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MPTCP PERFORMANCE ENHANCEMENT USING NETWORK PARAMETER OPTIMIZATION APPROACH

Saurabh Bhutani[1], Nitin Jain[2]

[1,2] Electronics & Communication Engineering Department, BBD University Lucknow - 226028, India.

Email: [1]saurabhbhutani2412@gmail.com, [2]hod.ece@bbdu.ac.in

Corresponding Author: **Saurabh Bhutani**

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Abstract

This study investigates the issues of energy usage in multipath wireless networks utilizing the Multipath Transport Control Protocol (MPTCP) under application-level timing knobs implemented in socket logic*, which allows numerous TCP connections via different pathways. Due to route heterogeneity, MPTCP consumes more energy. Currently, many research works have provided several techniques to optimize energy efficiency; however, they focused on individual systems rather than total performance. This work proposed a stochastic multipath scheduling technique that considers the fluctuations in data transmission rate and path capacity. The scheduling mechanism is associated with the optimization problem to achieve the objectives of maximizing throughput, avoiding congestion, and improving stability. An algorithm is developed to solve multipath data transmission issues by utilizing the drift-based constraints. Simulations are performed to generate results for the comparison of three different optimized MPTCP schemes in the application layer with baseline and conventional protocols. The results are showing considerable improvements in throughput and end-to-end latency.*

Keywords: Multipath Transmission, Optimization, Energy Efficiency, TCP.

I. Introduction

The growth of the Internet in the contemporary period has transformed the multimedia environment, ushering in a new paradigm. The growing demand for multimedia services (video streaming, gaming, computing, cloud data storage, and social web apps) has resulted in record traffic volumes. Mobile video traffic accounts the 75% of all mobile data traffic in 2020, and is expected to grow at a 43% growth between 2020 and 2026 [VII]. To handle the rise in traffic, several networking technologies (4G-LTE, 3G-UMTS-HSPA+, and 5G), WLAN, and broadband metropolitan area networks (WiMAX) [VI] have been implemented. The development of MPTCP [XXIV] improved network performance by providing seamless access to different resources, increasing efficiency, and delivering high-quality services. MPTCP has received substantial attention for its function in improving multipath access in wireless networks [II, XXIII, XXV, XXVII, XXIII].

Energy efficiency in multipath transmission has received attention as a result of the growing usage of multihomed wireless devices that have several network interfaces but are restricted by battery power. To improve energy efficiency, early multipath systems prioritized device power conservation by picking the most effective interface based on network circumstances. Another strategy focuses on channel characteristics, seeking to reduce delays caused by channel impairments [II, IX]. However, these strategies are primarily intended for certain types of data transfer and do not completely meet the needs of real-time applications. A third type of research has looked into optimal proportion-based algorithms and approaches for integrating congestion control mechanisms using fluid-based models. These techniques may be expected to enhance throughput as well as energy efficiency for transmission under multipath schemes [IV, V, VI, X, XVI, XX, XXII, XXVI, XVIII].

This work focuses on an optimization-based approach for scheduling the data packet transmission using the queuing system. It incorporates an effective and optimized method that selects the optimum path based on data availability while restricting the transmission window size to minimize the channel congestion. The proposed scheme changes the default and virtual queuing procedures based on the objective function under the optimization process for achieving more stability and a lower congestion level in the network. The proposed work reduces the overall energy cost of multiple transmission paths while increasing throughput. The optimization procedure is applied for finding a robust and dependable queuing system. Unlike conventional methods, which rely on projected bandwidth or round-trip time (RTT), the proposed work optimizes data transmission efficiency by taking into account additional metrics such as available sending window size and packet loss probability. This article contributes to addressing challenges in MPTCP with a novel approach that have high level of feasibility. This implementation finds the optimum route solution in the simulation environment with the objectives of improving performance under MPTCP.

This proposed work integrates three modern biologically inspired optimization methods (PSO, ACO, and GWO) for the enhancement of MPTCP platform data transmission performance, artificial throttling, and pacing at the application layer. These algorithms are developed to find the optimum value of three parameters at the server and client ends, known as Server/Client retry request time (SCRRT), Server/Client wait time to connect (SCWTC), and Server/Client pause time before retry (SCPTBR) timing knobs implemented in MATLAB socket logic. The L9 orthogonal array is generated using the Taguchi method to describe the design of the experiment set as a search domain for these three parameters. The fitness function follows is defined to reflect the network performance, where minimization represents the reduction of the overall average delay. This fitness function is the summation of packet loss, read, write, and propagation delay. There is no interaction with the kernel-level MPTCP stack, nor are the congestion control algorithms (such as coupled congestion control, window increase/decrease rules, and subflow prioritization) altered. Explicitly separating application-layer pacing effects from transport-layer MPTCP behavior is claimed only.

