# Stochastic Optimization of Multipath TCP for Energy Minimization and Network Stability over Heterogeneous Wireless Network

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## Abstract

Multipath Transport Control Protocol (MPTCP) is a transport layer protocol that enables multiple TCP connections across various paths. Due to path heterogeneity, it incurs more energy in a multipath wireless network. Recent work presents a set of approaches described in the literature to support systems for energy consumption in terms of their performance, objectives and address issues based on their design goals. The existing solutions mainly focused on the primary system model but did not discourse the overall system performance. Therefore, this paper capitalized a novel stochastically multipath scheduling scheme for data and path capacity variations. The scheduling problem formulated over MPTCP as a stochastic optimization, whose objective is to maximize the average throughput, avoid network congestion, and makes the system more stable with greater energy efficiency. To design an online algorithm that solves the formulated problem over the time slots by considering its min-drift-plus penalty form. The proposed solution was examined under extensive simulations to evaluate the anticipated stochastic optimized MPTCP (so-MPTCP) outcome and compared it with the base MPTCP and the energy-efficient MPTCP (eMPTCP) protocols. Simulation results justify the proposed algorithm's credibility by achieving remarkable improvements, higher throughput, reduced energy costs, and lower-end to end delay.

***Keywords:*** Multipath Transmission, Energy Efficiency, Stochastic Optimization

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## 1. Introduction

The proliferation of the current Internet era has expanded the wireless multimedia world into a new paradigm. The fast advancement of the multimedia services such as live multimedia moving picture applications, gaming and mobile computing, extensive data storage over Internet cloud, and always-connected mobile online social web applications has caused the Internet traffic requirements as high as ever before. According to Cisco sources [1], mobile video traffic influenced 60% of the overall mobile data traffic in 2016. Which, mounting at a compound annual increase rate of 47% from 2016 to 2021. Several wireless networking technologies are handy, e.g., a cellular network (3G-UMTS-HSPA+, 4G-LTE also 5G), wireless local area network (WLAN, IEEE 802.11 variance) and the broadband metropolitan area wireless networks (WiMAX, IEEE802.16) [2], to deal with the massive volume of traffic. The development of MPTCP [3] provides seamless access to several resources and countless befits, improves overall network performance, and brings up a network with high-quality services. Consequently, MPTCP attains much attraction in multipath access to wireless networks [4-15].

Energy efficiency with multipath transmission got much attention because of the multi-homed wireless devices' support, with multiple interfaces and limited battery power. To make such devices energy-efficient initial multipath solutions focused on saving the devices' influence by restricting them to use the best available interface based on the network conditions [16, 17]. The other solution focuses on the channel characteristic. It minimizes the delay caused by the channel impairments [10, 18]. These examined techniques are mainly suited for one type of data transmission, which does not include real-time applications to meet the current user requirements.

The other category of work is focused on the different optimal proportion-based algorithms and methodologies, which consider the congestion control mechanism by applying the fluid-based model to achieve energy efficiency and better throughput for multipath transmission [2, 10, 19-26].

However, this paper adopts a stochastic optimization-based approach by introducing a queuing mechanism for packet scheduling. Later, it presents an efficient, optimized algorithm for selecting the best path based on the data requirements and limiting the transmission window size to make the system less congested. The default and the virtual queuing work updates are according to the objective function defined in the stochastic process; this enables the system to remain less crowded and stable. Thus, the presented system adopts a method to minimize the link's overall energy cost to enhance the system's throughput. The system's optimization is achieved diligently to accomplish a much stable and reliable queuing system. The existing metrics used by the standard scheduler consist of estimated bandwidth or the RTT values, while the proposed system will include the available sending window size and the packet loss probability of the paths before sending the data.

The main contributions summarized as follows:

- To propose an algorithm for considering the system's challenges and novelty and further proved its feasibility.
- A stochastic-based solution for MPTCP is specified to enhance the overall throughput, energy cost optimization, and stabilize queue.
- The projected solution implemented in the simulation environment, the outcomes revealed an improved performance, as compared with 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 remainder of the paper is organized as follows. The theoretical background and related work are defined inSection 2. The system model detailed in Section 3, problem formulation, and algorithm designed is discussed in Section 4, 5, respectively. The main results, Mathematical proof, are given in Section 6. Section 7 presents the simulation results. Finally, the conclusion is detailed in Section 8.

## 2. Related Work

Energy consumption in multipath transport protocol is still a significant concern and needs further improvements to enhance network throughput and stability by optimizing the network level's energy requirement. To ease additional energy consumption issues at the devices with multiple wireless interfaces, many researchers attempted to solve such problems by adopting different techniques, both at the instruments and network levels [27-31].

Wu et al. [2] proposed a multipath TCP-based energy-efficient distortion aware (EDAM) algorithm for the heterogeneous network, designed an analytical model based on the utility maximization theory. It analyzes energy consumption to enhance the user video quality experience. The experimental analysis shows significant improvement as compared with the standard MPTCP model. However, the retransmission or packets via lowest energy paths, in case of congestion, is challenging to achieve, as practically it makes the normal transmission process more complicated and put additional constraints to the system

Peng et al. [19] the author proposed the MP-TCP algorithm for mobile devices; the focus is to minimize the energy and enhance the throughput for real-time applications and file transfer applications. The network utility maximization task is achieved through different path selection mechanisms to achieve the desired parameters. There are few observations; the path selection process cannot only be selected based on the available bandwidth, but it needs to look at other parameters, i.e., RTT values. The network size or topology is not appropriately defined; in this context, the results are minimal; however, mathematical proofs are given to validate the theoretical discussions. The device cannot automatically switch from one network to another, based on the input file, either for video delivery. The maximum window size is not clearly defined, which controls the congestion; they used the standard congestion control mechanism.

Wu et al. [20-23] the author intended different extensions to multipath TCP protocol over the heterogeneous wireless network for achieving energy-efficient video streaming over the mobile devices. The design mechanism optimized the network efficiency in terms of energy consumption and to achieve perceived video quality. However, the designed system mainly focuses on congestion control but does not consider efficient scheduling and does not fulfill its bandwidth requirement [24].

