Inria International programme
Associate Team proposal 2019-2021
Submission form

Title: Efficient Dynamic Resource Allocation in Networks

Associate Team acronym: EfDyNet

Principal investigator (Inria): Frédéric GIROIRE — COATI

Principal investigator (Main team): Brigitte JAUMARD — Computer Science and Software Engineering (CSE) Department, Concordia University, Montréal, Québec, Canada

Key Words:

A- Research themes on digital science: A1.2.1. Reconfiguration dynamique; A1.2.3. Routage; A1.6. Efficacité énergétique; A7.1.3. Algorithmique des graphes; A8.2.1. Recherche opérationnelle;

B- Other research themes and application areas: B6.3.3. Gestion des réseaux

1 Partnership

1.1 Detailed list of participants

COATI, Inria Sophia Antipolis & I3S laboratory (CNRS, UNS)

- Frédéric Giroire — CR CNRS — http://www-sop.inria.fr/members/Frederic.Giroire/
- David Coudert — DR Inria — http://www-sop.inria.fr/members/David.Coudert/
- Joanna Mouliérac — MCF UNS — http://www-sop.inria.fr/members/Joanna.Moulierac/
- Andrea Tomassilli — PhD student since Oct. 2016 — http://www-sop.inria.fr/members/Andrea.Tomassilli/
- Adrien Gausseran — PhD student since Oct. 2018

Expertise: Algorithms, Discrete Mathematics, Combinatorial Optimisation, Network design, Routing algorithms.

CSE Department, Concordia University

- Brigitte Jaumard — Professor — https://www.brigittejaumard.com/
- Huy Duong — PhD student since June 2018
- Quang Anh Nguyen — PhD student since Sept. 2018
- Shima Ghanei Zare — PhD student since Sept. 2018
- Adham Mohammed — M.Comp.Sci. 2017-2019

Expertise: Optimization, Networking, Mathematical Programming, in particular Decomposition Techniques.

1.2 Nature and history of the collaboration

There exists a longstanding collaboration between the team of Brigitte Jaumard at Concordia University and COATI with reciprocal visits leading to joint publications (see Section 6.1). The two teams address design and management optimization problems in networks (WDM, wireless, SDN) with complementary tools and expertise. The team of Brigitte Jaumard brings its expertise in Operations Research and in particular in decomposition methods for mathematical programming. COATI brings its expertise in graph theory and combinatorial optimization and in particular in the design of exact and approximate algorithms.

David Coudert and Brigitte Jaumard started collaborating on protection mechanisms in optical networks [14, 15] with the support of FQNRT/INRIA project DynOpt (2006) and an accessit to the Associated-team program (project OPTINET, 2007). Later, they worked on the design of robust wireless backhaul networks [11, 12] and on routing and spectrum assignment in flexible optical networks [13].

Recently, Brigitte Jaumard started to collaborate with CIENA[1] on the defragmentation and migration problems in optical networks. Both problems involve network reconfiguration, a problem on which David Coudert had significant contributions in the past [34, 21, 22, 38, 41]. Also, they have started a new collaboration on this topic [1, 2, 5].

In addition, Frédéric Giroire, Nicolas Huin, and Andrea Tomassilli have started to work in 2016 with Brigitte Jaumard on virtualization in Software Defined Networks (SDNs). In particular, they studied methods to place chains of network functions [9, 10]. This collaboration has been strengthen by the post-doc of Nicolas Huin in Concordia (Nov. 2017 till Aug. 2018), and by the 3 months internship of Andrea Tomassilli in Concordia (Sep.-Dec. 2017).

