Network-side Multipath Access Management in Wireless Networks with Software-defined Networking
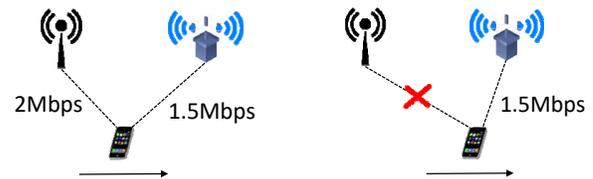
Kang Chen, *Member, IEEE*, Xin Xing, Mijanur Rahaman Palash, Jianwei Liu
and James Martin, *Member, IEEE*

Abstract—The emergence of multipath transmission control protocol (MPTCP) enables mobile devices to use multiple wireless network access paths simultaneously. However, we find that unconstrained multipath users could negatively impact the performance of wireless networks in terms of throughput and fairness. Meanwhile, when solving this issue, it is desirable to keep the multipath access as much as possible due to its attractive benefits. Therefore, in this paper, we first identify a solution strategy that can effectively balance the network performance and multipath benefits. We then implement the strategy through a software-defined networking (SDN) based bandwidth usage management system. Our method identifies a primary path for each multipath user. When congestion happens at an access point (AP), non-primary connections of multipath users are suppressed, thus protecting the network performance. Otherwise, no intervention is imposed, which offers maximal benefits to multipath users. Thus, multipath access is dynamically scaled to achieve a balance between the two aforementioned goals. This process is done in a repetitive manner to be adaptive to user dynamism (e.g., mobility). The proposed solution strategy and system apply to both downlink and uplink traffic. Extensive real deployment experiment and NS3 simulation with Linux Kernel MPTCP implementation demonstrate our findings as well as the effectiveness of the proposed solution.

Index Terms—MPTCP, Wireless Network, Performance, SDN

I. INTRODUCTION

MULTIPATH transmission control protocol (MPTCP) [1], [2] has attracted much interest recently due to its ability to enable a TCP connection to exploit multiple paths transparently. Such a feature enables mobile devices to use multiple access points (APs) of the same or different networks at the same time, i.e., multipath access. Consequently, the network performance of mobile devices can be improved in terms of bandwidth (i.e., by aggregating bandwidths from multiple APs) and mobility resilience (i.e., by transparently adding new APs to access and switching away from poor/disconnected APs while keeping the TCP connection alive), as shown in Fig. 1a and Fig. 1b, respectively. More importantly, those advantages are enabled at the TCP level, which makes mobile applications able to

Kang Chen, Xin Xing, and Mijanur Rahaman Palash are with the Department of Electrical and Computer Engineering, Southern Illinois University, Carbondale, IL 62901 USA email: {kchen, xin.xing, mijanur.palash}@siu.edu. Xin Xing and Mijanur Rahaman Palash contributed to this work during their study at SIUC.

Jianwei Liu and James Martin are with the School of Computing, Clemson University, Clemson, SC 29634 USA Email: {jianwel, jmarty}@clemson.edu

Kang Chen is the corresponding author.

(a) Bandwidth aggregation at TCP level.

(b) Transparent mobility resilience at TCP level.

Fig. 1: Benefits of MPTCP based multipath access in wireless networks.

use the multipath access and receive its benefits transparently. To this end, we define multipath users as mobile devices that enable multipath access through MPTCP.

However, while state-of-art researches mostly focus on the benefits of the MPTCP based multipath access from the perspective of mobile devices [3]–[8], how would this new network access manner affect the performance of wireless networks has not been sufficiently discussed. Without sufficient understanding of this aspect, the overall values of multipath access in wireless networks remain incomplete and obscure. This concern is driven by two facts. First, multipath users do not create additional capacity for wireless networks. They just access multiple APs in parallel. Second, due to the unique features of wireless communication, the maximal throughput of a wireless AP is correlated with the number and qualities of associated connections [9]. The more connections, especially the more low-quality connections, the lower maximal throughput a wireless AP can achieve.

Our initial study in [10] revealed that the throughput of the wireless network and the fairness to single-path users (i.e., devices that only use a single AP) are deteriorated under the existence of multipath users. This is caused by the additional wireless connections brought about by multipath users (particularly the additional weak connections). Therefore, it is necessary to control MPTCP based multipath access in wireless networks. However, blind suppression would lose the benefits of multipath access completely. We then exploited an important observation to handle this challenge. That is, multipath users should be allowed to obtain idled bandwidth through multipath access freely, since this does not throttle other users' network performance. Thus, we can dynamically scale the multipath access based on the availability of idled bandwidth, thereby achieving a balance between overall network performance and multipath benefits.

