A method for suppressing disorderly scheduling in multipath transmission scenarios using time delay offset

Shuxing Zhu*
Beijing Jiaotong University, Beijing, China

Abstract

Multipath transmission enables packets to be distributed over different paths for transmission, and this method has made full use of individual link resources. However, most existing multipath transmission schemes lack suitable scheduling mechanisms and suffer from high disorder and packet loss. To address the disorder problem, this paper designs a delay offset method combined with link rejection or adaptive delay adjustment mechanism to suppress the packet disorder problem in multipath transmission scenarios based on an in-depth study of the background related to multipath transmission. Finally, a multipath link topology is built on the P4 simulation platform to implement the above method in code simulation, and the experimental results are compared and analyzed with other two scheduling mechanisms. The experimental results show that this method maintains the disorder level within 5% compared with the single-path transmission and the equivalent multipath method, but the transmission bandwidth is increased by nearly two times.

Keywords: Software-defined network (SDN), programmable protocol independent message processing (P4), multipath, packet sequencing

1 Introduction

In recent years, the rapid rise of new network applications such as big data [1], cloud computing [2], and edge computing [3] have led to the rapid development of Internet technologies. As one of the important infrastructures of the Internet, data centers are currently undergoing massive construction worldwide, with Google alone having as many as 40 data centers worldwide [4]. The dramatic expansion of data center scale makes its internal nodes face a large amount of traffic injection at any time due to various different network demands. Various new applications [5] have put forward higher demands on the reliability, effectiveness, and bandwidth of transmission, and how to achieve flexible management of data center equipment so that the huge internal load can be effectively balanced is an urgent problem to be solved, and it is difficult to meet the future network requirements by improving the traditional network architecture alone.

At the same time, with the rapid development of communication technologies such as 5G [6] and WiFi [7], there are more and more ways to transmit data, and the transmission speed of data is getting faster and the determinism of the network is getting higher [8], which has played a certain role in alleviating the above data center traffic injection problem, but it cannot solve the problem at the root. Therefore, multipath transmission comes into being, and multipath transmission can make full use of each link in the system, thus greatly improving network performance.

With the implementation of multipath transmission, many of its problems have been exposed, such as the lack of a holistic view for packet scheduling, failure to fully utilize each link for data transmission,

Research Briefs on Information & Communication Technology Evolution (ReBICTE), Vol. 7, Article No. 11 (October 25, 2021)
DOI:*10.22667/ReBiCTE.2021.10.25.011*

*Corresponding author: Beijing Jiaotong University, No.3, Shangyuan Village, Haidian District, Beijing, China, Email: 21120184@bjtu.edu.cn, Tel: +86-188-1088-0758

unreasonable packet allocation, and disordered packets at the receiving end. Therefore, it is necessary to solve the above problems one by one.

In this paper, we design a scheduling algorithm to suppress the packet disorder problem, the delay offset method and the corresponding link rejection and adaptive delay adjustment mechanisms, i.e., we first perform link rejection or adaptive delay adjustment to make each link meet the delay offset method conditions, and then send the packets with small sequence number on the link with large delay first, and send the packets with large sequence number on the link with small delay to offset the link delay difference, so that the packets arrive in sequence at the receiving end.In addition, this paper also investigates the multipath disorder suppression scheduling mechanism in an SDN network environment. The results show that the delay offset method fully exploits the advantages of the centralized architecture of SDN compared with other schemes, and the method improves the transmission bandwidth by nearly two times while keeping the disorder level within 5%.

In addition, Section 2 of this paper introduces the multipath transmission method at each level under the seven-layer network system, Section 3 introduces the related scheduling algorithm, Section 4 introduces the principle of the delay offset method, Section 5 presents the experimental results and analyzes them, and Section 6 concludes the whole paper.

2 Multipath transmission methods at each network level

When implementing multipath transmission technology, two problems need to be solved: first, different networks may use different technical specifications, have different link characteristics and network characteristics, and cannot interoperate with each other efficiently, and the heterogeneity of paths can cause packet disorder and other problems during multipath transmission, resulting in degraded network transmission performance; second, for the traditional TCP/IP protocol stack, it only supports end-to-end connection between a pair of addresses and cannot effectively use multiple heterogeneous links between terminals. To solve the above problems, various solutions have been proposed at various layers of the network [9][10][11], which are described below.

2.1 The application layer

In the application layer, in order to achieve the goal of multipath parallel transmission under heterogeneous links [12], a common approach is to add middleware between the transport layer and the application layer. middleware functions as the distribution of application data distribution and the management of interfaces, and in middleware, there are explicit middleware and implicit In explicit middleware, the services required by the application layer are provided by modifying part of the protocol between the application layer and the transport layer, such as MuniSocket [13], ALP-A (Application Layer Protocol based Aggregation) [14], etc. To implement these solutions, it is necessary to modify the application so that the functional modules of the control interface are embedded in the application, which not only greatly increases the complexity of the current application, but also cannot be adapted to all applications. Implicit middleware provides the same semantics and interface to the application as the transport layer, which has the advantage of ease of deployment and good compatibility with existing applications, without the need to rewrite new applications, but its disadvantage is the complexity of the implementation process. If built on top of existing transport protocols, mechanisms are needed to suppress packet disorder, such as disorder suppression scheduling on the receiving or sending side of the packet or reordering of received disorder packets on the receiving side, and the implementation of these algorithms requires corresponding adjustments to the network or server. In order to prevent the network or server from limiting the implementation of the above algorithms, the ”request-response” communication model can be used to assign multiple interfaces to HTTP, or to cut the data into a certain number of pieces and create a corresponding number of TCP connections to complete the transmission of data pieces.

