IJE TRANSACTIONS B: Applications Vol. 39, No. 02, (February 2026) 534-546

International Journal of Engineering

Journal Homepage: www.ije.ir

Adaptive and Optimized Scheduling Mechanism for Heterogeneous Wireless Networks Using an Explicit Flag Based Reinjection Approach

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PAPER INFO

Paper history:
Received 17 January 2025
Received in revised form 20 March 2025
Accepted 05 April 2025

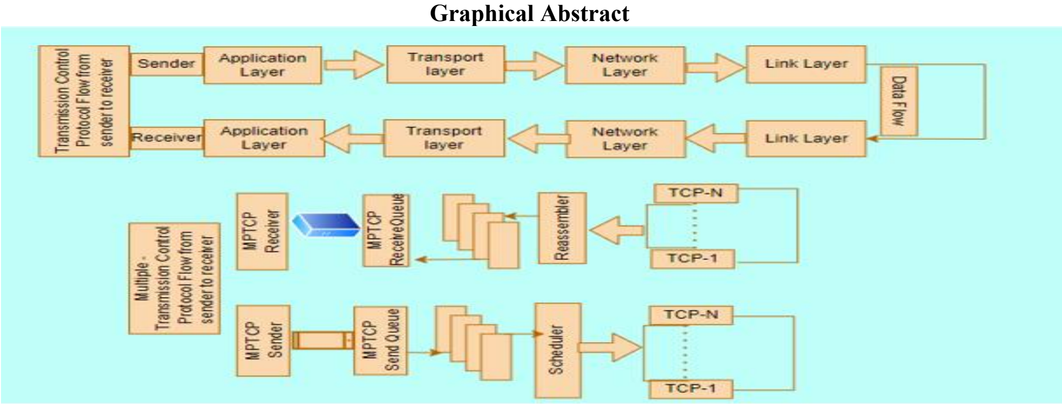
Keywords:
Algorithm
Flow Control
Buffer
Sender
Latency

ABSTRACT

The use of mobile devices with multiple interfaces has transformed communication by enabling simultaneous data transfers. This capability has driven the adoption of the Multipath Transmission Control Protocol (MPTCP), which leverages multiple interfaces to transmit data concurrently over different paths, improving overall connectivity. However, several factors affect MPTCP performance, including fluctuations in sub-flows, out-of-order (OOO) packet delivery, and inefficiencies in retransmitting lost packets. Addressing these challenges is crucial for enhancing MPTCP efficiency. Optimizing retransmission strategies can improve both throughput and reliability while mitigating sub-flow irregularities ensuring stable communication. Although various methodologies have been proposed, most existing approaches primarily focus on packet scheduling, with limited emphasis on lost packet retransmission as a distinct issue. This work highlights the importance of retransmission alongside scheduling mechanisms. The proposed approach consists of three key modules, identification of packets requiring retransmission, selection of the optimal path, and transmission of these packets through an active and available route. To achieve this, our methodology marks lost packets with a retransmission flag and efficiently routes them through the selected path, enhancing MPTCP and minimizing delays in data delivery. The proposed scheme was implemented in NS-3.4 and evaluated using delay-sensitive applications. The results demonstrate that our methodology significantly outperforms existing approaches, making it a promising solution for improving MPTCP performance. Specifically, FBMPTCP-CWND and FBMPTCP-SSTHRESH achieve superior performance over the existing methodology by increasing throughput by 5%, reducing jitter by 13%, lowering packet retransmissions by 33%, and decreasing delay by 8%.

***doi**: 10.5829/ije.2026.39.02b.19*

Graphical Abstract



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Please cite this article as: Raghavendra Rao K, Ramya Kalangi R, Balaji B, Agarwal V. Adaptive and Optimized Scheduling Mechanism for Heterogeneous Wireless Networks Using an Explicit Flag Based Reinjection Approach. International Journal of Engineering, Transactions B: Applications. 2026;39(02):534-46.

1. INTRODUCTION

MPTCP, a promising transport layer protocol, plays a vital role in enhancing data transmission by leveraging multi-homing devices and heterogeneous access technologies across multiple pathways. This approach allows MPTCP to effectively harness the extensive bandwidth and reliable connectivity features offered by 5G networks (1). By transmitting data simultaneously through various paths, it ensures improved throughput and reduced latency, catering to the demands of modern high-speed applications. Furthermore, MPTCP's ability to distribute traffic across different interfaces enhances network resilience, providing seamless communication even during failures or disruptions. Its integration with 5G technologies makes it a cornerstone for achieving efficient and scalable next-generation networking solutions (2). The IETF recommends MPTCP as a key transport protocol for multi-path parallel transmission. Figure 1 illustrates data communication in MPTCP using multiple interfaces. Optimizing retransmission is critical for improving MPTCP performance and enhancing mobile streaming quality. This work improves the RTX-CR policy, considering CWND and RTT, and proposed MRTX-CWND and MRTX-SSTHRESH protocols for retransmitting dropped and out-of-order packets (3). However, packet losses in sub-flows occur infrequently. The methodology (CMT-SCTP) Concurrent Multipath Transmission Stream Control Transmission Protocol protocol proposes five retransmission techniques to address this issue. Request For the Comment (RFC) 4460 recommends for a Retransmission-Congestion Window (RTX-CWND) & Retransmission – Slow - Start - Threshold methodology (RTX-SSTHRESH), with RTX-CWND as the default for efficient retransmission. Applying MRTX-CWND and MRTX-SSTHRESH to MPTCP improves packet retransmission, resolves receiver buffer block issues, and boosts throughput during high packet losses, ensuring better reliability and network performance in diverse conditions (4). By leveraging both 5G and MPTCP, the protocol reduces latency, optimizes network utilization, and enhances the user experience for multimedia streaming applications (5). MPTCP establishes multiple simultaneous pathways between endpoints, improving transmission efficiency, network performance, and user satisfaction. These features are particularly beneficial as mobile devices increasingly support heterogeneous access technologies (6). The Multi-Path TCP supports multiple simultaneous connections, boosting efficiency and user experience, especially for mobile devices. However, retransmission faces challenges with out-of-order packets. RFC 6824 outlines MPTCP's retransmission strategies, including an opportunistic approach (7). Distributing traffic intelligently, MPTCP enhances resilience and maintains seamless communication even under challenging conditions.

