A Stochastic Optimal Scheduler for Multipath TCP in Software Defined Wireless Network

Kai Gao[1], Changqiao Xu[1], Jiuren Qin[1], Lujie Zhong[2] and Gabriel-Miro Muntean[3]
[1]State Key Laboratory of Networking and Switching Technology,
Beijing University of Posts and Telecommunications, Beijing 100876, China
[2]Information Engineering College, Capital Normal University, Beijing 100048, China
[3]School of Electronic Engineering, Dublin City University, Dublin, Ireland
Email: {gaokai, cqxu, jrqin }@bupt.edu.cn, zljict@gmail.com, gabriel.muntean@dcu.ie

***Abstract*—Multipath TCP (MPTCP) can take advantage of multiple paths to transmit data and has been deeply optimized by many researchers. However, most researchers only devote themselves to improve the transmission performance, neglecting the price cost which is another factor that users are concerned about. This paper proposes a novel stochastic optimal scheduler for MPTCP (SOS-MPTCP) that utilizes Lyapunov optimization technique in software defined wireless network (SDWN). SOS-MPTCP analyzes and solves the trade-off problem between the performance and price cost from users' perspective. Besides, with the help of centralized optimization in SDWN architecture, the controller can feed status information of each path back to mobile terminals for SOS-MPTCP to make decisions. SOS-MPTCP includes three control decisions: 1) packets admission control; 2) packets distribution control; 3) data traffic purchasing control. SOS-MPTCP aims to maximize the throughput and minimize the price cost for users. Experiment results have proved the efficiency of trade-off optimization and the transmission system can achieve the expected stability.**

***Index Terms*—MPTCP, scheduler, SDWN, stochastic optimization**

I. Introduction

Software defined network (SDN) is the critical technique in the deployment of the fifth generation communication (5G). The advantage of SDN has been introduced into the wireless network, which can simplify wireless resource management, balance traffic and so on [1][2]. The architecture of software defined wireless network (SDWN) is designed to optimize network performance [3]. While current SDN protocols, e.g. OpenFlow, are only in charge of interaction among network devices, for example, the controllers and switches. They do not take the mobile terminals into consideration. [4][5] make up the gap to extend the control function to mobile terminals. Taking advantage of this thought, the controller belonging to network side can feed corresponding information back to endpoint side for making decisions. At the same time, network side can participate in the control of endpoint side in the extended SDWN architecture. Hence the combination of network side and endpoint side can improve the fine-graind Quality of Service (QoS).

Especially, more and more mobile terminals are equipped with multiple interfaces such as WiFi, LTE, Bluetooth, WiMax, etc [6][7]. Data transmission and processing is an important part in different networks [8][9]. The extended SDWN architecture can realize the handover control, source control, destination control, path control for endpoints [4][5]. Besides, Multipath TCP (MPTCP) can utilize multiple interfaces simultaneously in order to aggregate bandwidth, load balance and improve robustness. Scheduler algorithm is one of the most important influence factor for MPTCP. The default scheduler of MPTCP in the linux kernel is lowest-round-trip-time (LRTT) [10]. Round-Robin (RR) and Redundant are the other optional schedulers. Also, there are many researchers devoting to optimize scheduler from different perspectives. [11][12] proposed a loss aware scheduler over highly lossy heterogeneous networks. [11] predicted the data amount by using maximum likelihood estimation with packet loss rate and time offset. And [12] distributed redundant segments when detecting the path in highly lossy state. To tackle the head-of-line (HoL) blocking, [13] designed a send-window blocking estimation scheduler. [14] put forward a special scheduler for thin streams through probing unused subflows and measuring one-way delay. [15] introduced largest packet credits (LPC) and largest estimated throughput (LET) schedulers for video streaming. Similarly, [16] proposed and evaluated three alternative schedulers: Highest Sending Rate (HSR), Largest Window Space (LWS) and Lowest Time/Space (LTS). Besides, our team proposed a pipeline network coding-based multipath data transfer method, which can realize quality-aware data distribution scheduling [17].

All above schedulers of MPTCP mainly focus on the transmission performance for improving the throughput and decreasing the delay. But none of them take the price cost into consideration. In the heterogeneous wireless network, the cost of each path is quite diverse and depends on the amount of packets assigned by the scheduler. From the users' perspective, the cost on paying for each path is another concerned issue besides the transmission performance. Most users would like to pay less as long as their service demand can be guaranteed.