2.2 The transport layer

The transport layer is located between the application layer and the network layer, which is well shielded from the underlying network devices and can provide end-to-end data transmission services to the upper layer applications, and it has the advantages of solving fairness and packet disorder.Currently, the main transport layer protocols are Transmission Control Protocol (TCP), User Datagram Protocol (UDP), and Stream Control Transmission Protocol (SCTP), however, all three protocols use only a single path for data transmission. In order to achieve the purpose of multipath transmission in heterogeneous networks, the above protocols need to be extended, so many protocols have emerged. Non-TCP-based multipath transport protocols are mainly extensions of the SCTP protocol, including Concurrent Multipath Stream Control Transmission Protocol (CMT-SCTP), Bandwidth Aggregation Based on SCTP (BA-SCTP) and Load Sharing-SCTP (LS-SCTP) [15], etc. TCP-based multipath transport protocols are extensions of TCP protocols, mainly including Parallel TCP (pTCP), Reliable Multiplexing Transport Protocol (R-MTP) and Multi-path Transmission Control Protocol (MPTCP).

2.3 The network layer

The network layer is located between the transport layer and the data link layer, also called the IP layer, which shields the transport layer from the specific physical transmission processes of the physical layer.In the network layer, the network layer protocols are modified to enable the transport layer protocols to operate effectively on various network interfaces, thus achieving the purpose of multipath transmission.Due to the widespread use of TCP protocol, most network layers implementing multipath parallel transmission use TCP protocol as the transport layer protocol. In the transport layer, in order to establish a TCP connection for data transmission, IP addresses and port numbers at both ends of the transmission are usually used, but in parallel transmission in heterogeneous networks, there is more than one IP address. In this case to achieve multipath transmission, multiple IP addresses can be fused and encapsulated, such as IP-in-IP encapsulation techniques [16] and Enhancements for TCP On a Mufti-homed mobile router (ETOM) .

2.4 The data link layer

The data link layer is located between the network layer and the physical layer [17]. In the data link layer, through resource integration and link binding, a virtual logical link with larger bandwidth can be obtained, and during transmission, packets of the same IP stream are allocated to multiple links for transmission by means of virtual logical links, which can realize heterogeneous multipath transmission at the bottom layer and get multi-link transmission bandwidth integration gain.In order to achieve the above-mentioned high-bandwidth transmission by using different network links simultaneously and efficiently in multipath parallel transmission, the existing solution is to add Generic Link Layer (GLL) and Mufti-Radio Resource Management (MRRM) to the data link layer to manage the network bandwidth resources of different heterogeneous links and to allocate and distribute packets to the links. Among them, the GLL provides a unified link layer packet transmission interface to the upper layer and allocates the packets coming down from the upper layer to different heterogeneous links; while the MRRM plays the role of managing the resources of multiple links; based on the above proposed methods, traffic allocation and resource management schemes such as maximizing system capacity or energy efficiency have been proposed based on various transmission requirements.

In summary, it is possible to implement multipath parallel transmission of heterogeneous links in multiple layers of the Internet model, and different layers have different characteristics, so different approaches can be chosen according to the needs of different problems, but if a specific layer is chosen, it is bound by the characteristics of that layer at the same time. For example, in the application layer, the transmission requirements of each application can be better understood, and therefore, it can facilitate the distribution of the whole data on links with different transmission characteristics, but in the process of distribution, it will increase the complexity of processing data for the application; in the network layer, the higher layers can know the status of the whole network and be downward compatible with the network infrastructure of the bottom layer, but in this layer, there will be packet disorder In the data link layer, it can better access the underlying information in the channel link and make better adjustments for channel changes, but the layer is too far away from the applications above and is not directly connected, so it is not conducive to the end-to-end transmission of upper layer data, and the network link environment of different operators may be different, so it also needs special Software or hardware to solve this problem. From the above analysis, it is clear that solutions closer to the bottom layer are more adaptable to the changes of the underlying physical links, but farther from the upper layer applications and without a global view to effectively perform end-to-end overall path quality management and congestion control [18], while solutions on the upper layer are not well adapted to the dynamic changes of the underlying physical links.Therefore, this paper investigates the multipath transmission technique at the partial intermediate level of the network layer and combines the SDN-based P4 language to control the forwarding of packets across the link from a global perspective to suppress out-of-order scheduling in order to improve transmission performance and resource utilization efficiency.