This paper is organized as follows: Section 2 gives the literature review and covers the relevant research. Section 3 describes the system model; it discusses the issues and algorithm design. Section 4 contains the primary findings, together with the mathematical proof. The simulation results are examined in Section 4, and the conclusion is presented in Section 5.

II. Related Work

Energy consumption is a major concern in multipath transport protocols, requiring an optimization process to improve network performance and stability while reducing energy needs at the network level. Numerous wireless network transmission schemes proposed by researchers provide a variety of solutions at both the device and network levels. An energy-efficient distortion-aware multipath TCP (EDAM) scheme is proposed for heterogeneous networks, based on maximization theory [XXVII]. The results show a significant improvement as compared to the conventional MPTCP model. But the limitation that is observed in this work was that retransmission of data packets over the lowest energy channels under congestion is difficult since it disturbs the regular transmission. A MP-TCP method for mobile devices reduces energy usage while increasing throughput in real-time file transfers [X]. The network utility maximization challenge is addressed using a variety of path selection strategies. A procedure for the selection of the best path falls behind in taking into account more parameters other than available bandwidth, such as RTT. Network size and topology are also not well characterized, which limits the network performance. The maximum window size, which is critical in congestion management, is not clear. Many improvements to the multipath TCP protocol developed for heterogeneous wireless networks, with the goal of achieving energy-efficient video streaming on mobile devices [IV, V, XVI, XXVI]. This design technique improves network efficiency by lowering energy usage and increasing perceived video quality. However, these approaches prioritize congestion control above effective scheduling and fail to fulfill bandwidth requirements [XX]. Raptor codes proposed to improve video quality by reducing wireless channel faults and eliminating head-of-line blocking in multipath situations [XI]. This approach reduces the energy usage, but it does not include an estimate of the energy costs associated with providing high-quality video services. The mVeno protocol, which uses different weighting factors to manage route flow and alter the data flow rate of sub-flows upon receiving acknowledgments [XXII]. It promotes fairness and load balancing, but does not focus on the energy efficiency of networks under high congestion situations.

A congestion management algorithm prototype known as BaLiA (Balanced Linked Adaptation) [II] design was proposed. It is based on MPTCP's fluid model and considers equilibrium stability, fairness, and system responsiveness. The system efficiently handles congestion by shifting data flow to less crowded routes. It faces limitations in maximizing energy efficiency within the suggested framework. Evolutionary algorithms were used to create an effective congestion management system that maximized power consumption and throughput [XVIII]. The method redistributes traffic from a busy route to a less congested route. While the technology significantly reduces energy usage, the process of finding and tracking low-congestion routes generates computational overhead.

An energy-efficient model proposed for throughput tradeoff based on Lyapunov optimization, with a particular emphasis on congestion reduction using fluid modeling [XV]. It improved the Opportunistic Linked Increases Algorithm (OLIA) for multipath congestion reduction by including efficiency into queue management. The results show better throughput and energy efficiency. Continuous transmission flow causes receiver saturation, which increases power consumption and overall efficiency.

In summary, the research works that are addressed here under the MPTCP scheme face difficulties, including congestion control, scheduling, and transmission, with the goal of increasing throughput while also improving energy economy to some extent. However, the proposed work in this article addresses these issues by adding an optimized route decision scheme that gives a more regulated approach, resulting in better performance than previous methods.