Inspired by [18], we make a trade-off scheduler designment for MPTCP between the throughput utility and the cost. We present a novel stochastic optimal scheduler for MPTCP (SOS-MPTCP) in software defined wireless network. The new scheduler is based on the Lyapunov optimization technique [19], which can make online control decisions for data scheduling. Currently, Lyapunov has been applied in a lot of

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optimization problems, for example wireless resource scheduling, routing strategy, energy or delay constraint, maximum profit and so on[20]. This innovative scheduler can not only satisfy the demand of service, but also minimize the cost as much as possible. By taking advantage of queue stability, SOS-MPTCP intends to fill the gap with the Lyapunov optimization technique between the performance and the cost. To realize the aforementioned requirements, there are three important control decisions to be made: 1) how many packets of different connections can be admitted into transmission layer; 2) how to distribute the admitted packets to each path; 3) how to purchase data traffic for different paths in advance. What's more, the SDWN architecture can assist the endpoints to make decisions. SDN controller can collect and analyze network status information, then feeds them back to endpoints.

Based on the above description, the main contributions of our work are summarized as follows:

- We design a novel stochastic optimal scheduler for MPTCP in the extended SDWN architecture where S-DN controllers in network side can communicate with endpoints each other.
- The proposed scheduler not only considers the transmission performance, but also the payment cost of users. We utilize the Lyapunov optimization theory to make online and fine-grained control decisions for the scheduler.

The novel SOS-MPTCP is simulated in matlab and NS-3.29 where we build a multipath heterogeneous wireless network environment. The experiment results verify the proposed scheduler can achieve the desired effect.

II. System model

Fig.1 shows the system architecture of SOS-MPTCP in software defined wireless network. The system contains MPTCP sender, MPTCP receiver, SDN controller and wireless networks environment. The SOS-MPTCP scheduler is designed in the MPTCP sender. Application data of various service are assigned to different wireless paths by SOS-MPTCP scheduler. SDN controller collects and feeds the network information to the MPTCP sender. Once the data arriving at the MPTCP receiver, the receiver assembles and delivers them to the application layer. The detailed description about the system model is as follows.

The multipath transmission control system for MPTCP consists of a data scheduler platform and a number of paths denoted by $J = \{1, 2, ..., j, ..., n\}$. All paths are used to transport data packets for various services such as video, online games, files transmission and so on. Therefore, the system can serve different connections $I = \{1, 2, ..., i, ..., m\}$ of packets with diverse arrival rates from the application layer. In order to facilitate the analysis, we consider the system as a discrete time-slotted model divided by t in $\{1, 2, ..., \tau\}$.

In each time slot t, a number of packets belonging to the i-th connection arrive at the system randomly. Let $R_i(t)$ denote the number of data packets of connection $i \in I$ in time slot t. We assume the random variable $R_i(t)$ is independent and identically distributed (i.i.d). And the time averaged rate of

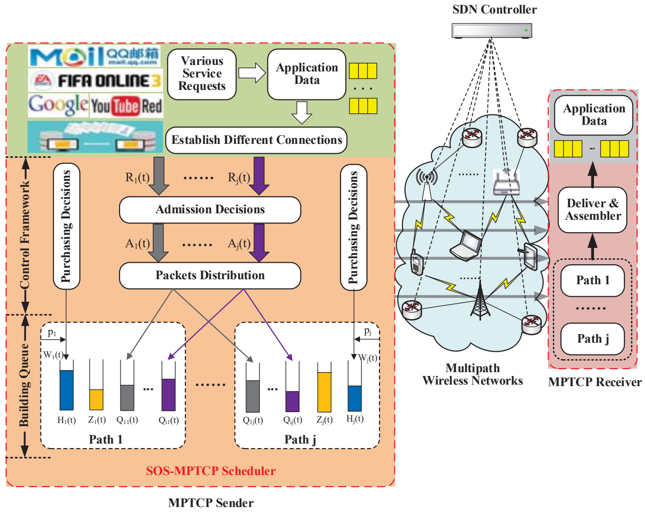

Fig. 1. SOS-MPTCP transmission system architecture in SDWN.

