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Parameter Optimization Approach for MPTCP Performance Enhancement

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Abstract:

This study investigates the issues of energy usage in multipath wireless networks utilizing the Multipath Transport Control Protocol (MPTCP), which allows numerous TCP connections via different pathways. Due to route heterogeneity, MPTCP consumes more energy. Previous research provided several techniques to optimizing energy efficiency; however, they focused on individual systems rather than total performance. We offer a unique stochastic multipath scheduling technique that takes into account fluctuations in data and path capacity. The scheduling problem is presented as an optimization problem in order to maximize throughput, avoid congestion, and improve stability. The algorithm is designed to solve problems over several time intervals utilizing drift-based constraints. Extensive simulations were performed to compare proposed optimized MPTCP to baseline and protocols. The results show considerable improvements in throughput and end-to-end latency, demonstrating the efficacy of the suggested strategy.

Keywords: Multipath Transmission, Energy Efficiency, Stochastic Optimization

1. 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 accounted for 70% of all mobile data traffic in 2018, and it is expected to expand at a 47% growth between 2018 and 2024 [1]. To handle the rise in traffic, several networking technologies (3G-UMTS-HSPA+, 4G-LTE, and 5G), wireless LAN (WLAN), and broadband metropolitan area networks (WiMAX) [2] have been implemented. The development of MPTCP [3] 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 [4-15].

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 [16, 17]. Another strategy focuses on channel characteristics, seeking to reduce delays caused by channel impairments [10, 18]. 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 aim to increase energy efficiency and throughput for multipath transmission [2, 10, 19–26]. This study takes an optimization-based approach to packet scheduling, using a queueing system. It presents an effective and optimized method that selects the optimum way based on data needs while restricting the transmission window size to prevent congestion. The system changes both default and virtual queuing procedures based on the stochastic process's objective function, resulting in a more stable and less crowded network. Using this strategy, the suggested system reduces the overall energy cost of lines while increasing throughput. The optimization procedure is meticulously planned to produce a robust and dependable queuing system. Unlike typical schedulers, which rely on projected bandwidth or round-trip time (RTT) numbers, the suggested system optimizes data transmission efficiency by taking into account additional metrics such as available sending window size and packet loss probability.

Contributions of this article are summarized below:

- An algorithm is proposed to address the system's challenges and novelty, and its feasibility is further proven.
- The proposed solution specifies a stochastic-based approach for MPTCP to enhance overall throughput, optimize energy costs, and stabilize the queue.
- The implementation of the projected solution in the simulation environment revealed improved performance compared to other available solutions.

Further, the anticipated scheduler optimality is analyzed to achieve a lower energy cost, lower delay, stable queuing, higher throughput, and, most importantly, a stable network. The rest of the paper is organized as follows: Section 2 gives theoretical foundation and covers relevant research. Section 3 describes the system model; discuss issue formulation and algorithm design, respectively. 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.