III. Methodology

In this work Matlab software is used for developing the algorithm. For this purpose, the instrumentation control toolbox is used for applying TCP client and server function commands [IX, X]. Two different codes are written for defining the operation of the client end and server end. The two instances of independent MATLAB were launched on the same PC. In this work a MPTCP model is implemented using a simulation design on MATLAB software. One instance is used to run server-side operations, and another instance is used for the client side in parallel. In the figure 1, the implemented topology is shown. Here, S is the server, and C is the client. The multipath is established by providing four routers, R1, R2, R3, and R4. In Figure 1, the subflow of text data is carried out through the four possible routes S-R1-R3-C, S-R1-R4-C, S-R2-R3-C, and S-R2-R4-C. The data that is transferred from the server to the client for communication is the text data. In each subflow, 10 alphanumeric characters are sent randomly from any of the four paths. In the figure 2, the source side data in text format is shown. This text data is sent from the server through router R1 and R4 randomly. In Figure 3, the text data subflow from routers R2 and R3. Here, it may also be observed that the packet id is shown in the title. Total 20 packets are sent through the multipath approach. In this proposed work, different parameter sets are considered at the server and client sides for maintaining the best QoS by minimizing delay and packet losses. The parameters that are selected are (1) S1: server waiting time for client to connect (2) S2: delay inserted prior to next retry by server (3) C1: client waiting time for client to connect (4) C2: delay inserted prior to next retry by client and the response are TSreq: Time delay in accepting the request of server by the client, TSWrite,: Time delay in writing packet from S to C PLoss: Packet loss (0/1), TCDelay: time delay in transmitting data in propagation from S to C and TCRead: Time delay at the client end to read the data. All the responses are observed at different combinations of parameter set {S1, S2, C1, C2} as shown in Table 1.

There are nine different orthogonal combinations of S1, S2, C1, and C2 MPTCP opted using the Taguchi Method. These are the minimum number of combinations that cover the maximum domain of parameter values for finding the optimum set. S1 and C1 are taken ➔ [1.5, 2.5, 3.5] in sec, S2 and C2 ➔ [2, 3, 4]. In this way, 3 values of S1, 3 values of S2, 3 values of C1, and 3 values of C2 are considered that may create 3x3x3x3=81 combinations, but using Taguchi methods, only 9 combinations as a design of experiment set are generated as orthogonal combinations. This may help in finding the optimum solution in a faster way by consider small number of solution sets that covers maximum search space domain. In Figures 1 to 4, the text message data subflow is shown that is forwarded from server S to client C through route R1 or R2. The events with packet loss may be seen as the absent text message at different routes. During the data subflow, the performance is measured and shown in Figure 5 in terms of request time, write time, read time, and propagation delay at different packet id under different experiments performed at a specific combination of network parameter sets. It may be observed that the request time and propagation delay vary from 0 to $5x10^{-5}$ sec, and red write time varies from 0 to 0.01 sec.

Algorithm

Step 1: Define min/max range of server/client (S/C) side solution variables, i.e., S/C_{RRT}, $S/C_{WTC,}$ and $S/C_{PTBR.}$

Step 2: Apply the Taguchi method to generate the L9 orthogonal array for the S/C side solution variables.

Step3: Import Twitter text data from csv. file.

Step 4: Define Server/Client parameters, localhost address.

Step 5: Segment imported text data into packet segments.

Step 6: Define MPTCP network architecture with S, R1, R2, R3, R4, and C location as server, routers, and client.

Step 7: Define population size.

Step 8: Initialize solution variable set X in terms of $[S, R1, R2, R3, R4, \text{and } C]_{RRT, WTC, PTBR}$.

Step 9: Find fitness value 'F' of each solution set as the summation of $[S, R1, R2, R3, R4, \text{and } C]_{\text{packet loss, read, write, and propagation delay.}}$

Step 10: Apply optimization algorithm (PSO or ACO, or GWO) to search the optimum value of the solution set X that provides the route with the best fitness value as F_{min}.

Particle Swarm Optimization Algorithm (PSO)

The PSO technique is efficiently used in the MPTCP framework of this article to reduce packet transmission by an optimized route identification method. Packet forwarding strategy prioritizes local searching over network exploration, making it ideal for improving routing tables and simplifying local data transmission. Typical PSO runs slower rate, weight update to particle inertia helps to speed of optimization process and gives fast convergence. The effectiveness of MPTCP networks is dependent on the strategic deployment of data packets across several routes, which ensures optimal network performance with minimum delay or packet losses:

$$T_r=1/(a.b) \tag{1}$$

'a' and 'b': probability values used to calculate the transmission cost of forwarding packets. The server manages data flow requests by allocating channels to client connections, resulting in efficient data transfer.

The PSO-based route analysis is used to handle multidimensional issues while improving the data transmission flow. A network of random packets is first established. The optimum solution is obtained by iterative modifications across numerous iterations. The objective is to achieve maximum accuracy while reducing time, error, and packet losses. In each iteration local best solution, denoted as p_{best}, indicates the initial fitness value, and g_{best} (global best) is kept to follow the best path. Random displacement (hop updates) generates a fresh solution by modifying network parameters using standard particle velocity update formulae. By adding velocity updates to displacement, new potential solutions are generated with a higher likelihood. The developed solutions are examined using the values they hold to decide if the process should come to a termination criterion. If the procedure is interrupted, the fitness value is updated promptly. The weight factor for the ideal path, along with the response metric of a route, improves performance by lowering latency. A route with high link quality is chosen to transport data from the source to the destination. It presents a unique PSO-based technique under MPTCP for quickly determining the best route for multi-path transmission. The fitness is calculated using Equation (2):

$$Fit(k)=f(k)+p(k) \tag{2}$$

f(k) represents the global search update, whereas p(k) symbolizes the destination function, which is defined by the transmission cost function.

