Focus on Multipath TCP: Introduction, Benefits and Future Research Trends

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Abstract

With the rapid development of mobile video technology and the increasing demand for online video applications, people have higher demands on the transmission performance and user experience of real-time Internet applications such as video. Multipath transmission is considered as an ideal solution to improve video transmission performance and user experience quality in wireless network environment. In recent years, the academic research on multipath transmission protocol focuses on data scheduling, energy consumption optimization, fairness, congestion control and so on, but the research on network security is insufficient, especially the research on the anti-damage analysis and robustness optimization of multipath transmission. Based on a comprehensive analysis of the latest research trends, this paper makes a beneficial exploration of the future development of end-to-end multipath transmission over the Internet based on Multipath TCP (MPTCP).

Keywords: multipath transmission, MPTCP, robustness, network security

1 Introduction

As a interactive, personalized and real-time characteristics of the large-scale deployment of Internet applications, a growing number of terminal equipment is configured with a variety of different standard network interface (multi-host) and have the ability to access multiple network, people to the Internet applications such as video transmission performance and quality of experience have a higher demand. However, because the traditional transmission mode based on single-address connection only supports single path transmission, the multi-interface resources are not fully utilized, which further affects the transmission quality of real-time network applications such as video. Obviously, this transmission mode cannot meet the high-speed development of the Internet in the future. In contrast, the multipath transmission mode has the characteristics of bandwidth fitting and multipath concurrent transmission. Data communication based on this technology can fit the bandwidth resources of heterogeneous network, which can greatly meet the high bandwidth requirements of real-time applications such as video. It can be seen that multipath transmission is considered as an ideal solution to improve video transmission performance and user experience quality in wireless network environment.

How to organically integrate a variety of wireless access technologies (Bluetooth, WiFi, 4G, 5G, etc.), rationally use heterogeneous wireless network resources, so as to improve the quality of application data transmission service, has become a hot topic in the current academic research. In recent years, the

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Internet Engineering Task Force (IETF) has proposed the Stream Control Transmission Protocol (SCTP) [1] and Multipath TCP (MPTCP) [2], whose purpose is to enable multiplex terminals to access multiple networks at the same time, and to achieve multipath data transmission by fitting the bandwidth of multiple links, so as to improve the data transmission rate and maximize the utilization of network resources. In order to enable the large-scale application and deployment of multipath transmission technology in the future Internet, IETF also formulated a series of heterogeneous network configuration standards supporting the dynamic allocation and mapping of network address and network selection optimization for multi-host connection [3]. It can be predicted that multipath transmission protocol will become the core transmission protocol of the future Internet.

Although the corresponding standard drafts and application specifications of multipath transmission technology are constantly proposed, some technical solutions supporting multipath transmission have not been standardized in the industry due to the lack of backward compatibility of current Internet equipment. For example, Concurrent Multipath Transfer for SCTP (CMT-SCTP) based on the extension of SCTP is still under discussion. Among these multipath transmission protocols, MPTCP provides concurrent multipath data transmission for users while maintaining backward compatibility with existing Internet devices. MPTCP is also expected to play a huge role in the future of Internet data transmission services. Therefore, the research of MCTCP based multipath transmission theory and algorithm is of great significance to the future development of Internet applications.

This paper makes a comprehensive and systematic analysis of the latest developments of MPTCP from two aspects of standard formulation and theoretical research. In terms of theoretical research, this paper briefly summarizes the theoretical research status of MPTCP from seven aspects including data scheduling algorithm optimization, MPTCP fairness, energy consumption optimization and network security, and finally concludes that the research of MPTCP in network security is seriously insufficient. In view of this research situation, this paper proposes that the future research work can integrate machine learning and dynamic system modeling theory and other related methods to further study the robustness optimization of MPTCP transmission system. In this paper, based on the analysis of the current situation, the future development of the Internet end-to-end multipath transmission based on MPTCP has been beneficial exploration.

The rest of the paper is structured as follows. The second part is the research status and analysis of the Internet end-to-end multipath transmission based on MPTCP. The third part is the trend and prospect of the Internet end-to-end multipath transmission based on MPTCP. The fourth part is the summary of this paper.