Summary of reciprocical visits

- David Coudert visited Concordia University in 2005 (1 week), 2006 (2 weeks), 2007 (1.5 month) and 2017 (2 weeks), resulting in several joint publications [1, 2, 5, 11, 12, 13, 14, 15].
- Frédéric Giroire visited Concordia University in 2016 (2 weeks) and 2017 (2 weeks), resulting in several joint publications [3, 4, 6, 7, 8, 9, 10].
- Nicolas Huin, former PhD of Frédéric Giroire, did a Post-doc with Brigitte Jaumard from Nov. 2017 till Aug. 2018. Prior to that, he did a 3 months internship at Concordia in 2016, supported by an Inria-MITACS grant, resulting in 2 joint publications [9, 10].
- Andrea Tomassilli (COATI) visited Concordia Univ. (Oct-Dec 2017, 3 months) to work on the placement of functions in SDN [4, 7, 8, 10].
- Former PhD students of David Coudert made internships at Concordia, resulting in joint publications: Florian Huc (1.5 months in 2006) [14, 15], Alvinice Kodjo (1 month in 2013) [11, 12].
- Brigitte Jaumard visited COATI in 2006 (1 week), 2012 (3 weeks), 2013 (2 weeks), 2014 (1 week), and 2017 (1 week), resulting in joint publications [1, 2, 9, 10, 11, 12, 13, 14, 15]. She was in the PhD committee of Alvinice Kodjo (2014) and Nicolas Huin (2017). She will be in the HDR committee of Frédéric Giroire (Oct. 2018).

[1] CIENA Corporation (http://www.ciena.com) is a United States-based global supplier of telecommunications networking equipment, software and services that support the delivery and transport of voice, video and data service. Its products are used in telecommunications networks operated by telecommunications service providers, cable operators, governments and enterprises. They have offices in Canada. CIENA Canada, Inc., is a network strategy and technology company, which is engaged in developing and applying technologies that facilitate virtualization, automation, and collaboration.

2 Scientific program

2.1 Context

Networks are evolving rapidly in two directions. On the one hand, new network technologies are developed for different layers, and in particular flexible optical technologies (enabling to allocate a fraction of the optical spectrum rather than a fixed wavelength), Software Defined Networks, and Network Function Virtualization. On the other hand, the traffic patterns evolve and become less predictable due to the increase of cloud and mobile traffic. In this context, there are new possibilities and needs for dynamic resource allocations. We will study this problem mainly in two directions: network reconfiguration and the allocation of virtualized resources.

Network Reconfiguration. Network reconfiguration is required in order to adapt to traffic changes, network failures, or new deployment of network resources. It occurs at the optical layer in order to make sure that the upper layer traffic, e.g., IP layer traffic, can be efficiently carried. In such a case, we deal with lightpath reconfigurations and the primary objective is to reduce disruptions to user traffic carried by existing lightpaths, measured by the number of disrupted lightpaths or the duration of lightpath disruptions [28, 20, 39]. Network reconfiguration may also arise at the logical layer, in order to attain a better resource utilization [38, 42]. In heavily loaded networks, dynamic connection addition and drop actions may result in a set of connections where some paths are not the shortest possible ones, leading to poor resource utilization compared to an optimal or at least optimized state. Thus, global connection re-optimization is proposed at certain time intervals (e.g., daily, weekly) to improve the network performance. While several works already exist on network reconfigurations, most of the approaches used in practice (i.e., by network operators) are greedy heuristics, with no information on the quality of their solutions. Our recent joint investigations on reconfiguration both for optical [5] and for the logical layer [1, 2] let us think that it is possible to solve the reconfiguration problem exactly and at scale, in addition to be able to estimate the maximum load that should be allowed in the network in order to be able to do it without any disruption, or a very limited number of them. We will benefit from a collaboration of Brigitte Jaumard with CIENA, which is helping us for assessing the accuracy of our algorithmic solutions.