Ant Colony Optimization (ACO)

Ants use "stigmergy" or indirect communication to discover the quickest path to reach the food source. They leave pheromone trails behind them. Upon returning, they continue to leave pheromones, with the concentration often influenced by the path to reach the food source. Over time, these pheromones gradually evaporate. Ants traveling along shorter path tracks pheromone trail more rapidly than longer routes.

As a result, other ants are naturally drawn to paths with higher pheromone, increasing the likelihood of following the most efficient route. ACO is a key method for finding the best route. The main notion is to deploy artificial ants that travel network routes, acquire information, and deposit virtual pheromones at network nodes (clients or routers). In practical applications, these ants operate as agents, which are often represented by specific packets. Each router has a pheromone routing database, which contains pheromone concentrations associated with various destination nodes. The choice to send a packet via a connection is determined by the eventual destination and present pheromone concentration. Proper pheromone management provides adaptation to changing network conditions, such as congestion or outages, while also minimizing topological stagnation. A pheromone routing table for a node (client) R_i has two nearby nodes, R_j and R_k, via which all nodes are connected. The suitability of the trip to each feasible destination via these neighbours was assessed by the pheromone concentrations listed in the table. This contains a set of parameters for node R_i, which include S1, S2, C1, and C2. The routing protocol examines the pheromone table and chooses the outgoing interface with the highest pheromone concentration for a particular destination, resulting in the shortest path.

Grey Wolf Optimization (GWO) Algorithm

A metaheuristic algorithm inspired by nature, the GWO mimics the cooperative hunting methods and hierarchical leadership of grey wolves. α, β, Δ and Ω are the four roles into which wolves are divided. While betas help and deltas oversee omegas, who follow others, the alpha takes the lead and directs the search. Tracking, surrounding, and assaulting prey are all parts of the hunting process, which in optimization stands for the stages of exploration and exploitation. The system is able to efficiently balance local refinement and global search by updating the prey's (best solution) position depending on the positions of leading wolves.

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_p}(k) - \vec{X}(k)\right| \quad (3.1)$$

$$\vec{X}(k+1) = \overrightarrow{X_p}(k) - \vec{A}.\vec{D} \quad (3.2)$$

k: current iteration, $\vec{X}$: position vector, $\vec{X}_p$ position vector of the prey, $\vec{A}$ & $\vec{C}$: coefficient vectors expressed as:

$$\vec{A} = 2\vec{a} * \vec{r} - \vec{a} \quad (4)$$

$$\vec{C} = 2 * \vec{r} \quad (5)$$

$\vec{a}$: decreases linearly from 2 to 0, $\vec{r}$: random number between 0 and 1.
The search agent position, as (x, y) coordinates, undergoes adjustments according to the position of prey obtained as (x^*, y^*). $\vec{A}$ and $\vec{C}$ adjusts in the direction of attaining the best agent located at different positions. During the hunting phase (better route is searched under MPTCP), α-wolves are followed by other wolves. Initially, α represents the best route at 1st rank, β represents the route at 2nd best rank, and similarly, Δ considers the best route at 3rd rank in the MPTCP simulation environment. The three best routes used in updating the location of the solution at a lower rank, considering Ω-wolves. $\vec{X}(K+1)_1$ is the new proposed route as the average/common of all routes represented by α, β, and Δ. The attack phase supports identifying local possible routes. The local searching phase follows a variation in $\vec{A}_1$ in the range [-2a to +2a]. If the coefficient vector value $|A| < 1$, then local searching of the route is followed up. These operations are performed for updating & searching the route in terms of server/client/router node, is performed for obtaining the optimum route. The phase of search new route helps to diverge the current proposed routes to find a better solution and converge to attack the prey (opt for the final route). If $|\vec{A}| > 1$ then search diverges and find a new route.