3 The relevant scheduling algorithm

A number of scheduling algorithms already exist, and in this section, the adaptive incremental delay algorithm, the delayed programmable scheduling algorithm, and the Equal-Cost Multipath Routing are selected and presented.

3.1 Adaptive Incremental Delay Algorithm (RAID)

RAID algorithm [19] is a multipath transmission algorithm deployed on MMR-AR systems. RAID algorithm and MMR-AR system make up a multipath transmission scheme for high-speed mobile scenes. With this solution, current smart devices, such as smartphones and laptops, can get higher bandwidth in high-speed mobile scenarios. The MMR-AR system with RAID algorithm is a full duplex communication system. Figure 1 shows the system structure of the MMR-AR system with with RAID algorithm.

The MMR-AR system is divided into two parts: a multipath mobile router (MMR) and an aggregate router (AR). Both parts have RAID algorithms deployed. MMR is deployed on mobile vehicles. It has multiple network adapters and access to different wireless networks, including Wi-Fi, 3G, 4G and satellites. Passengers can access the MMR via Wi-Fi. With MMR, passengers can access the Internet using heterogeneous networks. AR is deployed on the ground. All packets from the user should be summarized in AR. The MMR-AR system is a variant of the IP-in-IP package, which establishes a virtual tunnel between the MMR and AR through a heterogeneous network. When a smart device accesses the Internet, packets are sent first to the MMR. When the packet reaches the MMR, it is encapsulated with a new IP header with the destination address AR. Next, the MMR selects the appropriate path based on the scheduling algorithm to send new packets to the AR. When the AR receives the packet, it eliminates the IP header for unpacking. Once unpackaged, processed packets are sent to the server.

With accurate network quality estimation, the current multipath transmission algorithm can eliminate

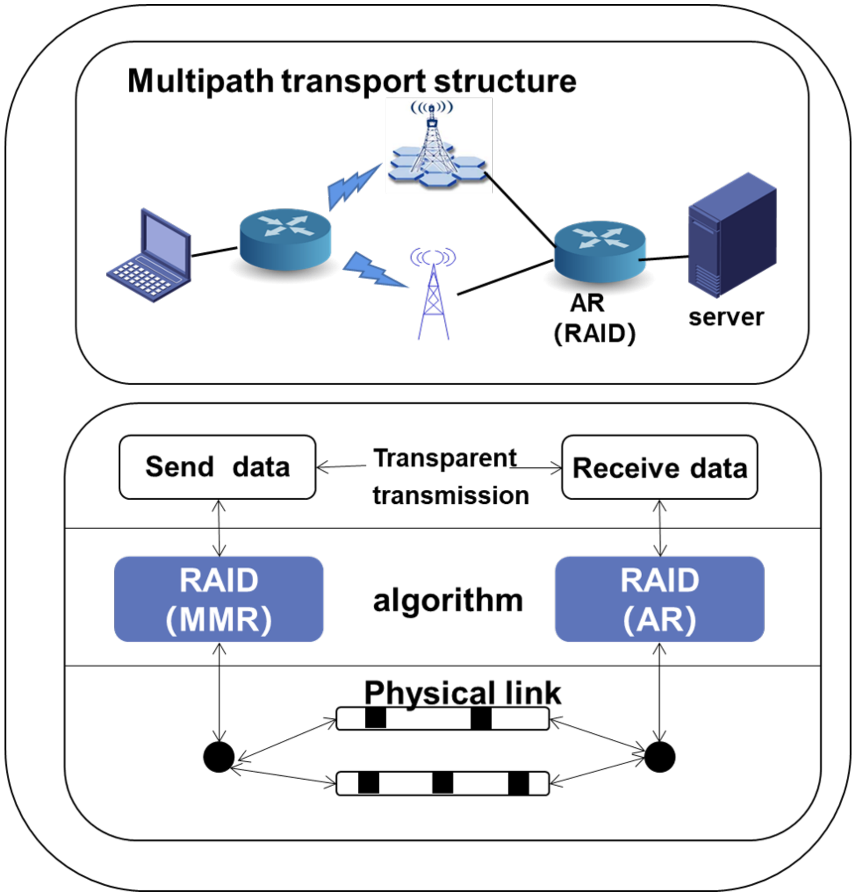


Figure 1: Adaptive incremental delay algorithm diagram.

the sender's disorderly packets. However, the current multipath transmission algorithm is difficult to obtain accurate network quality estimation in high-speed mobile scenes. RAID algorithm is an algorithm with greater tolerance for estimating errors in network quality. It establishes an automatic reorder buffer at AR. When packets reach the receiver, they first enter the automatic classification buffer. Second, the ordered packets are forwarded to the server and out-of-order packets are cached in the buffer. With the receive buffer in mind, a different delay is added to each packet. Messages received by AR can be forwarded to the server in the order in which the MMR is sent.

This method eliminates the delay difference between different links by increasing the queued delay of the last router, and achieves the goal of suppressing the arrival of disorder, but in this way, the delay transmitted by data in all queues is the closest to the maximum delay in all links, increasing the queue delay of the link with small delay, and not making full use of the low delay link.