The author Kwon et al. [32] used rap-tor codes to improve the video attribute by mitigating the wireless channels' errors and assuaging the head-of-line blocking problem for the multipath environment. Also, the proposed protocol maximizes the energy consumption at the receiver without degrading the video quality. The work performed on the real system did not provide the energy cost for delivering high-quality video services.

Similarly, Dong et al. [25] proposed a new protocol, mVeno, by applying different weighting parameters to control each path's flow and adjust the data flow rate of sub-flows upon receiving a further acknowledgment; the author claim to have better fairness and load balancing. The author fails to provide the energy efficiency of the links under severe congestion conditions.

Peng et al. [10] the author intensely studies the MPTCP with different aspects and proposed a new congestion control algorithm prototype named Balia (balanced linked adoption). The design is based on the fluid mode of MPTCP and studies the stability of equilibrium, friendliness, and the system's responsiveness. The prototype implemented in the Linux kernel, and the results revealed a significant improvement in the desired parameters. The designed system takes care of the system's congestion control by switching the connections to lower congested paths; however, the efficient energy connection with the proposed scheme is not satisfied.

Wang et al.[26] Using the genetic algorithm and fluid model techniques to achieve an energy-efficient congestion control algorithm to optimize the power and the throughput at the receiver end. The idea works in shifting some part of the traffic from highly congested paths to lower overfilled tracks for throughput enhancements. The proposed system reduces the power consumption at each link, but the processing time and searching for low congested routes require a method to search and keep tracking the system that can put extra load at the receiver and cause energy degradation to the overall system.

Cui et al. [33] proposed an energy-efficient (EE) model for throughput tradeoff using the Lyapunov optimization method. The focus is to control the congestion window via the fluid model. It utilized the congestion Opportunistic linked increases algorithm (OLIA) and improved it for multipath congestion control to add energy efficiency by stabilizing the queuing. The central focus part is at the receiver end, where the queuing efficiency is improved. The achieved results reflect an improvement in throughput and energy efficiency. However, the receiver end is more saturated; due to the continuous transmission flow, the receiver efficiency is compromised, which can consume more power and degrade the energy efficiency.

In short, the summarized work highlights the multipath-related issues in terms of congestion control, scheduling, and transmission part of achieving better throughput and, to some extent, achieve better energy efficiency. However, the proposed solution subsides the related issues by considering a detailed model to provide a more controlled way to obtain better performance enhancements than the available results.

## 3. System Model

The system model shown in **Fig. 1** is a multi-radio heterogeneous network. It supports simultaneous connectivity options to the end-user devices. Such equipment is also equipped and capable of forming multiple connections simultaneously, achieving better connection feasibility, and gaining higher throughput and reliability. MPTCP is the most appropriate protocol to enable mobility between networks and multipath connectivity (heterogeneous) network environment.

Let us suppose $n$ transmission paths exist, and each one of them is defined as $p_i$ (**Fig. 1**, there are three paths, LTE, WiFi, and mmWave). For simplifying the analysis, we divide the time into multiple slots $\mathrm{T} \overset{\Delta}{=} \{1, 2, \ldots, T\}$. At each time $t$, assuming the arrival packets are $a(t)$, the scheduled transmission packets $p_i$ are defined $x_i(t)$. Consider the mobile client maintains a queue whose length is determined $Q_i(t)$, the dynamic of $Q_i(t)$ at $t$ can be described as:

$$Q_i(t) = Q_i(t-1) + a(t) - \sum_{i=1}^{n} x_i(t) \tag{1}$$

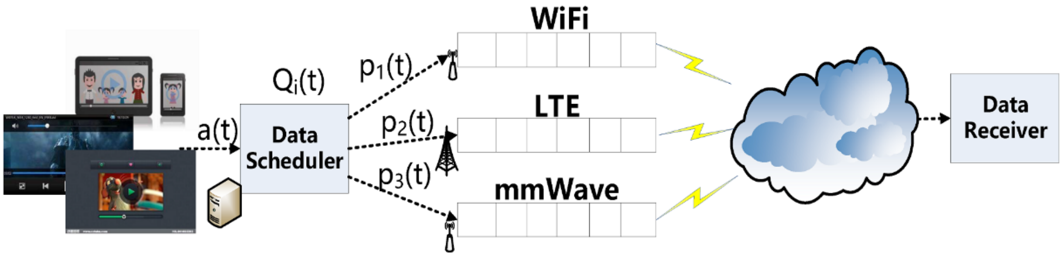


**Fig. 1.** System Model

The congestion window depends upon the ACK received from the sub-flows, which significantly relies on the shorter paths with lower loss rates and shorted round-trip time (RTT) values. It increases the window size and consumes much of the energy because of the higher overfilled paths. There is a need to stabilize the queening to control the overloaded window size and lower energy costs. The transmission rate of a particular sub-flows very much depended on the congestion window. Thus, Queuing Stability and the transmission delay ensure that all generated packets should transmit within finite time.

Thus, defining the stability of the Queue $Q_i(t)$ as

$$\limsup_{t\to\infty} \mathrm{E}\{Q_i(t)\} < \infty$$

or equivalently, the expected $\mathrm{E}$, $\limsup_{t\to\infty} \mathrm{E}\{Q_i(t)\} = 0$. Apparently, according to the little equation, when the queue length is finite, the transmission delay is bounded. Thus, the stable of $Q_i(t)$ ensures the boundless transmission delay.

## 3.1 Packet Loss Model

Assuming the transmitted data $x_i(t)$ will be divided into multiple packets whose size is limited by the MTU, then at each $t$, $[\frac{x_i}{MTU}]^+$ packets will be delivered, where $[a]$ indicates the smallest integer is more substantial than $a$. They are denoting a set of packets $\{c_j \mid j = 1, 2, \ldots, [\frac{x_i}{MTU}]^+\}$. Given the available sending window $B_i(t)$ and the packet loss probability $\mu_i$ for the path $p_i(t)$, the expected success delivered packets under $B_i$ during $t$ can be $(1-p)B_i$.