$R_i(t)$ is denoted as $\overline{r_i} = E\{R_i(t)\}$. We assume that $R_i^{\max}$ is the maximum value of $R_i(t)$, which is denoted as $0 < R_i(t) < R_i^{\max}, \forall i \in I$. In addition, the cost of each path is quite diverse and depends on the amount of packets assigned by the system. We assume that the unit price of path j is denoted by $p_j, \forall j \in J$. Generally, each user will prepay to different Communication Operator for the traffic.

A. Control Framework

1) Admission Control: The first control decision of the system is whether to admit the different types of packets being accepted by the transmission control system. In each time slot, a lot of packets arrive at the system. To prevent the system from congestion, the admission control module decides that the total number of packets denoted by $A_i(t), \forall i \in I$ can be admitted into the system. Therefore, $A_i(t)$ should less than the number of arriving packets, which satisfies $0 < A_i(t) < R_i(t)$.

2) Packets Allocation: After the packets of connection i are admitted into the system, the packets allocation module assigns packets to each path. The number of packets of connection i distributed to path j in time slot t is denoted as $A_{ij}(t), \forall i \in I, \forall j \in J$. And this assignment should satisfy the constraint: $A_i(t) = \sum\limits_{j \in J} A_{ij}(t)$. Each path maintains a queue for each connection of packets which can be transmitted later. We define the queue backlog $Q_{ij}(t)$ of i-th connection of packets assigned on the j-th path as the number of pending packets waiting in the queue. We also define $S_{ij}(t)$ as the number of packets which have been sent successfully and acknowledged.

3) Purchasing Data Traffic: In order to satisfy the service demand of users, they will purchase data traffic in advance from the communication operator. We use $W_j(t)$ to denote the cost of paying for the path j belonging to respective operator in the time slot t. The total cost of the multipath transmission control system can be denoted by $H_j(t)$ to maintain the consumption of path j for the users.

B. Building Queue

According to the control framework described above, the dynamic updating of queue backlog can be defined as the equation:

$$Q_{ij}(t+1) = \max[Q_{ij}(t) - S_{ij}(t), 0] + A_{ij}(t) \quad (1)$$

where $Q_{ij}(0) = 0, \forall i \in I, \forall j \in J$. And the queue stability can be defined as the following equation:

$$\bar{Q} \triangleq \lim_{\tau\to\infty} \frac{1}{\tau} \sum_{t=0}^{\tau} \sum_{i\in I} \sum_{j\in J} Q_{ij}(t) < \infty \quad (2)$$

Similarly, $H_j(t)$ denotes the cost queue size of path j in the time slot t. Under the control decision of purchasing data traffic, the queue can be expressed as follows,

$$H_j(t+1) = H_j(t) - \sum_{i\in I} S_{ij}(t)p_j + W_j(t) \quad (3)$$

where $H_j(0)$ can be any positive value according to the actual payment of users.

III. Problem Formulation and Transformation

The performance of transmission system contains the throughput and cost function. We define the time averaged throughput $\overline{Thr_i} = \sum\limits_{i\in I} \lim\limits_{\tau\to\infty} \frac{1}{\tau} \sum\limits_{t=0}^{\tau} E\{A_i(t)\}$. Then the throughput utility is defined as $\Phi(\overline{Thr_i})$. The throughput utility can be expressed by the function $\Phi(\overline{Thr_i}) = ln(1+\alpha\overline{Thr_i})$, where α is a positive constant.

On the other hand, the time averaged cost for purchasing data traffic from path j is defined as $\overline{W_j} = \sum\limits_{j\in J} \lim\limits_{\tau\to\infty} \frac{1}{\tau} \sum\limits_{t=0}^{\tau} E\{W_j(t)\}$. It is challenging to tradeoff the transmission throughput and cost function. Therefore, we need to construct an objective to take both sides into consideration.

The goal of the new scheduler is to maximize the system performance, which admits appropriate number of packets entering into transmission system, distributes these packets to each paths, and purchases the data traffic for different paths. Therefore, the problem of maximizing the total transmission utility can be defined as

$$\begin{aligned} &Max\{\sum_{i\in I} \Phi(\overline{Thr_i}) - \eta \sum_{j\in J} (1-\sigma_j)\overline{W_j}(t)\} \\ &s.t. \qquad \overline{Thr_i} \le \overline{r_i}, \forall i \in I \\ &Q_{ij}\ is\ stable, \forall i \in I, \forall j \in J \end{aligned} \quad (4)$$

where η is a parameter to adjust the relationship between the throughput and cost. When $\eta = 0$, the scheduler does not consider the cost of user, while $\eta \to \infty$, the scheduler does not consider the transmission performance. And σ_j is the packet loss factor of path j. σ_j is calculated by $\sigma_j = \frac{PL_j}{\sum_J PL_j}$, where PL_j is the packet loss of path j. PL_j can be calculated by SDN controller which can collect and analyze flow entry from base stations, WiFi access points and others' access points. We use the OpenNetMon proposed in [21] as the measurement method of PL. Then the controller feeds the PL_j back to the endpoints according to [4].