3.2 Equal-Cost Multipath Routing (ECMP)

Current mainstream topologies such as Fat-Tree can provide multiple equivalent paths for data transmission, and ECMP algorithm is a load sharing strategy designed based on the characteristics of multiple equivalent paths. The most used ECMP load balancing algorithm in enterprises or data centers is based on hash, and its basic principle is: assign corresponding numbers to multiple equivalent paths in order, and when a packet arrives at the network, extract the contents of the packet header field for hashing and modulo operation with the number of equivalent paths, and set the final result as the path number for data forwarding, so as to determine an available path for data forwarding. The final result is set as the path number for data forwarding, so as to determine an available path for data forwarding. In addition, because all packets of the same data stream will be transmitted through a selected path, the problem of packet sequencing is effectively resolved. The ECMP algorithm has low complexity and can significantly improve the link transmission rate, but this method only distributes the traffic load to each link equally when processing the data stream. This static allocation method fails to take the real-time state information of the network into account when formulating the policy, making the allocation for data streams out of the actual situation of each path in the network, causing congestion on some links [20], resulting in the links failing to maximize their utility.

Meanwhile, with the increasing size of data centers, the maximum number of equivalent multipaths provided by the current ECMP algorithm can no longer meet its load balancing requirements. The algorithm also has a serious impact on the bandwidth utilization when the links are not fully equivalent due to various factors in the actual deployment. Therefore, the biggest drawback of the ECMP algorithm is that the algorithm is deployed without considering the actual situation that the data center traffic changes in real time, and only achieves the equal distribution of traffic in terms of quantity.

3.3 Delayed Programmable Scheduling (DPS)

DPS [21] is a practical solution that can run in parallel with the sender scheduling policy described above and is easy to deploy on network edge devices because it runs without changing TCP senders or receivers. The mechanism attempts to consider both load balancing and out-of-order scheduling based on a transport layer solution. Specifically, the approach uses a virtual link loop, which can be used to buffer out-of-order packets with a fixed delay. To determine the number of packets to be transmitted in each virtual link loop, the DPS runs an intelligent control module that adaptively generates transmission policies based on real-time network state. When the data transfer module receives packets, it first converts them into scheduling parameters (e.g., cycle time for out-of-order packets). Then, the data transfer module efficiently schedules packets to achieve programmable transmission delays.

While this method can change the delay of a link by adding virtual link loops to suppress disorder, actually adding a router to the network for the purpose of adding loops increases the overhead in the network.

4 Algorithmic principle

The scheduling algorithms listed above are more or less problematic. RAID achieves the goal of suppressing chaotic arrivals by increasing the queuing delay at the last router to eliminate the difference in delay between different links, but in this way, the delay of data transmission in all queues moves closer to the largest delay among all links, increasing the queuing delay of links with small delay and not making good use of low-latency links. ECMP performs weight assignment without considering the link's capacity has been used, this drawback of the weighting algorithm makes ECMP ineffective in balancing traffic between multiple paths that may exist on the network. although DPS can change the delay of a link by adding virtual link loops to suppress disorder, actually adding a router to the network for the purpose of adding loops will increase the overhead in the network.

In order to solve the above problems, while taking into full consideration the delay differences between different links in the network [22], this paper designs the delay offset method, i.e., sending packets with small sequential numbers on links with large delay first and combining with link rejection or adaptive delay adjustment mechanism to offset the delay differences so that the packets arrive in sequence at the receiving end. This is illustrated below with specific models.

4.1 The system model

Single path transmission method and delay offset method system model are shown in Figure 2 Figure 3, respectively, from the cell phone side to the computer side, there are two communication links, respectively, the lower delay 5G communication and higher delay WiFi communication, when the system selects a single path for transmission, it usually selects the lower delay 5G to transmit data, at this time, only one link is used for data transmission, not fully utilizing all links

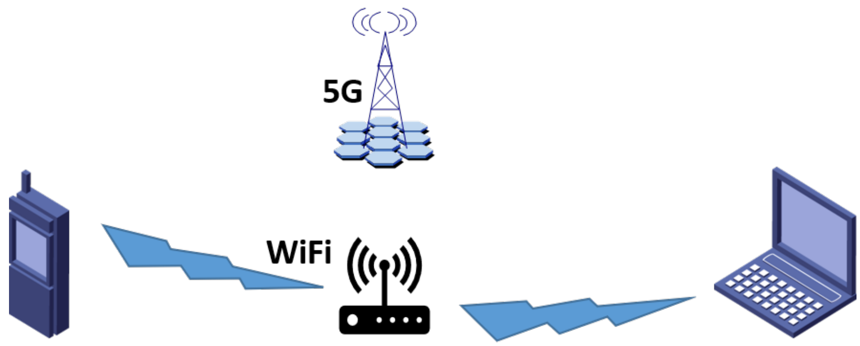


Figure 2: A single-path transport model.