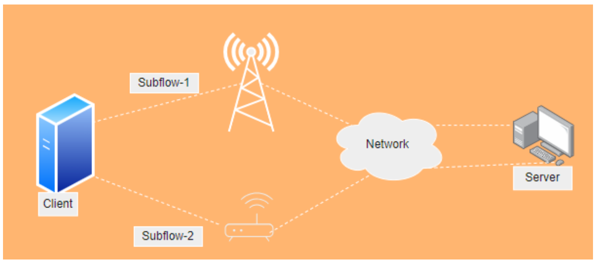

Figure 1. Data communication in MPTCP utilizes multiple network interfaces

Its integration with 5G's advanced features makes it a key enabler for supporting modern, high-speed, and reliable network applications. It reduces latency, improves network utilization, and enhances multimedia streaming (8). The MPTCP transport layer protocol takes leverages multi-homing and heterogeneous access technologies to transmit data across multiple pathways, effectively utilizing the high bandwidth and reliable connectivity of 5G networks. This capability ensures optimized data delivery, reducing delays and improving overall network efficiency (9). The two techniques define the MPTCP retransmission mechanism, as detailed in 6824. The first is an opportunity-driven opportunistic retransmission strategy, where lost packets are retransmitted via alternate, less-congested channels (10). The second is the cautious retransmission method, which retransmits packets along the same pathway. If a sub-flow becomes unavailable, MPTCP may fail to deliver packets within the allocated timeframe (11). This can lead to packets arriving via faster paths occupying the receiver buffer space ahead of those from slower paths, resulting in out-of-order delivery (12). While MPTCP offers numerous benefits on mobile devices, its retransmission mechanism still encounters challenges and has limited impact in some scenarios. Retransmission management in MPTCP can be complex due to out-of-order packet delivery (13). A well-optimized retransmission mechanism mitigates these bottlenecks and enhances transport layer throughput. The retransmission plays a crucial role in addressing the Receiver Buffer Block issue, ensuring smoother data flow within the network (14). By promptly handling lost data packets, it minimizes delays and maintains consistent data packet delivery. Additionally, robust retransmission strategies enhance overall network performance and reliability, making them essential for modern communication systems (15). Such mechanisms are particularly vital in dynamic and high-demand environments, where uninterrupted connectivity is a priority. Research on retransmission mechanisms has garnered substantial attention recently (16). A fast-coupled retransmission technique has been proposed to resend packets through open, uncongested links. The Retransmission-Congestion & Roundtrip Time (RTX-CR) policy, which selects paths based on factors like the Congestion Window (CWND) and Roundtrip Time (RTT), was improved by the author. Additionally, the Multi-Path Retransmission-Congestion Window (MRTX-CWND) & Multi-Path Retransmission-Slow Start Threshold (MRTX-SSTHRESH) protocols were suggested for retransmitting lost or disordered packets. However, these protocols rarely address scenarios where a sub-flow experiences multiple packet loss or drops (17). The methodology focuses on faster data downloads, cost-effective transfer, and seamless transitions between heterogeneous wireless interfaces, particularly Wi-Fi and cellular networks (18). The Concurrent Multi-Path Transmission- Stream Control Transmission Protocol (CMT-SCTP) has proposed five retransmission mechanisms, but Request For Comment (RFC) 4460 has recommended only two of them RTX-CWND and RTX-SSTHRESH packets (19). This approach can be especially problematic for low-latency required applications and real-time applications like online gaming and video conferencing, where even slight delays can be felt by the user and cause significant disruptions. The only choice is to wait for a successful retransmission (20). MPTCP is proposed to aggregate multiple interfaces, enhancing resilience and throughput in multi-homed devices. A novel approach was developed for retransmitting packets through a non-congested path. To minimize application delivery delay at the receiver end, the system detects lost connection and reinjects missing packets into the faster flow (21). To improve sub-flow selection, factors like RTT and packet loss rate can be utilized. Current MPTCP implementations rely on static sub-flow management, limiting adaptability to dynamic network conditions (22). Packet loss and sub-flow heterogeneity reduce MPTCP throughput due to Out-of-Order packets. To address this, researchers have proposed various schedulers. Summarizes these and suggests a reliable scheduler to minimize Out-of-Order packets and improve MPTCP performance. They analyzed 5G performance, developing a custom tool on a smartphone to work on TCP and MPTCP behavior (23). The primary goals are to protect Forward Error Correction (FEC) and maintain its retransmission method. He proposed an equation to predict retransmissions based on propagation delay, packet loss, RTT, sub-flow latency, and retransmission timeouts (24). Algorithms improve retransmission rates and flow completion efficiency in 5G networks. Various retransmission strategies, including diverse routes, lead to differences in Round Trip Time (RTT), throughput, and jitter, causing out-of-order packets and unnecessary retransmissions (25). HaghzadKlidbary and Javadian (22); Kuna and Kumar (26) evaluated the system based on throughput and packet delivery ratio before introducing a two-step security mechanism to address the node or cluster head issue. They proposed a novel method for selecting cluster heads based on energy levels and distance, with a primary focus on optimizing energy efficiency (26). However, the current strategy proved ineffective at this stage. Jameii and Khanzadi (23) proposed a new method to reduce application latency, recognizing it as a critical factor in online gaming. To identify the node capable of minimizing user latency, Sridher et al. (27) recommended utilizing the RL (Reinforcement Learning) approach. A Global Positioning System (GPS) signal is essential for tracking systems or objects but faces issues in various scenarios. Trajectory Tracking and Positioning (TT&P) methodology effectively supports object tracking using Simultaneous Localization and Mapping (SLAM) and demonstrates high effectiveness. However, SLAM has limitations. To enhance efficiency, proposed the use of the Crow Search Algorithm (CSA) (28). The antenna plays a vital role in enhancing this performance. Sarma proposed a novel antenna alignment method that significantly improves received signal strength (29). His work focused on energy-efficient, congestion-free data transport using the Conglomerate Efficient Protocol, achieving higher throughput and lower delay than existing methods (6). Wireless Body Area Network (WBSN) faces design challenges due to equipment limits. To ensure secure data transmission and enhance Quality of Service (QoS), communication protocols were developed, improving earliest deadline first (EDF) and least laxity first (LLF) scheduling algorithms (30). Proposed the Seagull Optimization Algorithm with Task Scheduling (SOATS) for load balancing, cost, and energy efficiency, outperforming existing algorithms in reducing waiting time and energy consumption (31). 5G supports applications like cloud computing and the Internet of Things (IoT), relying on low latency and efficient battery usage (32). Nanomaterials-based energy collectors with PVDF nanofibers harvest vibration energy, enabling sustainable power for IIoT in Industry 4.0 (33). This work also comprehensively analyzes key factors influencing mobile social media marketing acceptance, emphasizing that profitability, risk avoidance, effective strategies, and technological innovation are essential for improving customer engagement, loyalty, and adoption (34). OSN’s extensive communication infrastructure has played a significient role in its growing popularity. The focus was primarily on safeguarding personal information and exploring various methods and algorithms to enhance its security (35). The main focus is on how individuals and organizations utilize work benefits and how this reflects on the end user. Understanding these dynamics helps in optimizing resource allocation and improving overall efficiency (36). Because of the internet's widespread accessibility, ensuring security and privacy has become highly challenging. Many individuals attempt to gain unauthorized access to others' personal information online (37). Privacy was his primary concern. To tackle these issues, businesses now require advanced security intelligence systems to restrict unauthorized access to data. Strengthening the protection of sensitive and vulnerable information can also enhance security, ensuring smooth operations (38). As the tendency grows, challenges also arise. Even in the healthcare system, resources are integrated with IoT. This technology enables faster and more efficient treatment (39).