### 3.2 Link Capacity Model

Given the $cwnd_i(t)$ as the sending window for $p_i$, $\Delta t$ as the time interval between any two neighboring time slot, then the maximum size of transmission data can be defined as $\frac{MTU * cwnd_i(t)\Delta t}{RTT(t)}$, where the $RTT(t)$ is the round-trip time estimated at $t$.

### 3. 3 Energy Consumption

Consider each transmission path $p_i$. The corresponding consumed energy for delivering the unit amount of data is defined as $c_{i,d}$ (J/Kbps). The energy consumption $p_i$ is determined as $c_{i,e}$ (J/s). Thus, let the impulse function $y_i(t)$:

$$y_i(t) = \begin{cases} 1, deliver\ data\ over\ p_i \\ 0, otherwise \end{cases} \tag{2}$$

Therefore, the energy consumption at a time $t$ can be given by,

$$E(t) = \sum_{i=1}^{n} \left( y_i(t) c_{i,d} x_i(t) + (1 - y_i(t)) c_{i,e} \Delta t \right) \tag{3}$$

## 4. Problem Formulation

According to the above description, the data scheduler's goal in heterogeneous networks is to minimize the total energy consumption under the queue's available transmission rate and stability constraints. Namely, we can formulate the following stochastic optimization problem:

$$\min \lim_{T\to\infty} \sum_{t=1}^{T} E(x(t)) \tag{4}$$

$$s.t \frac{1}{t} \lim_{T\to\infty} \sum_{t=1}^{T} \left( x_i(t) - (1-p) \frac{MTU * cwnd_i(t)\Delta t}{RTT(t)} \right) \leq 0, \forall i \tag{5}$$

$$Q(t)\ is\ stable \tag{6}$$

$$x_i(t) \in X \tag{7}$$

where (4) aims to minimize the time average energy consumption, (5) limits the $x_i(t)$ over the path should be limited by the available bandwidth at $t$, (6) indicates that the queue is stable so that the transmission delay is bounded.

To solve the problem (4-6), we first rephrase the (5) as a virtual queue $W_i(t)$ whose dynamic can be updated by:

$$\left(W_i(t-1)+x_i(t)-(1-p)\frac{MTU*cwnd_i(t)\Delta t}{RTT(t)}\right)^+ \tag{8}$$

Where $(a)^+$ indicates the $\max\{0,a\}$. Assuming the $W_i(0)=0$, then, by the form of $W_i(t)$, following equality holds:

$$\frac{W_i(t)}{t}-\frac{W_i(0)}{t}\le\frac{1}{t}\sum_{\tau=1}^{t-1}g_i(\tau) \tag{9}$$

Where $g_i(x_i,t)=x_i(t)-(1-p)\frac{MTU*cwnd_i(t)\Delta t}{RTT(t)}$. According to the definition of *stable*, the following holds when $W_i(t)$ it is stable,

$$\frac{1}{t}\sum_{T\to\infty}\sum_{t=1}^{T}g_i(t)\le\frac{1}{t}\sum_{t\to\infty}W_i(t)=0 \tag{10}$$

It means that the *stable* of the virtual queue ensures the stratification of (5). Thus, according to [34], solving (4)(5)(6) is equal to solve the following problem at each time $t$:

$$\min VE(x_i(t))+\sum_{i=1}^{n}W_i(t)g_i(t)+Q_i(t)\left(a(t)-\sum_{i=1}^{n}x_i(t)\right) \tag{11}$$

s.t $x_i\in X$

Where V is a nonnegative control parameter that is chosen as desired. Apparently, (11) is linear and let the $U(x_i(t),t)=VE_i(t)+\sum_{i=1}^{n}W_i(t)g_i(x_i,t)+Q_i(t)\left(a(t)-\sum_{i=1}^{n}x_i(t)\right)$, we can provide the solving iteration for the above problem is:

$$x(t)=\arg\min_{x\in X}U(x,t) \tag{12}$$

$$W_i(t)=W_i(t-1)+g_i(t),\forall i \tag{13}$$

$$Q_i(t)=Q_i(t-1)+\left(a(t)-\sum_{i=1}^{n}x_i(t)\right) \tag{14}$$

According to the iteration, the client first allocates $x_i(t)$ for each path by minimizing $U(x,t)$ and updating the queue $W_i(t)$ , $Q_i(t)$. Following theoretical results will provide the optimal bound of $x_i(t)$ and stability of the queue $W_i(t)$, $Q_i(t)$.

## 5. Algorithm Design

The proposed stochastic optimized process is outlined in Algorithm 1. The activity starts with the values defined under the initialization. First, it carryout $Q_i(t)$, and dictate $x_i(t)$ each path by perceiving the arrival rate $a(t)$. It determines the $x_i(t)$ as per described, and late updated the queuing accordingly.

In the standard process, the data cloud server has multiple ways to transmit inputs, as per the user requirement. The server has the privilege to select the optimal path to ensure network stability. The virtual queuing and real queuing update process is entitled here; according to the channel state, the queuing update process will continue until it finds the optimal data transmission path. The virtual queuing phenomenon is helpful and supportive according to the network conditions.

**Algorithm 1:** Stochastic Optimized Algorithm for Multipath Transmission.

```
Input: $n, a(t), x_i(t), Q_i(t), W_i(t), V$
Output: Optimum $x_i(t)$ = for every $i, Q_i(t-1)$
Initialization:
    $V = 100, t = 0, Q_i(t), W_i(t) = 0, \forall_i$
While, for each path, $x_i \in X$ do,
    $\min VE(x_i(t)) + \sum_{i=1}^{n} W_i(t) g_i(t) + Q_i(t)\left(a(t) - \sum_{i=1}^{n} x_i(t)\right)$
    For $x_i(t)$ optimum data rate selection,
    $x_i(t) = E^{-1}[\frac{Q(t) - \sum_{i=i}^{n} W_i(t)}{V}]$
    Update Queue:
```

$$Q_i(t)=Q_i(t-1)+[a(t)-\sum_{i=1}^{n}x_i(t)]$$

$$W_i\left(t\right)=W_i\left(t-1\right)+g_i\left(t\right),\forall i$$

**End**

## 6. Main Results

Here we provide two main results: queue stability of paths and boundless of an optimal gap for the proposed algorithm.

