Central Control over Distributed Asynchronous Systems: A Tutorial on Software-Defined Networks and Consistent Network Updates

Klaus-Tycho Foerster
klaus-tycho.foerster@univie.ac.at
Faculty of Computer Science, University of Vienna
Vienna, Austria

ABSTRACT

This tutorial will give an introduction to a topic that lies at the intersection of distributed computing and networking, and combines asynchronous distributed systems with central control, namely consistent updates in Software-Defined Networks (SDNs). We will give an overview on current models and algorithms, but also selected related topics, in particular those of potential interest to the PODC community, showcasing avenues for further research.

In more detail, SDNs have been an intensively studied topic in networking over the last years, but much of its focus has been on (logical) central control, abstracting away most of its underlying foundation, namely that a network is still a distributed asynchronous system at its core. Summarized in a simplified way, SDNs come with the promise that the network state can be optimized and updated from a global point of view. However, such a simplification becomes especially problematic when consistency guarantees have to maintained. In asynchronous distributed systems, it is not possible to simultaneously change the state of all nodes, such a naive approach will lead to an inconsistent mix of old and new states, introducing e.g. forwarding loops. Notwithstanding, most approaches tackle these issues from the viewpoints of the networking/systems communities, and we believe could henceforth greatly benefit from connections to and ideas from the PODC community.

CCS CONCEPTS

• **Networks → Network management**; • **Theory of computation → Design and analysis of algorithms**; • **Computing methodologies → Distributed computing methodologies**.

KEYWORDS

Software-Defined Networks, Asynchrony, Consistency, Congestion, Loops, Blackholes, Middleboxes, Migration, Updates

ACM Reference Format:
Klaus-Tycho Foerster. 2019. Central Control over Distributed Asynchronous Systems: A Tutorial on Software-Defined Networks and Consistent Network Updates. In *2019 ACM Symposium on Principles of Distributed Computing (PODC '19), July 29-August 2, 2019, Toronto, ON, Canada.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3293611.3338024

PODC '19, July 29-August 2, 2019, Toronto, ON, Canada

ACM ISBN 978-1-4503-6217-7/19/07.
https://doi.org/10.1145/3293611.3338024

MATERIAL AND LITERATURE

The tutorial will be based on self-contained slides, please contact the author to obtain a copy or see http://www.foerster.me. While not all aspects of the tutorial are covered in the literature, a recent survey with an algorithmic focus can be found in [11]. Regarding consistency, we will follow the taxonomy introduced by Mahajan and Wattenhofer [8, 17], covering, e.g., 2-phase commits [20], loop freedom [2, 6, 13, 16], and congestion freedom [1, 3, 4, 14]. We will briefly note that even with perfectly timed synchrony [18], consistent updates are not trivial [5, 12, 22, 23]. Moreover, we will also showcase connections to topics such as proof labeling schemes [7, 15, 19, 21] and distributed control planes [9, 10, 21].

BIO

As of 2018, Klaus-Tycho Foerster is a postdoctoral researcher at the University of Vienna, Austria, working with Stefan Schmid. In 2017 he was a postdoc at Aalborg University, Denmark. He was a visiting researcher at Microsoft Research, Redmond, USA, working with Ratul Mahajan for Fall 2016. He received his PhD degree from ETH Zurich in September 2016, supervised by Roger Wattenhofer in the Distributed Computing Group, supported by Microsoft Research. He received best paper awards at IFIP Networking 2019 and at ICDCN 2016. His research interests revolve around algorithms and complexity for networked and distributed systems.

ACKNOWLEDGMENTS

The author would like to thank the PODC Workshop and Tutorial Chair Avery Miller for his support.

REFERENCES

[1] Saeed Akhoondian Amiri, Szymon Dudycz, Stefan Schmid, and Sebastian Wiederrecht. 2018. Congestion-Free Rerouting of Flows on DAGs. In *ICALP (LIPIcs)*, Vol. 107. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 143:1–143:13. https://doi.org/10.4230/LIPIcs.ICALP.2018.143

[2] Saeed Akhoondian Amiri, Arne Ludwig, Jan Marcinkowski, and Stefan Schmid. 2016. Transiently Consistent SDN Updates: Being Greedy is Hard. In *SIROCCO (Lecture Notes in Computer Science)*, Vol. 9988. 391–406. https://doi.org/10.1007/978-3-319-48314-6_25

[3] Sebastian Brandt, Klaus-Tycho Foerster, and Roger Wattenhofer. 2016. On consistent migration of flows in SDNs. In *INFOCOM*. IEEE, 1–9. https://doi.org/10.1109/INFOCOM.2016.7524332

[4] Klaus-Tycho Foerster. 2017. On the consistent migration of unsplittable flows: Upper and lower complexity bounds. In *NCA*. IEEE, 153–156. https://doi.org/10.1109/NCA.2017.8171348

[5] Klaus-Tycho Foerster. 2018. On the Consistent Migration of Splittable Flows: Latency-Awareness and Complexities. In *NCA*. IEEE, 1–4. https://doi.org/10.1109/NCA.2018.8548339