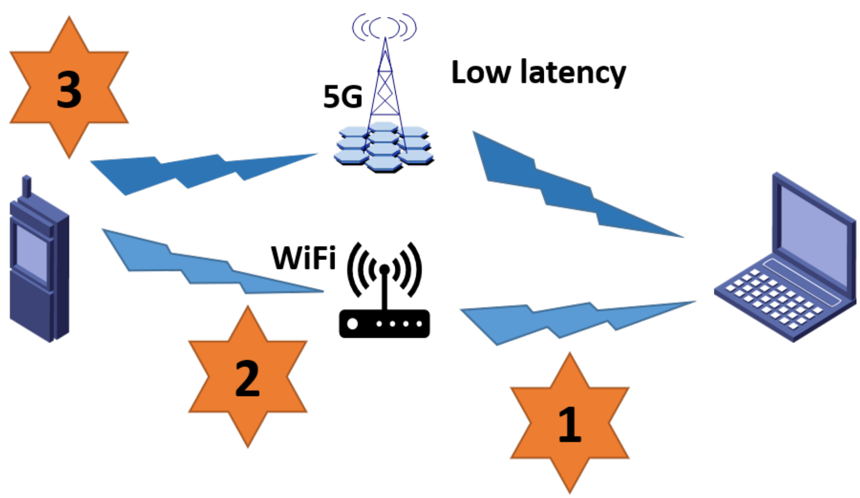


Figure 3: The delay offset method system model.

And when the system selects the delay offset method for data transmission, it will make full use of the above two links. In order to offset the transmission delay difference between the two links, the system will choose to send packets on the high delay link first, and then send packets on the low delay link, and the interval of sending packets can exactly offset the delay difference between the two links, at which time, the receiving end can receive the packets in order.

4.2 Algorithmic analysis

The following definitions are given for the analysis of delay offset method, in order to facilitate model analysis. A collection of available links between the sender and the receiver $PATH = \{path_i | i = 1,2,3\ldots s\}$, A collection of packets sent at the originating end $PAC = \left\{pac^i_{send} | i = 1,2,3\ldots n\right\}$, The receiving end receives the packet $PAC = \left\{pac^i_{recv} | i = 1,2,3\ldots n\right\}$, Defines the calculator to get the packet sending time series number $N(*)$, such as $N(pac^i_{send})$, Define the calculator to get the current moment $T(*)$, such as $T(pac^{i+1}_{recv})$, Define the link delay collection $RTT = \{RTT_i | i = 1,2,3\ldots s\}$. In the process of heterogeneous link transmission, the receiving side packets may not arrive sequentially, in order to suppress the disorder of packets received by the receiving end, the packets sent continuously by the sending side should be satisfied to reach the receiving end over different links

$$N(pac^{i+1}_{recv}) \geq N(pac^i_{recv}) \tag{1}$$

That is, packets sent first should arrive before and after

$$T(pac^{i+1}_{recv}) \geq T(pac^i_{recv}) \tag{2}$$

Defined $E_j(i)$ as the current time, an end-to-end delay in packet i transmission over a link j. If packets arrive sequentially, they are available during transmission

$$T(pac^{i+1}_{send}) + E_j(i+1) \geq T(pac^i_{send}) + E_k(i) \tag{3}$$

Therefore, it is available to suppress the disorder scheduling algorithm to send packets on the link with large delay to offset the delay difference, and to achieve the goal of sequential arrival.

4.3 Link rejection mechanism

In multipath transmission scenarios, there are usually multiple links in the system, and when the delay difference between links is too large, the delay offset method proposed above may fail and the degree of packet disorder received at the receiving end will be greatly increased, so it is necessary to perform a screening of the links and eliminate the links with too large a delay difference before assigning packets to specific links. The specific algorithm is as follows.

$$Max.RTT - Min.RTT < \frac{tps}{8MTU} \tag{4}$$

As shown in Equation (4), defined $Max.RTT$ the maximum latency value for each link, the $Min.RTT$ minimum latency value for each link, tps the send rate for the router, and the number of MTU packet bytes, When there are multiple links in the system, first take out the maximum and minimum delay links, and then their delay to do the differential operation, if the difference is less than the throughput divided by eight times the maximum data unit, then determine that the system delay difference is not large, do not cull the link, if the conditions of Equation (4) are not met, then the system delay the largest link culling, and repeat the above operation, until the requirements are met.

4.4 Adaptive delay adjustment mechanism

When the delay difference between the links is large, the links with large delay may not be eliminated and the method of adaptive delay adjustment is used to achieve the purpose of both making full use of the links and achieving the packet arrival in order, the link elimination is to prevent the delay difference from being so large that the packet sent after the link with small delay reaches the receiving end first, and the

Table 1: Experimental parameter settings

Simulation platform	P4
The type of protocol	UDP
End-to-end delay	6ms 12ms
Data load	1470bytes
duration	10s 15s 20s 25s 30s

specific idea of adaptive delay adjustment is as follows. As shown in Equation (5), the set of link delay is ranked in order from largest to smallest, and when the difference in delay between links is too large, packets will obviously arrive in disorder at the receiving end, at this time, the queuing delay of packets transmitted on the latter link can be made to increase adaptively, which is equivalent to increasing the round-trip delay of the latter link in disguise, and after adaptive adjustment, the delay of the latter link is defined as $RTT_{i+1}{}^{*}$, then after the link delay difference satisfies equation (6), the packets at the receiving end can arrive in order.

$$RTT_i - RTT_{i+1} > \frac{tps}{8MTU} \tag{5}$$

$$RTT_i - RTT_{i+1}{}^{*} < \frac{tps}{8MTU} \tag{6}$$

The algorithm's overall implementation process is as Figure 4.