Virtualized Software Defined Networks. Software-defined networking (SDN) has been attracting a growing attention in the networking research community in recent years. SDN is a new networking paradigm that decouples the control plane from the data plane. It provides a flexibility to develop and test new network protocols and policies in real networks, see e.g. the experiment of Google for its inter-datacenter network [33]. Network Function Virtualization (NFV) is an emerging approach in which network functions are no longer executed by proprietary software appliances but instead, can run on generic-purpose servers located in small cloud nodes [27]. Examples of network functions include firewalls, load balancing, content filtering, and deep packet inspection. This technology aims at dealing with the major problems of today's enterprise middlebox infrastructure, such as cost, capacity rigidity, management complexity, and failures [35]. One of the main advantages of this approach is that Virtual Network Functions (VNFs) can be instantiated and scaled on demand without the need of installing new equipment. These new technologies bear the promise of important cost savings and of new possibilities but introduces new complex problems [23, 26, 27], which need to be addressed: how to do efficiently (dynamic) resource allocations (paths and virtualized resources)?

2.2 Objectives (for the three years)

We will design exact and approximate methods for optimizing the usage of network resources. We will consider resource allocation and network reconfiguration in physical and logical networks as well as in SDN. Our main objectives are:

Network Reconfiguration. Reconfiguration can be performed with two strategies. For both strategies, we assume that we are given the current network provisioning, and we aim at moving to an optimized one, requiring less bandwidth while granting the same set of requests. Along the first strategy, the idea is to compute an optimized provisioning, and then find the most seamless transition from the current provisioning to the optimized one [36, 39, 41]. In the second strategy, the idea is to iteratively improve the current provisioning with one rerouting at a time [1, 2, 40, 42], assuming each rerouting can be made before the break move, i.e., a rerouting with no disruption. While with the first strategy, we usually reach a more efficient provisioning, it is at the expense of a number of disruptions. Based on the expertise of B. Jaumard for solving efficiently the RWA (Routing and Wavelength Assignment) and RSA (Routing and Spectrum Assignment) problems [16, 17, 18] and the expertise of D. Coudert on graph algorithms [25] and routing reconfiguration [34, 20, 21, 38, 41], our objectives are as follows:

- Investigate further the RWA reconfiguration problem. We currently completed a first study with the minimization of the number of disruptions. We plan to extend it as explained in the following in the plan for next year.
- Study the RSA reconfiguration problem, as backbone networks are moving towards it, following the huge increase in bandwidth requirements. This is an even more challenging optimization problem than for RWA.
- Use the gained expertise to study network reconfiguration in SDN, possibly including the live migration of virtual machines or functions.

Virtualized Software Defined Networks. The same virtual function can be replicated and executed on several servers. It follows that a fundamental problem arising when dealing with network functions is *how to map these functions* to nodes (servers) in the network while achieving a specific objective. Moreover, SDN allows to do the allocation dynamically on the fly, when new requests arrive. This means that classic networking problems (e.g. routing, scheduling, failure protection) have to be readdressed in a new context in which virtualized resources may be allocated, migrated, and removed on the fly on top of a physical infrastructure.

To address this problem, we will use the expertise of both groups, in particular the corpus of works done in the context of WDM optical networks. Indeed, optical networks also are layered graphs in which a logical topology has to be mapped onto a physical fiber topology. Similarly, a set of virtualized resources has to be mapped into the physical network. We will explore different directions.

- Complex optimization methods, such as decomposition techniques, and in particular column generation. These techniques are used when classical optimization techniques such as integer linear programs do not scale. The main idea is to decompose the problem into subproblems, which can then be solved independently and efficiently. Brigitte Jaumard is specialist in optimization methods and will bring her expertise to the project.
- Algorithmics and in particular approximation algorithms. If, as stated, the main problems are very complex, some the subproblems may be solved efficiently. In particular, some variant of constrained shortest paths or of covering problems appear. COATI is expert in this area.

- Last, we will use the knowledge gained working on optical and IP network reconfigurations to study how to re-optimize on the fly the usage of virtual resources (e.g. virtual network functions). Indeed, a shared virtual resource may have to be updated and/or moved when the demand has evolved. We will study the problem in the context of *network slicing* which is the topic of the Ph.D. of Adrien Gausseran (supervised by J. Moulierac). A network slice is a virtual network that is embedded on top of a physical network in a way that creates the illusion of the slice tenant of operating its own dedicated physical network. Network slicing is foreseen to be a key component of 5G to provision isolated and personalized network services to different applications (e.g., connected vehicles, smart factories) [24, 29].