2. Related Works

Energy consumption is a major concern in multipath transport protocols, necessitating more optimization to improve network performance and stability while reducing energy needs at the network level. To address excessive energy consumption in devices with numerous wireless interfaces, researchers investigated a variety of solutions at both the device and network levels [27-31]. Wu et al. [2] proposed an energy-efficient distortion-aware multipath TCP (EDAM) method for heterogeneous networks, using utility maximization theory to create an analytical model. This model assesses energy usage to enhance the user's video quality experience. The experimental findings show a substantial improvement over the typical MPTCP model. However, retransmitting packets over the lowest energy channels under congestion is difficult since it disrupts regular transmission procedures and adds new limits to the system. Peng et al. [19] suggested an MP-TCP method for mobile devices that reduces energy usage while increasing throughput in real-time file transfers. The network utility maximization challenge is addressed using a variety of path selection strategies. Several major findings arise from the study. The path selection procedure should take into account more than just available bandwidth, such as RTT. Furthermore, network size and topology are not well characterized, which limits the depth of the results. However, mathematical proofs are provided to aid in theoretical discussions. Furthermore, this scheme does not have the capacity to automatically switch between networks based on the input file type, such as video transmission. Finally, the maximum window size, which is critical in congestion management, is not clearly determined because the study uses the typical congestion control technique. Wu et al. [20-23] developed many improvements to the multipath TCP protocol for heterogeneous wireless networks, with the goal of achieving energy-efficient video streaming on mobile devices. Their design technique improves network efficiency by lowering energy usage and increasing perceived video quality. However, the system prioritizes congestion control above effective scheduling and fails to fulfill bandwidth needs [24]. Kwon et al. [32] proposed using Raptor codes to improve video quality by reducing wireless channel faults and eliminating head-of-line blocking in multipath situations. Their approach improves energy usage at the receiver while maintaining video quality. While the study was done on an actual system, it did not include an estimate of the energy costs associated with providing high-quality video services. Dong et al. [25] created the mVeno protocol, which uses different weighting factors to manage route flow and alter the data flow rate of sub-flows upon receiving acknowledgments. mVeno promotes fairness and load balance. However, the study does not look at the energy efficiency of networks under high congestion situations. Peng et al. [10] investigated MPTCP from multiple perspectives and proposed a congestion management algorithm prototype dubbed Balia (Balanced Linked Adaptation). The design is based on MPTCP's fluid model and considers equilibrium stability, friendliness, and system responsiveness. The prototype was included into the Linux kernel, resulting in considerable improvements in key performance indicators. While the system efficiently handles congestion by shifting connections to less crowded pathways, it falls short of maximizing energy efficiency within the suggested framework. Wang et al. [26] used evolutionary algorithms to create an effective congestion management system that maximized power consumption and throughput. The method redistributes traffic from a busy to a less congested corridor. While the technology significantly cuts power usage, the process of discovering and tracking low-congestion pathways generates computational overhead. This extra complexity at the receiver end resulted in greater energy usage, which impacted the entire system's energy efficiency.

Cui et al. [33] suggested an energy-efficient model for throughput tradeoff based on Lyapunov optimization, with a particular emphasis on congestion reduction using fluid modeling. They improved the Opportunistic Linked Increases Algorithm (OLIA) for multipath congestion reduction by including efficiency into queue management. While the results show better throughput and energy efficiency, continuous transmission flow causes receiver saturation, which increases power consumption and, eventually, reduces total system efficiency. In summary, the evaluated research address multipath-related difficulties, including congestion control, scheduling, and transmission, with the goal of increasing throughput while also improving energy economy to some extent. However, the suggested techniques address these issues by adding precise models that give a more regulated approach, resulting in greater performance increases than previous methods.

3. Methods

In this software instrumentation control toolbox is used for applying functionality using TCP client and server function commands [18, 19]. Two different codes are written for defining operation of client end and server end. The two instances of independent running MatLab is launched on same PC. In this work a MPTCP model is implemented using simulation design on MatLab software. One instance used to run server side operation and another instance for 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 server to client communication is the text data. In each subflow 10 alpha numeric 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 server through router R1 and R4 randomly. In figure 3 the text data subflow from routers R2 and R3. Here we may also observe that packet id is shown in title. Total 20 packets are sent through multipath approach. In this proposed work different parameter set are considered at server and client side for maintaining best QoS by maintaining minimum delay and packet lossees. 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 TS_{req}: Time delay in accepting the request of server by the client, TS_{Write},: Time delay in writing packet from S to C P_{Loss}: Packet loss (0/1), TC_{Delay}: time delay in transmitting data in propagation from S to C and TC_{Read}: Time delay at the client end to read the data. All the response are observed at different combination 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 Taguchi Method. These are minimum number of combination that cover maximum domain of parameter values for finding the optimum set. S1 and C1 is 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 and 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 design of experiment set are generated as orthogonal combination. This may help in finding the optimum solution in faster way by consider small number of solution set that covers maximum search space domain.

