Universität Stuttgart

INSTITUT FÜR
KOMMUNIKATIONSNETZE
UND RECHNERSYSTEME
Prof. Dr.-Ing. Andreas Kirstädter

Institute of Communication Networks and Computer Engineering
University of Stuttgart
Pfaffenwaldring 47, D-70569 Stuttgart, Germany
Phone: ++49-711-685-68026, Fax: ++49-711-685-67983
Email: mail@ikr.uni-stuttgart.de, http://www.ikr.uni-stuttgart.de

Using Intent Directed Acyclic Graphs in Multi-Domain IP-Optical Networks

Filippos Christou
Institute of Communication Networks and Computer Engineering (IKR)
University of Stuttgart
Stuttgart, Germany
filippos.christou@ikr.uni-stuttgart.de

Andreas Kirstädter
Institute of Communication Networks and Computer Engineering (IKR)
University of Stuttgart
Stuttgart, Germany
andreas.kirstaedter@ikr.uni-stuttgart.de

***Abstract*—The global internet relies on a well-coordinated operation of distinct networking domains. This renders multi-domain networking at the heart of today's massive digital information exchange. Although Software-Defined Networking (SDN) undoubtedly helps advance network operation within a single organization, non-centralized multi-domain networking has received less attention. To significantly advance the state of networking, we are inherently bound to provide progress and evolve the current multi-domain networking scheme. This work exploits the Intent-Based Networking (IBN) paradigm and the Directed Acyclic Graphs (DAGs) data structure to design a novel architecture for multi-domain IP-Optical networking. We highlight the benefits of our approach leading to seamless operation of non-centralized networks, such as optically transparent domain boundaries and cross-domain grooming. We evaluate this approach in a realistic scenario using our novel open-source tool MINDFul.jl, which we shortly introduce and can be broadly used for related research.**

***Index Terms*—architecture, intent-driven, multi-domain, optical bypass**

I. Introduction

Networking enables information exchange all over the world. Thus, it is fundamental that communication should be independent of the underlying technology or organization, as these can vary. The backbone of today's network is implemented using optical fibers and involves several technical disciplines and distinct organizations. There has been a growing focus on optical disaggregated networking [1], which strives to achieve seamless technological interoperability between separate networking domains. On top of that, during the last years, we have witnessed strong centralization, which led to the paradigm of Software-Defined Networking (SDN). SDN decouples the control and data planes by concentrating the knowledge and decision-making in a single logical unit. As a result, individual networks increasingly enjoy the benefits of centralized control. However, centralization is often not possible for multi-domain (MD) operation.

After many decades of progress in networking, coordinating MD networks in a non-centralized fashion efficiently is still a challenge. It has become clear that traditional protocols, like Border Gateway Protocol (BGP), are not entirely appropriate for IP-optical network operations [2]. Although there have been proposals for more optical-friendly protocols [3], the community is still searching for new approaches. Current efforts have proposed an intent-driven solution [4] to the coordination problem. Intent-Based Networking (IBN) introduces an abstraction layer where the operator's intentions (i.e., intents) are defined at a high level and whose implementation is automatically handled from the intent system. This approach allows us to reconsider the problem differently and push toward a solution that will benefit optical interoperability.

In this paper, we present a flexible intent architecture enabling seamless non-centralized cooperation between IP-optical domains. We take advantage of the intent constraints scheme to transfer responsibilities between domains. We describe how we can deploy intent Directed Acyclic Graphs (DAGs) in a MD environment, such that end-to-end IP-optical grooming is supported by enabling optical bypass in domain boundaries instead of doing Optical-Electrical-Optical (O-E-O) conversion. Finally, we shortly present *MINDFul.jl* [5], an open-source tool providing a Framework for Intent-driven MD Network coordination. We use this tool to evaluate our approach with proof-of-concept simulations.

This paper is organized as follows. The forthcoming subsection provides the background and relevant studies on the matter. Section III describes the main contribution as an architecture. Section IV uses the aforementioned architecture to develop algorithms appropriate for MD use. Section V presents a proof-of-concept deployment of the architecture and algorithms in a simulated environment and the evaluation of those with respect to previous work. We conclude the paper in Section VI.