2.3 Work-program (for the first year)

During the first year of the project, we will address the following tasks:

Network reconfiguration. (COATI: D. Coudert, A. Gausseran — CSE: H. Duong, B. Jaumard, Quang Anh Nguyen)

- Write a survey on the lightpath reconfiguration problem in WDM networks. To this end, we need to compare existing methods and build a framework for experiments (implement all models, build traffic instances, etc.)
- Investigate tradeoffs in the RWA reconfiguration problem. The number of disruptions in the migration depends on the optimized RWA provisioning. Can we define metrics enabling to build an optimized RWA solution inducing the minimum number of disruptions? Can we avoid disruptions while maintaining the quality of the provisioning ?
- Start studying the RSA reconfiguration problem. Based on the particularities of RSA, we plan to look at how to combine the push-pull mechanism proposed for dynamic RSA [32] with the classical reconfiguration tools in order to minimize the number of disruptions. Additionally, we would like to extend our recent work on the logical layer [1, 2] in order to design a scalable model and algorithm for the RWA reconfiguration problem.

Tolerance for failures and dynamics of virtual resources. (COATI: F. Giroire, A. Gausseran, J. Moulierac, A. Tomassilli — CSE: B. Jaumard, Shima Ghanei Zare, Adham Mohammed)
Network flows are often required to be processed by an ordered sequence of network functions. For instance, an Intrusion Detection System may need to inspect the packet before compression or encryption are performed. Moreover, different customers can have different requirements in terms of the sequence of network functions to be performed [31]. This notion is known as Service Function Chaining (SFC) [30]. This is a very complex objective as it adds a constraint of *order* to a set of already NP-complete problems. In the first year, we will consider this problem of mapping with the additional constraints (i) first of tolerating failures and (ii) second of considering very dynamic traffic.

(i) Indeed, failures are very frequent in network and data centers. In particular, it is reported in [37], that, in the monitored Data Center Network, each link experienced in average 16 failures per year, considering a five years time period [37]. We will investigate with A. Tomassilli different protection techniques (link or path protection, dedicated or shared protection) for different kinds of failures (link failures, node failures, network function failures). In collaboration with B. Jaumard and during the visit in Concordia of F. Giroire, we will build scalable decomposition models to solve the problem, first in a static case in which the requests are given offline. The next step will be to consider the dynamic case.

(ii) We will consider a dynamic setting in which network slices requiring virtual resources have to be set up on the fly for clients. From time to time, the virtual resources have to be updated. We will investigate how the use of reconfiguration algorithms may improve their usage. This will be the goal of the 3 month visit of A. Gausseran and of the 2 week visit of J. Moulierac in Concordia in 2019.

Expected visits

- D. Coudert, J. Mouliérac and F. Giroire will spend 2 weeks each in Concordia
- A. Gausseran will spend 3 months in Concordia.
- B. Jaumard will spend 2 weeks at Inria. During the academic year 2019-2020, she will be on sabbatical and plan to spend 3 months at Inria (exact dates to be fixed).
- H. Duong will spend 2 months at Inria.

3 Budget

3.1 Budget (for the first year)

The first year is a critical time to expand and intensify exchanges among the partners.

Estimated budget for missions.

Inria to Concordia	People	Duration	Estimated cost (including travel)
Researchers	3	3 * 2 weeks	9k euros
Ph.D. student	1	3 months	6k euros
Estimated total cost			15k euros

Concordia to Inria	People	Duration	Estimated cost (including travel)
Researcher	1	2 weeks	3k euros
Ph.D. student	1	2 month	4k euros
Estimated total cost			7k euros

Other sources of funding.

