

Evolving Optical Core Networks: Understanding the Impact of Topology Redesign using Space and Wavelength Domains on Network Throughput

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Abstract In this work, the benefits of network re-design with spatial division multiplexing (SDM) and ultra-wideband (UWB) are investigated. For the first time a comprehensive study of 200 generated topologies and optimal routings show throughput-cost trade-off of re-designing networks with UWB and SDM.

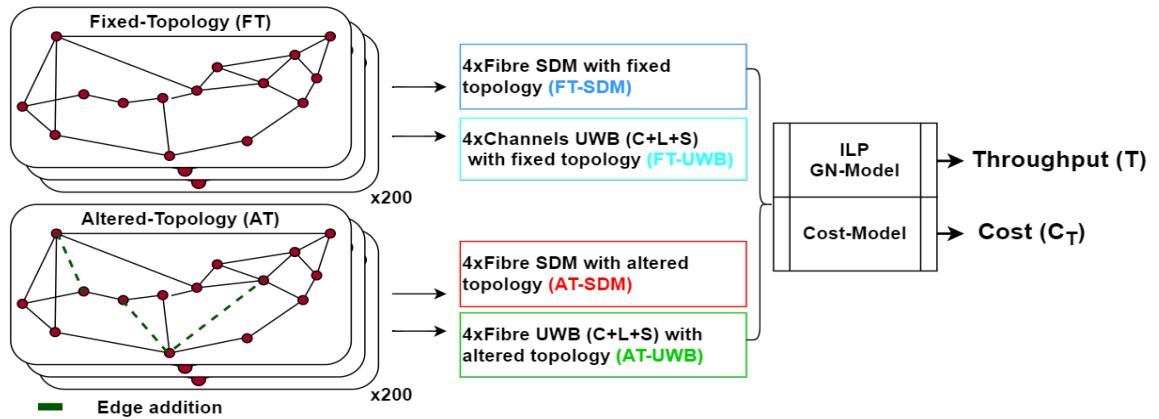


Fig. 1: Data generation process for fixed and altered topology scenarios.

Introduction

Optical networks form the backbone of the digital communications infrastructure and enable the transport of 100/1000s Tbps of data over many 100/1000s of kilometres. This currently is achieved using wavelength division multiplexing (WDM), typically within the C-band^[1]. Traffic growth of 20–60% year-on-year, is likely to exceed the capacity of conventional WDM networks^[2] with (i) ultra-wide band (UWB) transmission and (ii) spatial division multiplexing (SDM) as possible solutions. Expanding the usable optical fibre transmission window beyond the C-band (i) leads to increased physical layer impairments, including inter-channel stimulated Raman scattering^[3]. In (ii), throughput is increased by using different spatial domains, including multiple fibre cores, modes or multi-fibre bundles. Although network operators are hesitant of deploying new fibre, since the addition of new fibres is costly, they realise that as traffic demands change over time, existing network topology may not efficiently support new traffic demands. Understanding how to cost-effectively deploy new resources, when and where they are needed, is therefore key.

Previous work compared UWB and SDM upgrades, however usually the performance was evaluated for a single topology, with sub-optimal routing heuristics to gauge the network performance^{[4]–[6]}. In this work, different upgrade strategies are investigated: SDM, UWB, as well as the addition of new selected network links using a genetic algorithm (GA) in parallel with either SDM/UWB. The role of network structure within the upgrade strategies, in conjunction with SDM and UWB, has not previously been evaluated, especially through the use of global optimal methods such as integer linear programming (ILP). The upgrade strategies were evaluated via their cost and their maximum achievable throughput.

Methodology

In this work, 200 topologies were sampled from a geometric generative graph model, previously shown to give structures close to those observed in real core optical networks^[7], using NSFNET's node locations^[7].

