了 1 Mb/s, 这是因为 AP3 比 AP1 的信道利用率低, AP2 比 AP4 信道利用率低, 且剩余带宽都为 1.5 Mb/s, 机器人分别关联 AP3 和 AP2, 带宽都能得到满足.这和本文的算法的关联结果是一样的. 在 [1, 65] 时间段内, 相比于基于信道利用率的 AP 选择算法, 本文算法使得机器人的平均通信带宽提高了 24%, 这主要源自本文算法产生的切换时延较低. 其它两个算法的平均通信带宽较低, 与它们选择的 AP 和切换延时都有关系.

接下来, 测试 AP 容量不同的情况. 按照表 8 配置 AP 容量和网络中的数据流量, 令服务器向指定的 4 个 STA 发送 UDP 流量. 首先让机器人静止, 测量在此配置下各个 AP 的 MAC 层传输速率, 并计算出各自的应用层剩余带宽, 如表 9 所示.

表 8 AP 容量和网络流量配置

流量源	流量目的地(STA)	关联的AP	AP带宽(Mb/s)	服务器发送速率(Mb/s)
server	1	AP1	2	1.5
server	6	AP2	11	3.5
server	3	AP3	2	1
server	9	AP4	2	1.2

表 9 表 8 配置下的动态无线地图 (部分)(单位: Mb/s)

AP列表	队列总长度	当前带宽(物理层)	总带宽(物理层)	剩余带宽(应用层)
AP1	500	1.88	2	0.1
AP2	500	8.56	11	1
AP3	500	1.24	2	0.6
AP4	500	1.48	2	0.4

令机器人从起点向终点移动, 服务器以 500 Kb/s 向机器人发送数据, 测试不同的 AP 选择算法下机器人的平均通信速率, 实验结果如图 7 所示, 表 10 为不同算法选择的 AP 切换序列.

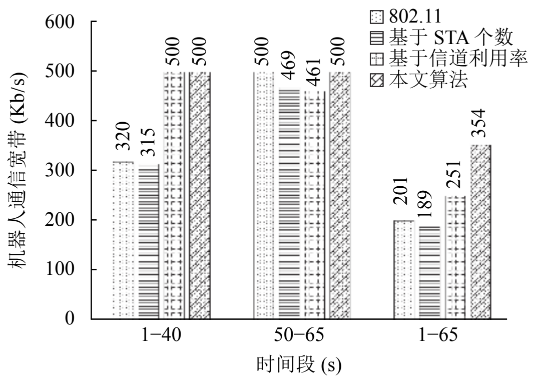

图 7 机器人在不同时间段内的平均通信带宽

使用 802.11 的 AP 选择算法, 机器人在 [1, 40] 时间段内的平均通信带宽仅为 320 Kb/s, 根据表 9, AP1 剩余带宽为 0.1 Mb/s, 达不到机器人的带宽需求, 从而机器人关联 AP1 后产生大量的丢包. 在 [50, 65] 时间段内机器人接受带宽为 500 Kb/s, 因为 AP2 剩余带宽为 1 Mb/s, 能够满足机器人的带宽需求. 使用基于 STA 个数的 AP 选择算法, 机器人在 [1, 40] 和 [50, 65] 时间段内的平均通信带宽均未达到 500 Kb/s, 由表 9 可知, AP1 和 AP4 虽然关联的 STA 个数最少, 但是剩余带宽却是最低的, 仅剩 0.1 Kb/s 和 0.4 Kb/s, 无法满足机器人带宽需求. 使用基于信道利用率的 AP 选择算法和本文算法, 机器人在 [1, 40] 时间段内的平均通信带宽达到了需求的 500 Kb/s, 此时两个算法都选择了 AP3, 而 AP3 比 AP1 的信道利用率低, 剩余带宽为 0.6 Mb/s, 满足机器人的需求带宽, 但是 [50–65] 时间段内, 基于信道利用率的算法选择了 AP4, 机器人通信带宽仅为 461 Kb/s, 低于 500 Kb/s, 由表 9 发现 AP4 无法满足机器人带宽需求. 本文算法根据应用层剩余容量选择了 AP2, 可以满足带宽需求. 在 [1, 65] 时间段内, 采用本文算法的机器人平均通信带宽最高, 这是因为其它算法或者无法全程满足机器人的带宽需求, 或者由于切换延时较高产生较多的丢包.

表 10 4 种 AP 选择算法产生的 AP 切换序列

AP选择算法	AP切换序列
802.11	{AP1, AP2}
基于STA个数	{AP2, AP4}
基于信道利用率	{AP3, AP4}
本文算法	{AP3, AP2}

综合以上实验可以看到, 本文算法在切换延时和通信带宽保证方面均优于已有的 AP 切换算法.

5 总结

本文面向工业机器人场景提出了一种基于动态无线地图的带宽保证快速切换技术框架,并在网络仿真平台 NS3 上进行了实现和评估. 与已有的 AP 切换算法相比,本文方法可以极大地减小机器人的切换延时,同时满足机器人的通信带宽需求.

参考文献

1 Balasubramanian A, Mahajan R, Venkataramani A, *et al*. Interactive WiFi connectivity for moving vehicles.

Proceedings of ACM SIGCOMM 2008 Conference on Data Communication. Seattle, WA, USA. 2008. 427–438.

2 Yoon M, Cho K, Li J, *et al*. AdaptiveScan: The fast layer-2 handoff for WLAN. Proceedings of the 2011 8th International Conference on Information Technology: New Generations. Las Vegas, NV, USA. 2011. 106–111.