II. Background

In this section, we lay the basis by describing related past work. In the past, an architecture for MD IBN [6] was introduced using a multi-step compilation procedure and *intent trees*, where an intent is recursively compiled down to lower-level child intents. The intent tree data structure can expand across domains with *intent delegation*, where an intent replica is issued to the neighboring domain. This architecture allows

This work has been performed in the framework of the CELTIC-NEXT EUREKA project AI-NET-ANTILLAS (Project ID C2019/3-3), and it is partly funded by the German BMBF (Project ID 16KIS1312).

flexible and scalable domain interactions since the delegated intents can vary and be implemented differently per domain. Moreover, this approach promotes accountability, as a failed intent can always be traced back to the responsible domain. Confidentiality is also respected since the delegated intent's implementation is not shared. In [7], the architecture was refined by substituting the intent trees with intent DAGs for single-domain networks. Intent DAGs enable the migration of any grooming-enabled Routing, Modulation, and Spectrum Assignment (RMSA) algorithm [8] into the intent-based regime. This support is given because low-level intents (i.e., resources) can be shared between higher-level intents.

This work adapts the intent DAGs into MD networks. We do so by defining some intent constraints. An intent constraint is a condition that needs to be respected on top of the general intent nature so that the intent is satisfied. Based on that, we extend an advanced RMSA heuristic [9] to operate in a MD environment. This work holds the same assumptions as the predecessors, namely that all the involved domains respect an IBN Northbound Interface (NBI). Although efforts toward a common NBI exist [10], there is no such standard at the moment. With this work, we highlight the benefits of having a common NBI and contribute our perspective to vital features that should be supported.

III. Architecture

This section describes the considerations needed to adapt intent DAGs for MD scenarios. Namely, we introduce two intent constraints.

- An *OpticalTerminateConstraint (OTC)*
- An *OpticalInitiateConstraint (OIC)*.

An OTC signifies that the connectivity intent does not terminate in the electrical layer in a router but rather on the optical layer in an Optical Cross-Connect (OXC). An OIC, on the contrary, signifies that the connectivity intent starts on the optical layer in an OXC. OTCs and OICs are complementary and used sequentially. When an intent terminates in the optical layer, another intent will pick the signal up by starting in the optical layer. A lightpath intent can have four combinations, as shown in Table I.

TABLE I
Lightpath intents with different constraints

Lightpath intent type	starts	ends
Full	electrical	electrical
Starting (OTC)	electrical	optical
Ending (OIC)	optical	electrical
Segment (OTC, OIC)	optical	optical

An *ending* or a *lightpath segment* needs further details to determine the properties of an already deployed *starting* or *lightpath segment*. These lightpath requirements should contain the necessary information to transfer a lightpath to a new entity, such as the spectrum slots, the data rate, the optical reach. For example, Fig. 1 shows how these intent constraints could be used together with intent DAGs to allow optical bypass in domain border nodes. The connectivity intents recursively break into lower-level intents, forming DAGs [7] with different types of intents involved. Depending on the intent compilation strategy, different (blue) low-level intents will be generated as leaf nodes responsible for the network's hardware resource allocation. The purple text inside the intent box signifies the constraint. The OIC constraint is used during intent delegation to secure spectrum continuity in combination with the OTC constraint, which is handled in the domain internally. As a result, the end-to-end connection is composed of a starting and an ending lightpath. Across the optical circuit, the spectrum slots 5:9 are used in the fiber links, as noted from the *NodeSpectrumIntents*. The purple rings in the graph denote activity in the electrical layer, which is missing for the border nodes *E* and *F*, entailing the absence of O-E-O conversion.