Table 1: Design Table (L9 Orthogonal Array): Below is the experimental plan:

Experiment	S1	S2	C1	C2
1	1.5	2	1.5	2
2	1.5	3	2.5	3
3	1.5	4	3.5	4
4	2.5	2	2.5	4

5	2.5	3	3.5	2
6	2.5	4	1.5	3
7	3.5	2	3.5	3
8	3.5	3	1.5	4
9	3.5	4	2.5	2

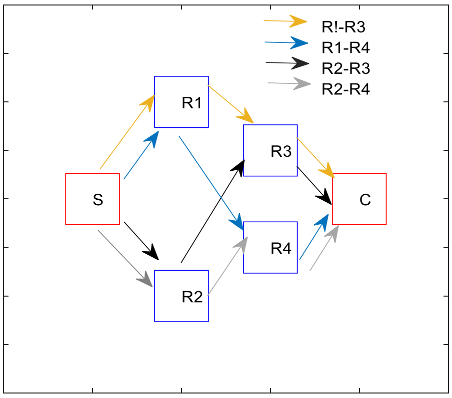

Figure 1: MPTCP network architecture representing paths for data subflow

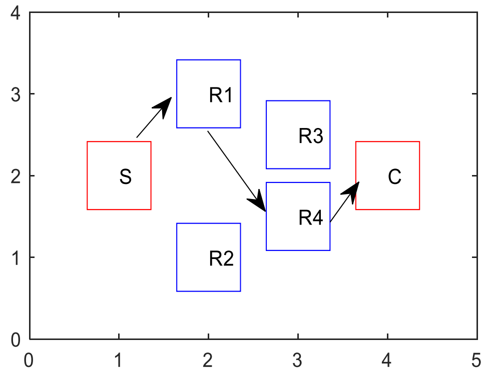

Figure 3: Transmission of text data packet id 13 from path S-R2-R3-C

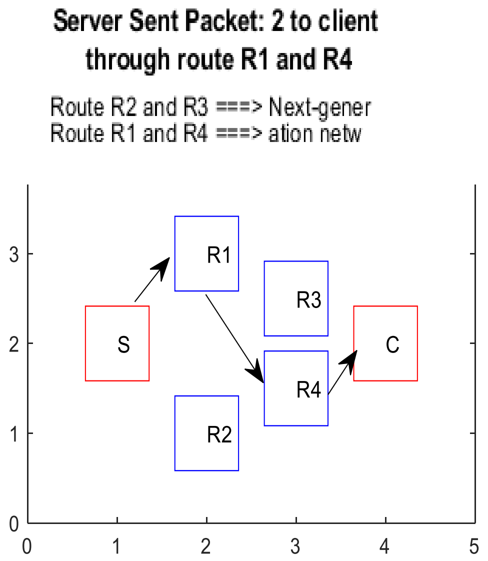

Figure 2: Transmission of text data packet id 2 from path S-R1-R4-C

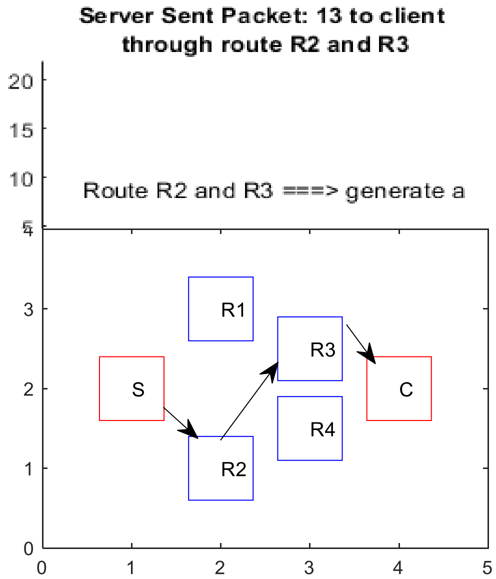

Figure 4: Transmission of text data packet id 13 from path S-R2-R3-C

In the figure 1 to 4 the text message data subflow is shown that are 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 experiment performed at specific combination of network parameter set. It may be observed that request time and propagation delay is varying from 0 to $5x10^{-5}$ sec and red write time varying from 0 to 0.01 secs.