2. BACKGROUND AND MOTIVATION

The multipath requires packet retransmission, and modern algorithms in CMT_SCTP and MPTCP have introduced various methods to improve the user experience. These approaches are widely known as standard retransmission processes (40). By efficiently managing lost packets, these methods ensure seamless data flow and enhance overall network performance. Additionally, they play a critical role in reducing latency and maintaining throughput, even under adverse network conditions (41). The continuous advancement of retransmission techniques highlights their significance in ensuring reliable and efficient communication across diverse network conditions. In this article, a concise review of standard retransmission procedures is presented, including methodologies Retransmission-Same (RTX-SAME) methodology, Retransmission - As Soon As Possible (RTX-ASAP), Retransmission - Loss Rate (RTX-Loss Rate), Retransmission-Congestion Window (RTX-CWND), and Retransmission-Slow Start Threshold (RTX-SSTHRESH) approach. Additionally, two proposed MPTCP retransmission methods, Flag-Based Multi-Path Retransmission-Slow Start Threshold (FBMRTX-SSTHRESH), and Flag-Based Multi-Path Retransmission - Congestion Window (FBMRTX–CWND), are introduced. MPTCP is to optimize the utilization of open and unobstructed routes. However, if all data packets are transmitted, but the final packet in the flow arrives out of order due to congestion on one of the available paths, an alternative approach would be to retransmit those packets from congested routes to less congested ones. MPTCP utilizes the conservative retransmission strategy (RTX-conservative), where retransmitted data packets follow the same path as the original transmission. An alternative flow is selected for the packet once a retransmission timeout occurs (42). Cybersecurity attacks are becoming increasingly prevalent and network threats can be identified using optimization techniques. To enhance threat detection and prevention, a modified version of the genetic algorithm and the grasshopper algorithm has been proposed (43). The Internet of Things (IoT) reduces the demand for spectrum utilization by optimizing communication efficiency. Additionally, IoT devices operate under strict power constraints, requiring energy-efficient protocols. To enhance security, physical layer encryption and key generation techniques are employed, ensuring data integrity and protection against cyber threats. Moreover, advanced authentication mechanisms are integrated to mitigate unauthorized access and enhance overall network reliability (44).

2. 1. Regular Retransmission Mechanism

In the RTX-SAME process, the data is distributed and transmitted, all retransmitted data will continue to follow the same path unless that path becomes unavailable.

In the RTX-ASAP process, When retransmitting data, the sender utilizes any path with available CWND space. If several paths have enough CWND space, one is chosen at random for retransmission.

RTX-LOSSRATE: A flow with the lowest loss rate is designated for retransmitting lost packets. If multiple flows meet the criteria, one is randomly selected for retransmission.

RTX-CWND: A flow with the largest CWND at the sender's end is selected for data retransmission. If multiple flows meet the criteria, one is randomly chosen for retransmission.

RTX-SSTHRESH: A flow with the highest ssthresh at the sender's end is selected for data retransmission. If multiple flows meet the criteria, one is randomly chosen for retransmission. According to RFC4460, only the Retransmission-Congestion Window & Retransmission-Slow Start are recommended methods as concurrent retransmission mechanisms for multi-path SCTP and MPTCP, while other methods are limited to experimental purposes.

2. 2. Proposed Method for Packet Re-injection with Flag

As explained in Section 2.1, the MPTCP transmission performance is affected by the inability of standard MPTCP to retransmit packets promptly through non-congested channels. By integrating the RTX-SSTHRESH and RTX-CWND into MPTCP, and retransmitting packets while preserving the flag and selecting the best path, this issue can be addressed through a proposed novel technique. This section introduces the packet retransmission method using a flag notification mechanism to enhance efficiency and performance in MPTCP. Subsection 2.2.1 details the calculation of the reinjection timer, subsection 2.2.2 outlines the process of identifying packets for retransmission, subsection 2.2.3 explores the selection of the optimal path, and subsection 2.2.4 describes the retransmission of the chosen packets. This led to the development of a new methodology based on the Flag-

Based Multi-Path Retransmission-Congestion Window (FBMRTX-CWND) and Flag-Based Multi-Path-Slow Start Threshold (FBMRTX-SSTHRESH). The approach is divided into four modules being the first module is the Reinjection Timer Calculation Module (RTCM), the second module is the Gathering of the Retransmission Data Packets & Flag Set Module (GRDP&FSM), the third module is the Selection of Optimal Active Sub-Flow Path Module (SOASPM), and the fourth module is Retransmission of Collected Data Packets Module (RCDPM). Figure 2 represents, that once two channels have been created between the MPTCP sender and recipient, the packets are equitably dispersed over the two paths. Data Sequence Number (DSN) 1-3 packets are sent by the sender via Sub-flow-1, whereas DSN 4-6 packets are sent via Sub-flow-2. The DSN-2 packet is missing and is not able to get to the recipient in time. FBMRTX-CWND and FBMRTX-SSTHRESH will successfully gather the retransmission data packet information. The packet will then be retransmitted using a higher performance optimal path, with a flat bit set and the largest congestion window or ssthresh. In the MPTCP, the efficient, reliable, and straightforward retransmission procedures promptly resolve Receiver Buffer Block (RB2LOC) issues. It calculates the retransmission timer, identifies packets, marks them with the PSH flag, and selects the optimal path for delivery. This approach optimizes performance and reliability by efficiently using the PUSH (PSH) flag.