We have further proposed a network side flow management system to implement the above idea. The system exploits software-defined networking (SDN) [11] to monitor and control flows to and from end devices. A regulation center is

developed to control flows from multipath users periodically based on bandwidth availability on APs. The regulation algorithm owns a low complexity. Besides, each implementation of the system serves a local area independently. Therefore, the proposed design can easily scale up for a large area through multiple parallel implementations.

On the basis of the initial work [10], this paper substantially extends the research to provide a comprehensive study of how multipath access impacts the performance of wireless networks and the mitigating solution. Particularly, we have 1) enhanced the background introduction and related work; 2) provided more explanations for key ideas; 3) expanded the study to include uplink and confirmed that the issue also exists in the uplink; 4) adapted the solution system to handle the issue in the uplink; 5) studied how to handle user dynamism such as mobility; and 6) enhanced the performance evaluation by adding real deployment based experiments and testing under more network scenarios.

We use AP to uniformly represent the access point for wireless network service, such as WiFi AP and LTE base station (BS). User, device, and UE (i.e., user equipment) are interchangeably used in this paper. In this paper, we focus on the wireless hop by assuming it is the bottleneck of network access, as in many wireless network studies [12]–[14].

In the remaining of this paper, related work is presented in Section II. Section III models the problem through experiments, simulation, and analysis. Section IV introduces the solution strategy. Section V presents the proposed solution system. The performance of the system is evaluated in Section VI. Finally, Section VII concludes the paper.

II. RELATED WORK

A. Exploiting Multiple Paths in Wireless Networks

Exploiting multiple concurrently-available wireless network access paths has been traditionally studied under the concept of heterogeneous wireless networks (HetNets).

The first group of works focuses on client side RAT (radio access technology) selection in HetNets [12], [15]–[19]. MOTA [12] designs a service model that helps UEs associate interfaces to operators and application traffic to interfaces. The work in [15] models the RAT selection in HetNets as a game among UEs and proves its ability to converge. Orsino *et al.* [16] integrate multiple BS and UE parameters into the RAT selection process in 5G Multi-RAT network. Similarly, the work in [17] and [18] exploits network side information, e.g., cost and Quality of Service (QoS), and context information, e.g. network parameters and user preferences, respectively, to improve overall network performance through RAT selection. Keshavarz-Haddad *et al.* [19] extensively study the client side RAT selection game under two classes of throughput modeling. They find that Nash equilibria and optimality are attainable only in certain scenarios. We see that those algorithms cannot adapt to network load dynamism effectively due to being located on the client side.

To solve this drawback, researchers have proposed to dynamically allocate resources and/or schedule flows in HetNets [13], [14], [20]–[23]. The work in [20] models the network resource allocation problem in accessing multi-radio networks in parallel to maximize the throughput. ATOM [13] proposes a practical flow scheduling system for integrated LTE-WiFi network that can maximize the overall network utility. Sivchenko *et al.* [21] propose an integrated mobility and resource management framework for HetNets. The work in [22] adopts SDN to instruct packet forwarding and resource allocation rules. Chen *et al.* [14] propose an SDN based flow scheduling system to achieve transparent mobility and optimal flow scheduling in integrated LTE-WiFi networks. The work in [23] optimizes the quality of experience (QoE) of vehicle-to-infrastructure (V2I) video communication under heterogeneous LTE and WiFi networks through SDN based resource allocation and flow management. However, the improvement headroom in those works is limited due to the difficulty in seamless flow mobility. Existing seamless flow mobility schemes, such as IFOM [24] and the schemes in [25] and [14], require additional components on either the mobile device or the network side, which can not be satisfied easily.