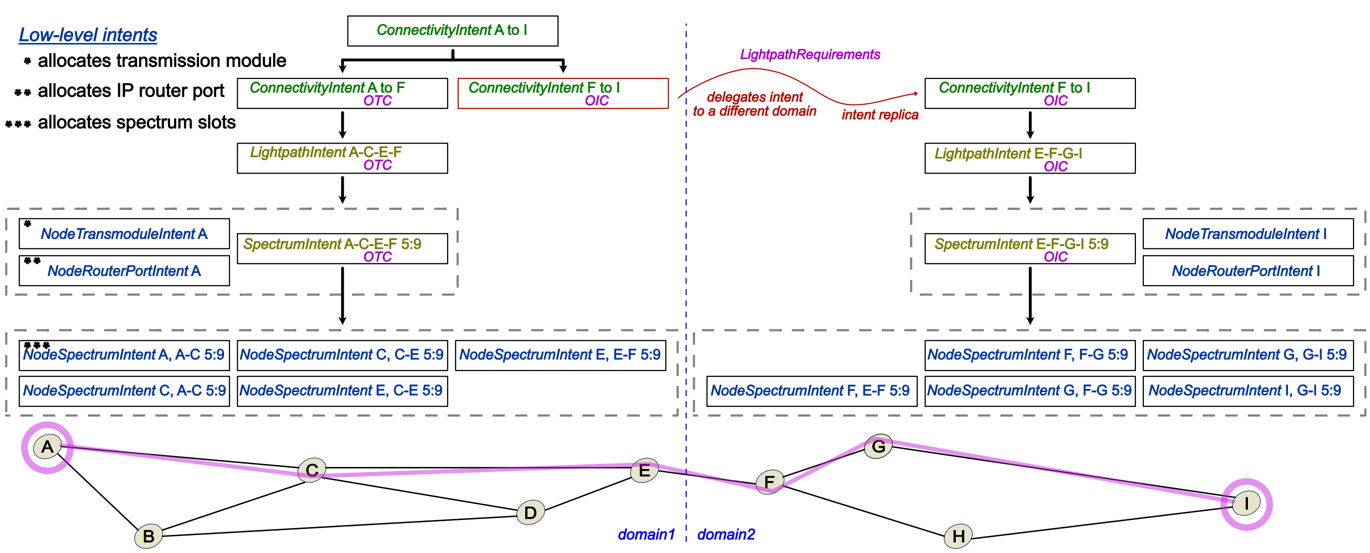

Fig. 1. Example of intent delegation for cross-domain lightpath deployment using intent constraints.

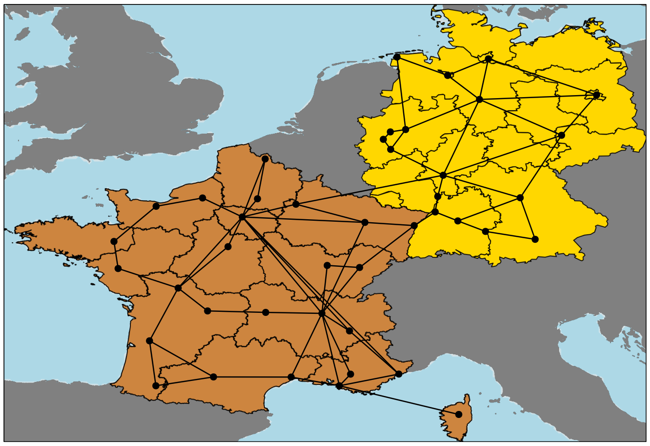

Fig. 2. Simulation topology

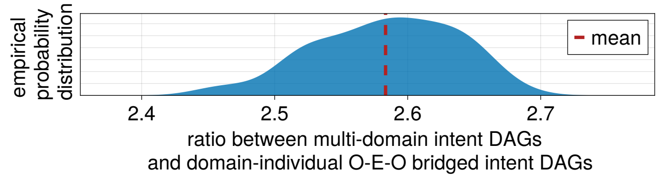

Fig. 3. Empirical probability distribution of the traffic ratio over 50 seeds

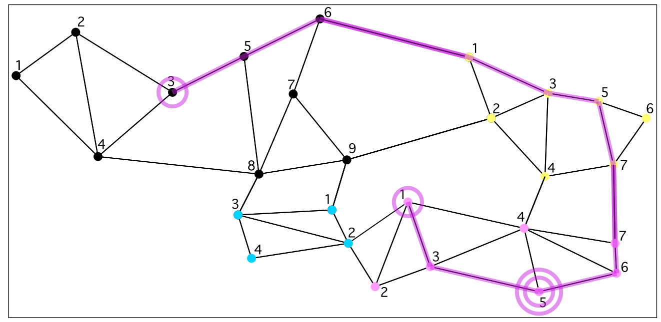

Fig. 4. A simulated end-to-end connection crossing three networking domains. Simulation visualization generated by MINDFulMakie.jl

IV. Algorithms

Intent compilation algorithms are used to expand a user intent into an intent DAG implementation. Any RMSA algorithm found in the literature could be adapted to a MD intent compilation version using the described design. In the frame of this work, we adapt a grooming-enabled RMSA heuristic algorithm from [7], [9]. The original algorithm operates by building a multilayer multigraph out of the IP-optical network and expanding it with additional lightpath links. With every new connectivity request, a variation of the Dijkstra shortest path algorithm is invoked that calculates a set of candidate paths with the same source and destination. These candidate paths later compete, and one is selected that minimizes an objective function at best.