5 Simulation experiments and analysis

This section presents a simulation analysis of the previously proposed delay offset algorithm for suppressing disorderly scheduling at the network layer. First, the simulation algorithm flow and environment parameters are introduced, and then the experimental results of the delay offset method are compared and analyzed with the experimental results of single-path transmission and ECMP in terms of disorder degree and transmission bandwidth.

5.1 Introduction to simulation environment and parameters

Based on the P4 platform, this experiment builds a heterogeneous network system as shown in Figure 5. It consists of four parts: transmitter h1, receiver h2, P4 router r1 directly connected to h1 and router r2 connected to h2, and two links between r1 and r2 with different latency. In the experiment, iperf was used to send a UDP stream from host h1 to h2 for ten seconds, the parameters are shown in Table 1.

5.2 Experimental results

The experimental results of disorder level are shown in Figure 6. The experimental results of bandwidth are shown in Figure 7. It can be seen that with the increase of time, the transmission bandwidth of delay offset method increased by nearly two times compared with ECMP and single-path transmission when the disorder degree was maintained within 5%.

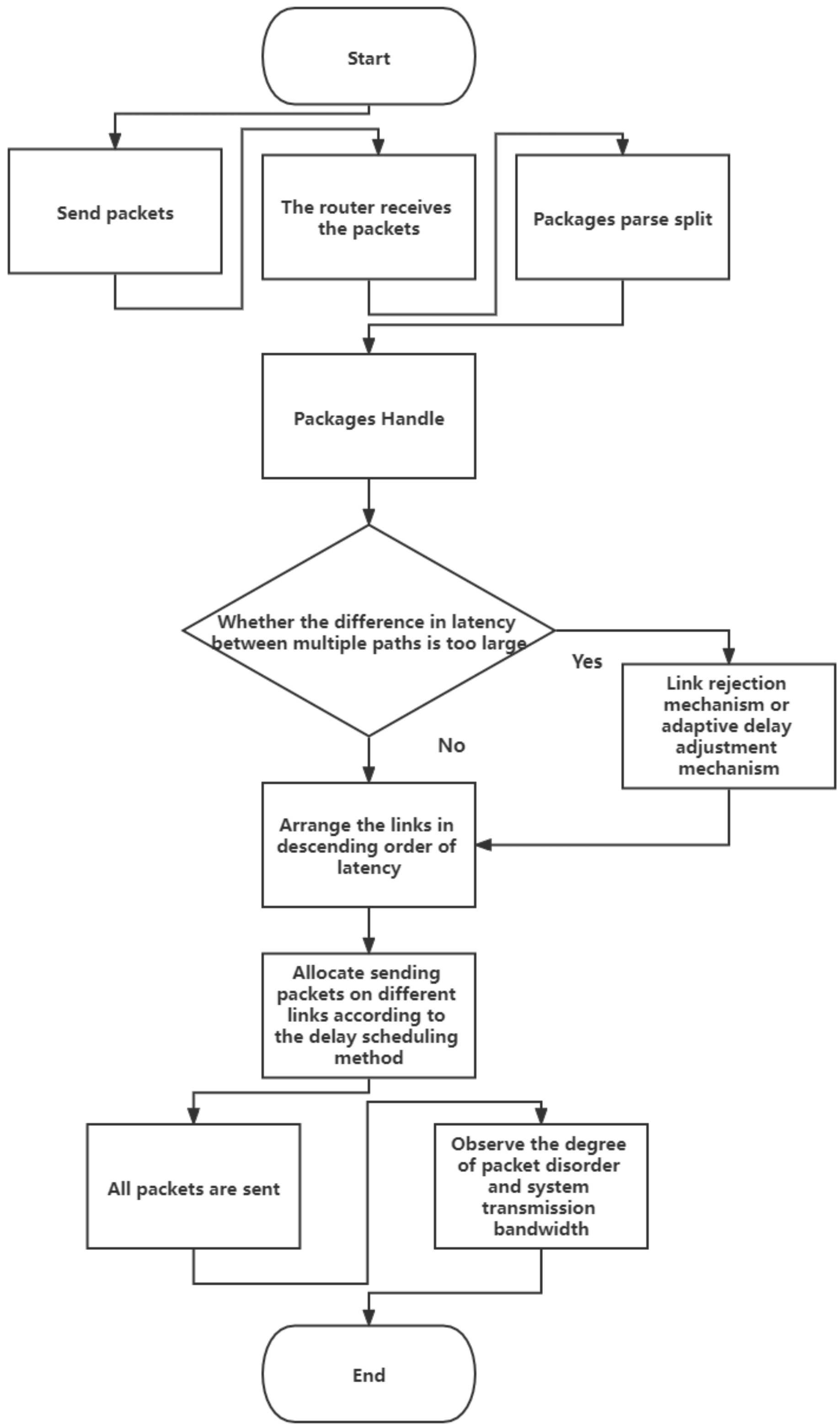


Figure 4: Algorithmic process.

