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Dimensioning Wavelength-Routed Multi-Fiber WDM Networks with Limited Number of Wavelength Converters

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Abstract: Sparse-partial wavelength conversion in WDM networks has been shown as a very efficient network architecture. We present a network analysis and network dimensioning approach for stochastic path requests based on a reduced load approximation. This model enables us to dimension the number of WDM-systems per link and the number of wavelength converters per node needed to guarantee a maximum blocking probability for a given traffic matrix. The key feature of our approach is that the traffic dynamic is one of the free model parameters. This allows us to model the wide range between static traffic and Poisson traffic. A numerical example shows how the dimensioning result depends on the traffic dynamic.

Keywords: Network dimensioning, multi-fiber WDM network, stochastic wavelength path requests, wavelength continuity constraint, share per node wavelength converter model.

1. INTRODUCTION

Dimensioning dynamic WDM networks is similar to dimensioning connection oriented telephone networks. The main difference is given by the wavelength continuity constraint. This property forces that a light path uses the same wavelength from the source to the destination node unless optical cross connectors (OXC) are equipped with wavelength converters that can change the wavelength from an incoming link to another wavelength at an outgoing link. The usage of wavelength converters can significantly improve the link utilization in a network [16]. But it is also shown that blocking probabilities of a network with a small number of wavelength converters are close to the performance of a network with full wavelength conversion capability [3]. As wavelength converters are expensive parts, the network dimensioning has to deal with an additional problem: How much converters are useful in each node? This is also known as the wavelength converter placement problem [3].

The exact analytical methods in the literature are restricted to simplified network models. The performance of a network with single fiber links is analyzed in [6]. Analytical models for the analysis of a single OXC with limited conversion capacity are given in [2] and [13]. Approximate results for arbitrary network topologies with single fiber links and fixed routing are derived in [15]. The reduced load approximation is used in [1] for calculating the blocking probability of networks with single fiber links, no wavelength converters, fixed routing as well as least loaded routing (LLR). An exact method for calculating the blocking probabilities in multi-fiber networks without wavelength conversion is given in [9]. The authors state that the performance of the network is comparable to the performance of networks with wavelength conversion, if the ratio of the number of fibers per link and the number of wavelengths per fiber is around 20 % - 25 %. A recursive formula for estimating the blocking probability of multi-fiber networks without wavelength conversion is given in [11].

For analyzing and dimensioning real WDM networks, our model allows multi fiber links, different number of WDM systems per link, and a share per node wavelength conversion. The traffic is routed on disjunctive paths based on routing costs that are derived from the path lengths and the blocking probabilities on the highest loaded link of each path. The offered load between two nodes is characterized by the two parameters of an Engset model: the mean offered load A and the coefficient of variation z which is defined as the variance to mean ratio of the offered load. Simulations in [14] indicate that the performance is mainly influenced by the variation of the arrival process. As we assume that the demand for wavelength paths is caused by a large number of small bandwidth request compared to the bandwidth per wavelength, the variance of the offered load for wavelength paths is expected to be small. Therefore, the Poisson assumption seems to be not valid in general.

Our paper is organized as follows: In section 2, we define the network model and the traffic parameters. In section 3, we describe our approach for analyzing dynamic WDM networks with partially wavelength conversion, multiple fiber links, and a very general weighted cost routing policy. Section 4 presents a heuristic algorithm for dimensioning the number of WDM-systems per link and the number of wavelength converters per node. Numerical examples, based on a typically German network topology are given in section 5.

2. MODEL ASSUMPTIONS

In the following analysis and dimensioning of partial wavelength conversion networks, we assume that the network is given by N nodes and L links. The C_i wavelength converters at node n_i are shared by all wavelength requests at node n_i. The capacity of each link l_j is given by the number of WDM systems C_j. Each WDM system is modeled with Λ wavelengths.

The dynamic requests d_i for wavelength paths between two nodes n_s and n_d are given by the mean offered load A_i and the peakedness of the offered load z_i which is defined as the variance to mean ratio of the offered load. For $z_i < 1$, this traffic model is known as the Engset model where the requests are generated by a finite number of sources. Both, the inter-arrival times as well as the holding times are assumed to be exponentially distributed with rate λ_i and rate μ_i, respectively. This allows us to model a wide range of traffic like the Erlang traffic with $z_i = 1$ and nearly static traffic with z_i nearby 0.

Traffic d_i is routed onto one of the R_i disjunctive paths. For each request the path with the smallest routing costs is chosen. The routing costs are determined as weighted costs from the path length and the blocking probability at the link with the maximum blocking probability of a path. This enables us to model different routing policies: shortest path routing, least loaded routing, and a combination of both.

3. NETWORK ANALYSIS

Network analysis means that the converter capacities at each node and the link capacities are given. The results of the network analysis are the QoS parameter in terms of the blocking probability $B(d_i)$ of traffic d_i and the performance parameters of the network like the link utilization $U(l_i)$ and the blocking probability $B(l_i)$ at link l_i.