3.1 Particle Swarm Optimization Algorithm

The Particle Swarm Optimization (PSO) technique is efficiently used in Multipath TCP (MPTCP) to reduce cyclic packet processing during the route identification period. PSO incorporates a variety of speed models to provide variation. Packet behavior prioritizes local searching over network exploration, making it ideal for improving routing tables and simplifying local data transmission. Because the typical PSO model runs at a slower rate, we've added latency-weighted speed tweaks to help convergence. The effectiveness of MPTCP networks is dependent on the strategic deployment of data packets across several routes, which ensures optimal network performance with little disturbance. The transmission cost is specified by Eq. (5)

$$T_r=1/(a.b) \qquad (5)$$

Here, 'a' and 'b' are the probability values used to calculate the transmission cost of forwarding packets. The server manages data flow requests by allocating channels to client connections in the area, resulting in efficient data transfer. The PSO-based routing analysis is used to handle multidimensional issues while improving the process flow. The reserved balance time has been significantly decreased, and the necessary QoS modifications are modest. Each bit in the process contributes to a potential solution, which improves total network efficiency.In PSO, a network of random packets is first established. The ideal solution is obtained by iterative modifications across numerous generations. The objective is to achieve maximum accuracy while reducing time, error, and expense. To do this, each attempt is allocated two best values. The first best solution, denoted as p_{best}, indicates the initial fitness value. Another ideal value, known as g_{best} (global best), is kept to follow the best PSO path. A high probability threshold, usually between 0.8 and 0.95, is established for decision-making. Random displacement generates a fresh solution by modifying network parameters using velocity formulae. By adding velocity updates to displacement, new potential solutions are generated with a higher likelihood, resulting in further improvements via transformation effects.

The developed solutions are examined using the values they hold to decide if the procedure should be came to an end. 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. This paper presents a unique PSO-based technique under MPTCP for quickly determining the best route for multi-path transmission. In addition to reducing network latency, the major goal is to control network throughput. The accuracy value is calculated using Equation (6).

$$Fit(k)=f(k)+p(k) \qquad (6)$$

f(k) represents the global search update, whereas p(k) symbolizes the destination function in PSO, which is defined by the transmission cost function. The sequential updating of particle displacement is directed by PSO's velocity evaluation formula. This displacement moves the parameter values for S1, S2, C1, and C2 to the next set of values. PSO is an advanced approach for identifying optimum solutions and creating search ranges. The selection, transformation, and update procedures comprise a population-based meta-heuristic for routing. PSOs occasionally converge to a local optimum. To improve efficiency, PSO identifies high-quality connecting nodes. Iterative enhancement of solution quality is an important component in optimizing PSO performance. The suggested technique is used in MPTCP to find the best route while eliminating the necessity for traffic signal needs in real-channel development.

3.2 Ant Colony Optimization

Ants can use "stigmergy," or indirect communication, to discover the quickest path to a food source. While hunting, ants leave pheromone trails behind them. Upon returning, they continue to leave pheromones, with the concentration often influenced by the quality of food source. Over time, these pheromones gradually evaporate. Ants traveling along shorter paths reinforce 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 most efficient route. Over time, collective behavior of swarm leads to selection of the shortest path to best food source. Research has shown that process is statistical, meaning sub-optimal paths may also emerge. This natural behavior served as inspiration for development of ant-based routing algorithms.

ACO is a key method for routing protocols. The main notion is to deploy artificial ants that travel network pathways, acquire information, and deposit virtual pheromones at network nodes (clients). In practical applications, these ants operate as agents, which are often represented by specific signaling 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. Effective pheromone management is critical for creating routing protocols that efficiently select the best pathways. Proper pheromone management provides adaptation to changing network conditions, such as congestion or outages, while also minimizing topological stagnation. Evaporation, aging, limiting, smoothing pheromone levels, and preferential pheromone lying are among the most important pheromone control processes.

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 neighbors was assessed by the pheromone concentrations listed in the table. Nodes also include a statistical parametric model matrix, which helps the ant-routing algorithm make pheromone control and routing decisions. This matrix contains a set of parameters for node R_i, which include S_1, S_2, C_1, and C_2. 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 based on the pheromone control metric. Because pheromone concentrations change owing to dynamic network circumstances, a new optimum path is selected whenever another interface acquires the greatest concentration.