Some of the most important further additions that need to be integrated into the MD intent compilation version are:

- new links are added to the multilayer multigraph not only for full lightpaths but also for starting, ending, and lightpath segments.
- not only candidate path comparison with the same source and destination nodes is needed, but also with different ones. As there might be many possible border nodes to transit to the next domain, the algorithm must decide which one to prefer. Currently, the selection procedure is a simple extension of having the same source and destination nodes, but more advanced techniques could be integrated [11].

An implementation of the adapted algorithm is available in the MINDFul.jl [5] umbrella.

V. Evaluation

This section uses MINDFul.jl to conduct simulations to validate our approach. MINDFul.jl is an effort to provide the scientific networking community with a flexible, easy-to-use tool aimed at state-of-the-art research in the algorithms, control, and architecture of MD intent-driven IP-Optical networks. It provides a stateful representation of common metro/core network equipment and facilitates event-based simulations with a hackable interface and visualization support.

We will showcase a simple scenario involving the operation between two core networks of France [12] and Germany [13], as shown in Fig. 2. The individual core networks have only access to the whereabouts of the border nodes of the other domain and nothing more. Everything else is handled successfully by the intent DAG delegation scheme. The networks are multilayer in the sense that each node is composed of an IP router and an OXC. The available transmission modules are derived from [14]. We generated traffic between all cross-domain network nodes following a positively truncated normal distribution with a mean of $100\,\mathrm{Gbps}$. Each demand yields an inter-domain connectivity intent serially fed into the intent system. Since the adapted [9] remains a greedy algorithm, a different order of connectivity intents will lead to different configurations. Hence, we conducted 50 differently seeded simulations to mitigate the randomness.

We compared a scenario where intent DAGs are used individually per domain, i.e., without inter-domain lightpaths, against our implementation where intent DAGs expand across domains with intent delegation and the appropriate constraints to allow optical bypass in the border nodes and also grooming of the cross-domain lightpaths. Fig. 3 shows the routed (i.e., non-blocked) traffic ratio for the two scenarios as an empirical probability distribution over all seeded simulations using Kernel Density Estimation (KDE). We see that multi-domain intent DAGs withstand, on average, almost 2.6 times more traffic. As the algorithm from [9] is not optimal, more efficient inter-domain lightpath deployment can be achieved by adapting other existing algorithms like [15], [16] to the

MD intent DAG delegation concept.

Finally, our approach can scale with more networks, as shown in Fig. 4, with a four-domain network. The node colors denote the different domains. The purple line is the path, and the rings show IP port allocation (double ring for signal regeneration). Here, a cross-domain lightpath is provisioned using a starting, an ending, and a lightpath segment. A starting lightpath is used between node 3 of the black domain and node 1 of the yellow domain. A lightpath segment is used between node 1 of the yellow domain and node 7 of the pink domain. An ending lightpath is used between node 7 and node 5 of the pink domain. The optical signal is regenerated at node 5, and a full lightpath is deployed until node 1 of the same domain. Having as building blocks the lightpath types of Table I and the intent constraints OTC and OIC, the same approach can be applied to arbitrary MD network topologies.

VI. Conclusion

This work builds upon and extends previous efforts to develop an efficient intent-based MD architecture. Using hierarchical multi-step intent compilation and intent delegation fosters MD flexibility, promotes accountability, and respects confidentiality. We presented how intent DAGs can further increase interoperability and enable cross-domain grooming with optical bypassing in border nodes. We shortly introduced MINDFul.jl, an open-source tool for intent-driven MD research, which we expect to be further useful for the community. Using MINDFul.jl, we conducted a proof-of-concept evaluation with simulations to demonstrate the validity of our approach. As IBN becomes more pertinent, we can leverage the high-level abstractions to achieve drastically more efficient and interactive MD operation.