2 Research status and analysis

The large-scale application of various wireless network technologies enables mobile Internet to provide high quality network services with ubiquitous heterogeneity and multi-access. The integration of multi-interface technology and the parallel transmission of user application data through multiple paths is considered as an important way to improve throughput performance, balance network load and maximize network resource usage. Figure 1 shows a simple example of multipath parallel transmission. As shown in Figure 1, the multi-host terminal device can simultaneously use multiple paths (path A and path B) to communicate with the video server when playing videos. This multipath transmission technology based on MPTCP is likely to greatly improve the system throughput performance, so MPTCP is considered as one of the most representative research achievements in the current multipath transmission technology, and may replace TCP as a universal transmission layer protocol in the future.

This part mainly analyzes and expounds the latest research trends of MPTCP from the aspects of standard formulation and theoretical research. Among them, section 2.2 mainly introduces the Internet

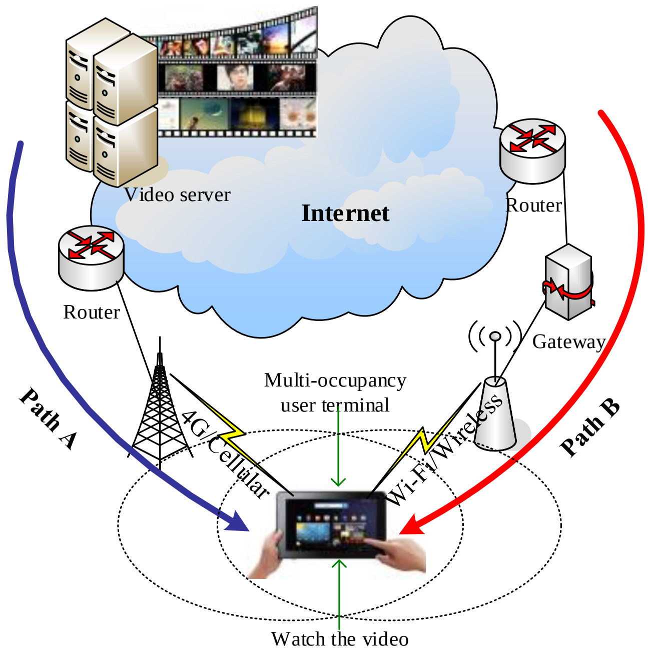

Figure 1: The example of multipath parallel transmission.

based on MPTCP end-to-end multipath transmission in data scheduling algorithm optimization, MPTCP fairness, optimization of energy consumption, network security and so on seven aspects of dynamic theory research, the final analysis it is concluded that the Internet based on MPTCP end-to-end multipath transmission research in the field of network security research is relatively scarce.

2.1 Research trends in standard formulation

In terms of standard formulation, the MPTCP working group under the IETF has been committed to the research and development of MPTCP related technical standards and the formulation of application specifications for many years. In 2013, RFC 6824 was released as the experimental standard of MPTCP. Subsequently, IETF published an extended draft of the MPTCP experimental standard in February 2019 [4]. Due to its backward compatibility with existing Internet devices and application interfaces, MPTCP has attracted great attention from academia and industry, and the corresponding research on scalability is also deepening. M. Scharf *et al.* [5] studied and summarized the considerations of MPTCP application interface in the proposed standard draft. In the proposed standard draft, M. Bagnulo *et al.* [6] analyzed the potential threats of MPTCP mechanism and proposed corresponding countermeasures. C. Xu *et al.* [7] designed an MPTCP extension protocol supporting partially reliable transmission in the proposed standard draft. M. Xu *et al.* [8] developed an MPTCP congestion control algorithm based on delay in the proposed standard draft. J. Zhao *et al.* [9] proposed an extended MPTCP solution to improve the experience quality of Dynamic Adaptive Streaming over HTTP (DASH). J. Ye *et al.* [10] proposed an improved MPTCP in Data Center Networking (DCN) to achieve the dual goals of low latency and high throughput. The development of these draft standards and application specifications provides a theoretical basis for the large-scale application of MPTCP in the future Internet.