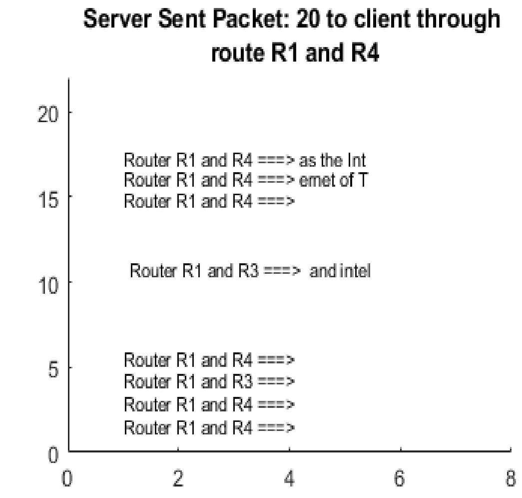

Figure 5a: Transmission records of text data on router R1.

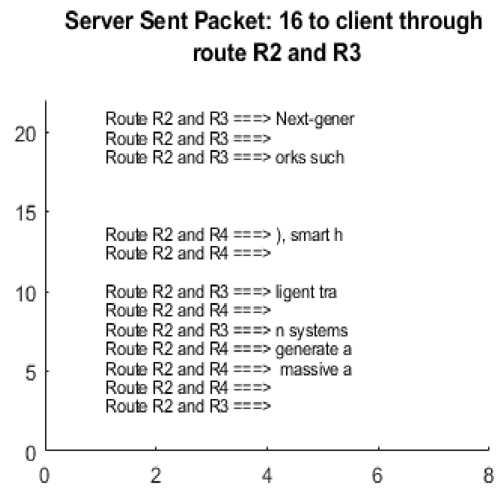

Figure 5b: Transmission records of text data on router R2.

4. Results

The variation in performance is further observed in more elaborated way in figure 6 as the boxplot to visualize maximum, minimum and average value under different experiment id. 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 rrequest and propagation delay is negligible main time consumed in read/write operation. Minimum packet loss of 24% is observed for experiment S5.

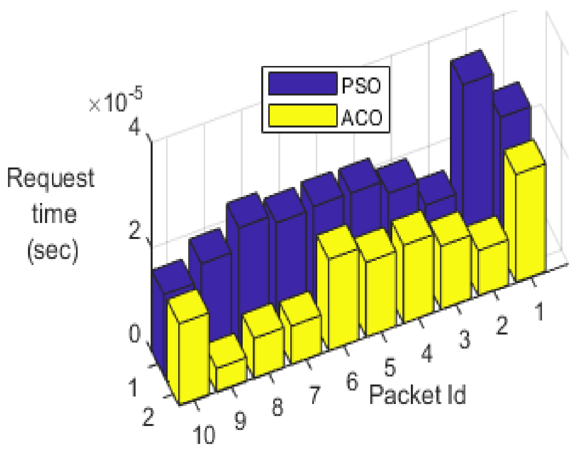

Figure 6a: Time taken during request under MPTCP for each packet id under different experiments.

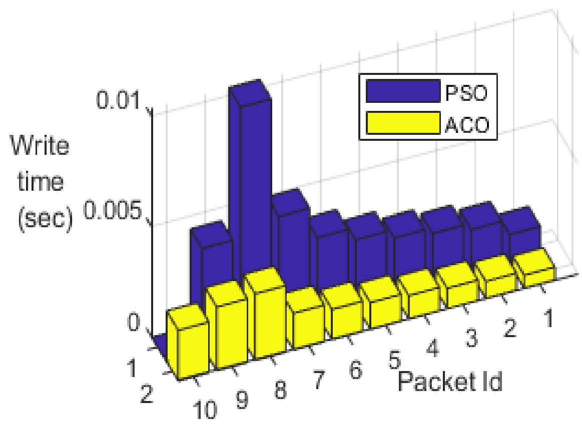

Figure 6b: Time taken during write operation under MPTCP for each packet id under different experiments.