***Theorem 1***. The flow control mechanism we proposed yields the stable of queues corresponding to each path, especially, we have followed the upper bound,

$$\lim_{T\to\infty}\sup\frac{1}{T}\sum_{t=0}^{T}E\{Q_i\left(t\right)\}\le\frac{B+V\left(\psi\left(\text{ò}\right)-\dfrac{1}{T}\sum_{t=1}^{T}\mathrm{E}\{E\left(x_i\left(t\right)\right)\}\right)}{\text{ò}}\tag{15}$$

***Proof.*** According to the feasibility of problem (4)(5)(6)(7), there exist random policy $x^R\left(t\right)$ yields for every time slot,

$$\mathrm{E}\{E\left(x_i^R\left(t\right)\right)\}=\psi\left(t\right)\tag{16}$$

$$\mathrm{E}\{a\left(t\right)-\sum_{i=1}^{N}x_i^R\left(t\right)\}\le-\text{ò}\tag{17}$$

$$\mathrm{E}\{g\left(x_i^R,t\right)\}\le 0\tag{18}$$

As our algorithm derives the minimizer of $U\left(x_i\left(t\right),t\right)$, then we have,

$$\begin{aligned}&VE_i\left(t\right)+\sum_{i=1}^{n}W_i\left(t\right)g_i\left(x_i,t\right)+Q\left(t\right)\left(a\left(t\right)-\sum_{i=1}^{n}x_i\left(t\right)\right)....\\&\overset{a}{\le}V\psi\left(t\right)+\sum_{i=1}^{n}W_i\left(t\right)g_i\left(x_i^R,t\right)-\varepsilon Q\left(t\right)\overset{b}{\le}V\psi\left(t\right)-\varepsilon Q\left(t\right)\end{aligned}\tag{19}$$

Where $a$ holds by (18), and $b$ by (19), respectively. We define the Lyapunov function of (4), (5), (6), and (7) as follows,

$$L(t)=\frac{1}{2}\sum_{i=1}^{n}w_i^2(t)+\frac{1}{2}Q^2(t) \tag{20}$$

We have defined the difference of the Lyapunov function at each moment, Namely,

$$\Delta L(t)=L(t+1)-L(t) \tag{21}$$

Further, according to [34], we have found the upper bound of $\Delta L(t)$, that is

$$\Delta L(t)\le B+\sum_{i=1}^{n}W_i(t)\mathrm{E}\{g_i(x_i,t)\,|\,L(t)\}+Q_i(t)\mathrm{E}\{a(t)-\sum_{i=1}^{n}x_i(t)\,|\,L(t)\} \tag{22}$$

Where $B$ is constant and bounded by

$$B\ge\frac{1}{2}\sum_{i=1}^{n}\mathrm{E}\{g_i^2(x_i,t)\,|\,L(t)\}+\frac{1}{2}\mathrm{E}\{\Big(a(t)-\sum_{i=1}^{n}x_i(t)\Big)^2\,|\,L(t)\} \tag{23}$$

Therefore, combining with the above formula, we get the following formula,

$$\begin{aligned}&V\mathrm{E}\{E_i(x_i(t),t)\,|\,L(t)\}+\Delta L(t)\le B+V\mathrm{E}\{E_i(x_i(t),t)\}\\&+\sum_{i=1}^{n}W_i(t)\mathrm{E}\{g_i(x_i,t)\,|\,L(t)\}+Q_i(t)\mathrm{E}\{a(t)-\sum_{i=1}^{n}x_i(t)\,|\,L(t)\}\end{aligned} \tag{24}$$

Combining (19) and (24), we have obtained the following inequalities, therefore,

$$Q_i(t)\le\frac{V\psi(t)-V\mathrm{E}\{E_i(x_i(t),t)\,|\,L(t)\}+\Delta L(t)}{\epsilon} \tag{25}$$

Recall $L(0)=0$. Summing the above inequalities at all slot $t$ and taking its iterated expectations,

$$\frac{1}{T}\sum_{t=0}^{T}E\{Q_i(t)\}\le\frac{B+V\left(\psi(\epsilon)-\frac{1}{T}\sum_{t=1}^{T}\mathrm{E}\{E_i(x_i(t))\}\right)}{\epsilon} \tag{26}$$

Hence, we prove the theorem. To validate the optimality of our algorithm, we defined the *regret* of the algorithm as the gap between time expectation of accumulating $E_i(x_i(t))$ and fixed optimal solution as following:

$$G_t = \frac{1}{t}\sum_{\tau=1}^{t} E\left(x_i\left(\tau\right)\right) - E\left(x^*\right) \tag{27}$$

***Theorem 2***. The Gap yielded by the algorithm we proposed is bounded and satisfies the following:

$$\lim_{t\to\infty}\sup G_t \le B + \frac{B + V\left(E_{\max} - E_{\min}\right)}{\epsilon}$$

where $E_{\max}$ and $E_{\min}$ are the maximum and minimum time average achievable by any policy satisfying (5)-(7)

