Automatically Driven Optical Networks
Réseaux optiques autonomes

Résumé en Français

Contexte

Les réseaux optiques restent aujourd'hui opérés de manière très manuelle, soit en envoyant des techniciens sur le terrain, soit via des commandes envoyées manuellement via un système de contrôle centralisé. Ceci induit des erreurs de configurations ou l'impossibilité de réaliser des configurations complexes, au détriment de la performance du réseau en termes de transmission (par exemple, distance ou débit).

Une des problématiques principales lors de l'automatisation des réseaux est la nécessité de préserver la performance des services préexistants. Or, les performances des services traversant les mêmes composants dans un réseau, comme des fibres ou des amplificateurs, sont corrélées : la modification d'une caractéristique physique d'un service peut influer sur les caractéristiques physiques d'autres services se co-propageant dans les mêmes composants, via divers effets physiques, comme les effets non-linéaires ou les effets Raman dans les fibres. Cette interrelation entre les services rend l'optimisation des réseaux complexe, l'optimisation d'un service pouvant dégrader d'autres services.

Pour cette raison, il est important d'étudier des mécanismes d'optimisation qui garantissent la performance des services déjà existants dans les réseaux. De tels mécanismes pourront se reposer sur une optimisation continue du réseau (au contraire d'une optimisation périodique, qui pourrait laisser le réseau dans un état sous-optimal); sur des variations lentes des différents actuateurs (aux dépends de la vitesse d'établissement de nouveaux services); et sur des outils de prédiction avancés de la performance, qui permettent de prédire, dans le cadre d'un jumeau numérique, l'impact de toute décision avant de l'effectuer, et d'ajuster les décisions de contrôle en fonction de leur impact prévu.

Au cours de la thèse, l'étudiant pourra s'appuyer sur un banc de test de réseau très réaliste, émulant un réseau maillé jusqu'à 8 liens, constitué uniquement de matériel commercial. Les études seront réalisées grâce au plan de contrôle AI-Light qui a été développé par l'équipe de recherche de Huawei pour tester des mécanismes d'optimisation de réseau.

Problème et principaux défis scientifiques

Les réseaux optiques requièrent de nombreuses étapes manuelles lors de leur opération, de plus, toute reconfiguration est lente du fait des composants eux-mêmes, et des marges sont utilisées pour masquer la connaissance imparfaite de la couche physique lors de l’opération, et garantir qu’une reconfiguration n’impacte pas les services existants. Ces marges réduisent le débit des réseaux.

La problématique est la suivante:

- Optimisation rapide: si la couche physique change, trouver une sequence d’actions pour réoptimiser la qualité de transmission de l’ensemble des services supportés par le réseau, tout en garantissant que tous les services continuent à fonctionner sans interruption, et en maximisant le debit total du reseau (ou la marge opérationnelle). L’objectif secondaire est d’optimiser le processus d’optimisation.

- Réseaux autonomes: démontrer l'opération autonome des réseaux optiques par exemple via la reconfiguration autonome en cas de changement sur la couche physique.

Objectifs et déroulement

12 mois: état de l'art. Développement d'un modèle de l'impact de la reconfiguration de la couche physique sur les services existants. Algorithme pour sélectionner la séquence d'actions optimale pour réoptimiser la couche physique d'un réseau. Validation sur un banc de test en boucle ouverte (en partant d'un état dégradé, déclencher manuellement l'optimisation).

12 mois: à partir de la tâche précédente, accélération de l'algorithme. Validation sur un banc de test en boucle ouverte.

6 mois: à partir des 2 tâches précédentes, fermeture de la boucle et démontrer une optimisation du réseau de manière complètement autonome sans créer d'interruption de service en cas de dégradation non prévue de la couche physique.

6 mois: écriture de la thèse.

Note: The Ph.D. candidate will be accompanied by some experiments whenever possible and/or needed. This will give a hands-on experience to the Ph.D. applicant in fiber optics. Members of the transmission team in Huawei France will help with the experimental part.