IV. Results

The variation in performance is further observed more elaborately in Figure 6 as a boxplot to visualize the maximum, minimum, and average value under different experiment id. The fitness function is used as the sum of the scaled values of T_{req}, T_{write}, T_{read} & T_{delay}. The T_{req} & T_{delay} lie in the range of 1.5×10^{-5} to 2.5×10^{-5}, while the T_{write} & T_{read} lie in the range 1.0×10^{-3} to 2.5×10^{-3}. In this way, the direct sum of all four parameters does not justify the weightage of T_{req}, & T_{delay} since they are about 10^3 times lower. The fitness function is updated as the sum of parameters by multiplying with scaling factors w_1 to w_4 to bring all the parameters at similar range. The T_{req} & T_{delay} are scaled up by 10 times, and T_{write} & T_{read} are scaled down by 10 times by multiple trials of S_4 to S_4 to bring a balanced fitness function given as:

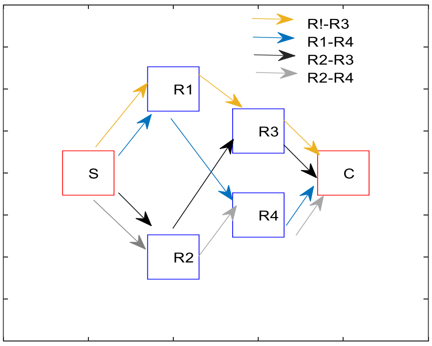

Fig. 1. MPTCP network architecture representing paths for data subflow.

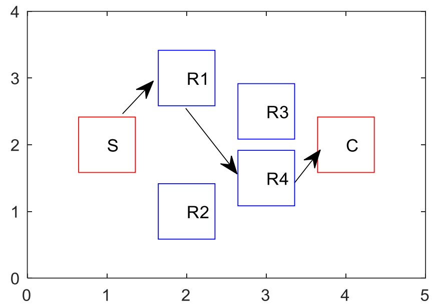

Fig. 3. Transmission of text data packet id 13 from path S-R2-R3-C.

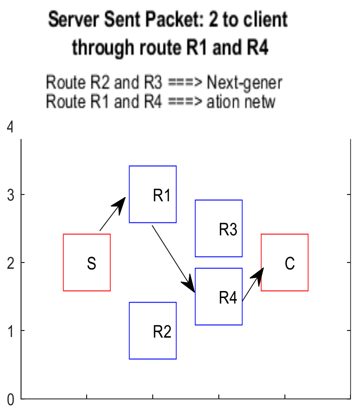

Fig. 2. Transmission of text data packet id 2 from path

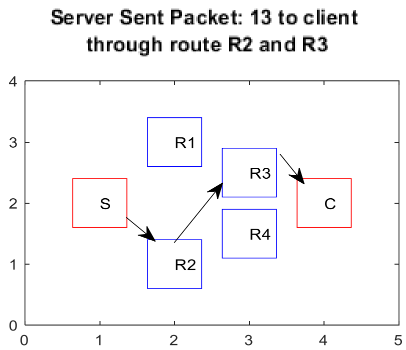

Fig. 4. Transmission of text data packet id 13 from path S-

$$\text{Fitnes function} = F = \text{Min}\,(w_1 * T_{req} + w_2 * T_{write} + w_3 * T_{read} + w_4 * T_{delay}) \qquad (6)$$

The variation in the scale factor shows the impact on change in performance of network characteristics. The higher priority of the w_4 forced to minimize the propagation delay, and the rise in w_2 and w_4 enhanced the relaxation in read and write time, and decreased the packet loss. The response towards an increase in w_1 improves both packet loss and propagation delay. The changes in packet loss and propagation delay result in a variation in throughput. Thus, the performance is dependent on the weightage given to the T_{req}, T_{write}, T_{read} & T_{delay}, and vary the packet loss and propagation delay, and consequently impacts the throughput. The sensitivity analysis shows high dependence on w_1, moderate dependence on w_3 and w_4, and small sensitivity to changes in w_2. Final combination is observed to be 20% weightage to w_1, 25% weightage to w_2, w_3, and 30% weightage value to w_4, giving all responses at the best level.

The lowest sum of T_{req}, T_{write}, T_{read} & T_{delay} is observed for experiment id 9 for the parameter set {S1, S2, C1, C2}➔{3.5, 4, 2.5, 2}. It shows that the request and propagation delay are negligible in read/write operations. Minimum packet loss of 24% is observed for GWO.