The process begins with the computation of the retransmission timer, followed by identifying the retransmitted packets and marking them with the PSH flag. The proposed packet retransmission mechanism is designed to utilize the unique characteristics of each path. The accompanying algorithms define the variables involved in MPTCP retransmission. Subsequently, the algorithm selects the optimal transmission path and directs the packets accordingly. This approach ensures that the retransmission mechanism efficiently leverages the Push (PSH) flag to deliver packets over the most suitable path, optimizing performance and reliability.

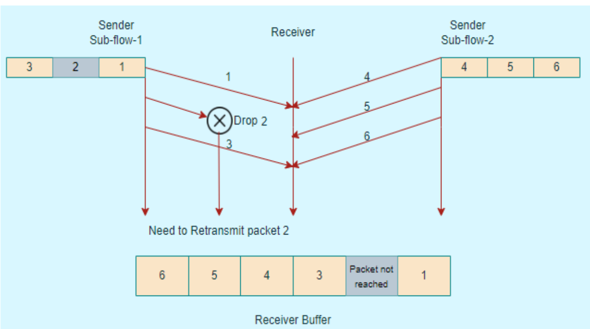

Figure 2. Transmission of data using Multi-Path Transmission Control Protocol (MPTCP) occurs from the sender to the receiver

2. 2. 1. Reinjection Time Calculation Module (RTCM) In the absence of information regarding intermediate data-link levels at the end hosts, identifying a connection loss caused by issues in the intermediate network segments between the client and server becomes challenging. Due to the absence of information on intermediate data-link levels at the end hosts, identifying connection losses caused by failures within intermediate network segments between the client and server is challenging. This limitation arises as end hosts operate at higher network layers, lacking visibility into lower-level link dynamics. Consequently, detecting and addressing such failures often require additional monitoring or external intervention. To mitigate this issue, an additional mechanism is required for reinjecting lost packets. When a sub-flow retransmission timeout (RTO) occurs, MPTCP reinjects fresh packets, ensuring that unacknowledged packets from the affected sub-flow are retransmitted through subsequent sub-flows. The RTO timer serves as the primary trigger for packet reinjection methodology. The retransmission timeout mechanism has been adapted from Single Path Transmission Control Protocol (SPTCP) to MPTCP, while packet reinjection in MPTCP is delayed by the extension tail-loss probe (TLP), originally introduced in SPTCP to enhance retransmission behavior. The reinjection timer was previously computed under general conditions; however, the recommended formula for its calculation has now been revised. The packet interval time is determined using two approaches the first considers the time between consecutive packet transmissions at a fixed rate, while the second measures the time required for a single packet to travel from source to destination. The latter approach has been selected, as latency and individual packet performance are critical for network diagnostics and performance evaluation.

Packet Interval time = μ,

Propagation Delay =α,

$$\alpha\text{=Adjust factor based on RTT} \quad (1)$$

$$REJ = SRTT + K * RTT_{VAR} - \alpha \quad (2)$$

This work presents an innovative approach integrating Flag-Based Multi-Path Slow Start Threshold (FBMRTX-SSTHRESH) and Flag-Based Multi-Path Retransmission-Congestion Window (FBMRTX-CWND) to enhance retransmission efficiency in multipath communication. The methodology consists of four key modules, RTCM calculates the reinjection timer, GRDP&FSM gathers lost packets and assigns retransmission flags, SOASPM selects the optimal sub-flow path, and RCDPM executes retransmission to improve network performance. Figure 2 illustrates the even distribution of packets across two established paths in an MPTCP connection. While packets are transmitted via different sub-flows, DSN-2 is lost due to delay.

FBMRTX-CWND approach & FBMRTX-SSTHRESH approach systematically collect retransmission data, selecting the optimal path—based on a flat bit set and the highest congestion window (ssthresh)—to efficiently retransmit the lost packet. The proposed methodology employs a structured retransmission mechanism to address Receiver Buffer Block (RB2LOC) issues. It systematically computes the retransmission timer, identifies and flags lost packets with PSH, and selects the most efficient delivery path. By leveraging the PUSH (PSH) flag, this approach enhances transmission efficiency, reliability, and network performance.

The topology used in the simulation is illustrated in Figure 3. As depicted in the diagram, this scenario involves two source-to-destination flows, each with unique attributes. The proposed retransmission mechanism utilizes the unique characteristics of each path, as illustrated in Figure 4. It determines the retransmission timer, identifies the packets, assigns them the PSH flag, and selects the most suitable path for delivery. By effectively using the PUSH (PSH) flag, this method enhances both performance and reliability.

Algorithm 1. Reinjection time calculation module

Step 1: Start Step 2: Input the following parameters. 2.1Set Distance(D) 2.2 Set Propagation speed (PS) 2.3 Set Packet Size (PS_Z) 2.4 Link Capacity. Step 3: Identify the Propagation delay. Propagation delay = Distance/propagation speed $PD = \frac{D}{PS}$ Step 4: Calculate Transmission Time. Transmission time Packet size / Link capacity $TT = \frac{PS_Z}{LC}$ Step 5: Calculate Packet Interval Time. Packet Interval Time = Transmission Time + propagation Delay. PIT = TT + PD. Step 6: Output the Packet Interval Time. Step 7: End