2.2 Research trends in theoretical research

In terms of theoretical research, current academic scholars' research on MPTCP mainly focuses on data scheduling algorithm optimization. K. Xue *et al.* [11] proposed a dynamic packet scheduling algorithm based on forward prediction. B. Kimura *et al.* [12] discussed the impact of three data scheduling mechanisms: data scheduling based on the highest transmission rate, data scheduling based on the maximum transmission window and data scheduling based on the lowest transmission delay on MPTCP throughput performance respectively. E. Dong *et al.* [13] designed a wireless packet loss and delay fusion multipath data scheduler to enhance MPTCP transmission performance in high packet loss network environment. P. Hurtig *et al.* [14] proposed a new scheduling algorithm that can provide good user experience for delay-sensitive applications even in the case of asymmetric interface quality. K. Noda *et al.* [15] proposed a new MPTCP packet scheduler, which suppressed the fluctuation of Quality of Service (QoS) while maintaining the minimum throughput required by network services and improved the experience quality of network services. H. Zhang *et al.* [16] proposed an MPTCP scheduler based on reinforcement learning. Z. Arain *et al.* [17] defined the scheduling problem on MPTCP as a stochastic optimization problem and proposed a stochastic multipath scheduling scheme for data and path capacity changes, which made the system more stable and had higher energy efficiency. W. Yang *et al.* [18] proposed a loss-aware throughput estimation scheduler. J. Han *et al.* [19] proposed a coupled congestion control algorithm and scheduling algorithm to ensure the stability of the network when physical link changes and asymmetric links occur.

At the same time, using network coding technology and cross-layer design means to optimize the performance of MPTCP has become a research hotspot. In terms of fusion network coding technology, C. Xu *et al.* [20] designed an MPTCP multipath data distribution mechanism based on pipeline network coding by introducing pipeline network coding technology into MPTCP mechanism. The performance of multipath transmission system is improved while the encoding delay is reduced. A. Elgabli *et al.* [21] implemented a multipath video streaming algorithm at the application layer by introducing Scalable Video Coding (SVC) technology into the MPTCP mechanism, and reduced the quality decision of video blocks to an optimization problem. J. Hu *et al.* [22] designed an adaptive package spraying based on code, which uses the forward error correction technology to encode short streams and adjusts the coding redundancy according to the blocking probability, effectively alleviating the negative impact of short streams and long streams on each other.

In terms of integrated cross-layer design, H. Sinky *et al.* [23] analyzed problems related to network switching based on transmission layer, and on this basis proposed an MPTCP congestion control algorithm combining network switching awareness and cross-layer optimization. M. Fukuyama *et al.* [24] proposed a cross-layer optimization scheme based on frame loss monitoring in the data link layer to improve MPTCP throughput performance at the transmission layer. Y. Xing *et al.* [25] proposed a cross-layer MPTCP solution FSA-MPTCP, which can automatically provide flexible and optimal transmission policies for different data flows to improve the transmission performance of MPTCP. T. Zhu *et al.* [26] proposed a Graph Neural Network (GNN) based multipath routing model, and based on this model, proposed an MPTCP routing cross-layer optimization system, which can predict throughput under the condition of given network topology and multipath routing, and then guide the optimization of multipath routing. Y. Cao *et al.* [27] creatively proposed a cross-layer solution centered on the receiver to help MPTCP achieve efficient parallel multipath data transmission in wireless environment.

Recently, the research on MPTCP fairness and energy consumption optimization has been carried out extensively. In terms of fairness research, S. Ferlin *et al.* [28] introduced a simple and practical shared bottleneck detection algorithm into the MPTCP mechanism, so that MPTCP could meet the requirements of network fairness and bottleneck fairness as much as possible. M. Palash *et al.* [29] proposed a path scheduling scheme called MPWiFi that can guarantee the fairness of the client, which allows the