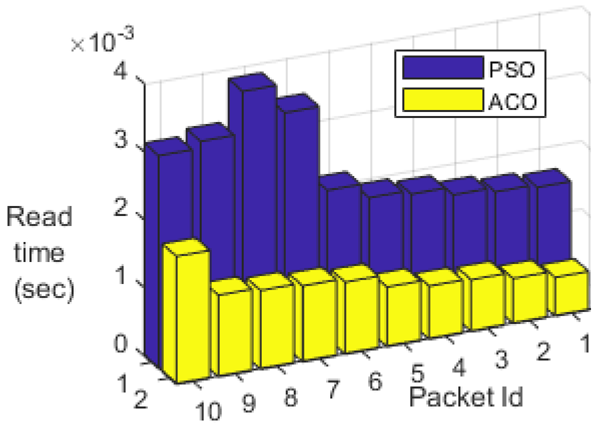

Figure 6c: Time taken during read operation under MPTCP for each packet id under different experiments.

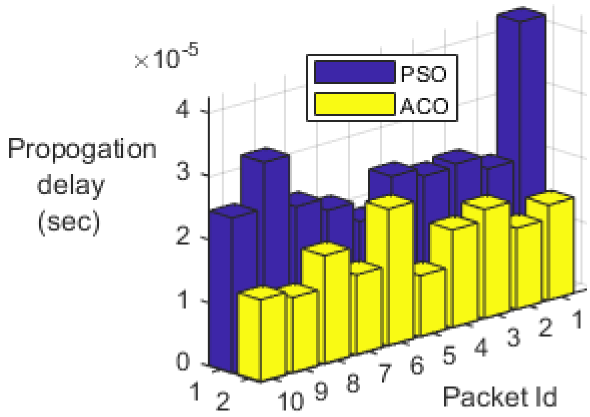

Figure 6d: Time taken during propagation delay under MPTCP for each packet id under different experiments.

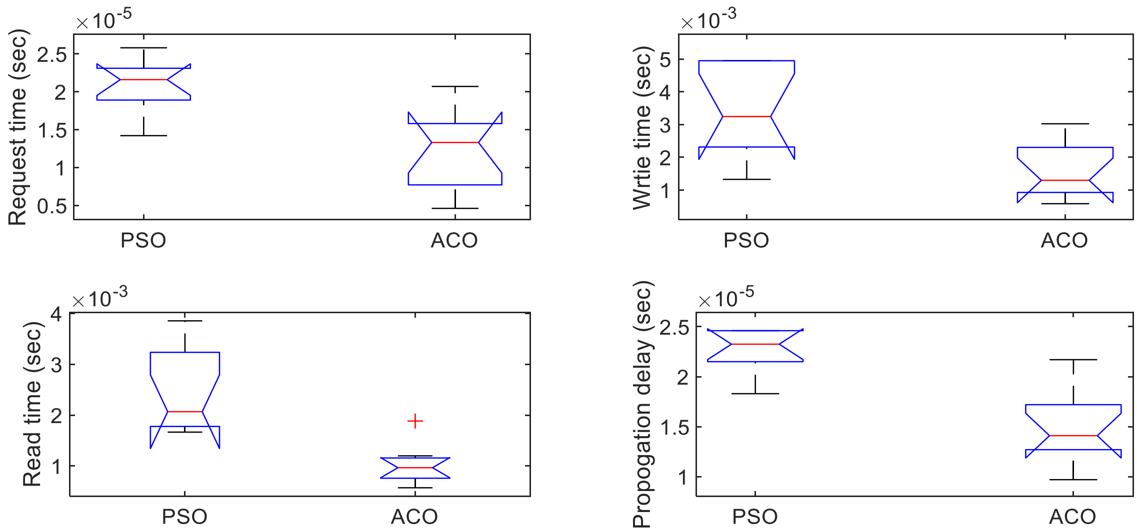

Figure 7: Boxplot for showing maximum, minimum range of request, write, read and propagation delay time

5. Conclusions

MPTCP transmission associated packet loss and delay are observed to be uncoupled and independent behavior but causes congestion and reduce the throughput on data share under 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 path status appropriate parameter set is identified for smoothing the data transmission under 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 (RTOs).

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