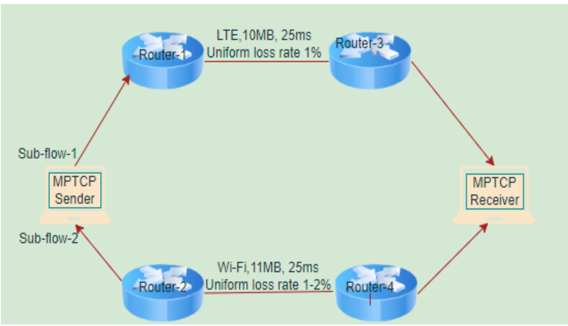

Figure 3. Topology design for Multipath simulation

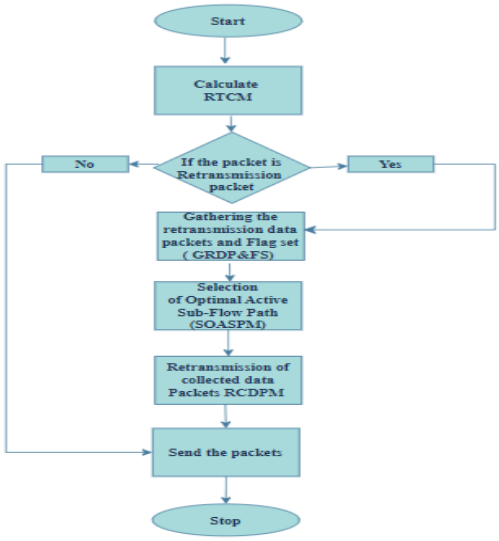

Figure 4. Flowchart representation of MPTCP with PSH-based reinjection

2. 2. 2. Gathering the Retransmission Data Packets and Flag Set (GRDP&FS) Module

The module responsible for gathering retransmission data packets collects the necessary packets and sets a flag to ensure their immediate retransmission without delay. This process facilitates swift packet handling and minimizes latency during retransmission. GRDP&FS begins compiling a list of retransmission packets list (denoted by Plist), which is used to store the packets flagged for retransmission list if there are "N" Sub-flows present (Sf1, Sf2, Sf3, ..., Sfn) in MPTCP association. The process involves checking each open path to determine if a packet requires retransmission by examining the packet retransmission flag. If retransmission is necessary, the packet details are added to the collection. The corresponding pseudocode is presented in Algorithm 2.

Algorithm 2. Gathering of retransmission packet Information and flag set

Initialization:
P_i: i_{th} retransmitted packet information.
P_{List}: List of retransmitted packet information.
S_F: sub-flow in the MPTCP connection.
S_{List}: list of all active sub-flow lists.
P_{Flag}: The packet needs to be retransmitted.
 	
Step 1: Start
Step 2: For each active sub-flow path Sf_i does.
If the state of the sub-flow = active then.
Put sub-flow into SF_{list}.
End if
End for
Step 3: For each sub-flow SF_{list} do.
If P_{flag} == RTX then.
Put P_i into P_{list}.
End of.
End for.
Step 4: End.

2. 2. 3. Selection of Optimal Active Sub-Flow Path (SOASPM) Module The module for optimized reinjection flow selection prioritizes flows with the largest congestion window (or higher Slow Start Threshold values) and the lowest RTT among the available options, ensuring efficient and reliable reinjection. Algorithm 3. Shows the pseudocode of optimal active sub-flow path selection module.

2. 2. 4. Retransmission of Collected Data Packets (RCDPM) Module Using the three modules mentioned above, RCDPM promptly transmits the packet. In cases where multiple sub-flows have identical CWND and ssthresh values, the algorithm evaluates which sub-flow has the lowest RTT and selects that flow for retransmitting the packets. Algorithm. 4 shows the Retransmission of the collected data Packets module.

3. SIMULATION AND ANALYSIS

The simulation topology is used to assess MPTCP's performance and explains the different retransmission mechanisms utilized by MPTCP.

Algorithm 3. optimal active sub flow path module

```
Initialization:
SF_list:            :  List of all active available sub-flow paths.
SF_i^CWND           :  CWND of the i_th sub-flow path
SF_i^SSTHRESH       :  SSTHRESH values of the i_th sub-flow.
SF_list(i)^cwnd     :  the list of all active sub-flow paths cwnd.
SF_list(i)^SSTHRESH :  The list of all active sub-flow SSTHRESH.
: The path selected to retransmit the packets.

Step 1: Start.
Step 2: Set SF_m^cwnd= SF_list(0)^cwnd,SF_m^ssthresh = SF_list(0)^sstrresh.
Step 3: If M_PTCP R_TX P_OLICY = FBMRTX - CWND then.
Step 4:     For each active sub-flow SF_list do.
                If SF_m^cwnd<SF_list(i)^cwnd then.
                    Set m = i
                    Set SF_r^path =SF_list(i)
                Else if SF_m^cwnd = SF_m^cwnd then.
                    Else if SF_m^rtt<SF_list^rtt
                        Set m = i
 Set the SF_r^path which has minimum rtt value.
            End if
        End for.
    End of.
Step 5: If M_PTCP R_TX P_OLICY = FBMRTX - SSTHRESH then.
Step 6: For each active sub-flow SF_list do
                If SF_m^ssthresh<SF_list(i)^ssthresh then.
Set m = i
                Set SF_r^path =SF_list(i)
                        Else if SF_m^ssthresh = SF_m^ssthresh
then.
                        Else if SF_m^rtt<SF_list^rtt
Set m = i
Set the SF_r^path which has minimum rtt value.
                End of.
        End for.
        End of.
Step 7: End.
```

Algorithm 4. Retransmission of Collected Data packet Module

```
Initialization:
: List of all active sub-flow paths.
P_i     : i_th path needs to retransmit the packet.

SF_r^path: The path selected to retransmit data when the packet is sent.
Step 1: Start
Step 2: For each active path in SF_list do.

Step 3: If SF_i.path! =SF_r^path then.
            Retransmit the SF_i by SF_r^path.
    End of.
    End for.
Step 4: End.
```

3. 1. Experimental Setup Details To achieve a more accurate and realistic network simulation, it is essential to properly configure traffic generators for both TCP and UDP. Currently, TCP traffic accounts for approximately 80–83% of all Internet traffic, while UDP traffic makes up the remaining 17–20%. Across all paths, 80% of the traffic is alocated to TCP, with 20% is assigend to UDP. This ensures the simulation reflects actual network conditions, providing a reliable environment for testing. By maintaining these proportions, the performance and behavior of protocols can be analyzed more effectively under real-world traffic patterns. Every traffic generator on the router (R1, R2, R3, and R4) has a reasonable 100 Mb network capacity with a 25 ms propagation latency. The work was conducted and experimented in simulator NS-3.4 to achieve better results. The sender and receiver in this topology have two distinct paths called sub-flow-1 and sub-flow-2. A Long Term Evolution (LTE) interface with a 10 MBPS bandwidth, a propagation delay of 10 ms to 25 ms, and a uniform loss rate of 0.1 to 1.0 is deployed using Sub-flow 1. Additionally, sub-flow-2 is depicted for a Wi-Fi link with an 11 MB bandwidth and a propagation delay of 10 to 25ms. Sub-flow-1 sets the packet loss rate level between 0.1 and 1.0, and sub-flow-2 sets it between 1.0 and 2.0.

MPTCP incorporates opportunistic retransmission and penalization, allowing it to reduce the window size of a slow path by half while redirecting unacknowledged packets to alternative, less congested paths when congestion occurs. This approach is effective for long data flows but may not be suitable for shorter ones. It works when all packets in a flow are transmitted, and at least one packet is received out of order.

The remaining parameters utilize NS-3.4 as default values and the simulation parameters are as shown in Table 1.