MPTCP client to freely obtain resources on the optimal WiFi path and suppress subflows on other paths when congestion occurs, effectively ensuring the fairness of the MPTCP client. J. Ye *et al.* [30] proposed a novel sharing bottleneck detection scheme EMPTCP, which can capture the real congestion state of sharing bottleneck, thus improving network efficiency and fairness. M. Kheirkhah *et al.* [31] proposed an adaptive multipath congestion control mechanism, which can significantly improve network fairness between multipath and single-path runoff. G. Kim *et al.* [32] adaptively adjusted congestion window (cwnd) reduction to achieve better throughput in the non-shared bottleneck, while maintaining fairness of MPTCP flows in the shared bottleneck. W. Wei *et al.* [33] proposed congestion control and packet scheduling scheme called BCCPS by taking advantage of bottleneck bandwidth and round trip propagation time and considering bottleneck fairness to improve the performance of MPTCP in heterogeneous wireless network environment.

In terms of energy consumption optimization, J. Wu *et al.* [34] proposed a bandwidth fitting scheme based on power quality perception, aiming at the contradiction between high energy consumption caused by MPTCP multiplexing and limited battery energy of mobile terminals, to reduce multipath concurrent transmission energy consumption while ensuring real-time video transmission quality. W. Wang *et al.* [35] proposed a Device-to-Device (D2D) communication scheme with high efficiency and energy saving, which reduced the energy consumption of D2D communication by balancing the traffic to the link with less energy consumption. M. Palash *et al.* [36] proposed to integrate the improvement of energy efficiency into the process of meeting bandwidth demand, and continuously help mobile devices balance bandwidth demand and energy efficiency. J. Wu *et al.* [37] proposed a delayed energy quality sensing MPTCP solution called DEAM to realize real-time video transmission in an energy-saving way. J. Zhao *et al.* [38] improved energy efficiency of MPTCP mechanism in DCN by minimizing completion time of flow. M. Aljubayri *et al.* [39] used Opportunistic Routing (OR) technology to reduce the delay of MPTCP by reducing the number of transmissions, further improving the startup delay and energy efficiency of MPTCP. M. Morawski *et al.* [40] adopted a formal optimization method and proposed a system tuning method of MPTCP architecture module with energy consumption as the target.

Recently, the combination of MPTCP, new network architecture and network security has aroused academic research interest. J. Pang *et al.* [41] creatively introduced MPTCP and segment routing technology into DCN. A. Hussein *et al.* [42] introduced the centralized management concept in Software Defined Network (SDN) into MPTCP, so as to improve the utilization rate of network resources and MPTCP performance. Z. Jiang *et al.* [43] designed a load-balancing-oriented MPTCP data flow scheduling mechanism according to the characteristics of SDN and satellite network. J. Hwang *et al.* [44] proposed an MPTCP fast retransmission mechanism to optimize the transmission quality of delay-sensitive data in DCN. S. Pang *et al.* [45] proposed an MPTCP transmission control method based on queue cache balance factor to solve the problem of throughput collapse in DCN, which can realize the load balancing of MPTCP data transmission. J. Hu *et al.* [46] designed a flow-aware load balancing scheme to improve the throughput performance of data transmission in DCN.

In terms of converged network security, M. Jadin *et al.* [47] proposed a response measure to MPTCP traffic attack in view of the possibility that attackers may listen on MPTCP substreams through bypass and inject forged MPTCP packets. A. Munir *et al.* [48] proposed an MPTCP path management and energy consumption optimization scheme aware of Low-rate Distributed Denial of Service (LDDoS). Y. Cao *et al.* [49] proposed a LDDoS aware energy-saving MPTCP solution, $\mathrm{MPTCP}-\mathrm{La}/\mathrm{E}^2$. Y. Cao *et al.* [50] proposed a novel measurement method to evaluate the robustness performance of MPTCP transmission system under network attacks with incomplete network information. G. Lei *et al.* [51] simulated and analyzed the queue occupancy rate of LDDoS attack flow in MPTCP transmission system, and then extracted the basic characteristics of LDDoS attack to improve the robustness of MPTCP transmission system.

In view of the latest research trends, we find that, so far, the research on MPTCP mechanism focuses on data scheduling, green energy saving, fairness issues and the combination of network coding, cross-layer design, new network architecture and so on, while the discussion of MPTCP security related issues is still in its infancy.

