On the Relationship Between Network Topology and Throughput in Mesh Optical Networks

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Keywords: Wavelength routed optical networks, Fibre based networks, physical layer aware networking, maximising network throughput

Abstract

The relationship between topology and network throughput of arbitrarily-connected mesh networks is studied. Taking into account nonlinear channel properties, it is shown that throughput decreases logarithmically with physical network size with minor dependence on network ellipticity.

1 Introduction

Optical networks underpin the infrastructure of the modern Internet. To maximise the throughput of these networks, physical propagation effects must be taken into account. Thus, the network throughput becomes a nonlinear function of fibre parameters, link distances and lightpath configurations, and networks can no longer be only characterised only by logical topologies, i.e. a set of vertices and edges.

The development of low complexity transmission models of nonlinear fibre propagation enabled their incorporation in network algorithms. As a consequence, various studies have suggested new optimisation strategies for wavelength and route assignments [1-4], launch power optimisations and the use of various modulation formats and code rates [5, 6] within the same network, tailored to the lightpath quality.

While many works analyse specific topologies, often derived from existing/published networks, more general relationships between physical network topology and throughput are largely nonexistent. Most work [7, 8] analysed network performance as a function of node, link number and connectivity matrix in the absence of physical transmission properties. However, physical transmission properties must now be included in order to calculate both throughput as well as derive scaling laws that lead to a more intelligent use of current optical networks.

In this work, arbitrarily-connected mesh optical networks (ACMN) were analysed to analyse the relationship between physical topology properties and network throughput. The focus of the work was two network properties - scaling the network size and paramerising network ellipticity.

2 Methodology and throughput estimation

To study the relationship between topology and network throughput, 1000 distinct logical topologies were generated with 14 nodes and 21 links each, as variants of the NSFNET topology [9], chosen as the reference network. Physical link lengths were randomly assigned to each network link (edge) according to a probability density function (PDF), as shown in Fig. 1. The link distances of NSFNET in [6] were converted to a continuous PDF by means of kernel density estimation. Using this approach, the generated ACMNs had similar number of node-pair realisations. For this work, the optical bandwidth was constrained to C-band (5 THz). Colourless, directionless

![Fig. 1: Flow chart of ACMN generation and throughput estimation. 1000 distinct topologies were generated where each was assigned 100 different link distance realisations. The throughput relaxation x ∈ [0, 1] was swept to maximise total network throughput and to trade-off individual lightpath capacity for decreased network congestion (i.e. increased N_λ).](image-url)
and contentionless reconfigurable optical add-drop multiplexers (ROADM) and Erbium-doped fibre amplifiers with 4 dB noise figure were assumed. 32 GBd, Nyquist-spaced WDM channels were considered and filtering effects and insertion loss of ROADMs were neglected.

For each physical topology, the throughput was calculated following in Fig. 1. The overall objective was to maximise the total network throughput. It was assumed that all 91 node-pairs are assigned the same number of lightpaths $N_{\lambda}$, which is then maximised within C-band. First, a noise-to-signal ratio (NSR), defined as inverse signal-to-noise ratio $\text{NSR} = \frac{1}{\text{SNR}}$, was assigned to each network link. The advantage of working with NSR is that the total NSR of a lightpath is simply the sum of its link NSRs. This allows the computation of the k-highest SNR paths for a given node-pair using a weighted k-shortest path algorithm. The NSR was calculated using a closed-form approximation of the Gaussian Noise (GN) model [10], modelling nonlinear interference as additive white Gaussian noise (AWGN) and capable of accounting for variably loaded network links. For the initial link NSR assignment, however, uniform signal spectra were assumed. The launch power was optimised for every channel in each link following the LOGON strategy [11].

Based on the link NSR, lightpath capacities $C_i$ were estimated using Shannon’s formula [12], yielding the maximised lightpath throughput for a given SNR. For each node-pair, NSR weighted k-shortest paths were used to determine all possible lightpaths within a certain capacity range. In particular, only lightpaths that satisfied $C_i \geq x \cdot \max (C_i)$ were kept for a throughput relaxation $x \in [0, 1]$ and where $i$ ranges over all possible lightpaths for a given node-pair. Increasing throughput relaxation $x$ generates a larger optimisation space, i.e more ‘equal-cost’ paths, for the routing and wavelength assignment (RWA) stage. For larger $x$, lightpaths can be rerouted over longer routes leading to lower network congestion and to more established lightpaths across C-band. However, longer routes exhibit lower throughput per lightpath. For this reason, $x$ was swept and optimised for each physical topology to maximise total network throughput.

