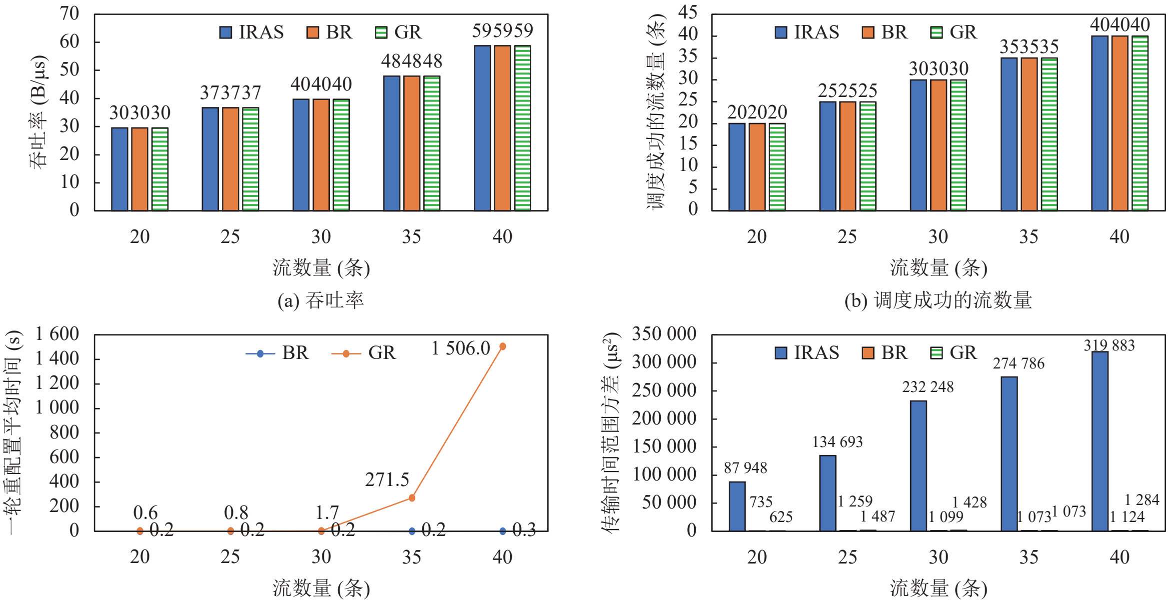
流数量的提升而急剧增长, 无法满足秒级时间要求. 在 45 条流时, GR 算法在 24 h 之后没有返回计算结果, 因此无法将 GR 扩展到流数量较多的大型网络中. 3) 在传输时间范围方差方面, BR 和 GR 均可有效减小该指标, 使得流的调度时间均匀到各个传输时间范围中.