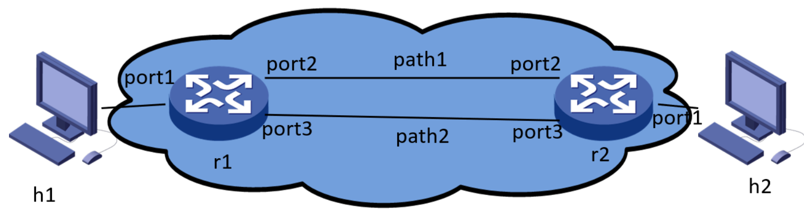


Figure 5: Experimental simulation network topology.

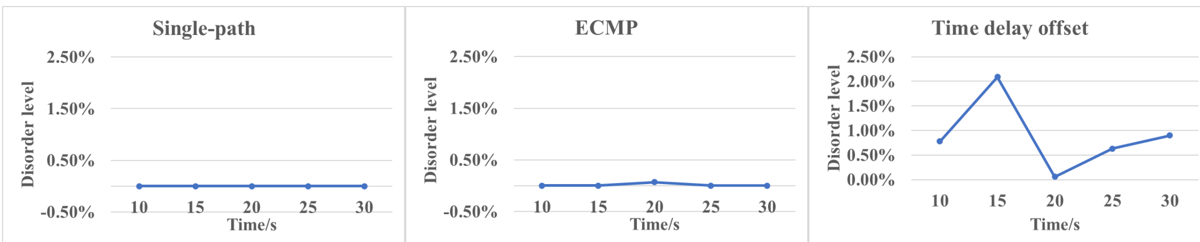


Figure 6: Compares the disorder level of the three scheduling methods.

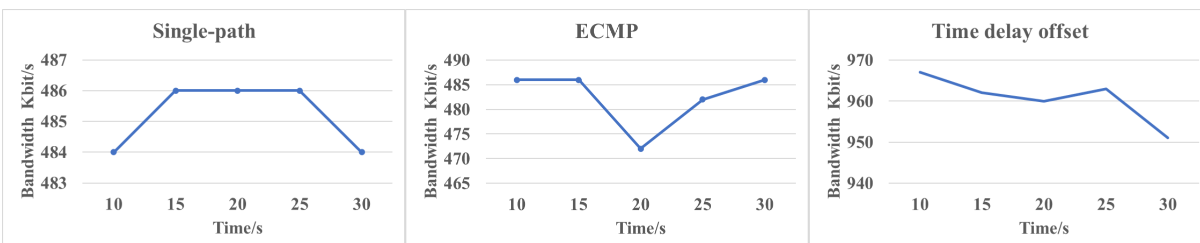


Figure 7: Compares the bandwidth of the three scheduling methods.

6 Conclusion

In this paper, we propose a delay offset method and corresponding link rejection and adaptive delay adjustment mechanisms for packet disorder suppression scheduling at the network layer, and it can be seen from the experimental results that compared with single-path transmission and equivalent multipath, the scheduling mechanism keeps the disorder level within 5%, and the transmission bandwidth is increased by nearly 2 times. At the same time, this method also overcomes the defects of RAID, ECMP and DPS in the network layer.

References

[1] A. Fahad, N. Alshatri, Z. Tari, A. Alamri, I. Khalil, A. Y. Zomaya, S. Foufou, and A. Bouras. A survey of clustering algorithms for big data: Taxonomy and empirical analysis. *IEEE Transactions on Emerging Topics in Computing*, 2(3):267–279, 2014.

[2] S. Singh, A. Singh, and V. Goyal. Cloud of things: A systematic review on issues and challenges in integration of cloud computing and internet of things. In *Proc. of the 3rd International Conference on Recent Innovations*

in Computing (ICRIC'20), Central University of Jammu, India, volume 701 of *Lecture Notes in Electrical Engineering*, pages 573–587. Springer, Singapore, March 2020.

[3] F. Song, M. Zhu, Y. Zhou, I. You, and H. Zhang. Smart collaborative tracking for ubiquitous power iot in edge-cloud interplay domain. *IEEE Internet of Things Journal*, 7(7):6046–6055, 2019.

[4] P. Minet, E. Renault, I. Khoufi, and S. Boumerdassi. Data analysis of a google data center. In *Proc. of the 18th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID'18), Washington, DC, USA*. IEEE, May 2018.

[5] P. Kumar, S. Garg, A. Singh, S. Batra, N. Kumar, and I. You. Mvo-based 2-d path planning scheme for providing quality of service in uav environment. *IEEE Internet of Things Journal*, 5(3):1698–1707, 2018.