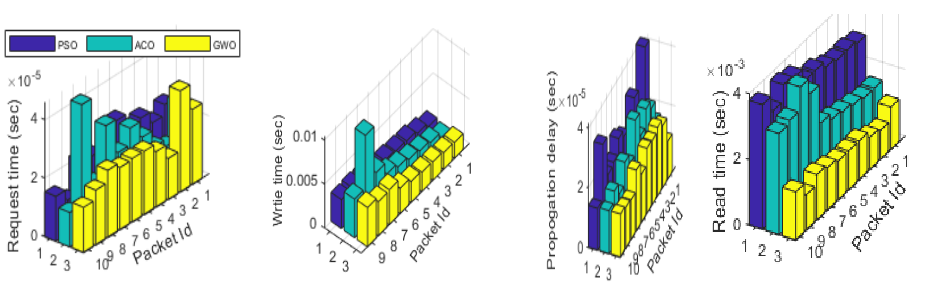

Fig. 5. Time taken during request under MPTCP for each packet id under different experiments.

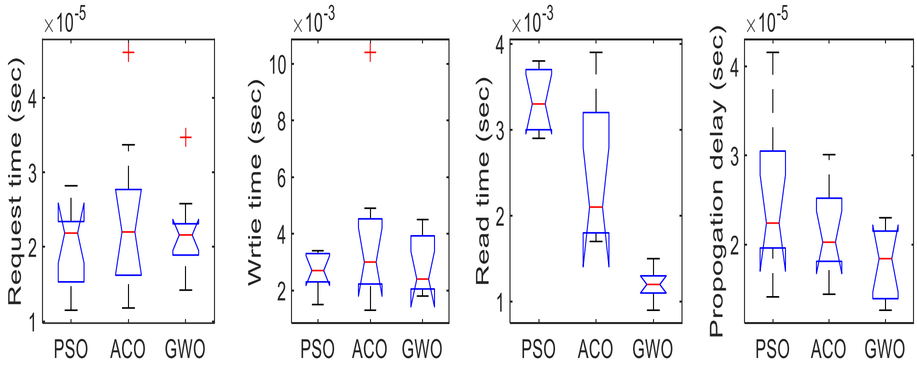

Fig. 6. Boxplot for showing the maximum, minimum range of request, write, read, and propagation delay time.

In Table 2, the simulation results for baseline and state-of-the-art techniques are shown under identical condition is shown. The optimization-based proposed method gives a low propagation delay and average packet drop. Due to this, the observed throughput is also higher, and the GWO-based scheme is giving the best performance. This shows no indication of any trade-off observation in the performance metrics.

Table 2: Comparisons with baseline and state-of-the-art techniques under identical simulation conditions.

Ref.	Method	Author	Year	Propagation Delay	Average Packet Drop Rate (pkt/sec)	Throughput (Mbps)
[XIV]	Cubic CC MpTCP	Yong Lee et al.	2023	$6.2 \times 10^{-5} \pm 0.90 \times 10^{-6}$	1.5± 0.3	4.53± 0.7
[I]	BALIA	Abbas, A.S et al.	2022	$4.3 \times 10^{-5} \pm 1.10 \times 10^{-6}$	2.0± 0.6	4.87± 0.8
[XVII]	wVegas	Łuczak, Ł. P	2023	$3.9 \times 10^{-5} \pm 0.64 \times 10^{-6}$	0.5± 0.4	5.32± 0.6
	MPTCP PSO			$2.3 \times 10^{-5} \pm 0.80 \times 10^{-6}$	0.52 ± 0.2	5.85± 0.8
	MPTCP ACO			$2.1 \times 10^{-5} \pm 0.54 \times 10^{-6}$	0.48± 0.1	6.25± 0.8
	MPTCP GWO	Proposed		$1.8 \times 10^{-5} \pm 0.40 \times 10^{-6}$	0.41± 0.1	7.84± 0.6

V. Conclusions

MPTCP transmission-associated packet loss and delay are observed to be uncoupled and independent behavior but cause congestion and reduce the throughput on the data share under a common bottleneck. In this paper, network parameter identification and optimization performed using orthogonal array selection via Taguchi method for finding under client and server-side behavior to minimize issue behind QoS degradation. Using information about the path status appropriate parameter set is identified for smoothing the data transmission under the simulation platform on MATLAB. The strategy reduces the aggressive growth in congestion inside MPTCP, eliminating buffer overflow, which can result in packet losses and timeouts. MatLab simulation results show that the suggested strategy significantly reduces MPTCP transfer completion time by minimizing the number of retransmissions and retransmission timeouts.

Conflict of Interest:

There was no relevant conflict of interest regarding this paper.

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