- Brigitte Jaumard has secured several contracts with CIENA on topics related to the ones of the associate team. Four Ph.D. students and one master student will thus be working in the next years 2 or 3 years on the optimization of next-generation networks. This will foster the collaboration between Concordia and COATI.
  - MITACS – Elevate Program (PhD Fellowship) with CIENA. Functionally Virtualized Networks. Nov. 2018-Nov. 2021 (3 years). $90,000
  - MITACS – Elevate Program (PhD Fellowship) with CIENA. Advanced, Intelligent, Analytics Driven Apps for Software Defined. Nov. 2018-Nov. 2021 (3 years). $90,000
  - MITACS – Elevate Program (PhD Fellowship) with CIENA. Cross-layer topology creation. Jan. 2019-Dec. 2021 (3 years). $90,000
  - MITACS – Elevate Program (PhD Fellowship) with CIENA. Spectrum assignment. Jan. 2019-Dec. 2021 (3 years). $90,000
  - MITACS – Converge research project (Master Fellowship) with CIENA, 2019 - 2020. Fiber network design. $25,000.
- Orange Ph.D. grant (CIFRE) of Giuseppe di Lena on resilient SDN/NFV architectures, co-supervised Ph.D. with Chidung Lac (Orange Lannion), Thierry Turletti (Diana, Inria), and Frédéric Giroire (COATI). Starting date: March 1st, 2018.
- Additionally, we plan to apply for Inria-MITACS grants to support one internship of a student from Concordia to Inria and one internship of a student from Inria to Concordia in 2018.

3.2 Strategy to get additional funding

We had applied in 2016 for an ANR PRCI between France and the NSERC in Canada on the topic of energy efficient virtualized software defined networks. The proposal involved the industrial partners Orange in France and CIENA in Canada. We have not been successful, but we are considering a future application to this program on the topic of the associate team. We are particularly monitoring the 2019 France-Quebec ANR PRCI call whose topics are under discussion.

We are planning to apply to the next year editions of France-Quebec calls. In particular, the program PSR-SIIRI[2] from Quebec. This program aims at supporting the implementation of international research and innovation projects between higher education, research and industry players and to increase high-level partnerships in research and innovation by supporting strategic international initiatives. Other programs include the calls "Coopération franco-québécoise - Appel à projets général 2019-2020"[3] and the new program Samuel-De Champlain of the Conseil franco-québécois de coopération universitaire (CFQCU)[4].

We will answer MITACS calls. MITACS is a non-profit, national research organization that manages and funds research and training programs for undergraduate, graduate students and postdoctoral fellows in partnership with universities, industry and government in Canada. MITACS also supports two-way research collaboration between Canada and international partners. In particular, Inria-MITACS calls fund student internships. Nicolas Huin, former Ph.D. student of COATI, spent 3 months in Concordia with such a funding in 2016.

Additionally, Brigitte Jaumard will be in sabbatical for the academic year 2018-2019 and plans to spend 3 months at Inria in Sophia Antipolis. We will ask for a funding from UCA to support her stay in Sophia Antipolis.

4 Added value

The support of the associated team program will help us to address two important and timely industrial problems: network reconfiguration as shown by ongoing collaboration of Concordia with CIENA, and network virtualization which is the main topic of the I/O Lab between Orange and Inria.

Both team have complementary expertise. The CSE department of Concordia is specialist in optimization methods. In particular, CSE investigates scalable decomposition models to solve large practical problems. The COATI team is expert in algorithmics, and in particular approximation algorithms, which are used to solve the subproblems defined in the decomposition models.

The recent joint work on network virtualization has demonstrated the potential of the decomposition methods of CSE to resolve the resource allocation problems in SDN studied in COATI. Moreover, COATI has a particular expertise in reconfiguration algorithms. Concordia will directly benefit from this expertise. On the other side, the associated team would be an occasion for COATI to confront the efficient theoretical algorithms proposed to a real-world scenario given by CIENA, which may lead to investigate other variants of the problem.