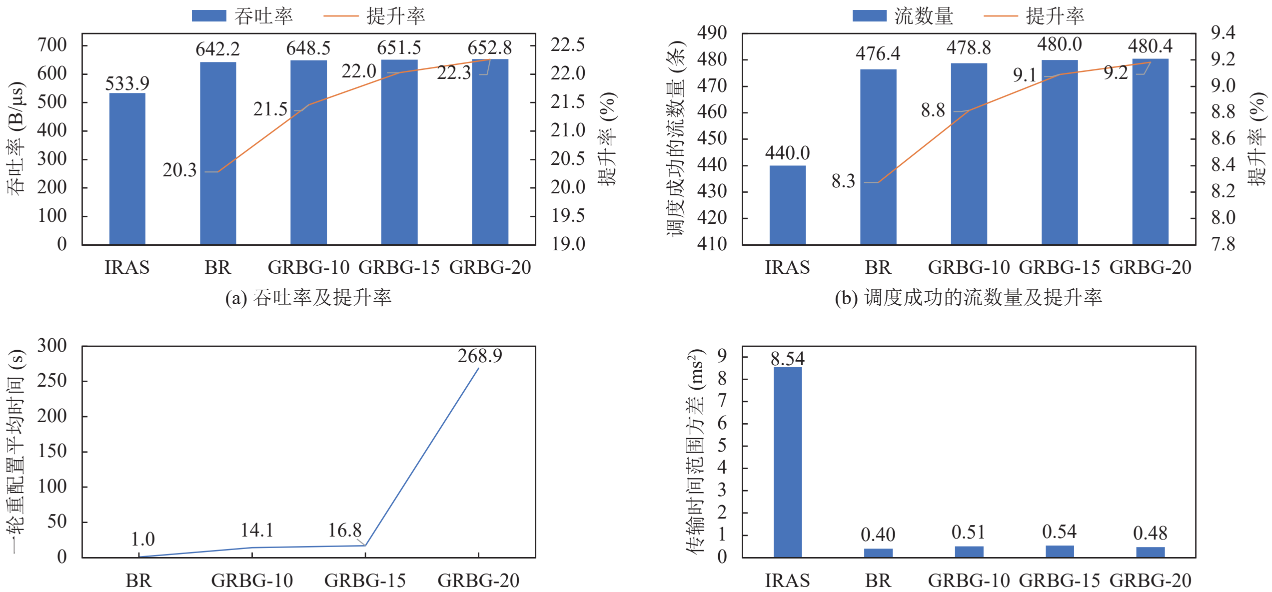
实验④的结果如图 6 所示, 1) 将流数量扩展到 500 时, 相比于 IRAS 算法, BR 在吞吐率方面大约有 20.3% 的提升, 在流数量方面提升了 8.3%. 相比于 GRBG, BR 在吞吐率上低 1%–2%, 在流数量上低 0.5%–1%. 2) BR 的计算时间在 1 s 左右, GRBG 的计算时间则随着分组数量的增大而急剧增长. 在分组数量为 20 时, 一轮重配置平均计算时间达到了 268 s, 无法满足动态调度的秒级时间要求. 3) BR 和 GRBG 有效降低了传输时间范围方差, 使流的调度时间更加均匀.




(a) 吞吐率 (b) 调度成功的流数量

(c) 一轮重配置平均时间 (d) 传输时间范围方差

图 5 实验③结果




(a) 吞吐率及提升率 (b) 调度成功的流数量及提升率

(c) 一轮重配置平均时间 (d) 传输时间范围方差

图 6 实验④结果

## 6 总结与展望

本文设计了时间敏感网络业务流动态调度场景中的批量重配置算法, 该算法在动态调度的基础上, 能够定期对部分业务流进行重新配置, 优化网络资源的分配. 实验结果表明, 该算法能够适用于上千条流的大型网络, 在吞吐率方面提高 16.5%, 在调度成功流数量方面提升 5.5%, 并且计算时间满足秒级要求. 与分组全局重配置算法相比, 该算法在计算时间上拥有巨大优势, 且在吞吐率和流数量上仅减少 2% 和 1% 左右.

在工业场景中, 可能会存在不同传输速率的异构交换机, 并且各交换机之间的线路长短也可能不一样. 因此探讨该算法在复杂网络场景下的适用情况, 是未来需要关注的一个问题.

### 参考文献


1 中国电子技术标准化研究院. 时间敏感网络白皮书. 北京: 中国电子技术标准化研究院, 2020.

2 Craciunas SS, Oliver RS, Chmelík M, *et al*. Scheduling real-time communication in IEEE 802.1 Qbv time sensitive networks. Proceedings of the 24th International Conference on Real-time Networks and Systems. Brest: ACM, 2016. 183–192. [doi: 10.1145/2997465.2997470]

3 Pozo F, Steiner W, Rodriguez-Navas G, *et al*. A decomposition approach for SMT-based schedule synthesis for time-triggered networks. Proceedings of the 20th Conference on Emerging Technologies & Factory Automation. Luxembourg: IEEE, 2015. 1–8. [doi: 10.1109/ETFA.2015.7301436]

4 Dürr F, Nayak NG. No-wait packet scheduling for IEEE time-sensitive networks (TSN). Proceedings of the 24th International Conference on Real-time Networks and Systems. Brest: ACM, 2016. 203–212. [doi: 10.1145/2997465.2997494]

5 IEEE. 802.1Q-2022 IEEE standard for local and metropolitan area networks-bridges and bridged networks. https://1.ieee802.org/maintenance/802-1q-2022-rev/. (2018-05-07).