3. 2. Results and Discussions for Proposed Methodologies and Existing Methodology In the simulation setup, Path-1 exhibits a consistent loss rate ranging from 0.1 to 1.0, while Path-2 simulates varying levels of packet loss with a dynamic loss rate between 1.0

TABLE 1. Configuration setup for simulation of sub-flow paths

Parameters	Sub Process 1	Sub Process 2
Technology (Wireless)	IEEE 804.18	1EEE 801.13b
Sub-flow process Bandwidth	10MBPS	11MBPS
Sub-flow link Propagation delay	10 to 25ms	10 to 25ms
Sub-flow queue length	50	50
Sub-flow queue type	Drop tail	Drop tail
Uniform loss rate	0.1 to 1.0	1.0 to 2.0
RTT (Round Trip Time)	40 to 60 ms (variable)	40 to 70 ms (variable)
Congestion Window Size	50 to 70 packets	45 to 75 packets
Packet Size	1000 bytes	1000 bytes
Retransmission Timeout (RTO)	200 to 300 ms	250 to 350 ms
Jitter (Variation in Delay)	5 to 10 ms	5 to 15 ms

and 2.0. The proposed methods, FBMRTX-CWND and FBMRTX-SSTHRESH, demonstrate the respective outcomes of these approaches. The experiment results show the conservative retransmission method in regular MPTCP, referred to as RTX-conservative. These methods are specifically designed to address the loss characteristics of the paths, showcasing their effectiveness in handling packet loss under different conditions. In the trials with various packet loss levels, it will fully utilize the average delay, average throughput, and metric is the number of retransmission data packets and jitter. In addition to the evaluation of RTX-Conservative's performance against the suggested packet FBMRTX-CWND and FBMRTX-SSTHRESH at various packet loss levels offers a practical solution for MPTCP and 5G deployment and optimization.

3. 2. 1. Average Throughput One of the most essential transport layer metrics is the average throughput, which enables the evaluation of each path's performance in MPTCP. When using 0.01, 0.02, 0.03, 0.04, 0.05, and 0.06 as the uniform los rate for path B, FBMRTX-CWND achieves higher average throughput than RTX-conservative, at 2.89, 2.92, 8.1, 9.2, 1.6, and 2%, respectively. FBMRTX-SSTHREH outperforms RTX-Conservative in terms of average throughput by approximately 0.87, 5.54, 2.79, 5.98, 0.24, and 4.5% when the uniform loss rate is the same as previously mentioned. When packet loss increased, the average throughput of RTX-conservative decreased. On the other hand, FBMRTX-CWND and FBMRTX-SSTHRESH achieve a specific level of average throughput. This can be explained by the fact that OOO area packets, caused by sub-flow diversity in heterogeneous local area networks, lead to a decrease in network throughput when Variable Bit Rate (VBR) packets are discarded. The MPTCP receiver buffer will be stored in anticipation of the slow sub-flow packets by the rapid sub-low packets, which will arrive early. The results indicate that the proposed methodology achieves exceptional performance in managing lost packet retransmissions. The proposed methodology FBMTRX-CWND achieves more and better average throughput performance compared to the FBMRTX-SSTHRESH methodology. Figures 5 to 10 illustrate the throughput comparisons of three methods, FMMRTX-CWND, FBMRTX-SSTHRESH & RTX-Conservative under an asymmetric scenario with loss rates ranging from 0.01 to 0.06.

Table 2 shows the comparison of the different metric with existing and proposed methodology. It clearly shows that the proposed methodology is out performs the existing methodology. Compared the two proposed methodologies using different metrics with the existing methodology. The results clearly indicate that the proposed approaches surpass the current ones. Table 3 Shows the variables used in the flab-based multi-path congestion window and flag based multi-path slow start threshold.

TABLE 2. Evaluation of packet reinjection methods

Methodology/ Metric	Average Throughout	Average Delay	Jitter	No. of Retransm issions
RTX-Conservative	3628	0.0678	0.0182	75
FBMRTX-CWND	3999	0.0627	0.0161	56
FBMRTX-SSTHRESH	4189	0.0619	0.0181	55

TABLE 3. Variables used for FBMRTX-CWND & FBMRTX-SSTHRESH

Variables	The corresponding definition of variables used in the proposed model
Sf	The sub-flow
cwnd	The congestion window of the sub-flow
Ssthresh	The Slow Start Threshold of the sub-flow
Rtx	The retransmission
sf_i	The sub-flow of the path i
sf^{cwnd}	The congestion window of the sub-flow-i

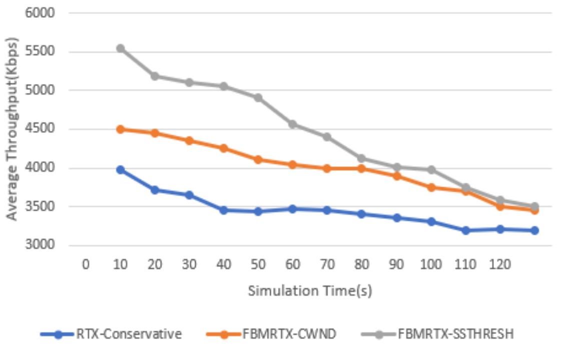

Figure 5. Throughput variations for existing and proposed methods at a sub-flow loss rate of 0.01

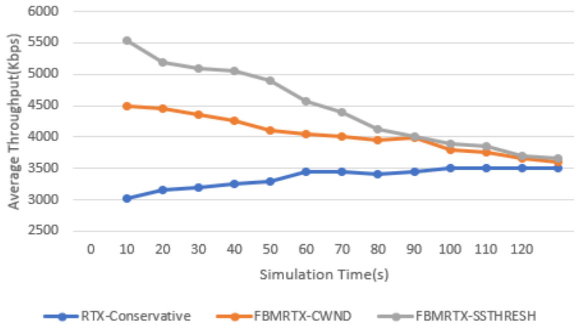

Figure 6. Throughput variations for existing and proposed methods at a sub-flow loss rate of 0.02

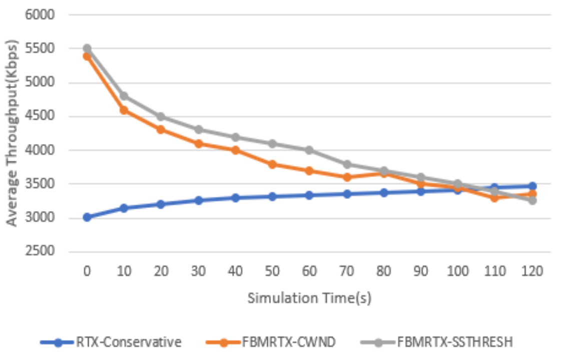

Figure 7. Throughput variations for existing and proposed methods at a sub-flow loss rate of 0.03

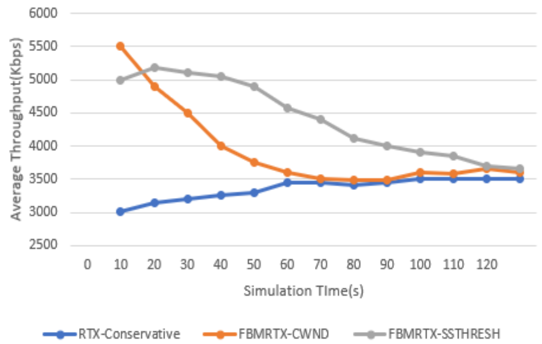

Figure 8. Throughput variations for existing and proposed methods at a sub-flow loss rate of 0.04.