3 Research trends and prospects

Through the dynamic analysis and summary of MPTCP multipath transmission research in section 2, it is not difficult to find that the current academic and industrial circles have great attention and research interest in MPTCP-based Internet end-to-end multipath transmission. However, the discussion on MPTCP security is still in its infancy, especially the research on the anti-damage analysis and robustness optimization of MPTCP multipath transmission system is seriously lacking.

3.1 The necessity of MPTCP security research

With the large-scale deployment and application of emerging technologies such as the Internet of Things and cloud computing, all kinds of network attacks have shown a significant increase, and the network security situation is becoming increasingly serious. In addition, due to the random movement of terminal devices, the random failure of network links often occurs in the process of data transmission. Random failure of network links and deliberate network attacks will have a serious impact on the network security of MPTCP-based multipath transmission system, resulting in the decline of the robustness of the MPTCP transmission system, thus affecting the performance of data transmission and reducing users' Quality of Experience (QoE) for video and other Internet applications [52].

In recent years, a variety of network attacks have emerged, posing increasing threats to network security, among which Distributed Denial of Service (DDoS) attack is the most popular. DDoS attack is an advanced version of Denial of Service (DoS) attack. It has evolved into a new LDDoS attack. DoS attacks use a host to send attack packets to the destination host. The most common DoS attacks include computer network bandwidth attacks and connectivity attacks. Different from DoS attacks, the DDoS attack one or more targets by using computers controlled by programs in a cluster manner. All available resources are consumed and legitimate requests from normal users cannot pass through [53]. On the basis of DDoS attacks, LDDoS attacks control puppet machine periodically sends small pulse traffic to the target host at a lower sending rate. When all pulses reach the target at the same time, they converge into a huge impact traffic to realize the attack [54]. Random network link failure may be caused by link disconnection, routing failure, wireless signal weakness and other factors.

Figure 2 shows a multipath transmission scenario in which the transmission signal is randomly disconnected due to terminal movement and the path fails due to network attacks. As shown in the figure, MPTCP is used to communicate between streaming media server and mobile terminal, and n paths $(\mathrm{p}_1, \mathrm{p}_2, \cdots, \mathrm{p}_\mathrm{n})$ transmits data. Assume that in the process of concurrent data transmission, path p_1 is attacked by network attacks or the signal is randomly disconnected due to terminal movement, which may lead to path transmission failure and the structural robustness of multipath transmission system decline. At the same time, MPTCP data flows transmitted on path p1 may lose packets. And when a lost packets (red mark) failed to arrive at the receiving end, because of the need to submit to the upper application layer sequential, the receiver will not have been receiving other data (blue mark) delivered to upper application, thus lead to these have been receiving video data in their playing time unable to deliver to the upper application. The performance of the application layer throughput and video service quality are affected, and the performance robustness of the MPTCP transmission system deteriorates. Therefore, it is necessary to carry out frontier research on the robustness analysis and optimization of MPTCP-based multipath transmission system.