The following scenarios were then investigated for all the generated 400 networks, shown in figure 1: (a) fixed topology (FT), 200 networks: the topology remains fixed, with only existing links in

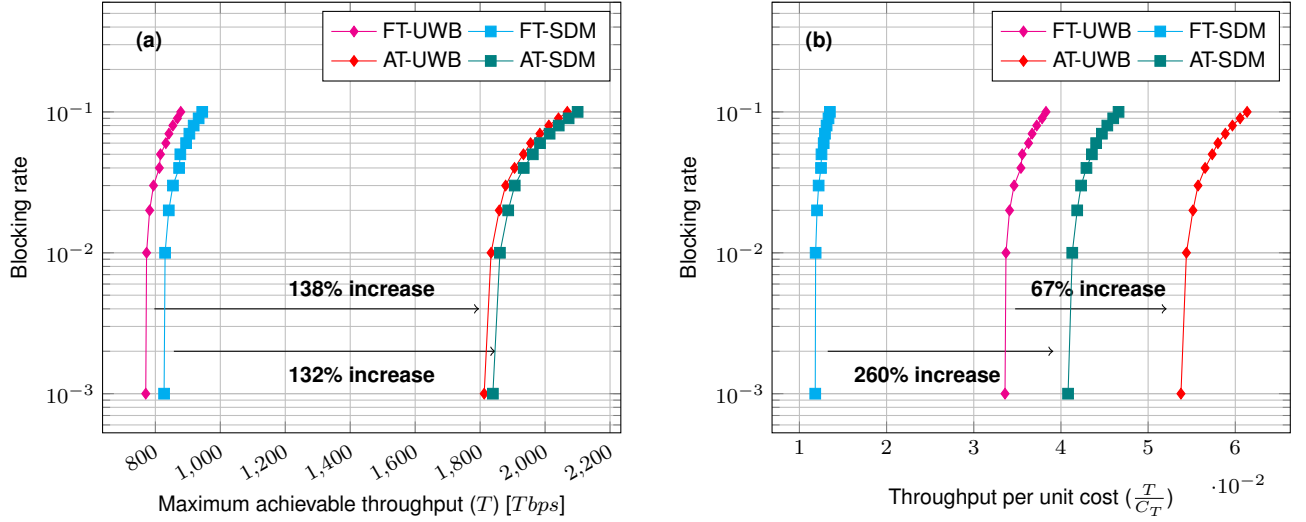


Fig. 2: (a) Maximum achievable throughput values for blocking rates between 0.1% and 10%. (b) Throughput normalised by the cost of the network for blocking rates between 0.1% and 10%.

the network upgraded via (i) UWB (C+L+S) on every edge of the base topology, termed FT-UWB (ii) SDM deployed with multiple-fibre bundles on the base topology, termed FT-SDM and (b) altered topology (AT) where links are added to the fixed-topology via a GA (200 networks) (iii) new edges added to the base topology and implemented with multiple-fibre bundles, termed AT-SDM (iv) using the same topologies as in (iii), however reducing the number of edges by deploying UWB, termed AT-UWB.

For all the scenarios the goal was to increase the resources by approximately a factor of 4. For FT-UWB, this was by deploying C+L+S, generating four times the number of channels and for FT-SDM this equated to deploying about four times the original topology's fibre length, also giving four times the original channels. For AT-SDM/UWB three other topologies were designed for each fixed-topology via a GA within 10% of the original total fibre length of the base topology. These were then combined to form a single SDM topology. The GA uses a binary encoding of the topology and optimises the topology according to the demand weighted cost metric (DWC)^[8], previously shown to maximise throughput in networks.

The next step was to determine the routing and wavelength assignments (RWA) calculated using the following integer linear programming (ILP) formulation. The variable $\delta_{z,k,w}$ describes whether a node-pair z , takes a path k over wavelength w , 1 if so, 0 otherwise. The variable M constrains the number of connections assigned given some acceptable blocking rate, β , and normalised traffic matrix T_c^z .