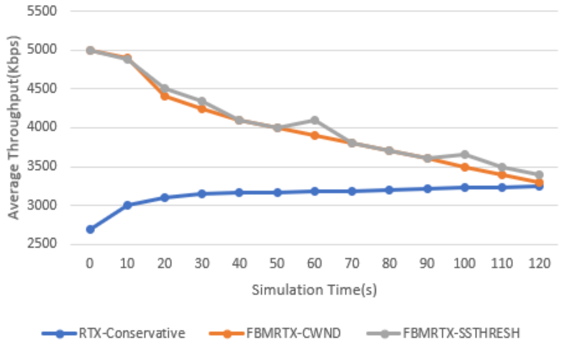

Figure 9. Throughput variations for existing and proposed methods at a sub-flow loss rate of 0.05.

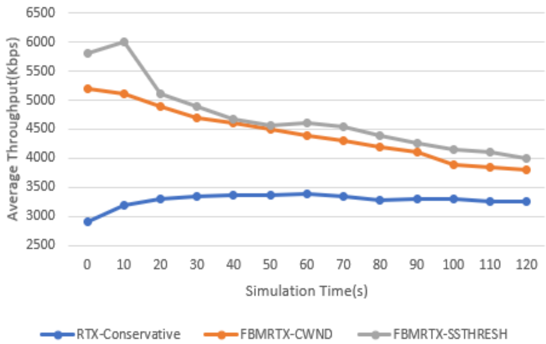

Figure 10. Throughput variations for existing and proposed methods at a loss rate of 0.06

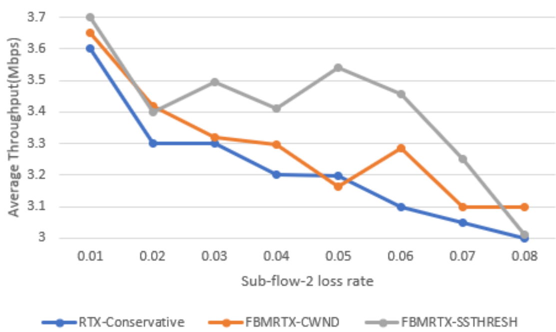

Figure 11. Comparison of the total average throughput between the proposed and existing methods

FBMRTX-CWND & FBMRTX-SSTHRESH both can outperform compared to RTX-conservative from Figure 11. in terms of average throughput. It illustrates an asymmetric scenario, depicting the total average throughput comparison of FBMRTX-CWND, FBMRTX-SSTHRESH, and RTX-Conservative for loss rates between 0.01 and 0.1 when Sub-flow-1 experiences a loss rate.

The variations in average throughput at various packet loss levels are displayed in the Figure 12. The proposed approach performs better than existing methods in effectively managing all the parameters related to

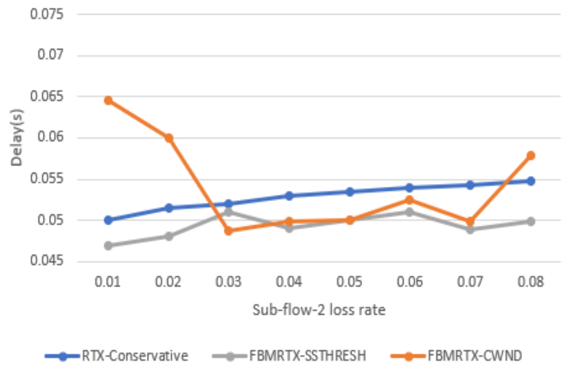

Figure 12. Comparison of total delays between the proposed and existing methods

packet retransmissions. The comparison of the total delay of FBMRTX-CWND, FBMRTX-SSTHRESH, and RTX-conservative in an asymmetric scenario with a slow sub-flow-1 loss rate of 0.01 to 0.1.

3. 2. 2. Average Delay Figure 13. Shows that the proposed FBMRTX-CWND AND FBMRTX-SSTHRESH performance have shorter average delays than existing RTX-conservative. The Comparison between the conservative retransmission mechanism vs the proposed flag-based multi-path retransmission. The rationale is that it promptly gathers retransmission packets and designs the MPTCP fast retransmission mechanism. Which can efficiently alleviate the receiver buffer block issue by retransmitting packets over non-congested pathways. The biggest delay is caused by RTX-conservative, followed by FBMRTX-SSTHRESH, FBMRTX-CWND, and so on. The average delay is a key metric for assessing the stability and efficiency of path performance. Figure 13 presents a comparison of the overall average delay between the proposed and existing approaches. For instance, at a loss rate of 0.08, the proposed method revealed that the current RTX-Retransmission technique experiences the highest delay, followed by FBMRTX-SSTHRESH, while FBMRTX-CWND demonstrates the lowest delay.