For the network analysis, we apply the reduced load approximation presented in [1], [3], and [10]. We use the following notations:

$\nu_{j,s}$ reduced arrival rate of type s traffic at link j.

$$\left(B_j^{TT}, B_j^{TC}\right) = \text{bppLoss}\left(A_j^{TT}, z_j^{TT}, A_j^{TC}, z_j^{TC}, C_j^{T} / \Lambda\right)$$

A_j^{TT} and z_j^{TT} are the reduced offered transit traffic and the peakedness for one of the Λ wavelengths at link j.

$$A_j^{TT} = \frac{1}{\Lambda}\sum_{s}\frac{\nu_{j,s}}{\mu_s} I\left(j \notin \text{first}\left(R_s\right)\right)$$

The peakedness of the transit traffic is obtained as the minimum of the peakedness of the original source traffic and 1- A_j^{TT}/D_j^{in}, where D_j^{in} is the number of input WDM systems at node n for traffic to link j.

The blocked traffic $A_j^{O} = B_j^{TT}\ A_j^{TT}$ is considered as overflow traffic. The overflow traffic from all links connected to a node n is the offered load at the converter pool of node n. The analysis of the converter pool is done with a D class bpp-model, where the node degree D is the number of links connected to node n.

The peakedness of each traffic class is approximately computed from a single class bpp-model [12] by determining the capacity C such that

$$B_j^{TT} = bppLoss\left(A_j^{TT}, z_j^{TT}, C\right) .$$

The peakedness of the overflow traffic is then obtained with the formula for the one class bpp-model:

$$z_j^{O} = \frac{A_j^{TT} + (C+1)\left(z_j^{TT} - 1\right)}{C + 1 + A_j^{O} - A_j^{TT}} + 1 - A_j^{O}$$

Finally, A_j^{TC} and z_j^{TC} are obtained from the mean and the variance of the traffic served at the converter pool with capacity K. We get for each node n:

$$\left(B_1^{C},\ldots,B_j^{C},\ldots,B_D^{C}\right) = \text{bppLoss}\left(A_1^{O}, z_1^{O},\ldots,A_j^{O}, z_j^{O},\ldots,A_D^{O}, z_D^{O}, K\right) \text{ and } A_j^{TC} = A_j^{O}\left(1 - B_j^{C}\right)$$

The formula for the peakedness is an approximation of the exact formula for the one class bpp-model:

$$z_j^{TC} = z_j^{O} + \frac{B_j^{C}}{1 - B_j^{C}}\left(\sum_{i=1}^{D} A_i^{TC} - K\right)$$

The capacity for source traffic in the next iteration (step 2A) is then obtained as:

$$C_j^{S} = \Lambda\left(C_j - A_j^{TT}\left(1 - B_j^{TT}\right) - A_j^{TC}\left(1 - B_j^{TC}\right)\right)$$

Continue with step 2A until the blocking probabilities B_j^S, B_j^{TT}, and B_j^{TC} remain unchanged.

For the blocking probability $b_{j,s}$, we get:

$$b_{j,s} = \begin{cases} B_j^{S}\text{ , if s is source traffic at link j} \\ \\ 1\text{-}\left(1\text{-}B_j^{TT} + B_j^{TT}\left(1 - B_j^{C}\right)\left(1 - B_j^{TC}\right)^{\Lambda - 1}\right)\text{, if s is transit traffic at link j} \end{cases}$$

Step 3: Computation of the routing probabilities for each path request.

The routing probabilities of each traffic s are adapted in each iteration step with the goal to equalize the routing costs on all alternative paths R_s. The routing costs RC_k of route $k \in R_s$ are defined as follows:

5. NUMERICAL EXAMPLES

5.1. The Example Network

In the following example, we consider a typical graph of a German core network (Figure 1) as defined in [8]. This graph consists of 17 nodes and 26 edges. The traffic matrix is derived from the static demand of STM-16 lines. We assume a mean offered load between each node pair equal to the static STM-16 demands [8]. The variance of the offered load is a free parameter that expresses the dynamic of the offered load. The symmetric matrix of the mean offered load is shown in Table 2. The overall network load is 2020 Erlang. Further parameters are the maximum number of alternate paths $R_s = 3$, the routing parameters $w_L = 1$, $w_B = 20$, and $\Delta_p = 0.01$.