The ILP maximises $\sum_{z \in Z} \sum_{k \in K} \sum_{w \in W} \delta_{z,k,w}$

subjected to Eq.(1), which constrains the allocated lightpaths (left side) to less than or equal to the requests (right side). Eq.(2) ensures that the number of blocked connections is smaller than or equal to the blocking rate, where $\epsilon = \lfloor \beta \cdot \sum_{z \in Z} [M \cdot T_c^z] \rfloor$. Both optimisations are subjected to the wavelength continuity constraint of Eq.(3).

$$\sum_{k \in K} \sum_{w \in W} \delta_{z,k,w} \leq [M \cdot T_c^z] \quad \forall z \in Z \quad (1)$$

$$\sum_{z \in Z} [M \cdot T_c^z] - \sum_{z \in Z} \sum_{k \in K} \sum_{w \in W} \delta_{z,k,w} \leq \epsilon \quad (2)$$

$$\sum_{z \in Z} \sum_{k \in K} \delta_{z,k,w} \cdot I(e \in k) \leq 1 \quad \forall e \in E \quad \forall w \in W \quad (3)$$

Using this ILP the optimal RWA for each of the 200 fixed-topologies and the 200 altered-topologies was found. The next step was to calculate the maximum achievable throughput for each topology, using a closed-form Gaussian noise (GN) physical layer impairments (PLI) model^[3] to estimate the SNR of the lightpaths allocated. A fully populated C-band (1520-1560 nm) for the SDM-based scenarios and C+L+S-band (1460-1625 nm) for the UWB scenarios were used, with 50 GHz Nyquist-spaced channels assumed in both cases, and a uniform length 80 km span considered for all links. Each span is amplified with identical erbium-doped fibre amplifiers for C and L bands (noise figures of 5.5 dB and 6 dB, respectively) and Thulium-doped fibre amplifiers for the S-band (noise figure of 7 dB)^[9]. They were interfaced with colourless, directionless and contentionless reconfigurable optical add-drop multiplexers. For each

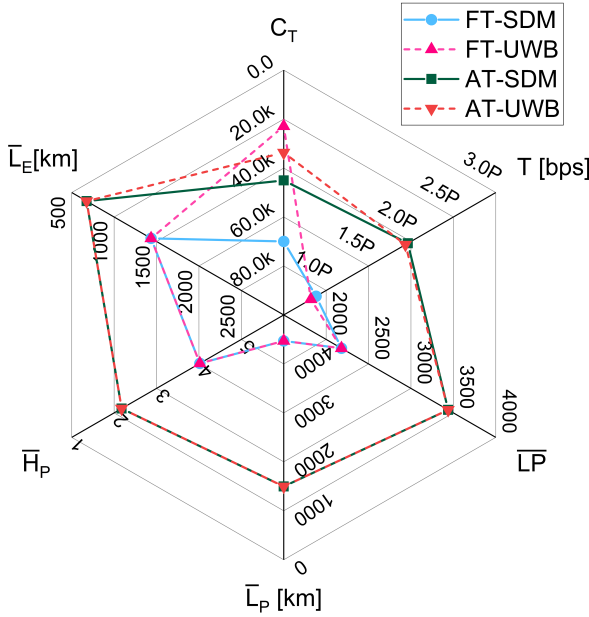


Fig. 3: Different network scenarios comparing network cost (C_T), maximum achievable throughput (T), number of connections allocated (L_P), average lightpath length ($\bar{L}_P$), average lightpath hops ($\bar{H}_P$) and average edge length ($\bar{L}_E$). one of the lightpaths, the SNR is calculated using a launch power profile optimisation algorithm^[10] with a step size of 0.5 dB. After finding the SNR of lightpaths, the capacity was calculated using the Shannon upper bound formula and summed over all lightpaths^[11].