Note: Le candidat au doctorat sera accompagné de quelques expériences chaque fois que possible et/ou nécessaire. Cela donnera une expérience pratique au candidat au doctorat en fibre optique. Des membres de l'équipe de transmission de Huawei France participeront à la partie expérimentale.

1 Preamble and Context

1.1 Industrial Lab

The Ph.D. will be held in the Optical Communication Technology Lab (OCTL) at Huawei Technologies France, under the supervision of Dr. Yvan Pointurier (Ph.D.). OCTL has currently more than 20 members, almost all with a Ph.D. The lab members have a long experience in different domains that include optical networking, fiber optics, coding for optics, Digital Signal Processing (DSP), devices and transmission. The OCTL is building new experimental labs using the high-end technology in optics. Dr. Yvan Pointurier has 20 years of experience in optical networking, he published above 20 patents and 120 articles in international journals and conferences (2 best paper awards, 11 top-scored papers). He is an associate editor of the IEEE/OSA Journal of Optical Communications and Networking and is on the TPC of several conferences, currently ECOC and ONDM. He has supervised 2 CIFRE Ph.D. students and was a team leader for 4 years at Nokia Bell Labs before joining Huawei in 2020, where he leads the activities on optical networking. The Ph.D. applicant will be in real industrial environment in which experiments and tests will be held on state-of-the-art equipment as well as on production Huawei equipment. This will give the Ph.D. applicant a hand-on experience that will be very useful for the Ph.D. execution and for the applicant career development.

1.2 Academic Lab

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1.3 Ph.D. Applicant

Chenyu Sun holds a BS from Huazhong University of Science and Technology (HUST), Wuhan, China and a MS from U. Paris Saclay / IP Paris ("ROSP": réseaux optiques et systèmes photoniques, a joint MS program between Télécom Paris, Télécom SudParis, and Institut d'Optique Graduate School). As a part of his MS curriculum, Chenyu was an intern with Huawei Paris Research Center for 6 months; he successfully implemented key features for the lab in-house software network defined (SDN) controller called AI-Light, resulting in an improved controller with both new and faster features. Chenyu is currently continuing his work in the same research team as a research engineer. The Huawei research team has been very satisfied with the work, and Chenyu has integrated very well within the team.

Since Chenyu has already worked for more than 6 months in the Huawei lab, there will be a continuity with his Ph.D. such that Chenyu will be operational and high performing immediately. The planned topic is in line with his activities as an intern, and he will use the same platform he used and actually contributed to improve during his internship.

2 Ph.D. Topic Abstract

Problem statement and key research bottlenecks:

- Bottleneck: Current networks are operated manually; reconfiguration is slow and margins are used to make up for lack of physical layer knowledge and guaranteeing any reconfiguration does NOT impact existing services. Those margins reduce the total network achievable throughput.
- Problem statement:
  - Fast network optimization: upon of a change of the underlying physical layer, find sequence of actions to re-optimize the quality of transmission of all services carried in the network, with guarantee that all services continuously operate error-free, and maximize the total network achievable throughput (or operation margin). As a secondary objective, speed up the optimization process.
  - Autonomous network: demonstrate autonomous network operation e.g. through automated reconfiguration upon change of underlying physical layer.