MPTCP solves the challenge of flow mobility by allowing a mobile device to use multiple access paths seamlessly [26], [27]. This attracts significant interests in applying MPTCP in wireless networks [3]–[8], [28]–[31]. The work in [3] systematically measures the performance of MPTCP in HetNets and concludes that MPTCP improves the transport performance in HetNets. Deng *et al.* [4] conduct similar research and find that MPTCP presents little or no improvement to short flows, and the benefits for long flows depend on configuration. The work in [5] categorizes the energy cost of using MPTCP in wireless networks and proposes an energy-efficient MPTCP. Croitoru *et al.* [6] exploit MPTCP for improved mobility resilience in WiFi by letting a device connect to and use multiple WiFi APs simultaneously. In the work of [7], MPTCP is adopted to provide seamless flow migration in scheduling flows in HetNets. Nikravesh *et al.* [8] also reveal some limits of MPTCP in HetNets through field measurement and propose a proxy-based improvement method. The works in both [28] and [29] study how to handle the path heterogeneity (i.e., in terms of data rate and round-trip time (RTT)) when using MPTCP in wireless networks. Plash*et al.* [30] propose a bandwidth-need driven energy efficiency improvement approach for using MPTCP in wireless networks.

However, we see that those MPTCP related works mainly focus on the benefits/performance of individual multipath users in wireless networks. How multipath users affect the overall network performance has not been well investigated. Such a fact motivates this research.

B. Combining MPTCP and SDN

There are already researches that combine SDN and MPTCP in the context of wireless networks [32], datacenter networks [33], [34], and satellite network [35]–[37]. These works mainly exploit the flexible control and global view of SDN to decide the number of subflows, select routing paths for subflows and enforce path selections for MPTCP. Consequently, the network resources are better utilized through a balanced load and a smooth handover process.
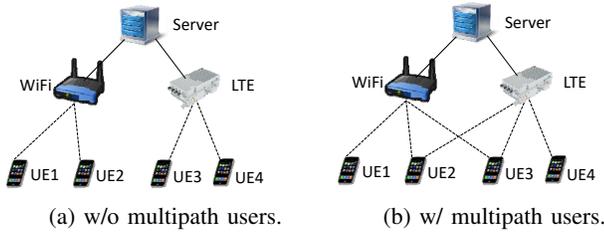
(a) w/o multipath users.   (b) w/ multipath users.

Fig. 2: Setup of real deployment based test.

Fig. 3: Result of the real deployment based test (note that "No-MP", "MP-Reno", and "MP-OLIA" denote the test without multipath users, with Reno enabled multipath users, and with OLIA enabled multipath users, respectively).

The above research efforts demonstrate the benefits of jointly using SDN and MPTCP in improving the network performance. However, these studies differ from the proposed work in terms of design goals. They mainly use SDN to facilitate the performance of MPTCP, while this work aims to balance the network performance and MPTCP benefits with SDN. As a result, these works cannot be used to solve the problem identified in this paper.

III. NETWORK MODEL AND RESEARCH PROBLEM

In this section, we first define the network model and performance metrics. We then present the measurement study and analysis that model our research problem. We focus on the downlink in Sections III-B and III-C. Afterward, we extend the discussion to the uplink in Section III-D.

A. Network Model and Performance Metric

In this research, we consider a network model in which mobile devices in a local area are served by a set of wireless networks (i.e., defined as **wireless network set (WNS)**). We primarily consider WiFi and LTE in this paper due to their wide adoption. Since WiFi APs are more densely deployed than LTE BS, we abstract the study scenario to contain one LTE BS and multiple WiFi APs. Mobile devices can be either multipath users (i.e., access both LTE and WiFi) or single-path users (i.e., access either LTE or WiFi). Our research is to study how the overall performance of the WNS is affected when multipath access is enabled.

Our major performance metric is the throughput that a WNS/AP/device achieves when all devices have backlogged traffic, i.e., when all are continually demanding for more bandwidth. We define it as the **achievable throughput** of a WNS/AP/device. We adopt this metric definition because 1) it practically and fairly reflects the worst case for the WNS/AP and 2) it shows mobile devices' ability to obtain bandwidth from the AP. Such a metric has been widely used in researches that improve wireless network performance through scheduling and resource allocation [12], [15], [20], [21].