[2] https://www.economie.gouv.qc.ca/index.php?id=21504
[3] https://quebec.consulfrance.org/Cooperation-franco-quebecoise-Appel-a-projets-general-2019-2020
[4] https://quebec.consulfrance.org/Lancement-du-programme-Samuel-De-Champlain

5 Other remarks

5.1 Industrial Links, impact and results

Concordia has an ongoing contractual collaboration with CIENA, on the network reconfiguration problem in WDM networks. Ongoing joint work between Concordia and Inria is for now independent from this contractual collaboration (e.g., Inria has no information on algorithms or data used by CIENA), but joint publications [1, 2] have already been approved and co-signed by CIENA (Ron Armolavicius). We expect that the advances that will be made thanks to the associated-team will lead to a new contractual collaboration with CIENA involving Inria. Intellectual Property rights (IPR) will be settled in this case. We will also consider possible industrial collaborations on this topic with companies such as Huawei, Orange, or Nokia.

On the topic of virtualized SDN networks, COATI has an ongoing collaboration with Orange Lannion and Inria project-team DIANA in the framework of the I/O Lab, which is a common virtual laboratory between Orange and Inria. The global goal of the laboratory is to strengthen the cooperation in the areas of virtualization of network functions and the convergence between communication networks and cloud computing. A co-supervised Ph.D. (CIFRE grant), Giuseppe di Lena, has started in March 2018 to work on resilient SDN/NFV architectures. The results of the associated team will reinforce this collaboration. We will comply with the IPR agreements of the I/O Lab.

Additionally, Andrea Tomassilli will carry out a 3 month internship in the Network, Protocols and System Research team of Nokia Bell Labs Saclay. The main areas of focus of the team are currently including Network Function Virtualization and Software Defined Networks.

Moreover, Nicolas Huin (former PhD student of COATI and PostDoc of CSE) has now a position at Huawei Research Lab in Paris (since Aug. 2018).

This shall foster collaboration in the field with Nokia and Huawei.

5.2 Others

In the last years, we made extensive use of visio-conference to collaborate (2 hours per week in average). Nonetheless, our experience shows that reciprocal visits are way more productive and efficient for sharing ideas and starting new research work.

5.3 Previous Associate Teams

AlDyNet —Algorithm for large and Dynamic Networks— 2013-2018.

French PI: Nicolas Nisse

Foreign PI: Karol Suchan, Adolfo Ibáñez University (Santiago, Chile)

6 References

6.1 Joint publications of the partners

[1] H. Duong, B. Jaumard, D. Coudert, and R. Armolavicius. "Efficient Make Before Break Defragmentation". In: *IEEE International Conference on High Performance Switching and Routing (HPSR)*. Bucharest, Romania, June 2018 (cit. on pp. 3–5, 7, 10).

[2] H. Duong, B. Jaumard, D. Coudert, and R. Armolavicius. "Modèle d'optimisation pour la défragmentation de la capacité". In: *ALGOTEL 2018 - 20èmes Rencontres Francophones sur les Aspects Algorithmiques des Télécommunications*. Roscoff, France, May 2018. URL: https://hal.inria.fr/hal-01773572 (cit. on pp. 3–5, 7, 10).

[3] N. Huin, B. Jaumard, and F. Giroire. "Optimization of Network Service Chain Provisioning". In: *IEEE/ACM Transactions on Networking (ToN)* 26.3 (2018), pp. 1320–1333. ISSN: 1063-6692. DOI: 10.1109/TNET.2018.2833815 (cit. on p. 3).

[4] N. Huin, A. Tomassilli, F. Giroire, and B. Jaumard. "Energy-Efficient Service Function Chain Provisioning". In: *IEEE/OSA Journal of Optical Communications and Networking* 10.3 (2018), pp. 114–124. ISSN: 1943-0620. DOI: 10.1364/JOCN.10.000114 (cit. on p. 3).

[5] B. Jaumard, H. Pouya, and D. Coudert. "Wavelength Defragmentation for Make-Before-Break Migration". In: *International Conference on Transparent Optical Networks*. Bucharest, Romania, July 2018, pp. 1–4 (cit. on pp. 3, 4).