To solve the problem aforementioned with Lyapunov optimization [20], we can transform the problem by introducing an auxiliary variable $a_i(t)$ for each $A_i(t)(a_i(t) < A_i(t))$, as shown in the following lemma.

Lemma 1: The problem (4) is transformed as follows,

$$\begin{aligned} &Max\{\sum_{i\in I} \Phi(\overline{a_i}) - \eta \sum_{j\in J} (1-\sigma_j)\overline{W_j}(t)\} \\ &s.t. \qquad a_i(t) < A_i(t), i \in I \\ &Q_{ij}(t), H_j(t)\ and\ Z_i(t)\ are\ stable \end{aligned} \quad (5)$$

where the virtual queue $Z_i(t)$ is also introduced, which can be expressed in each time slot as follows,

$$Z_i(t+1) = max[Z_i(t) - A_i(t) + a_i(t), 0] \quad (6)$$

Considering the current queue backlogs according to actual and virtual queues, we define the Lyapunov function as follows,

$$L(t) \triangleq \frac{1}{2}\sum_{i\in I}\sum_{j\in J} {Q_{ij}}^2(t) + \frac{1}{2}\sum_{j\in J} {H_j}^2(t) + \frac{1}{2}\sum_{i\in I} {Z_i}^2(t) \quad (7)$$

The meaning of $L(t)$ is a scalar measurement of queue congestion in the transmission system. The value of $L(t)$ is small which means all queue backlogs are small. The value of $L(t)$ is large which implies there exists at least one queue with large queue backlogs. A small value of $L(t)$ at all time slots t denotes that all queues are stable.

The vector $\varphi(t) = [Q(t), H(t), Z(t)]$ is defined to represent the matrix of all queues. Thus, we can introduce the one-slot condition Lyapunov drift, as follows,

$$\Delta(t) \triangleq \mathrm{E}\{L(t+1) - L(t)|\varphi(t)\} \quad (8)$$

It denotes the difference of Lyapunov function between a time slot and the next. Then we define the drift-minus-penalty function in order to minimize the Lyapunov drift and guarantee the performance of transmission system.

$$\Delta(t) - VE\left\{\sum_{i\in I} \Phi(a_i(t)) - \eta \sum_{j\in J} (1-\sigma_j)W_j(t)\right\} \quad (9)$$

where V is a variable parameter to tradeoff the system performance and stability. Through recombining the formula (9), we can calculate the upper bound for the formula (9). The proof is omitted due to space limit which is similar to [19].

Lemma 2: The upper bound of drift-minus-penalty function is expressed as the following inequality.

$$\begin{aligned} \Delta(t) - VE\left\{\sum_{i\in I} \Phi(a_i(t)) - \eta \sum_{j\in J} (1-\sigma_j)W_j(t)\right\} \le B \\ - \sum_{i\in I} E\{V\Phi(a_i(t)) - Z_i(t)a_i(t)\} \end{aligned} \quad (10)$$

$$-\sum_{i\in I} E\{Z_i(t)A_i(t) - Q_{ij}(t)A_{ij}(t)\} \tag{11}$$

$$+\sum_{j\in J} E\{V\eta(1-\sigma_j)W_j(t) + H_j(t)W_j(t)\} \tag{12}$$

$$-\sum_{j\in J} E\{\sum_{i\in I} Q_{ij}(t)S_{ij}(t) + H_j(t)S_{ij}(t)p_j\} \tag{13}$$

where the value of B is as follows,

$$\begin{aligned} B = (1/2)\{&|I|\,|J|\,(S^{max})^2 + |J| \sum_{i\in I} ({R_i}^{\max})^2 \\ &+ |J|\,[W^{\max} - S^{max}\sum_{j\in J} p_j]^2 + |I|\,{R_i}^{\max}\} \end{aligned} \tag{14}$$

Therefore, the problem (9) can be divided into four parts as (10)-(13). Next, we will design the scheduler according to the four parts.