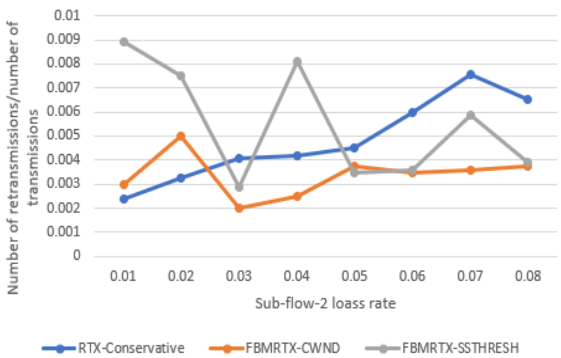

Figure 13. Percentage comparison of retransmitted packets

3. 2. 3. Jitter The jitter process was assessed by analyzing packet length and the most recent delay to ensure stable packet retransmission. This instability typically occurs when packets arrive out of sequence, caused by varying delays across different network sub-flows. Such variations may result in the loss of Variable Bit Rate (VBR) packets, which in turn reduces overall network throughput. Addressing jitter is crucial to ensure smooth data flow and reduce packet loss. By addressing these inconsistencies, network performance can be enhanced, ensuring reliable retransmission and stable throughput. In the experiment, path B has a uniform loss rate of 1–2%. Jitter fluctuations in 0s to 120s. RTX-conservative generates a higher number of out-of-sequence and delayed packets compared to the proposed methods. FBMRTX-CWND & FBMRTX-SSTHRESH exhibit lower jitter, retransmit dropped packets promptly, and minimize data reordering, improving performance over RTX-conservative. In the experiment, path B maintains a consistent loss rate between 1 and 2, while the jitter in FBMRTX-CWND and FBMRTX-SSTHRESH remains lower than that of the existing approach. The jitter metric is determined based on the final delay value and packet length. This metric effectively illustrates the reliability of concurrent multipath packet transmission in MPTCP.

3. 2. 4. The Ratio of Packets Retransmitted This metric serves as a critical indicator of out-of-order packets in multipath-TCP connections and highlights buffer congestion at the destination. To evaluate network performance, the retransmission percentage is calculated as the ratio of retransmitted packets to total transmissions. Figure 13 shows a steady increase in packet loss with RTX-conservative retransmissions due to its conservative approach, raising the uniform loss rate. While FBMRTX-CWND shows stable packet loss, FBMRTX-SSTHRESH exhibits more variation. Less frequent retransmissions involve reordering and out-of-order packets. Figure. 13 compares retransmission packets in FBMRTX-CWND, FBMRTX-SSTHRESH, and RTX-Conservative for sub-flow-2 loss rates of 0.01–0.1 in an asymmetric path scenario. The proposed methodology demonstrates superior performance in MPTCP retransmission by very effectively balancing both packets for the generation of present and fairness, resource utilization, and computational efficiency. Unlike traditional retransmission techniques, which often result in excessive delays and inefficient path selection, the proposed method leverages the PSH flag to enable immediate packet reinjection with minimal overhead. The results further validate the effectiveness of the proposed methodology, showing significant improvements in packet delivery rate, reduced latency, and optimized retransmission efficiency. By integrating a structured approach—reinjection timer calculation, intelligent packet gathering, optimal path selection, and efficient retransmission—it maximizes resource utilization while preventing unnecessary retransmissions. The results confirm that existing methodologies, such as RTX-SAME, RTX-ASAP, and RTX-Loss Rate, often lead to suboptimal bandwidth allocation and increased congestion, whereas the proposed approach dynamically adapts to network conditions using CWND and SSTHRESH parameters.

4. CONCLUSION

A new scheduling approach is proposed, incorporating a flag-based retransmission mechanism that efficiently retransmits lost packets through an optimal, congestion-free path. This work focuses on overcoming the challenges of out-of-order packet delivery and inefficiencies in retransmitting lost packets within MPTCP communication. The effectiveness of the proposed mechanism is thoroughly assessed using realistic simulations, considering essential metrics like average delay, throughput, jitter, and retransmission rate across different packet loss conditions. The findings indicate that our mechanisms, FBMRTX-CWND and FBMRTX-SSTRESH, consistently outperform the RTX-conservative approach by enhancing throughput and minimizing delay. Furthermore, the proposed mechanism addresses buffer-blocking challenges and significantly improves overall communication efficiency, making it a highly promising solution for optimizing MPTCP performance. In future work, aim to refine the proposed flag-based retransmission mechanism to adapt more dynamically to varying network conditions while maintaining efficient performance. By incorporating advanced machine learning algorithms, the mechanism can make smarter decisions in selecting the optimal path for retransmissions.

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Persian Abstract

چکیده

استفاده از دستگاه های تلفن همراه با رابط های متعدد با فعال کردن انتقال داده همزمان ، ارتباطات را تغییر داده است .این توانایی باعث شده است که پروتکل کنترل انتقال Multipath (MPTCP)، که از چندین رابط برای انتقال داده ها به طور همزمان در مسیرهای مختلف استفاده می کند و باعث بهبود اتصال کلی می شود.با این حال ، چندین عامل بر عملکرد MPTCP تأثیر می گذارد ، از جمله نوسانات در جریان های زیر ، تحویل بسته های خارج از سفارش (OOO) و ناکارآمدی در انتقال مجدد بسته های از دست رفته .پرداختن به این چالش ها برای افزایش کارآیی MPTCP بسیار مهم است .بهینه سازی استراتژی های انتقال مجدد می تواند هم عملکرد و هم قابلیت اطمینان را بهبود بخشد در حالی که بی نظمی های زیر جریان را کاهش می دهد و از ارتباط پایدار اطمینان می دهد .اگرچه روشهای مختلفی ارائه شده است ، بیشتر رویکردهای موجود در درجه اول روی برنامه ریزی بسته ها متمرکز شده اند ، با تأکید محدود بر انتقال مجدد بسته های از دست رفته به عنوان یک مسئله مشخص.این کار اهمیت انتقال مجدد را در کنار مکانیسم های برنامه ریزی برجسته می کند .رویکرد پیشنهادی شامل سه ماژول اصلی ، شناسایی بسته هایی است که نیاز به انتقال مجدد ، انتخاب مسیر بهینه و انتقال این بسته ها از طریق یک مسیر فعال و موجود دارند .برای دستیابی به این هدف ، روش شناسی ما بسته های از دست رفته را با یک پرچم انتقال مجدد نشان می دهد و آنها را از طریق مسیر انتخاب شده هدایت می کند ، MPTCP را تقویت می کند و به حداقل رساندن تأخیر در تحویل داده ها می شود.طرح پیشنهادی در NS-3.4 اجرا شد و با استفاده از برنامه های حساس به تأخیر ارزیابی شد .نتایج نشان می دهد که روش ما به طور قابل توجهی از رویکردهای موجود بهتر عمل می کند ، و آن را به یک راه حل امیدوارکننده برای بهبود عملکرد MPTCP تبدیل می کند .به طور خاص ، FBMPTCP-CWND و FBMPTCP-SSTHRESH با افزایش توان 5 ٪ ، عملکرد برتر را نسبت به روش موجود به دست می آورند ، 13 ٪ کاهش می یابد ، 33 درصد کاهش می یابد و تاخیر را 8 ٪کاهش میدهد.