3 Background and Approaches

3.1 Background and review of the state-of-the-art

Optical layer modeling

In optical networks, services are carried by modulated optical signals called "light paths" (the combination of a route and a piece of optical spectrum called "slot") over a physical infrastructure essentially; a light path traverses, at the optical layer, between the emitter and the receiver: optical fibers, amplifiers, and filters. Optical signals are wavelength multiplexed over the same routes, i.e., several light paths share the same transmission medium. Operators require that services are carried "error free", i.e., with a very low bit error rate (BER; e.g., BER<1e-15) after forward error correction (FEC) decoding. During propagation, optical signals sustain various impairments, which degrade their BER. The main sources of impairments are: optical amplifiers, through the so-called "amplifier spontaneous emission" (ASE) noise; optical fibers, through the nonlinear Kerr effects; filtering penalties; polarization-dependent losses; and receiver noise (including implementation penalty of the internal digital signal processing). In addition, in systems that use extended optical transmission bands such as the 6 THz C band or several bands at the same time (e.g., C+L bands), stimulated Raman scattering nonlinearly transfers optical power from short to long wavelengths.

Although most of the effects are now well modeled by physics, the behavior of some components is still difficult to predict; for instance, the gain spectrum hence output power spectrum of the main type of amplifiers used in optical communication systems, the Erbium Doped Fiber Amplifier (EDFA), is known to have a nonlinear response with the input load that physics cannot model well, such that engineers have looked at machine learning techniques for modeling. In addition, even when physical models exist to predict the behavior of components, the inputs of those models may not be fully known, leading to inaccuracies of the output of the said models. See [PointurierJOCN2021, AyassiJLT2021] and references therein.

To mitigate those sources of inaccuracies (both in terms of modeling, and model inputs), several techniques have been proposed [SeveJOCN2021, MoretteOFC2021, MoretteOFC2022]. In general, inaccuracies translate into higher margins to establish/operate services. [PointurierJOCN2017, KarandinECOC2022]. Lower margins can be traded for slower network operation, such that, during an event such as optical service restoration after a failure, fast service re-establishment is sought at the expense of consuming the margin and hence with a possibility that the re-established service performs sub-optimally in terms of BER [US9973295B2, ZhongOFC2021].

Network automation: the autonomously driven network

Given that, optical communication stakeholders work towards autonomously driven optical networks, similar to the car industry's promises of the advent of self-driving cars. In particular, the self-driving network will leverage the wealth of data made available by the new technologies deployed in optical networks including dedicated optical performance monitors but also other hardware initially dedicated to other functions, but that can be additionally used as optical performance monitors (for instance, use coherent receiver to measure signal to noise ratio); the autonomously driven network will then use this data to self-optimize, for instance, increase the transmitted capacity if margins prove to be larger than planned; the autonomously driven network will also self-diagnose and auto-reconfigure before a failure even occurs, for instance by decreasing transmitted data rate rather than losing signal completely in case of slow-varying degradation impairing a transmission line, or re-allocating network-wide resources to avoid losing a single service. In particular, the autonomously driven network will rely on a digital twin, which relies on real-time monitoring data to emulate optimization algorithms or determine an optimum configuration (e.g., in terms of BER) before pushing the configuration to the in-production physical layer. Digital twins have been used at the research level to perform power equalization in optical networks, to improve network resilience or throughput, see e.g. [FerrariOFC2022, YangECOC2022]. Regarding network re-optimization, finding sequence of actions to minimize downtime has been investigated before e.g. [NguyenJOCN2022] for spectrum defragmentation, but physical layer constraints were left out of the study.

3.2 Technical bottlenecks, Approaches and Methodologies

In this context, the Ph.D. candidate will generally work on topics that will enable autonomously driven optical networks. More specifically, the following topics are considered as both key to autonomously driven networks and falling in the domain of expertise of both the industrial and academic partners, such that the impact of the Thesis will be maximized.