IV. Scheduler Design

The optimal objection is to minimize the drift-minus-penalty in the formula (9). Our proposed online scheduler can divide the objection into four independent terms (10)-(13). And the values of $a_i(t)$, $A_i(t)$, $A_{ij}(t)$, $W_j(t)$ and $S_{ij}(t)$ can be calculated by the current queue status of $Z_i(t)$, $Q_{ij}(t)$ and $H_j(t)$. Next, every step is described in detail based on the proposed scheduler. And the SOS-MPTCP is further illustrated as in Algorithm 1.

(1) Auxiliary Variable Control

The auxiliary variable can be computed by maximizing the formula (10) as follows.

$$\max\{V\Phi(a_i(t)) - Z_i(t)a_i(t)\} \tag{15}$$

With the value of V and the derivative of the function $\Phi(x)$, the solution of the problem can be calculated to get formula (16).

$$a_i(t) = \begin{cases} \frac{V}{Z_i(t)} - \frac{1}{\alpha}, 0 < \frac{V}{Z_i(t)} - \frac{1}{\alpha} \le {R_i}^{\max} \\ 0, else \end{cases} \tag{16}$$

(2) Admission Control and Packets Assignment

It is crucial to make control decisions about how many packets coming into transmission system and how to distribute these packets to different paths. This part of decision is to maximize the formula (11), which can be shown as follows.

$$\max_{A_i(t),A_{ij}(t)} \{Z_i(t)A_i(t) - Q_{ij}(t)A_{ij}(t)\} \tag{17}$$

While the relationship between $A_i(t)$ and $A_{ij}(t)$ is $A_i(t) = \sum_{j\in J} A_{ij}(t)$ and they are coupled each other. We first consider the term $Q_{ij}(t)A_{ij}(t)$ and minimize the value of it. To solve the coupled problem, we can assign the packets to the paths with shortest queue, which can be denoted as the following proposition.

Proposition 1: If $j* = argmin_{i\in I} Q_{ij}(t)$, the optimal solution is given by

$$A_{ij}(t) = \begin{cases} A_i(t), j = j* \\ 0, else \end{cases} \tag{18}$$

Algorithm 1 : Stochastic Optimal Scheduler of MPTCP for Performance-Cost Trade-off

input: Queue backlogs of $Q_{ij}(t)$,$H_j(t)$,$Z_j(t)$ at time slot t; unit price p_j of path j;the value of V,η,σ_j;

while ($t \in [0, \tau]$):
  Admission Decision and Distribution Decision
  for each connection i:
    calculate $A_i(t)$ by solving problem (17);
      for each path j:
        collect status information and calculate PL in SDN controller;
        calculate $A_{ij}(t)$ according to the equation (18);
      end for
  end for
  Purchasing Decision
  for each path j:
    calculate $W_j(t)$ according to the equation (21);
  end for;
  Updating the queue $Q_{ij}(t)$,$H_j(t)$,$Z_j(t)$ according to equation (1), (3) and (5).
end while

Therefore, the problem (17) can be rewritten as

$$\max_{A_i(t)} \{Z_i(t)A_i(t) - Q_{ij*}(t)A_i(t)\} \tag{19}$$

Therefore, the problem (19) can be solved according to linear programming method. The value of $A_i(t)$ can be expressed as follows,

$$A_i(t) = \begin{cases} R_i(t), Z_i(t) > Q_{ij*}(t) \\ 0, else \end{cases} \tag{20}$$

When $Q_{ij*}(t)$, the backlog of the shortest queue for connection i, is smaller than the queue $Z_i(t)$, the arrived packets of connection i can be admitted into the transmission system. Besides, we also consider the cwnd of each path j. Based on the above calculation, $A_i(t)$ is assigned the value as $min(A_i(t), \sum_{j\in J} (cwnd_j - flight_j))$, where $flight_j$ represents the data that has been sent, but not yet acknowledged.