B. Measurement Study

We conducted tests through both real deployment and NS3 simulation to show how simultaneous multipath access affects overall network performance.
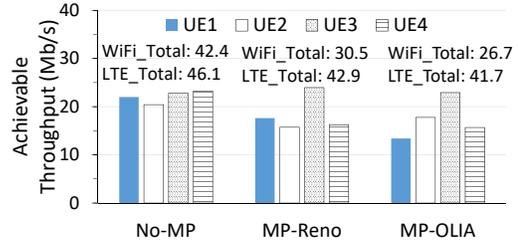
1) Real Deployment based Measurement: The test uses one WiFi AP, one LTE BS, and four laptops, as shown in Fig. 2. The WiFi AP is a TPLink wireless router configured on 802.11n. The LTE BS is a Lemko EZ LTE indoor base station [38] running on the 3.65 GHz CBRS band [39]. UE1 and UE2 are placed close to the WiFi AP, while UE3 and UE4 are close to the LTE BS. In the test, all UEs were downloading a large file from the server without a rate limit.

We measured the throughput of the four UEs without and with multipath users. In the former case, each UE only accesses the nearest AP/BS, as shown in Fig. 2a. In the latter case, UE2 and UE3 use both WiFi and LTE through MPTCP [40], as shown in Fig. 2b. We adopted both uncoupled TCP Reno [41] and coupled OLIA [42] as the congestion control algorithm for MPTCP in the experiment.

The results are shown in Fig. 3. We see from the figure that when UE2 and UE3 turn to multipath access, the achievable throughput of the WiFi AP decreases from 42 Mb/s to around 30 Mb/s, and that of the LTE BS decreases from 46 Mb/s to about 42 Mb/s. Meanwhile, the achievable throughput of single-path user UE1 (UE4) decreases from 22 Mb/s to 15 Mbs (23 Mb/s to 16 Mb/s). This shows that the achievable throughput of the network and the fairness to single-path users are deteriorated under multipath users. Besides, the results under "MP-OLIA" and "MP-Reno" are similar. The reasons for such results are explained in Sections III-C and IV-B.

2) NS3 based Simulation: Due to the scale limit of the real deployment, we further conducted NS3 simulation in a 200mX200m area, as shown in Fig. 4. The WNS includes three WiFi APs and one LTE BS (i.e., eNodeB)). In the setup, every wireless AP connects to an FTP server directly, which is not shown in the figure. We used NS3 direct code execution (DCE) [43] to integrate Linux Kernel MPTCP implementation into the test. Both TCP Reno and OLIA were adopted as the congestion control algorithm for MPTCP. To rule out the inter-AP interference, WiFi APs were configured on different channels.

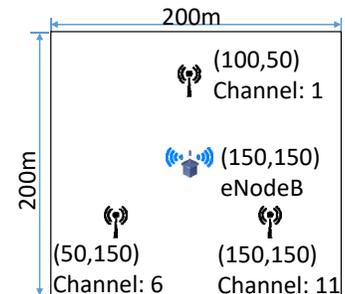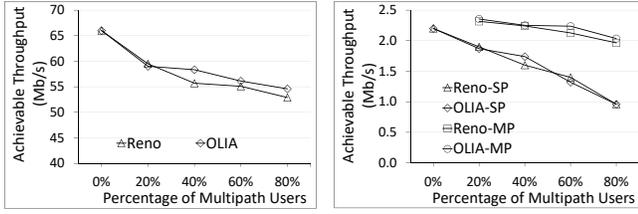We randomly placed 30 devices in the simulation

Fig. 4: NS3 measurement setup.

(a) Overall achievable throughput of the WNS.

(b) Average achievable throughput of single-path (SP) and multipath (MP) users.

Fig. 5: Result of NS3 based measurement.

area. We use $Th_m\%$ to denote the percentage of multipath users, i.e., $(100 - Th_m)\%$ of UEs are single-path users. We selected multipath users randomly. For a single-path user, it uses WiFi if its distance to the closest WiFi AP is smaller than a value (i.e., 50m). Otherwise, it uses LTE. We varied $Th_m\%$ from 0% to 80% and measured the throughput of each device. In the test, every device downloaded a 2GB file from the FTP server without a rate limit. Per the definition in Section III-A, the throughput achieved by devices in this test represents the achievable throughput. We thus use the term "achievable throughput" to present results directly.

The average result of 10 runs is shown in Fig. 5a and Fig. 5b, in which "Reno" and "OLIA" represent the results when multipath users adopt Reno and OLIA as the congestion control algorithm, respectively. We see that the achievable throughput of the WNS decreases when there are more multipath users. We further find that when the percentage of multipath users increases, the throughput of single-path users decreases rapidly, while that of multipath users keeps relatively stable. This indicates that multipath users hurt the throughput of the WNS and the fairness to single-path users. Also, Reno and OLIA lead to similar results. Such results confirm the observation in the real deployment based test.