6 Huang YD, Wang S, Huang T, *et al*. Online routing and scheduling for time-sensitive networks. Proceedings of the 41st International Conference on Distributed Computing Systems. Washington: IEEE, 2021. 272–281. [doi: 10.1109/ICDCS51616.2021.00034]

7 Bülbül NS, Ergenç D, Fischer M. Towards SDN-based dynamic path reconfiguration for time sensitive networking. Proceedings of the 2022 IEEE/IFIP Network Operations and Management Symposium. Budapest: IEEE, 2022. 1–9. [doi: 10.1109/NOMS54207.2022.9789890]

8 Jin X, Xia CQ, Guan N, *et al*. Real-time scheduling of massive data in time sensitive networks with a limited number of schedule entries. IEEE Access, 2020, 8: 6751–6767. [doi: 10.1109/ACCESS.2020.2964690]

9 Mahfouzi R, Aminifar A, Samii S, *et al*. Stability-aware integrated routing and scheduling for control applications in Ethernet networks. Proceedings of the 2018 Design, Automation & Test in Europe Conference & Exhibition. Dresden: IEEE, 2018. 682–687. [doi: 10.23919/DATE.2018.8342096]

10 Nayak NG, Dürr F, Rothermel K. Time-sensitive software-defined network (TSSDN) for real-time applications. Proceedings of the 24th International Conference on Real-time Networks and Systems. Brest: ACM, 2016. 193–202. [doi: 10.1145/2997465.2997487]

11 Nayak NG, Dürr F, Rothermel K. Incremental flow scheduling and routing in time-sensitive software-defined networks. IEEE Transactions on Industrial Informatics, 2018, 14(5): 2066–2075. [doi: 10.1109/TII.2017.2782235]

12 Li D, Wang ST, Zhu KL, *et al*. A survey of network update in SDN. Frontiers of Computer Science, 2017, 11(1): 4–12. [doi: 10.1007/s11704-016-6125-y]

13 Raagaard ML, Pop P, Gutiérrez M, *et al*. Runtime reconfiguration of time-sensitive networking (TSN) schedules for fog computing. Proceedings of the 2017 IEEE Fog World Congress. Santa Clara: IEEE, 2017. 1–6. [doi: 10.1109/FWC.2017.8368523]

14 赵奕, 王海涛. 时间敏感网络研究现状与关键技术探析. 邮电设计技术, 2022(10): 65–70. [doi: 10.12045/j.issn.1007-3043.2022.10.0013]

15 Said SBH, Truong QH, Boc M. SDN-based configuration solution for IEEE 802.1 time sensitive networking (TSN). ACM SIGBED Review, 2019, 16(1): 27–32. [doi: 10.1145/3314206.3314210]

16 Gutiérrez M, Ademaj A, Steiner W, *et al*. Self-configuration of IEEE 802.1 TSN networks. Proceedings of the 22nd IEEE International Conference on Emerging Technologies and Factory Automation. Limassol: IEEE, 2017. 1–8. [doi: 10.1109/ETFA.2017.8247597]

17 Li Q, Li D, Jin X, *et al*. A simple and efficient time-sensitive networking traffic scheduling method for industrial scenarios. Electronics, 2020, 9(12): 2131. [doi: 10.3390/electronics9122131]

18 Yan JL, Quan W, Jiang XY, *et al*. Injection time planning: Making CQF practical in time-sensitive networking. Proceedings of the IEEE INFOCOM 2020-IEEE Conference on Computer Communications. Toronto: IEEE, 2020. 616–625. [doi: 10.1109/INFOCOM41043.2020.9155434]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