The set of ‘equal-cost’ paths for each node-pair is then passed to the RWA. The objective of the RWA is to find a lightpath configuration that minimises the network congestion and in turn maximises the number of established lightpaths per node-pair $N_{\lambda}$ within C-band. This is done by rerouting lightpaths over longer paths such that physical wavelengths can be reused over physically diverse paths, without collision. A heuristic, which maximises $N_{\lambda}$ within a constrained optical bandwidth, was proposed in [8]. For each node pair, an arbitrary set of ‘equal-cost’ paths is required and the heuristic returns a wavelength and route configuration which minimises spectral occupation across all network links for a given $N_{\lambda}$. The heuristic has been shown to match results of ILP formulations for logical topologies, without taking physical transmission properties into account. Here, the heuristic is extended to include physical properties by carefully selecting the set of ‘equal-cost’ paths according to their physical transmission capacities. After each iteration of the RWA, $N_{\lambda}$ is incremented until the entire C-band is filled. In summary, the proposed approach finds the maximum number of lightpaths for each node-pair $N_{\lambda}$ that can be assigned over C-band, for a given optimisation space of ‘equal-cost’ paths, determined by the throughput relaxation $x$.

Finally, the throughput of each lightpath is computed based on the exact lightpath configuration returned by the RWA algorithm. The throughput of a particular lightpath is, hence, dependent on the transmitted distance, fibre parameters as well as number and channel spacing of co-propagating lightpaths in each link.

### 3 Scaling the size of optical networks

To study the impact of physical size on network throughput, the average link distance of each ACMN was scaled from 640 km to 3040 km, by scaling the assigned link distances by the factor $d_{1463km}$, where $d$ is the average link distance. The used average link distance of NSFNET is 1463 km. For comparison the average link distances, estimated as in [8], of the DTAG/T-Systems [13] and the Google B4 [14] topology are 236 km and 3910 km, respectively.
4 Scaling the ellipticity in optical networks

Another important property of a physical network is its shape. In this work we denote it by the term ‘ellipticity’ and define a normalised network diameter as $D = \frac{\text{network diameter (km)}}{\text{average node-pair distance (km)}}$, where the network diameter is the maximum shortest path distance in km over all node-pairs. If the diameter is then normalised by the average node-pair distance, it can serve as way of parameterising the impact of network shape and defines the ellipticity of a topology. In this work, for each logical topology, link distances were randomly assigned and only kept if they satisfied a fixed normalised network diameter $D$. The average node-pair distance was fixed to 3070 km, which is that of the used NSFNET topology. For comparison, NSFNET has $D = 2.13$, the DTAG/T-systems topology and the Google B4 topologies have $D = 2.04$ and $D = 2.79$.

Fig. [3] shows the results for the number of established lightpaths per node pair, average lightpath throughput and total network throughput as a function of ellipticity. It can be seen that Fig. [3a] shows a marginal decrease in the number of the established lightpaths, thus increasing congestion, as the ellipticity increases. Fig. [3b] shows an increase of the average lightpath throughput. Increasing ellipticity increases the distances for some lightpaths, and decreases the distances of the remaining ones. To aid the interpretation of the results, we looked at the scaling of the average throughput for two point-to-point links, where one is increased and the other decreased by $\Delta n_s$ fibre spans. The average throughput of two point-to-point links scales as $C_l \propto 2 \log_2 \left( \frac{\text{SNR}_1}{\text{SNR}_2} \right) - \log_2 \left( n_s \right)$ which, indeed, predicts an increase in average lightpath throughput as $\Delta n_s$ (the ellipticity) is increased. The marginally decreased $N_s$ is balancing the effect of increased average throughput, as ellipticity grows. Thus, the total throughput only marginally depends on ellipticity, as shown in Fig. [3c].

The analysis shows that throughout in optical networks is only weakly dependent on the topology ellipticity, for the ranges studied in this paper.

5 Conclusion

The relationship between physical network topology and throughput was studied by parametrising and analysing arbitrarily-connected mesh optical networks. It was found that, similarly to point-to-point links, network throughput decreases approximately logarithmically with physical network size while there is only a minor throughput dependence on the ellipticity of a topology. The study further suggests that network congestion only marginally increases with a uniform increase of physical network size and ellipticity.

Support for this work is from UK EPSRC under DTG PhD studentship to D. Semrau and EPSRC TRANSNET Programme Grant.
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