C. Cause Analysis

In this section, we analyze the causes of the issues identified in the measurement study.

1) Throughput Degrading: WiFi adopts a packet-level fairness resource allocation strategy and a distributed MAC scheme [13], [44]. The packet-level fairness means that the AP aims to transmit the same amount of packets for associated devices. Then, the throughput of an AP with N devices can be represented as

$$T_w = \frac{N * S_p}{\sum_{i=0}^{N-1} t_i} \qquad (1)$$

where S_p is the maximal packet size (we assume that devices use the maximal size under backlogged traffic). In addition, t_i denotes the average amount of time needed to transmit a packet for client c_i. t_i is affected by two factors: collision caused retransmission (i.e., $\bar{k}$ times on average) and physical layer data rate (i.e., r_i). It is represented by $t_i = \bar{k} * \frac{S_p}{r_i}$. Thus, we can convert Eq. (1) to the following

$$T_w = \frac{N}{\bar{k} * \sum_{i=0}^{N-1} \frac{1}{r_i}} = \frac{1}{\bar{k} * \bar{t}} \qquad (2)$$

where $\bar{t}$ denotes the average time needed to transmit one unit of data to a device when there is no retransmission and is calculated by $(\sum_{i=0}^{N-1} \frac{1}{r_i})/N$.

Eq. (2) explains how multipath users affect the achievable throughput of a WiFi AP. Specifically, when some single-path users (who rationally use the best wireless network) turn to multipath access and use both WiFi and LTE, both $\bar{k}$ and $\bar{t}$ will increase. First, since WiFi adopts the distributed MAC scheme, $\bar{k}$ is positively related to the amount of associated active devices. Thus, additional connections from multipath users would make $\bar{k}$ increase. Second, r_i is decided by the quality of the wireless link between the AP and the device. The lower quality the link has, the lower r_i is. Thus, multipath users that own a weak link to the WiFi AP (who may be single-path users over LTE previously) would cause $\bar{t}$ to increase. Those factors show that the achievable throughput of WiFi APs easily decreases under the existence of multipath users, due to additionally used connections. We have conducted a numeric simulation to illustrate the above analysis, in which weak connections from MPTCP users are continuously added to a WiFi AP. The result is shown in Fig. 6. We see that the throughput of the WiFi AP keeps decreasing when the number of weak connections increases.

LTE on the other side adopts a proportional fairness strategy on resource allocation and a centralized MAC [13], [45]. The centralized MAC scheme schedules all downlink and uplink transmissions, which avoids collisions. The proportional fairness strategy allocates resources (i.e., transmission opportunity in terms of airtime and channel) to devices in proportion to the link quality. Thus, the throughput of an LTE BS with N associated devices can be represented as

$$T_l = \sum_{i=0}^{N-1} \frac{w_i * r_i}{\sum_{j=0}^{N-1} w_j} \qquad (3)$$

where w_i and r_i represent the weight on resource allocation and the physical layer data rate of device c_i, respectively. Note that both w_i and r_i are positively related to the quality of the link between the device and the BS. For example, suppose there are two clients, i.e., clients A and B, under a BS with a weight of 2 and 1, respectively. Then, client A would obtain two times transmission opportunities of client B. Thus, the actual rate of client A is $\frac{2*r_a}{3}$, where r_a is client A's physical layer rate when it occupies the BS solely.

Eq. (3) shows that additional low-quality connections from multipath users also reduce the achievable throughput of the LTE BS. However, the reduction is not significant due to their small weight in resource allocation. This means that LTE is more resilient to the throughput loss under multipath users. Our numerical simulation result in Fig. 6 verifies this point. We see that when weak MPTCP connections are added, the LTE BS's throughput decreases much less than WiFi.