[6] Klaus-Tycho Foerster, Arne Ludwig, Jan Marcinkowski, and Stefan Schmid. 2018. Loop-Free Route Updates for Software-Defined Networks. *IEEE/ACM Trans. Netw.* 26, 1 (2018), 328–341. https://doi.org/10.1109/TNET.2017.2778426

[7] Klaus-Tycho Foerster, Thomas Luedi, Jochen Seidel, and Roger Wattenhofer. 2018. Local checkability, no strings attached: (A)cyclicity, reachability, loop free updates in SDNs. *Theor. Comput. Sci.* 709 (2018), 48–63. https://doi.org/10.1016/j.tcs.2016.11.018

[8] Klaus-Tycho Foerster, Ratul Mahajan, and Roger Wattenhofer. 2016. Consistent updates in software defined networks: On dependencies, loop freedom, and blackholes. In *Networking*. IEEE Computer Society, 1–9. https://doi.org/10.1109/IFIPNetworking.2016.7497232

[9] Klaus-Tycho Foerster, Juho Hirvonen, Stefan Schmid, and Jukka Suomela. 2019. On the Power of Preprocessing in Decentralized Network Optimization. In *INFOCOM*. IEEE.

[10] Klaus-Tycho Foerster, Janne H. Korhonen, Joel Rybicki, and Stefan Schmid. 2019. Brief Announcement: Does Preprocessing Help under Congestion?. In *PODC*.

[11] Klaus-Tycho Foerster, Stefan Schmid, and Stefano Vissicchio. 2019. Survey of Consistent Software-Defined Network Updates. *IEEE Communications Surveys Tutorials* (2019). https://doi.org/10.1109/COMST.2018.2876749

[12] Klaus-Tycho Foerster, Laurent Vanbever, and Roger Wattenhofer. 2019. Latency and Consistent Flow Migration: Relax for Lossless Updates. In *IFIP Networking*.

[13] Klaus-Tycho Förster and Roger Wattenhofer. 2016. The Power of Two in Consistent Network Updates: Hard Loop Freedom, Easy Flow Migration. In *ICCCN*. IEEE, 1–9. https://doi.org/10.1109/ICCCN.2016.7568583

[14] Chi-Yao Hong, Srikanth Kandula, Ratul Mahajan, Ming Zhang, Vijay Gill, Mohan Nanduri, and Roger Wattenhofer. 2013. Achieving high utilization with software-driven WAN. In *SIGCOMM*. ACM, 15–26. https://doi.org/10.1145/2486001.2486012

[15] Amos Korman, Shay Kutten, and David Peleg. 2005. Proof labeling schemes. In *PODC*. ACM, 9–18. https://doi.org/10.1145/1073814.1073817

[16] Arne Ludwig, Jan Marcinkowski, and Stefan Schmid. 2015. Scheduling Loop-free Network Updates: It's Good to Relax!. In *PODC*. ACM, 13–22. https://doi.org/10.1145/2767386.2767412

[17] Ratul Mahajan and Roger Wattenhofer. 2013. On consistent updates in software defined networks. In *HotNets*. ACM, 20:1–20:7. https://doi.org/10.1145/2535771.2535791

[18] Tal Mizrahi, Efi Saat, and Yoram Moses. 2016. Timed Consistent Network Updates in Software-Defined Networks. *IEEE/ACM Trans. Netw.* 24, 6 (2016), 3412–3425. https://doi.org/10.1109/TNET.2016.2529058

[19] Thanh Dang Nguyen, Marco Chiesa, and Marco Canini. 2017. Decentralized Consistent Updates in SDN. In *SOSR*. ACM, 21–33. https://doi.org/10.1145/3050220.3050224

[20] Mark Reitblatt, Nate Foster, Jennifer Rexford, Cole Schlesinger, and David Walker. 2012. Abstractions for network update. In *SIGCOMM*. ACM, 323–334. https://doi.org/10.1145/2342356.2342427

[21] Stefan Schmid and Jukka Suomela. 2013. Exploiting locality in distributed SDN control. In *HotSDN*. ACM, 121–126. https://doi.org/10.1145/2491185.2491198

[22] Jiaqi Zheng, Guihai Chen, Stefan Schmid, Haipeng Dai, Jie Wu, and Qiang Ni. 2017. Scheduling Congestion- and Loop-Free Network Update in Timed SDNs. *IEEE Journal on Selected Areas in Communications* 35, 11 (2017), 2542–2552. https://doi.org/10.1109/JSAC.2017.2760146

[23] Jiaqi Zheng, Bo Li, Chen Tian, Klaus-Tycho Foerster, Stefan Schmid, Guihai Chen, Jie Wu, and Rui Li. 2019. Congestion-Free Rerouting of Multiple Flows in Timed SDNs. *IEEE Journal on Selected Areas in Communications* 37, 5 (2019), 968–981. https://doi.org/10.1109/JSAC.2019.2906741