[6] A. Tomassilli, F. Giroire, N. Huin, and S. Pérennes. "Provably Efficient Algorithms for Placement of Service Function Chains with Ordering Constraints". In: *IEEE International Conference on Computer Communications (INFOCOM)*. Honolulu, Hawai, US, 2018 (cit. on p. 3).

[7] A. Tomassilli, N. Huin, B. Jaumard, and F. Giroire. "Path Protection in Optical Flexible Networks with Distance-adaptive Modulation Formats". In: *International Conference on Optical Network Design and Modeling (ONDM)*. Dublin, Ireland, 2018, pp. 30–35. DOI: 10.23919/ONDM.2018.8396102 (cit. on p. 3).

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[10] N. Huin, A. Tomassilli, F. Giroire, and B. Jaumard. "Energy-Efficient Service Function Chain Provisioning". In: *International Network Optimization Conference 2017*. Lisbonne, Portugal, Feb. 2017. URL: https://hal.inria.fr/hal-01513747 (cit. on p. 3).

[11] B. Jaumard, M. Kaddour, A. Kodjo, N. Nepomuceno, and D. Coudert. "Cost-effective Bandwidth Provisioning in Microwave Wireless Networks under Unreliable Channel Conditions". In: *Pesquisa Operacional* 37.3 (Sept. 2017), pp. 525 –544. URL: https://hal.inria.fr/hal-01738156 (cit. on p. 3).

[12] A. Kodjo, B. Jaumard, N. Nepomuceno, M. Kaddour, and D. Coudert. "Dimensioning microwave wireless networks". In: *ICC 2015 : IEEE International Conference on Communications*. London, United Kingdom: IEEE, June 2015, pp. 2803 –2809. URL: https://hal.inria.fr/hal-01198461 (cit. on p. 3).

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[14] B. Jaumard, N. Nahar Bhuiyan, S. Sebbah, F. Huc, and D. Coudert. “A New Framework for Efficient Shared Segment Protection Scheme for WDM Networks”. In: *11th International Conference on High Performance Switching and Routing (HPSR)*. Richardson, Texas, USA, Canada: IEEE, June 2010, p. 8. URL: https://hal.inria.fr/inria-00482119 (cit. on p. 3).

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6.2 Main publications of the participants relevant to the project

[16] J. Enoch and B. Jaumard. “Enhanced RWA Exact Solution with a New Lightpath Decomposition Algorithm”. In: *International Conference on Computing, Networking and Communications (ICNC)*. Maui, Hawaii, USA, Mar. 2018 (cit. on p. 5).

[3] N. Huin, B. Jaumard, and F. Giroire. “Optimization of Network Service Chain Provisioning”. In: *IEEE/ACM Transactions on Networking (ToN)* 26.3 (2018), pp. 1320–1333. ISSN: 1063-6692. DOI: 10.1109/TNET.2018.2833815 (cit. on p. 3).

[4] N. Huin, A. Tomassilli, F. Giroire, and B. Jaumard. “Energy-Efficient Service Function Chain Provisioning”. In: *IEEE/OSA Journal of Optical Communications and Networking* 10.3 (2018), pp. 114–124. ISSN: 1943-0620. DOI: 10.1364/JOCN.10.000114 (cit. on p. 3).

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[18] B. Jaumard and M. Daryalal. “Efficient Spectrum Utilization in Large Scale RWA Problems”. In: *IEEE/ACM Transactions on Networking* 25.2 (Apr. 2017), pp. 1263–1278. DOI: 10.1109/TNET.2016.2628838 (cit. on p. 5).

[19] M. Rifai, N. Huin, C. Caillouet, F. Giroire, D. Lopez, J. Moulierac, and G. Urvoy-Keller. “Minnie: An SDN world with few compressed forwarding rules”. In: *Computer Networks* 121 (2017), pp. 185 –207. ISSN: 1389-1286. DOI: 10.1016/j.comnet.2017.04.026.

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