2) Fairness: The fairness issue is caused by two facts. First, as shown in the previous discussion, the achievable throughput of wireless APs decreases upon the enabling of multipath access. Second, wireless APs do not differentiate the connections from multipath users and single-path users and treat them equally in resource allocation. This means that multipath
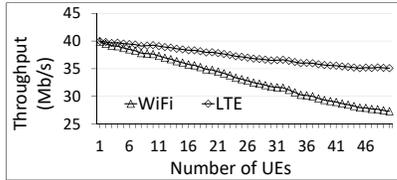
Fig. 6: Emulated WiFi AP/LTE BS throughput with different numbers of UEs

users gain an advantage by aggregating the bandwidth from both WiFi and LTE, while single-path users suffer a reduction on the throughput. Specifically, the achievable throughput of a multipath user c_i can be represented as $T_{mpi} = T_{wi} + T_{li}$, while that of a single-path user c_j is $T_{spj} = max\{T_{wj}, T_{lj}\}$, where T_w and T_l represents the device's achievable throughput from WiFi and LTE, respectively. Thus, single-path users obtain less bandwidth as more bandwidth is given to multipath users.

In summary, the fairness issue caused by multipath user is ubiquitous in both WiFi and LTE.

D. Issues in the Uplink

Based on the analysis in the downlink, the adverse impacts from multipath users also exist in the uplink. This is because uplink traffic from multipath users impact the performance of the AP in the same way as the downlink traffic.

First, additional connections from multipath users could lower the achievable throughput of the AP in the uplink. This is caused by the same two reasons in the downlink: 1) low-quality connections from multipath users own a low throughput and 2) the increased number of connections leads to more competition loss (i.e., in WiFi) or management over-head (i.e., in LTE). Both factors lower the efficiency of the channel resource (and thus the throughput) in the uplink.

Second, the fairness to single-path users is also impaired in the uplink. This is because both WiFi and LTE do not differentiate connections from multipath or single-path users and treat them fairly. Particularly, all connections compete fairly for the opportunity to transmit to the AP in WiFi, while the LTE BS schedules uplink transmission by following the same fairness strategy for all connections. This creates unfairness for single-path users, as multipath users naturally own more connections and thus gain more bandwidth.

E. Summary of Research Problem

In summary, allowing multipath access increases the number of connections served by the wireless network. Further, multipath users are more likely to use available connections aggressively. Those factors would 1) lower the achievable throughput of the network and 2) hurt the fairness to single-path users. Therefore, we believe that the problem commonly exists, which demands additional suppression over multipath access in wireless networks. However, blind suppression would lose the benefits of multipath access. Therefore, this paper aims to mitigate the adverse impacts of multipath access in wireless networks while keeping its benefits as much as possible.

IV. SOLUTION STRATEGY FORMULATION

A. Solution Strategy

We rely on an important observation to balance the adverse impacts of multipath access while keeping its benefits. Particularly, the lowering of the achievable throughput is meaningful only when devices served by the network need more throughput. Otherwise, the impact is not substantial as devices' bandwidth needs are satisfied. For example, suppose the throughput of a WiFi AP is lowered due to a multipath user, but all the bandwidth needs of all devices over the AP are still satisfied. In this case, the lowering of the AP's throughput does not cause any substantial hurts.

The impact of multipath users is substantial when the total bandwidth demand from served single-path devices is throttled, i.e., causes congestion. In this case, it is necessary to suppress the connections from multipath users to release resources and increase the throughput of the AP, thus preventing the adverse impact from turning to be substantial. The suppression should make either the congestion resolve or the throughput of MPTCP connections reach the minimal, whichever happens first. The former means that the adverse impact turns to be non-substantial (thus no further suppression is needed), and the latter is to keep the multipath access alive (i.e., keep the minimal multipath benefits).

However, this method may starve a multipath user when there are congestions on all of its paths, i.e., gets suppressed on all paths. To solve this issue, we pick the wireless connection that brings the most throughput to a multipath user as its primary connection and exclude it from the suppression. Consequently, the multipath user could obtain at least as much bandwidth as if using its primary connection only.

Combining the above logic essentially leads to the following solution strategy.

Both multipath users' and single-path users' ability to obtain resources from the wireless network should remain the same as when all users are single-path users.

When the above strategy is enforced, a multipath user uses its primary path freely and its non-primary paths in a dynamic way that only grabs idled capacity on wireless APs. As a result, the adverse impacts on the achievable throughput is prevented from turning to be substantial. Since both multipath users and single-path users compete for bandwidth with only one connection, the fairness to both is attained. Consequently, the benefits and adverse impacts of multipath access are dynamically balanced. This strategy also applies to uplink. This is because multipath users affect the overall network performance in the uplink in the same way as in the downlink, as explained in Section III-D.