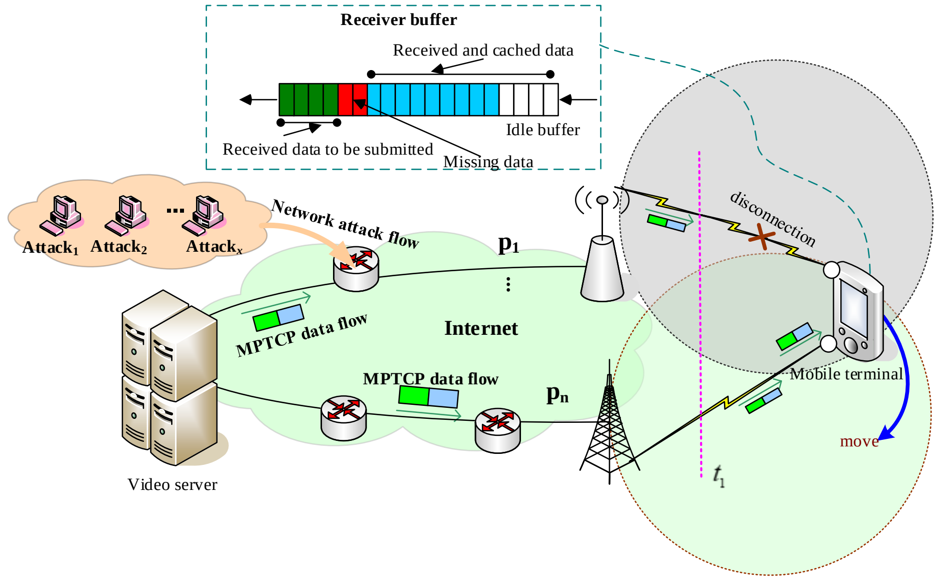

Figure 2: Schematic diagram of multipath transmission data disorder caused by terminal random mobile disconnection and network attacks.

3.2 The necessity of MPTCP security research

In the MPTCP multipath transmission system, each transmission path can independently transmit data based on its own network conditions. However, if a transmission path in the MPTCP transmission system encounters random failures or external network attacks, the degradation or failure of the transmission performance of the path affects the transmission performance of other transmission paths, thus adversely affecting the overall performance of multipath transmission. It can be seen that the MPTCP multipath transmission process presents obvious heterogeneity, integrity, uncertainty and other complex system behavior characteristics. Therefore, future research can integrate dynamic system modeling theory and complex network analysis method to establish the multipath transmission system robustness analysis model. However, it should be pointed out that there is no clear and unified robustness measurement index in academia. Therefore, in the process of studying the robustness analysis model, how to establish the robustness measurement index suitable for multipath transmission will also face some difficulties. In addition, the future research work can also take the network traffic in the MPTCP transmission system as a signal, combined with signal processing technology to realize the detection and defense of all kinds of network attacks [55], reduce the negative impact of deliberate network attacks on the MPTCP transmission system. For example, Wavelet Transform (WT), Empirical Mode Decomposition (EMD) and Ensemble EMD (EEMD) analysis methods.

Network behaviors, such as random link failures or deliberate network attacks, result in large differences in transmission quality parameters (such as bandwidth and delay) of paths in multipath transmission association. In this case, using the existing path management mechanism to simply fit all available network bandwidth resources for multipath transmission may cause problems such as data disorder arrival, cache blocking at the receiving end, and system robustness deterioration, which seriously affects the transmission performance of transmitted data such as video. Therefore, the existing MPTCP multipath management mechanism and heterogeneous network bandwidth fitting algorithm based on the traditional static mathematical model are often difficult to meet the requirements of complexity and accuracy. Therefore, future research work can integrate machine learning related technologies and methods [56] to study the robustness optimization method of multipath transmission system, and improve network resource utilization and system throughput while ensuring system robustness. However, the process of machine learning often realizes the result optimization at the cost of delay. Therefore, it will be a challenge to study the robustness optimization of multipath transmission system while considering the fairness and energy consumption optimization of the transmission system.

4 Conclusion

This paper makes a systematic and comprehensive analysis of the research on Internet end-to-end multipath transmission based on MPTCP in recent years from the aspects of data scheduling algorithm optimization, MPTCP performance optimization combined with network coding technology and cross-layer design means, fairness issues, energy consumption optimization and network security issues. Through the analysis, it is found that there is a serious lack of discussion and research on the anti-damage analysis and robustness optimization of MPTCP multipath transmission system. In heterogeneous wireless networks, random link failures and deliberate network attacks may degrade the robustness of the MPTCP multipath transmission system, affecting the transmission performance of application data, such as videos, and reducing the user'QoE for Internet applications.

Therefore, we can combine dynamic system modeling theory and complex network analysis method to study the multipath transmission system robustness analysis model in the future research work. Integrating signal processing method based on mathematical statistics, the detection and defense method of network attacks in MPTCP transmission system is studied. The robustness optimization mechanism of MPTCP multipath transmission system is studied by integrating machine learning related technologies and methods. It is an urgent and challenging trend to study the multipath transmission mechanism that can meet the needs of stable and reliable data transmission in the future, and to improve the damage resistance and robustness performance of multipath transmission system, which has extremely important research significance.

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