***Proof.*** Recall that the proposed algorithm yields the minimizer of (11); hence, we have the following:

$$\begin{aligned} &VE\left(t\right) + \sum_{i=1}^{n} W_i\left(t\right) g_i\left(x_i, t\right) + Q_i\left(t\right)\left(a\left(t\right) - \sum_{i=1}^{n} x_i\left(t\right)\right) \\ &\ldots. \le VE\left(x^*\right) + \sum_{i=1}^{n} W_i\left(t\right) g_i\left(x^*, t\right) + Q_i\left(t\right)\left(a\left(t\right) - \sum_{i=1}^{n} x_i^*\right) \end{aligned} \tag{28}$$

plugging the (21) and $g_i\left(x^*, t\right) \le 0$ into above inequality and rearrange, we have,

$$VE\left(t\right) - VE\left(x^*\right) + \Delta L\left(t\right) \le B + Q\left(t\right)\left(a\left(t\right) - \sum_{i=1}^{n} x_i^*\right) \tag{29}$$

The stability of the queue is satisfied by $x^*$; thus, a positive constant $C$ exists for all $t$ yielding,

$$a\left(t\right) - \sum_{i=1}^{n} x_i^* \le C$$

Taking the time average expectation on both sides of (29) of $t$, we have,

$$\begin{aligned} &\lim_{t\to\infty}\sup \frac{1}{t}\sum_{\tau=1}^{t} E\left(x_i\left(t\right)\right) - E\left(x^*\right) + L\left(t\right) \le B + \lim_{t\to\infty}\sup \frac{1}{t} C \sum_{\tau=1}^{t} Q_i\left(\tau\right)\ldots \\ &\overset{c}{\le} B + \frac{B + V\left(\psi\left(\varepsilon\right) - \frac{1}{T}\sum_{t=1}^{T} \mathrm{E}\{E_i\left(x_i\left(t\right)\right)\}\right)}{\varepsilon} \le B + \frac{B + V\left(E_{\max} - E_{\min}\right)}{\varepsilon} \end{aligned} \tag{30}$$

where $c$ holds due to the $Q\left(t\right)$ which is bounded by (26), hence we prove the theorem.

The above theorems show a $O\ \{\frac{1}{V}, V\}$ tradeoff between queue length and optimality.

Namely, if to enlarge the value $V$ , a lower queue length can be achieved (lower congestion level), yet there is a gap to the optimum. In contrast, lowering the $V$ gives better performance on throughput but worse in a congestion condition, thus inspiring us to carefully choose an optimal value $V$ .

## 7. Numerical Analysis

### 7.1 Implementation

The validity of the proposed solution is analyzed and verified under the simulation environment, as the main objective is to give the trustworthiness of the given resolution and compare it with the theoretical results. The stochastic optimization approach is adopted to achieve the desired outcomes; by introducing a queuing mechanism to authenticate and deliver the queuing stability and incorporate it with the scheduling in a multipath environment. Stochastic solutions are chosen to provide the multipath system with better stability. The problem specified in the proposed solution is the algorithm's class, parameterized as constant $V \geq 0$, selected as desired. The implemented results are reflected in the objective function defined in (11).

The performance metrics chosen for the analysis propose are the energy cost, system delay, window queuing stability, and throughput. The detailed algorithm1 reflects the flow of the queuing update process for the multipath transmission. Further, the proposed stochastic optimal MPTCP (so-MPTCP) is compared with the base MPTCP and the eMPTCP [35]. The estimated simulation parameters are revealed in **Table 1**. The simulation process follows the Poisson Distribution for the input arriving rate( $\lambda$ ). The implemented results reflect the objective function defined in (11).