[6] W. Lehr, F. Queder, and J. Haucap. 5g: A new future for mobile network operators, or not? *Telecommunications Policy*, 45(3):102086, 2021.

[7] H. A. Omar, K. Abboud, N. Cheng, K. R. Malekshan, A. T. Gamage, and W. Zhuang. A survey on high efficiency wireless local area networks: Next generation wifi. *IEEE Communications Surveys & Tutorials*, 18(4):2315–2344, 2016.

[8] F. Song, L. Li, I. You, and H. Zhang. Enabling heterogeneous deterministic networks with smart collaborative theory. *IEEE Network*, 35(3):64–71, 2021.

[9] K. Habak, K. A. Harras, and M. Youssef. Bandwidth aggregation techniques in heterogeneous multi-homed devices: A survey. *Computer Networks*, 92(P1):168–188, 2013.

[10] A. L. Ramaboli, O. E. Falowo, and A. H. Chan. Bandwidth aggregation in heterogeneous wireless networks: A survey of current approaches and issues. *Journal of Network and Computer Applications*, 35(6):1674–1690, 2012.

[11] Tarkoma, Sasu, Lukyanenko, Andrey, Li, Ming, Yla-Jaaski, Antti, Ou, and Zhonghong. Multipath transmission for the internet: A survey. *IEEE Communications Surveys & Tutorials*, 18(4):2887–2925, 2016.

[12] F. Song, Z. Ai, Y. Zhou, I. You, K.-K. R. Choo, and H. Zhang. Smart collaborative automation for receive buffer control in multipath industrial networks. *IEEE Transactions on Industrial Informatics*, 16(2):1385–1394, 2019.

[13] N. Mohamed, J. Al-Jaroodi, H. Jiang, and D. R. Swanson. A user-level socket layer over multiple physical network interfaces. In *Proc. of the 2002 International Conference on Parallel and Distributed Computing Systems (PDCS'02), Cambridge, USA*, pages 804–810. IASTED/ACTA Press, November 2002.

[14] Z. Tang, Z. Wang, P. Li, S. Guo, X. Liao, and H. Jin. An application layer protocol for energy-efficient bandwidth aggregation with guaranteed quality-of-experience. *IEEE Transactions on Parallel & Distributed Systems*, 26(6):1538–1546, 2015.

[15] A. Al, T. N. Saadawi, and M. J. Lee. Ls-sctp: a bandwidth aggregation technique for stream control transmission protocol. *Computer Communications*, 27(10):1012–1024, 2004.

[16] D. S. Phatak and T. Goff. A novel mechanism for data streaming across multiple ip links for improving throughput and reliability in mobile environments. In *Proc. of the 21st Joint Conference of the IEEE Computer & Communications Societies (INFOCOM'02), New York, NY, USA*. IEEE, June 2002.

[17] Y.-S. Chen, C.-H. Cho, I. You, and H.-C. Chao. A cross-layer protocol of spectrum mobility and handover in cognitive lte networks. *Simulation Modelling Practice and Theory*, 19(8):1723–1744, 2011.

[18] F. Song, Z. Ai, H. Zhang, I. You, and S. Li. Smart collaborative balancing for dependable network components in cyber-physical systems. *IEEE Transactions on Industrial Informatics*, 17(10):6916–6924, October 2020.

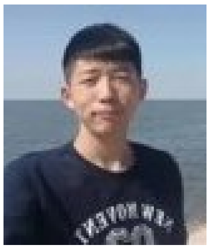
[19] Y. Zhang, P. Dong, S. Yu, H. Luo, T. Zheng, and H. Zhang. An adaptive multipath algorithm to overcome the unpredictability of heterogeneous wireless networks for high-speed railway. *IEEE Transactions on Vehicular Technology*, 67(12):11332–11344, December 2018.

[20] F. Song, Y.-T. Zhou, Y. Wang, T.-M. Zhao, I. You, and H.-K. Zhang. Smart collaborative distribution for privacy enhancement in moving target defense. *Information Sciences*, 479:593–606, 2019.

[21] L. Jin, W. Quan, G. Liu, D. Gao, and Q. Wang. DPS: A delay-programmable scheduler for the packet out-of-order mitigation in heterogeneous networks. In *Proc. of the 2020 IEEE International Conference on Communications Workshops (ICC Workshops'20), Virtual Conference*. IEEE, June 2020.

[22] C. Zhou, W. Quan, D. Gao, Z. Liu, C. Yu, M. Liu, and Z. Xu. AMS: Adaptive multipath scheduling mechanism against eavesdropping attacks with programmable data planes. In *Proc. of the 5th IEEE Advanced Information Technology, Electronic and Automation Control Conference (IAEAC'21), Chongqing, China*, pages 2357–2361. IEEE, 3 2021.

Author Biography



Shuxing Zhu received the B.S. degree from School of Electronic and Information Engineering, Beijing Jiaotong University in 2021. He is currently pursuing the master's degree at the National Engineering Laboratory for Next Generation Internet Technology, School of Electronics and Information Engineering, Beijing Jiaotong University. His current research interests include future network architecture and network transmission protocol.