The cost was modelled as node cost (C_i) and edge cost ($C_{i,j}$), where $i \in N$ and $(i, j) \in E$. Where $C_i = \lceil \frac{\delta_i}{wss_n - 1} \rceil \cdot \delta_i \cdot (C_{wss} + C_{tr})$ and $C_{i,j} = n_s \cdot (C_A + L_s \cdot C_f)$. Here δ_i is the degree of node i , wss_n is the wavelength selective switch (WSS) ports, C_{wss} is the WSS cost, C_{tr} is the transponder cost, n_s number of spans, C_A is the amplifier cost, L_s is the span length and C_f is the cost of fibre, including deployment cost. Finally, evaluating these costs with values taken from^{[4],[12]}, the costs from all nodes and edges are summed.

Results

The topologies are evaluated in terms of cost (C_T) and their maximum achievable throughput (T), over different blocking probabilities (0.1-10%), and the average of the 200 topologies for each blocking rate is plotted in figure 2.

Figure 2a shows the throughput hierarchy of the different upgrades, where FT-UWB performs worst in terms of throughput, with FT-SDM only showing a 7% marginal throughput increase. However, when altering the topology, one can see a 138% and 132% increase in the mean throughput for the AT-UWB and AT-SDM scenarios over their FT counterparts.

Using the cost to normalise the throughput, the

result is re-plotted in figure 2b, where the hierarchy slightly changes. For the fixed-topology results, FT-SDM outperforms FT-UWB upgrades by 7%, in terms of throughput. However, with a cost increase of 205%. For the altered-topologies it is slightly less drastic, with AT-SDM outperforming the AT-UWB topologies by only 1% in terms of throughput, however costing 33% more. In each case, the throughput per unit cost increases by 260% and 67% for FT-SDM to AT-SDM and FT-UWB to AT-SDM, respectively. This shows that altering the topology structure can be cost-efficient, if no dark fibres are available.

To demonstrate the impact of introducing new edges, we compared network cost, maximum achievable throughput, number of connections allocated, average length of routes taken by lightpaths, average number of hops taken by lightpaths and average edge length in figure 3. This shows that by minimising the DWC via a GA and implementing these new edges via SDM, the average edge length ($\bar{L}_E$) decreases by approximately 52%, in turn reducing the average lightpath length ($\bar{L}_P$) by 66%, with an average 45% fewer hops taken ($\bar{H}_P$), reducing the number of wavelength resources used. This translates into a 63% increase of lightpaths allocated (L_P), generating an increase of 132% in network throughput (T) with a 35% decrease in cost (C_T) compared to the FT-SDM topologies. Comparing the AT-UWB and FT-UWB scenarios one can see 138% higher throughput, however with an increase in cost of 47%. This is due to the new fibres deployed in the AT-UWB scenario, increasing the cost. Therefore, it is clear that if new fibres need to be deployed, altering the network's structure is hugely beneficial.

Conclusions

In this work we developed a framework to analyse the relative impact of space and wavelength dimensions, with and without topology redesign on network throughput and cost. By altering the topology one can increase connectivity, reduce routelengths and hops taken. This results in a higher number of allocated demands and, therefore leads to increased throughput by 132% at 35% of the cost compared to keeping the same network structure. This shows that if dark fibres are not available, then upgrades via UWB and altering the network structure are better options. Future work includes the investigation of the impact of different traffic distributions, distance scale networks, node number and reliability/resilience.