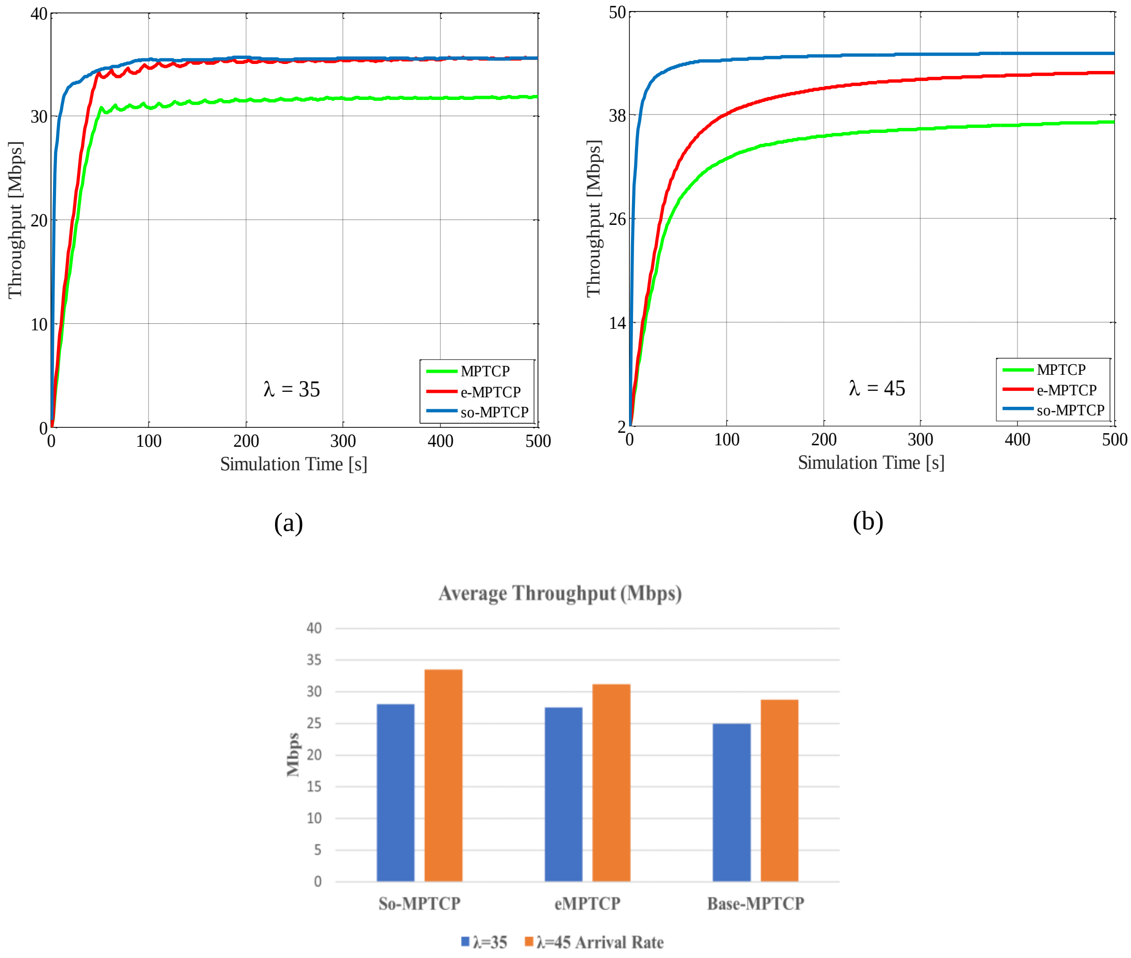
**Table 1.** Simulation Parameters

| Parameters | Values |
|---|---|
| The bandwidth of the three paths (Wi-Fi. LTE, and mmWave) | 300Mbps,600Mbps,2Gbps |
| Buffer size | One time to the BW |
| Energy Power | 5,10,20 Joules/Kbps |
| Channel Delay | 1/BW(BW=bandwidth) |
| Simulation Time | 500s |

### 7.1.1 Throughput

**Fig. 2** reveals a comparison of the proposed scheme's average throughput values with the base MPTCP and eMPTCP. There are two input arrival rates used to plot the graphs ( $\lambda = 35, 45$ ) for better result comparison. During the initial period of 0-30 seconds, the response is faster; the throughput of particular time slots is not saturated yet because particular sub-flows' transmission rate depends on the congestion windows. **Fig. 2(a)**, with lower input values, the proposed scheme has attained an average throughput, which reaches up to 35 Mbps approximately and showing a stable output, alongside the running simulation time. The higher output is achieved because all generated packets must transmit within finite time to ensure queueing stability and transmission delay. It initially has lower throughput values but later touches the higher peaks compared with the others. The base MPTCP yields lower outcomes among all, as the maximum output reaches up to 32 Mbps with slight initial variations. The eMPTCP schemes have also reached up to 35Mbps marks but with minor modifications. The existing schemes initially attain higher throughput but gradually decrease as the links get saturated. The proposed stochastic solution performs better among other plans because it limits time delay as it is sustainable and stable. In **Fig. 2(b)**, with higher input values, the proposed method again shows better performance as related to others, giving an output touching the most elevated peak up to 44 Mbps approx., while eMPTCP traces the 40 Mbps mark, and base MPTCP showing the lowest among all and giving an output that drops to 37 Mbps mark approx.

Where **Fig. 2(c)** shows the average throughput. The proposed scheme has a steady and stable response because of the stochastic optimization that allows the system to behave accordingly. It is observed and proved experimentally that the stochastic optimized solution provides higher and consistent throughput values.



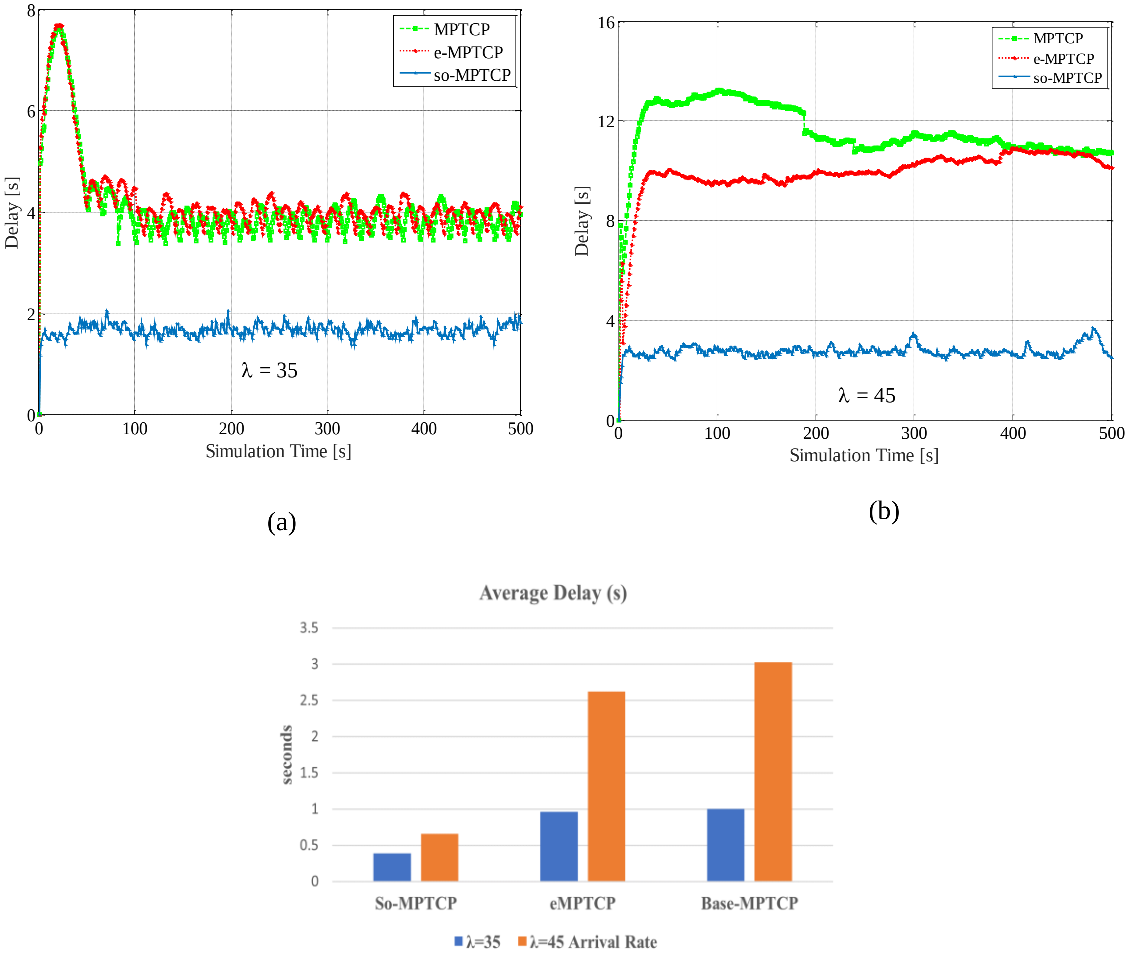
(a) (b)