References

[1] A. Sgambelluri, A. Giorgetti, D. Scano, F. Cugini, and F. Paolucci, "Openconfig and openroadm automation of operational modes in disaggregated optical networks," *IEEE Access*, vol. 8, pp. 190 094–190 107, 2020.

[2] E. Marín-Tordera, X. Masip-Bruin, M. Yannuzzi, and R. Serral-Gracià, "Multi-domain optical routing: Is there life beyond extending bgp?" *Optical Switching and Networking*, vol. 11, pp. 119–135, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1573427713000465

[3] M. Yannuzzi, X. Masip-Bruin, G. Fabrego, S. Sanchez-Lopez, A. Sprintson, and A. Orda, "Toward a new route control model for multidomain optical networks," *IEEE Communications Magazine*, vol. 46, no. 6, pp. 104–111, 2008.

[4] L. M. Contreras and P. Lucente, "Interconnection Intents," Internet Engineering Task Force, Internet-Draft draft-contreras-nmrg-interconnection-intents-03, Oct. 2022, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/draft-contreras-nmrg-interconnection-intents/03/

[5] F. Christou, "Mindful.jl: A framework for intent-driven multi-domain network coordination," Tech. Rep., 2023, gitHub repository https://github.com/UniStuttgart-IKR/MINDFul.jl. [Online]. Available: https://unistuttgart-ikr.github.io/MINDFul.jl/dev/techpaper/

[6] F. Christou, "Decentralized intent-driven coordination of multi-domain ip-optical networks," in *2022 18th International Conference on Network and Service Management (CNSM)*, 2022, pp. 359–363.

[7] F. Christou and A. Kirstädter, "Grooming connectivity intents in ip-optical networks using directed acyclic graphs," in *Photonic Networks; 24th ITG-Symposium*, 2023, pp. 1–4.

[8] F. Shirin Abkenar and A. Ghaffarpour Rahbar, "Study and analysis of routing and spectrum allocation (rsa) and routing, modulation and spectrum allocation (rmsa) algorithms in elastic optical networks (eons)," *Optical Switching and Networking*, vol. 23, pp. 5–39, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1573427716300741

[9] V. Gkamas, K. Christodoulopoulos, and E. Varvarigos, "A joint multi-layer planning algorithm for ip over flexible optical networks," *Journal of Lightwave Technology*, vol. 33, no. 14, pp. 2965–2977, 2015.

[10] S. Alalmaei, Y. Elkhatib, M. Bezahaf, M. Broadbent, and N. Race, "Sdn heading north: Towards a declarative intent-based northbound interface," in *2020 16th International Conference on Network and Service Management (CNSM)*, 2020, pp. 1–5.

[11] E. M. G. de Queiroz and A. C. César, "A heuristic approach for border node selection and traffic routing in multi-domain optical networks," *Optical Switching and Networking*, vol. 15, pp. 87–96, 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1573427714000721

[12] S. Knight, H. X. Nguyen, N. Falkner, R. Bowden, and M. Roughan, "The internet topology zoo," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 9, pp. 1765–1775, 2011.

[13] S. Orlowski, R. Wessäly, M. Pioro, and A. Tomaszewski, "Sndlib 1.0–survivable network design library," *Networks*, vol. 55, pp. 276 – 286, 01 2009.

[14] F. Christou, T. Enderle, and A. Witt, "Towards a hybrid architecture by introducing coherent pluggable transceivers in ip-optical core networks with optical cross-connects," in *Photonic Networks; 23th ITG-Symposium*, 2022, pp. 1–8.

[15] Q. Liu, M. A. Kök, N. Ghani, and A. Gumaste, "Hierarchical interdomain routing and light-path provisioning in optical networks," *J. Opt. Netw.*, vol. 5, no. 10, pp. 764–774, Oct 2006. [Online]. Available: https://opg.optica.org/jon/abstract.cfm?URI=jon-5-10-764

[16] A. S. Pontes, N. L. da Fonseca, and A. C. Drummond, "Schemes for inter-domain lightpath establishment based on pce architecture," *Optical Switching and Networking*, vol. 19, pp. 10–21, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1573427715000740