5.2. Analysis Results

Assuming the link capacities (number of WDM-32-systems) shown in Figure 1 and peakedness z = 0.5, we first compare the blocking probability of a transparent network with the blocking probability of a full conversion network. In the transparent network, 6.83 % of the offered load is blocked. If we use a full conversion model, the blocking probability is reduced to 1.2 %. The mean and the standard deviation of the number of busy converters per node is shown in Table 1. This result indicates that, compared to the full conversion network (with 6368 converters), only a small number of converters is necessary in order to significantly reduce the call blocking probability (from Table 1 we get: $\sum_{nodes}\lceil \mu_C + 3\sigma_C \rceil = 360$ converters). As shown in Figure 2, the reduced blocking probability leads to higher link utilization for most of the links. Some links of the full conversion network are less utilized. This is caused by changing the path costs according to the link blocking probabilities.

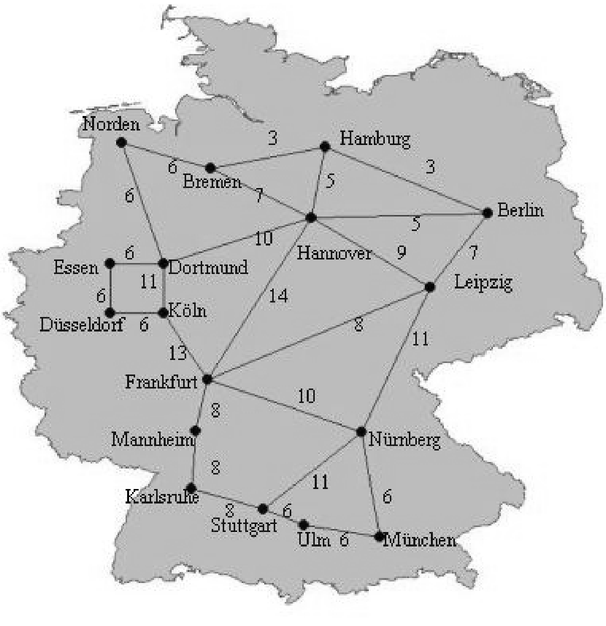

Figure 1: Example German core network

Node	Mean	Standard deviation
Berlin	13.34	2.30
Bremen	20.87	3.03
Dortmund	12.21	2.16
Düsseldorf	1.85	1.05
Essen	1.52	0.99
Frankfurt	40.40	3.15
Hamburg	1.26	0.79
Hannover	63.33	3.92
Karlsruhe	0.01	0.06
Köln	34.30	4.08
Leipzig	12.51	2.31
Mannheim	3.95	1.79
München	0.53	0.53
Norden	2.50	1.12
Nürnberg	35.07	3.73
Stuttgart	5.40	1.73
Ulm	1.22	0.89

Table 1: Statistics of the converter utilization.

dimensioned according to Table 3 with peakedness z = 0.5 for varying peakedness values. As expected, the loss probability increases significantly, if the traffic is more dynamic. On the other hand, modelling the traffic as Erlang traffic (z = 1) would lead to large analysis errors, if the peakedness of the optical network is in the range 0.1 to 0.5.

The following example investigates the dimensioning result if the traffic dynamic is varied from z = 0.1 to 1.0 (same mean offered load). As we can see from the results in Figure 5, the total number of WDM-systems increases from 169 to 174 (+ 3%). Much larger is the additional number of converters needed to meet the QoS requirements of the more dynamic traffic. The total number of converters increases from 101 to 664 (+ 557 %) converters.

Node	**# Converters per node**
Berlin	12
Bremen	46
Dortmund	31
Düsseldorf	5
Essen	6
Frankfurt	57
Hamburg	5
Hannover	88
Karlsruhe	9
Köln	41
Leipzig	34
Mannheim	18
München	18
Norden	3
Nürnberg	57
Stuttgart	14
Ulm	6
Sum	450

Link	**# WDM-32-systems**	**# channels**
Ber-Ham	3	96
Ber-Han	4	128
Bre-Nor	8	256
Dor-Ess	5	160
Dor-Koe	3	96
Due-Koe	7	224
Ess-Due	2	64
Fra-Han	20	640
Fra-Koe	11	352
Fra-Lei	6	192
Fra-Nue	12	384
Ham-Bre	1	32
Han-Bre	11	352
Han-Dor	9	288
Han-Ham	6	192
Kar-Man	3	96
Lei-Ber	6	192
Lei-Han	7	224
Man-Fra	6	192
Mue-Nue	8	256
Mue-Ulm	3	96
Nor-Dor	1	32
Nue-Lei	10	320
Stu-Kar	2	64
Stu-Nue	10	320
Ulm-Stu	4	128
Sum	168	5376

Table 3: Result of the link and the converter dimensioning.

number of fibres without violating the requested call blocking probability. A property of our dimensioning heuristic is that increasing the peakedness mainly increases the number of converters needed. The number of fibres per link remains nearly unchanged.

Due to the iterations in the reduced load approximation, network analysis is numerical costly. In our examples, the reduced load approximation took about 500 iteration steps until the routing reached a stable state. The dimension heuristic works with only one analysis step. Therefore, it runs in the same time scale.

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