(c)

**Fig. 2.** Throughput comparison of so-MPTCP with the e-MPTCP and base MPTCP for (a) $\lambda = 35$, (b) $\lambda = 45$. Where (c) shows the average throughput

### 7.1.2 Delay

**Fig. 3** plots the delay of the proposed and comparing schemes. With the smaller values of ($\lambda = 35$), in **Fig. 3(a)**, the proposed optimized protocol's delay is on the lower side in the range of 0.4 to 0.5 seconds. Other schemes are experiencing higher delay values initially, then lowering down going from 0.9 seconds while higher value touches 1.9 seconds; the queuing lengths are not bounded in these schemes. With more elevated amounts of ($\lambda = 45$), **Fig. 3 (b)**, the delay values are even higher than the other systems. In contrast, the proposed scheme is significantly showing a lower delay than others. Where **Fig. 3(c)** shows the average delay. As at the input, the amount of expected data shows randomness with higher waiting times, so the other schemes are squaring more delay as it is associated with window queueing lengths, which enhance significant variations in the queuing delays. The specified solution achieves queuing stability by limiting the time scale.



(a)

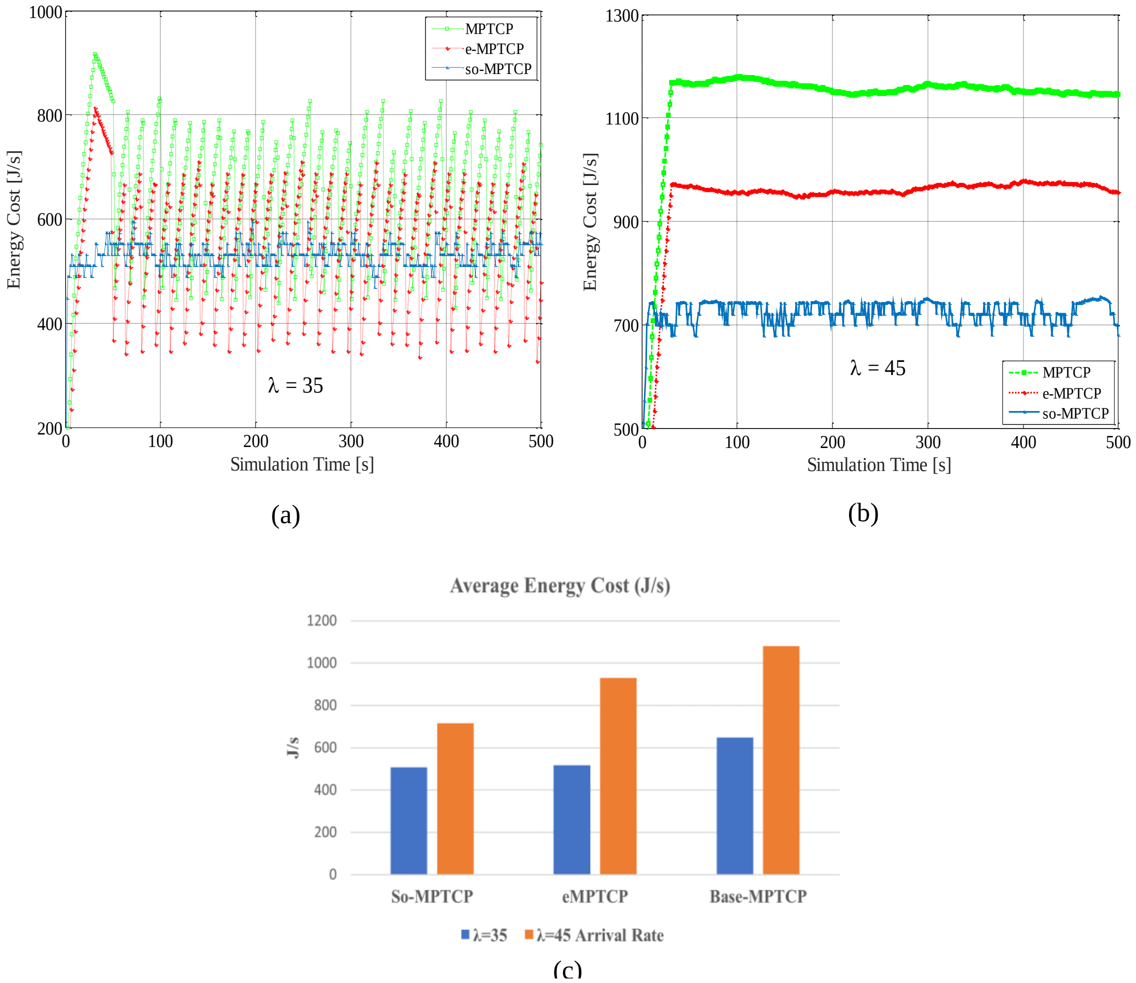
(b)

(c)

**Fig. 3.** Delay comparison of so-MPTCP with the e-MPTCP and base MPTCP for (a) $\lambda = 35$, (b) $\lambda = 45$. Where (c) shows the average delay

### 7.1.3 Energy Cost

Energy cost is related to the consumption of resources while transmitting or receiving particular data. **Fig. 4** plots the energy cost of all schemes used to analyze the performance of the system. **Fig. 4(a)** and **Fig. 4(b)** reflects that the base MPTCP energy consumption rate. That is much higher, even increasing with the rising of the input data, which touches the higher peaks up to 1100 Joules/sec. Where **Fig. 4(c)** shows the average energy cost. This rise indicates that base MPTCP does not include any energy-saving mechanisms, which affects the device performance by incorporating more processing time for fetching data inefficiently. In this paper, the proposed scheme allows the network to minimize energy consumption under the transmission rate constraints and the stable queue. Through the stochastic optimization process, the energy minimization is more effective, which fallouts in a stable system. The eMPTCP encompasses energy efficiency, but it shows more variations and nonstable behaviors than the proposed solution. The ultimate goal of the provided solution is to provide the network with more stability and lower overall energy costs for transmitting a certain amount.



