk get subjected to lesser FWM crosstalk leading to a more uniform distribution of overall optical signal-to-noise ratio for all the lightpaths across the network. Analysis of our results indicates that the proposed FWM-aware LTD scheme with the novel WA technique can achieve similar congestion levels (of lightpaths) and bandwidth utilization efficiency without any need of additional network resources as compared with the existing FWM-unaware LTD schemes.

1. Introduction

Optical networks employing wavelength-division multiplexing (WDM) technology are now regarded as the emerging solution for next-generation backbone networks [1–4]. Such networks consists of optical cross-connects (OXCs), interconnected by optical fiber links. Electronic devices, like IP routers, ATM switches and SONET/SDH terminals, remain connected to the OXCs to support various service options of a network. While wavelength-routing capability of OXCs in optical domain reduces electronic processing cost at intermediate nodes, optical-electrical-optical (OEO) conversion, if provided at OXCs, can allow more traffic to be groomed for efficient bandwidth utilization of lightpaths. However, direct lightpaths among all source-destination pairs might not be feasible due to limited resources and physical constraints. Thus, designing a logical topology formed by the lightpaths for a given physical topology and routing of traffic through the logical topology becomes an optimization problem;

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performance metric for such designs may be chosen as congestion, delay, average hop-count, blocking probability, throughput, traffic scale-up or some appropriate combination of them.

It may be noted that while constructing lightpaths, if physical-layer issues are not considered, the possible distinctions between a short lightpath (traversing a few fiber links) and a long lightpath (traversing larger number of fiber links) gets ignored. In order to make such distinction, optical signal-to-noise ratio (OSNR) performance at the lightpath end needs to be taken care of. The data streams flowing through different lightpaths may not have adequate OSNR resulting in increased bit-error rate (BER) for some of the lightpaths. Network services using these error-prone lightpaths may get significantly affected by such impairments due to frequent retransmissions of data as governed by higher-layer protocols. Thus, in order to ensure desired network performance, dominant physical-layer impairments need to be addressed critically while carrying out the task of lightpath topology design (LTD) in a wavelength-routed network.

In order to increase the capacity for future high-speed optical networks, two possible approaches or a combination of both can be adopted. One of them involves increasing the existing data rate of each individual channel, without increasing the number of WDM channels in a fiber. This technique would demand faster electronic end-equipments to process high data rate, which in turn may necessitate replacement of the existing network equipments. The second approach would be to increase the number of WDM channels within the operational transmission window of optical fiber, without increasing the existing data rate. Following the latter approach, total capacity of backbone network may be enhanced without disturbing the compatibility with the existing OEO-based end equipments. For optical communication systems with high data-rate (more than 40 Gbps), chromatic dispersion and polarization-mode dispersion effects would have significant impact on BER performance of lightpaths [5]. On the other hand WDM systems, with closely-spaced channels will get limited by fiber nonlinearities, such as, four-wave mixing (FWM) and its variants resulting from Kerr nonlinearity [5].

FWM is a nonlinear phenomenon in fibers wherein three lightwaves interact to produce a fourth one. In this process three frequencies f_p, f_q and f_r interact to generate new fields (lightwaves) at the frequencies $f_{pqr} = f_p + f_q - f_r$ $p, q, r \in [1, M], r \neq p, q$, with M as the total number of co-propagating channels in a WDM link. For all possible permutations of M co-propagating signals, altogether $M^2(M-1)/2$ FWM components will be generated [6]. An FWM component with a frequency the same as any of the M channel frequencies, will produce FWM crosstalk in that specific channel.

In order to mitigate the impact of FWM generation in a wavelength-routed optical network with the provision for dynamic lightpath setup, Fonseca et al. [7] explored some unique call admission control (CAC) schemes with controlled FWM-generation methodology. The lightpaths, which are eventually established, assume a wavelength and route approved by a CAC-RWA (routing and wavelength assignment) integrated scheme. The CAC-RWA integrated scheme has two variations, viz., relaxed algorithm (RA) and strict algorithm (SA). RA selectively employs either complete (involving estimation of FWM effect on all the existing as well as the new lightpath request) or partial (involving estimation of FWM effect on new lightpath request only) wavelength search depending on the system grid, lightpath length and input power level of the incident lightpath request. In SA, wavelength is allocated employing the complete wavelength search mechanism and no lightpath (existing as well as new) is allowed to degrade beyond a certain maximum threshold level (in terms of BER). Relative performances of RA, SA and FWM-blind (i.e., unaware of FWM) algorithm are studied.

In order to reduce FWM interference dynamically in an optical network, Ali et al. [8] have proposed a parameter called, FWM ratio (FWMR), which is defined as the ratio between the optical signal power and the FWM power at the receiving end of a lightpath. With the assumption that FWM statistics in one fiber link is independent from the FWM statistics of other links, variance of FWM noise and hence also FWMR^{-1} are assumed to add up on power basis. When a lightpath request arrives in the network, FWMR^{-1} for the free wavelengths in each fiber link is calculated and each fiber link is assigned a cost factor as FWMR^{-1}. Eventually by employing Dijkstra's algorithm, the route having the least total FWMR^{-1} is identified as the shortest path between source node and destination node. Two wavelength assignment (WA)[1] techniques, viz., first-fit (FF) and best-fit (BF) are employed, and their performances are assessed by the average connection disruption time caused by unacceptable BER for the assigned lightpaths (lightpath experiencing BER above 10^{-4} is assumed to be disrupted). While accommodating a new connection request, FF algorithm searches for the first wavelength which satisfies the performance requirement of BER $\leq 10^{-8}$, whereas BF searches for the best possible wavelength which provides the lowest BER.

Furthermore, in order to avoid the impact of FWM, some unequally-spaced channel-allocation techniques have also been proposed in [6,9–11]. Although these techniques, excepting [6] can completely avoid FWM interference on the desired WDM channels, they demand much larger fiber transmission window in comparison to the equally-spaced WA techniques, thereby degrading the bandwidth-utilization efficiency of the network.

In this paper, WDM network design has been considered as an optimization problem with an attempt to control the impact of FWM in the network. Following the earlier investigations [4,12,13], we have also split the optimization problem in two subproblems: heuristic-based virtual topology design by choosing a set of direct (i.e., single-hop) lightpaths between a set of candidate node pairs and RWA of these lightpaths over the physical topology, the combined task being referred to as the LTD subproblem, followed by the second subproblem of routing the network

[1] Hereafter, wavelength assignment and channel allocation are used interchangeably with the same physical significance.