3 Mishra A, Shin M, Arbaugh W. An empirical analysis of the IEEE 802.11 MAC layer handoff process. ACM SIGCOMM Computer Communication Review, 2003, 33(2): 93–102. [doi: 10.1145/956981.956990]

4 Majumder A, Nath S. Classification of seamless handoff process in wifi network based on radios. In: Smys S, Bestak R, Chen JIZ, *et al*., eds. International Conference on Computer Networks and Communication Technologies. Singapore. 2019. 1055–1065.

5 Jiang HL, Leung VCM, Gao CH, *et al*. Mimo-assisted handoff scheme for communication-based train control systems. IEEE Transactions on Vehicular Technology, 2015, 64(4): 1578–1590. [doi: 10.1109/TVT.2014.2332188]

6 Xue CJ, Li WZ, Yu LF, *et al*. SERO: A model-driven seamless roaming framework for wireless mesh network with multipath TCP. IEEE Transactions on Communications, 2019, 67(2): 1284–1296. [doi: 10.1109/TCOMM.2018.2880785]

7 Jeong JP, Park YD, Suh YJ. An efficient channel scanning scheme with dual-interfaces for seamless handoff in IEEE 802.11 WLANs. IEEE Communications Letters, 2018, 22(1): 169–172. [doi: 10.1109/LCOMM.2017.2763941]

8 Jin S, Choi S. A seamless handoff with multiple radios in IEEE 802.11 WLANs. IEEE Transactions on Vehicular Technology, 2014, 63(3): 1408–1418. [doi: 10.1109/TVT.2013.2283914]

9 Lal Tetarwal M, Kuntal A, Karmakar P. A review on handoff latency reducing techniques in IEEE 802.11 WLAN. International Journal of Computer Applications. 2014, NWNC(2): 22–28.

10 Das D. A fast handoff technique for wireless mobile networks. Proceedings of the 15th International Conference on Distributed Computing and Internet Technology. Bhubaneswar, India. 2019. 251–259.

11 Park SH, Kim HS, Park CS, *et al*. Selective channel scanning for fast handoff in wireless LAN using neighbor graph. Proceedings of IFIP TC6 9th International Conference on Personal Wireless Communications. Delft, the Netherlands. 2004. 194–203.

12 Ling TC, Lee JF, Hoh KP. Reducing handoff delay in WLAN using selective proactive context caching. Malaysian Journal of Computer Science, 2010, 23(1): 49–59. [doi: 10.22452/mjcs.vol23no1.4]

13 Kim SR, Kim KJ, Baek JJ, *et al*. A WLAN handoff scheme based on selective channel scan using pre-collected AP information for VoIP application. Proceedings of 2009 International Conference on Innovations in Information Technology. Al Ain, Abu Dhabi. 2009. 70–74.

14 Wang R, Mukerjee MK, Veloso M, *et al*. Wireless map-based handoffs for mobile robots. Proceedings of 2015 IEEE International Conference on Robotics and Automation (ICRA). Seattle, WA, USA. 2015. 5545–5550. [doi: 10.1109/icra.2015.7139974]

15 Wen YF, Shen JC. Load-balancing metrics: Comparison for infrastructure-based wireless networks. Computers & Electrical Engineering, 2014, 40(2): 730–753.

16 Lu MM, Wu J. Localized access point selection in infrastructure wireless LAN. Proceedings of MILCOM 2007-IEEE Military Communications Conference. Orlando, FL, USA. 2007. 1–7.

17 Vasudevan S, Papagiannaki K, Diot C, *et al*. Facilitating access point selection in IEEE 802.11 wireless networks. Proceedings of the 5th ACM SIGCOMM Conference on Internet Measurement. Berkeley, CA, USA. 2005. 26.

18 Sheu ST, Wu CC. Dynamic Load Balance Algorithm (DLBA) for IEEE 802.11 WireLess LAN. Tamkang Journal of Science and Engineering, 1999, 2(1): 45–52.

19 Nicholson AJ, Chawathe Y, Chen MY, *et al*. Improved access point selection. Proceedings of the 4th International Conference on Mobile Systems, Applications and Services. Uppsala, Sweden. 2006. 233–245.

20 Lee MT, Lai LT, Lai D. Enhanced algorithm for initial AP selection and roaming: US, 20040039817. (2004-02-26).

21 Chen JC, Chen TC, Zhang T, *et al*. WLC19-4: Effective AP selection and load balancing in IEEE 802.11 wireless LANs. Proceedings of IEEE GLOBECOM 2006. San Francisco, CA, USA. 2006. 1–6.

22 刘小花. IEEE 802.11b 物理层帧结构的研究与性能分析. 数据通信, 2012, (3): 38–40. [doi: 10.3969/j.issn.1002-5057.2012.03.014]

23 Heusse M, Rousseau F, Berger-Sabbatel G, *et al*. Performance anomaly of 802.11b. Proceedings of the 22nd Annual Joint Conference of the IEEE Computer and Communications. San Francisco, CA, USA. 2003. 836–843.

24 Ernst JB, Kremer SC, Rodrigues JJPC. A Wi-Fi simulation model which supports channel scanning across multiple non-overlapping channels in NS3. Proceedings of the 2014 IEEE 28th International Conference on Advanced Information Networking and Applications. Victoria, UK. 2014. 268–275.