(3) Data traffic purchasing

The users are concerned about the cost of purchasing data traffic. The decisions about how much to prepay for path j can be made through minimizing the term (12).

$$\min\{V\eta(1-\sigma_j)W_j(t) + H_j(t)W_j(t)\} \tag{21}$$

The operation of purchasing for all paths is independent with each other. This can be regarded as a linear equation to get the value of $W_j(t)$.

$$W_j(t) = \begin{cases} R_j(t), H_j(t) < V\eta(1-\sigma_j) \\ 0, else \end{cases} \tag{22}$$

The purchasing decision $W_j(t)$ is adjusted according to the queue size of $H_j(t)$. It can guaranteed that the users will not prepay too much or not enough for the service application.

(4) Packets transmission amount

For each path j, the amount of packets $S_{ij}(t)$ are related to the term (13). The decisions $S_{ij}(t)$ on different paths are independent, so maximize the term (13)

$$\max\{\sum_{i\in I} Q_{ij}(t)S_{ij}(t) + H_j(t)S_{ij}(t)p_j\} \tag{23}$$

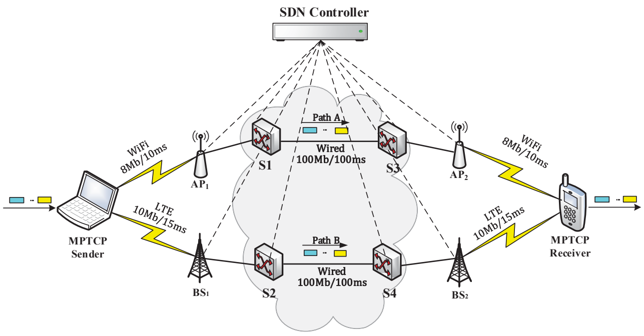

Fig. 2. The simulation topology.

The term (23) can be changed into $\max\{(\sum_{i\in I} Q_{ij}(t) + H_j(t)p_j)S_{ij}(t)\}$. Therefore, the value of $(\sum_{i\in I} Q_{ij}(t) + H_j(t)p_j)$ can be regarded as the coefficient of $S_{ij}(t)$. The larger the value of coefficient,the more amount of packets send successfully.

V. Performance Evaluation and Analysis

A. Implementation and Evaluation setup

We do the experiments in both Matlab and NS-3.29 [22] for numerical and actual simulations, respectively. The experimental topology is designed as Fig.2. MPTCP sender establishes two paths which are WiFi and LTE. We assume that the unit price of WiFi is 5, while the unit price of LTE is 10. In the setup of Matlab experiments, the number of MPTCP connections varies from 10 to 20 randomly. We assume that the arrival of packets obeys the Poisson distribution. The simulation time is 500s. Also, we set the parameters as follows: $V = 50, \eta = 0.6, \sigma_{WiFi} = 0.75, \sigma_{LTE} = 0.45$. In NS-3.29, we implement the proposed scheduler under Current Development of NS-3 submitted by Kashif Nadeem [23].

B. Evaluation results and analysis

1) Numerical simulation: In this section, we compare our proposed SOS-MPTCP with the Greedy scheme in [24]. The basic idea of Greedy scheme is admitting packets as much as possible and purchasing the data traffic as much as possible. We compare these two schemes from there aspects: time-average queue backlog, time-average utility and cost.

Fig. 3 shows the variation trend of time-average queue backlog. The results display that our proposed SOS-MPTCP can achieve stability earlier than the Greedy scheme. And the length of time-average queue backlog of SOS-MPTCP is less than the Greedy scheme because SOS-MPTCP can process packets effectively. Fig. 4 depicts the time-average utility of SOS-MPTCP and the Greedy scheme. Because the SOS-MPTCP takes the price cost into consideration, the utility of SOS-MPTCP is lower than that of Greedy scheme slightly. As Fig. 5 indicates, the cost of SOS-MPTCP is much lower than that of Greedy scheme. The Greedy scheme only considers the transmission performance and expects to process more packets as much as possible.

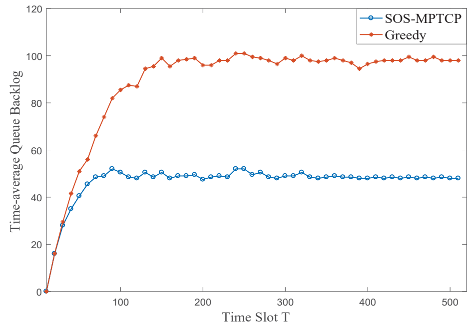

Fig. 3. Time-average queue backlog comparison between SOS-MPTCP and Greedy.