3.2.1 Feasible network optimization

Methods to re-optimize optical networks through per-channel launch power setting (known as "power equalization") have been proposed by many teams, including the industrial lab (Huawei Paris Research Center). In the publications by the team, the digital twin was used to validate the final power equalization state returned by the equalizer, then push this state in the network. Transients between the current (non-optimized) and the desired network states have been ignored, such that it is indeed possible that some services are impacted, possibly leading to outages, during the various reconfiguration steps. However, during network re-optimization, in the context of a running autonomous network, existing services should continue running error-free i.e. with no outage. As mentioned above, establishment or even power variation of one or several channels impact the quality of transmission of the other channels, through (nonlinear) inter-channel noise or power transfers. The industrial team has access to advanced physical layer models already implemented in a digital twin called "AI-Light". One goal of the thesis will be to find a sequence of reconfiguration steps to achieve the desired state as computed by the digital twin, such that existing services are maintained above the FEC limit. Inaccuracies inherent to the digital twin will be accounted for during reconfiguration via additional margins and slow, step-by-step actuation such that unforeseen degradations can be detected and accounted for by the digital twin to avoid outages. If no reconfiguration sequence that guarantees the absence of outages can be found, the primary objective will be to maximize the benefit of re-optimization (e.g., in terms of number of re-optimized services) while guaranteeing the absence of outage for the existing services.

3.2.2 Fast network optimization

Once a path towards re-optimization is found, effort will be taken to maximize the speed of optimization. As a baseline, each action (e.g., power change of one channel, on one link of an optical network) will be considered sequentially. A possible speed up consists of parallel optimizing powers on links carrying disjoint sets of services, such that a change on a given link does not change the performance of any other service on the other link optimized in parallel. More generally, many actions will have a small impact on existing services, and could be parallelized. In addition, not all actions may take the same amount of time. For instance, the reconfiguration time of the filters that set the per-channel power, and the reconfiguration time of the optical amplifiers, are not the same. In addition, the filter reconfiguration time is non-linear with the number of channels to reconfigure, such that it is beneficial in terms of total reconfiguration time to reconfigure many channels simultaneously at a given filter.

3.2.3 Network autonomy

As a last step, the various techniques investigated in the previous steps will be implemented on the AI-Light platform of the industrial partner. This platform, based on commercial equipment only, is very realistic and emulates long haul meshed transmission networks. The algorithms will be stressed e.g. through external changes of the physical layer (unplanned fiber cuts or losses) that disturb the physical layer of the network. The autonomous platform will detect the change in the physical layer, assess the optimality of the (remaining, in case of a link failure) services, and decide autonomously to start a re-optimization process that improves all (remaining) services, while creating no outage. The impact on restoration, e.g., faster restoration of services thanks to the continuous optimization of the optical layer, will also be assessed.

4 Plan, Execution and Outcomes

4.1 Plan

12 months: review of state of the art. Development of a model for the impact of reconfiguration of the physical layer on the existing services. Algorithm to select the optimum sequence of actions to perform to re-optimize optical network physical layer. Validation on testbed in open loop fashion (start from a degraded state and trigger optimization manually).

12 months: based on the previous task, speed-up of the algorithm. Validation on testbed in open loop fashion.

6 months: based on the previous 2 tasks, close the loop and demonstrate fully autonomous network optimization with no (further) outage in case of unplanned physical layer degradation.

6 months: write Ph.D. thesis.

Note: The Ph.D. candidate will be accompanied by some experiments whenever possible and/or needed. This will give a hands-on experience to the Ph.D. applicant in fiber optics. Members of the transmission team in Huawei France will help with the experimental part.

4.2 Collaboration between the two institutions

The Ph.D. applicant will spend 80% of his time in Huawei, OCTL lab and 20% at Eurecom. Joint meetings between the Ph.D. applicant and his academic and industrial advisors will be held mostly in Huawei. The Ph.D. applicant will follow tutorials and workshops in Huawei on different topics in optics. He will participate and attend lectures and workshops on optimization at Eurecom. He will be encouraged to give presentations and talks on his work in seminars and workshops in both institutions.

4.3 Expected Outcomes

The Ph.D. candidate is expected to contribute to the wide research aspects in optical networking as described in the research topic therein. He is expected to publish in top tier journals and conference proceedings. The research might also lead to patents that should be submitted according to Huawei rules and the collaboration agreement between the two institutions.

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