(a) (b)

(c)

**Fig. 4.** Energy Cost comparison of so-MPTCP with the e-MPTCP and base MPTCP for (a) $\lambda = 35$, (b) $\lambda = 45$. Where (c) shows the average energy cost

### 7.1.4 Window Queueing Lengths

**Fig. 5** depicts the queueing length of the three paths used in the simulations. The window queueing lengths depend upon the bandwidth of underline technology. In this paper, three different standards are used for heterogeneous connectivity; the mm-wave has the smallest window size because of the higher bandwidth values with lower round trip time (RTT).

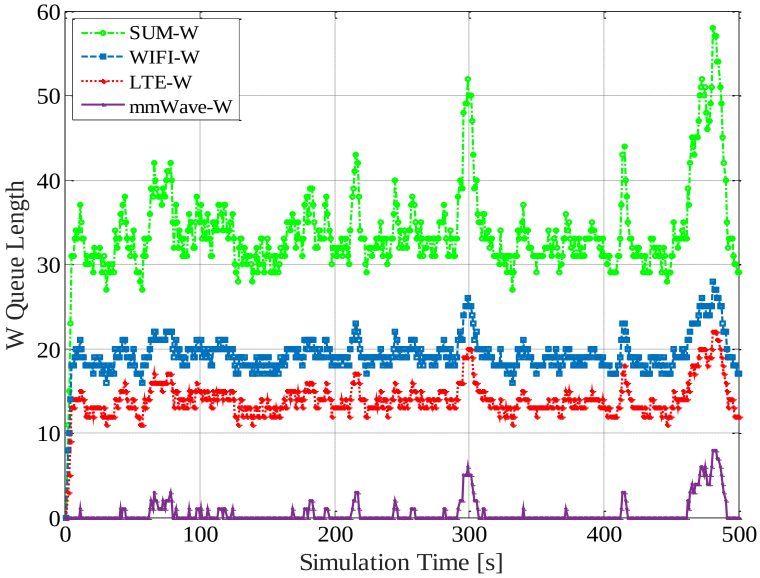


**Fig. 5.** Window Queueing Lengths for the Three Paths

## 8. Discussion

The comparison of existing solutions is reflected in **Table 2**; the comparison parameters are selected according to the proposed solution. Baseline MPTCP lacks performance degradation issues, especially with highly dynamic environments, mostly in heterogeneous wireless networks; such ambiguities lead to unpredictable behaviors. Mobile devices are favorably volatile in resource delivery, as task arrival patterns are time varying. Stochastic optimization accommodates such a dynamic system; for task allocation, designing an online task allocation schemes that allow long-term system optimality. Stochastic optimization methods give better control and liability as its implementation time is faster than other Heuristic optimization techniques. It provides long-time average optimization, as it requires the information of the current time slot. Some restrictions define the $V$ optimum factor's value, which acts as a penalty to optimize the solution. Higher values give lower queue length (lower congestion) while lower values can give better throughput to select an optimal value $V$ carefully.

The proposed scheme includes the scheduler, stochastic system, heterogenous network, energy efficiency, and congestion window control. The scheduler performs the decisions to distribute that data packet over multiple paths; worse scheduling decision brings head-of-line (HOL) blocking, congestion window limitations, specifically when the paths are heterogeneous. These are all factors that motivate us to formulate stochastic optimization solutions to overcome such issues. The details are mentioned in sections 3, 4, 5, and 6.

**Table 2.** Comparison of Existing Solutions

| References | Scheduler | Congestion control | Stochastic | Heterogeneous | Energy efficient |
|---|---|---|---|---|---|
| [3] | ✓ | ✓ | × | × | ✓ |
| [5] | × | ✓ | × | × | × |
| [6] | × | ✓ | × | × | × |
| [10] | × | ✓ | × | × | × |
| [12] | × | ✓ | × | × | × |
| [18] | ✓ | ✓ | × | ✓ | × |
| [19] | × | ✓ | ✓ | × | ✓ |
| [20] | ✓ | × | × | ✓ | ✓ |
| [24] | × | × | × | × | ✓ |
| [25] | × | ✓ | × | × | × |
| [26] | × | ✓ | × | ✓ | ✓ |
| [27] | × | × | × | × | ✓ |
| [28] | ✓ | × | × | × | ✓ |
| [30] | × | ✓ | × | × | × |
| [32] | ✓ | × | × | ✓ | ✓ |
| [33] | × | ✓ | ✓ | ✓ | × |
| [35] | ✓ | ✓ | × | × | ✓ |
| Proposed solution | ✓ | ✓ | ✓ | ✓ | ✓ |

## 9. Conclusion

This paper attempts to address the network's energy minimization and stability under the available transmission rate constraints and queueing constancy. A stochastic optimization-based approach was introduced through wide-ranging equations to solve the revealed problems for achieving desire goals. In the initial phase, the problem formulation builds by adding the virtual queueing mechanism and later proved its stability. Further, an objective function is introduced and to prove it via specific iterations. The mathematical proof part is justified via propositions, which also validate the proposed solution. Later, with the simulation's help, the proposed scheme is compared with the two existing solutions, base MPTCP and eMPTCP. The simulation results revealed a significant improvement in the throughput, reduces the delay, and minimizes the system's overall energy cost as the ultimate goal is to achieve network stability with minimum energy costs. The anticipated scheme has reached the desired goals with more excellent constancy of the network.

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