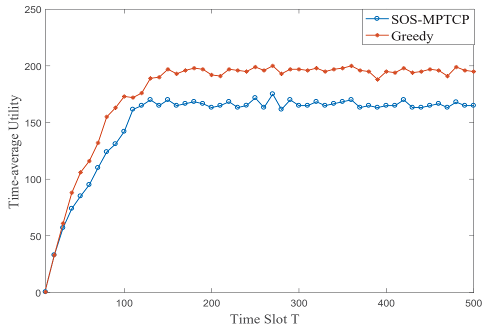

Fig. 4. Time-average utility comparison between SOS-MPTCP and Greedy.

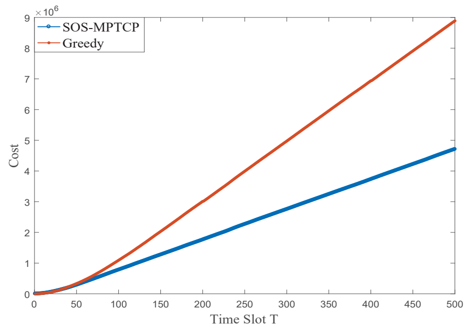

Fig. 5. Cost comparison between SOS-MPTCP and Greedy.

2) Actual simulation: After numerical simulation, we do the experiments in NS-3.29 according to simulation topology as shown in Fig.2. We compare our proposed SOS-MPTCP with LAMPS [12], which considers the packet loss of each path. Fig.6 illustrates the change of average throughput for each path and total paths in the duration of simulation. SOS-MPTCP not only considers the packet loss that is provided by SDN controller, but also refers to the price cost factor. We can see that the total throughput of SOS-MPTCP is a bit lower than that of LAMPS. Because the transmission quality of LTE path is better than WiFi path, LAMPS assigns more packets even redundant packets on LTE path without considering the price cost of LTE path is also more expensive than that of WiFi path. The average throughput of LTE(LAMPS) is more than that of WiFi(LAMPS). While SOS-MPTCP makes a trade-off decision between the transmission performance and cost intelligently. SOS-MPTCP can transfer part of traffic from LTE path to WiFi path. In addition, Fig.7 shows the cost of each path and total paths in the duration of simulation. The total cost of SOS-MPTCP is lower than that of LAMPS.

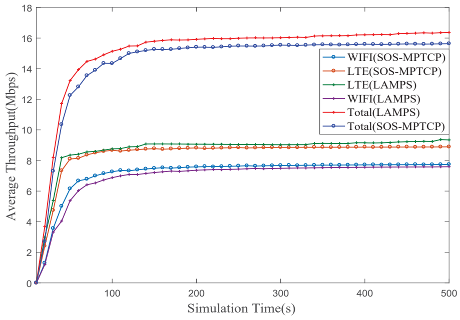

Fig. 6. Throughput variations of SOS-MPTCP and LAMPS.

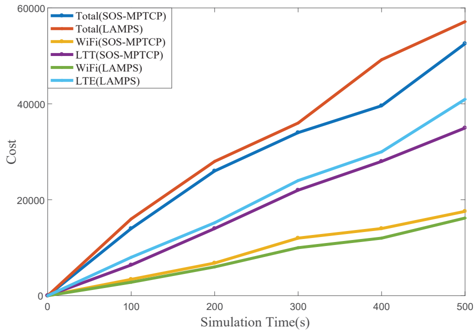

Fig. 7. Cost variations of SOS-MPTCP and LAMPS.

Actually, the cost of LTE is the most expensive than the other paths. Through making the trade-off decisions, SOS-MPTCP distributes more packets on the WiFi path comparing with LAMPS. Therefore, the cost of WiFi(SOS-MPTCP) is more than that of WiFi(LAMPS). The experiment results verify our proposed SOS-MPTCP can solve the trade-off optimization problem effectively between the transmission performance and cost.

VI. Conclusion

This paper proposes a novel stochastic optimal scheduler for MPTCP in SDWN. This new scheduler tackles the problem about the performance-cost trade-off for MPTCP. Through using Lyapunov optimization technique, SOS-MPTCP can make the control decisions to maximize the throughput and minimize the price cost for users. In addition, taking advantage of SDWN, the controller can feed network information back to mobile devices for assisting the decision-making of SOS-MPTCP. Numerical and actual simulation results prove that SOS-MPTCP can solve the trade-off problem effectively.

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