References

- [1] J. M. Simmons, *Optical Network Design and Planning* (Optical Networks), en. Cham: Springer International Publishing, 2014. [Online]. Available: <http://link.springer.com/10.1007/978-3-319-05227-4> (visited on 11/13/2020).
- [2] P. J. Winzer, "Spatial Multiplexing in Fiber Optics: The 10X Scaling of Metro/Core Capacities", *Bell Labs Technical Journal*, vol. 19, pp. 22–30, 2014, Conference Name: Bell Labs Technical Journal, ISSN: 1538-7305.
- [3] D. Semrau, R. I. Killey, and P. Bayvel, "A Closed-Form Approximation of the Gaussian Noise Model in the Presence of Inter-Channel Stimulated Raman Scattering", *Journal of Lightwave Technology*, vol. 37, no. 9, pp. 1924–1936, May 2019, ISSN: 0733-8724, 1558-2213. [Online]. Available: <https://ieeexplore.ieee.org/document/8625492/> (visited on 10/02/2019).
- [4] R. K. Jana, A. Iqbal, N. Parkin, *et al.*, "Multifiber vs. Ultra-Wideband Upgrade: A Techno-Economic Comparison for Elastic Optical Backbone Network", en, 2022.
- [5] E. Virgillito, R. Sadeghi, A. Ferrari, G. Borraellini, A. Napoli, and V. Curri, "Network Performance Assessment of C+L Upgrades vs. Fiber Doubling SDM Solutions", en, in *Optical Fiber Communication Conference (OFC) 2020*, San Diego, California: Optica Publishing Group, 2020, M2G.4, ISBN: 978-1-943580-71-2. [Online]. Available: <https://opg.optica.org/abstract.cfm?URI=OFC-2020-M2G.4> (visited on 09/22/2022).
- [6] R. K. Jana, A. Mitra, A. Pradhan, *et al.*, "When Is Operation Over $\mathbf{C+L}$ Bands More Economical than Multifiber for Capacity Upgrade of an Optical Backbone Network?", in *2020 European Conference on Optical Communications (ECOC)*, Dec. 2020, pp. 1–4.
- [7] R. Matzner, D. Semrau, R. Luo, G. Zervas, and P. Bayvel, "Making intelligent topology design choices: Understanding structural and physical property performance implications in optical networks [Invited]", EN, *Journal of Optical Communications and Networking*, vol. 13, no. 8, pp. D53–D67, Aug. 2021, Publisher: Optica Publishing Group, ISSN: 1943-0639. [Online]. Available: <https://opg.optica.org/jocn/abstract.cfm?uri=jocn-13-8-D53> (visited on 03/15/2022).
- [8] R. Luo, R. Matzner, G. Zervas, and P. Bayvel, "Towards a Traffic-Optimal Large-Scale Optical Network Topology Design", en, in *2022 International Conference on Optical Network Design and Modeling (ONDM)*, Warsaw, Poland: IEEE, May 2022, pp. 1–3, ISBN: 978-3-903176-44-7. [Online]. Available: <https://ieeexplore.ieee.org/document/9782843/> (visited on 09/17/2022).
- [9] N. Sambo, A. Ferrari, A. Napoli, *et al.*, "Provisioning in multi-band optical networks: A C+L+S-band use case", en, in *45th European Conference on Optical Communication (ECOC 2019)*, Dublin, Ireland: Institution of Engineering and Technology, 2019, 53 (4 pp.)–53 (4 pp.) ISBN: 978-1-83953-185-9. [Online]. Available: <https://digital-library.theiet.org/content/conferences/10.1049/cp.2019.0787> (visited on 12/14/2022).
- [10] D. Semrau, "Modeling of Fiber Nonlinearity in Wide-band Transmission", in *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, Mar. 2022, pp. 1–3.
- [11] C. E. Shannon, "A Mathematical Theory of Communication", en, *The Bell System Technical Journal*, vol. 27, pp. 379–423, Oct. 1948.
- [12] M. Nakagawa, T. Seki, and T. Miyamura, "Techno-Economic Potential of Wavelength-Selective Band-Switchable OXC in S+C+L Band Optical Networks", en, in *Optical Fiber Communication Conference (OFC) 2022*, San Diego, California: Optica Publishing Group, 2022, W2A.24, ISBN: 978-1-55752-466-9. [Online]. Available: <https://opg.optica.org/abstract.cfm?URI=OFC-2022-W2A.24> (visited on 12/14/2022).