B. Why MPTCP Congestion Control is not Enough

Advanced MPTCP congestion control algorithms, such as LIA [46], OLIA [42] and BALIA [47], have been proposed to achieve the following goals: 1) fairness: an MPTCP connection should not gain more bandwidth than if it was a single-path TCP over the best path; 2) friendliness: an MPTCP connection should shift its traffic away from the congested path as much as possible; and 3) responsiveness: an MPTCP connection should

be adaptive to path congestion change. We can see that those goals share a similar concept as our solution strategy, i.e., an MPTCP connection should dynamically avoid a congested path while maintaining the fairness on the best path. Thus, these algorithms are expected to lead to similar effects as the proposed solution strategy. However, they cannot tackle the adverse impacts sufficiently for the following two reasons.

- Struggling on achieving a balance: as mentioned in [47], [48], OLIA and BALIA achieve both friendliness and responsiveness by shifting aggressiveness from non-best subflows to the best subflow in a balanced manner. As a result, even under continuous congestion, subflows over non-best paths still maintain a certain aggressiveness to obtain some bandwidth (though not significant) for the sake of responsiveness.
- Interplay with the MAC layer fairness: these congestion control algorithms adjust subflows' bandwidth share by changing their aggressiveness. They generally assume that the aggressiveness of a subflow (which is decided by the congestion control) can determine the amount of bandwidth it can obtain over a shared link. However, wireless APs, on the other hand, usually adopt a certain MAC layer fairness policy for sharing the resources among associated UEs (e.g., packet-level fairness for WiFi and proportional fairness for LTE as aforementioned). Due to the fairness policy, subflows that have a low aggressiveness would still be treated fairly by the AP. In other words, they are not suppressed to the level as expected by the congestion control algorithm.

Therefore, due to the above two reasons, MPTCP congestion control algorithms cannot suppress subflows thoroughly under continuous congestion, as required in our solution strategy. This makes non-best subflows continuously lower the throughput of the network.

C. Solution Location

We further discuss the appropriate location to implement the proposed solution strategy. There are two possible candidate locations: end-host and network side. For the former, there are multiple methods. One example is to exploit the congestion control to implement the solution strategy, since it decides how a subflow gains bandwidth. We can use it to suppress non-primary MPTCP subflows upon congestions, as required in our solution strategy. Thus, the end-host side implementation does not need to change anything on the network side, which makes it easier to be deployed in practice.

However, further exploration reveals that the end-host based solution may not work in practice. It is a challenging task to guarantee that the solution is always enabled on end hosts. It is possible that the implementation is disabled or hampered by selfish users. For example, a host may adopt a congestion control algorithm that allows it to utilize multiple wireless paths freely. In this case, those selfish devices would impair the performance of the network through their excessive usage of low-quality links, as explained in Section III-C.

In our opinion, preventing the adverse impacts from multipath users is a task of network administrators. When the
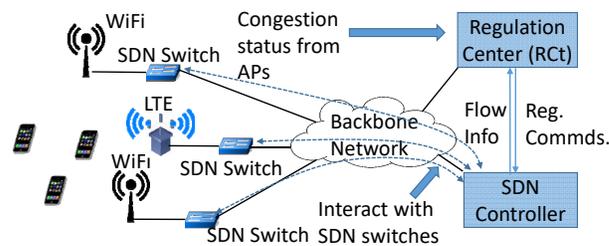

Fig. 7: Solution Overview.

solution strategy is enabled on the side work, the multipath access can be efficiently detected, and the required control logic over multipath users can be reliably enforced. Consequently, network operates can effectively prevent multipath users from lowering the overall network performance, thereby guaranteeing the quality of their services. Those facts motivate us to develop an efficient system on the network side to implement the solution strategy.

V. SOLUTION SYSTEM DESIGN

We propose an SDN based scheme on the network side to implement the aforementioned solution strategy. As shown in Fig. 7, the scheme contains two major components: a Regulation Center and an SDN system. For clarity, we assume the downlink scenario in introducing the two components in Sections V-A and V-B. We introduce how the solution system can be adapted to the uplink in Section V-C.

Scalability is one important requirement for such a network management system. The proposed system can satisfy this requirement since one deployment (i.e., Fig. 7) serves a local area independently. Thus, the whole network can be divided into many *control domains*, and each of which oversees a geographic area and is served by one deployment of the proposed system. The network operator can decide the granularity of the *control domain* based on its mission.

A. Regulation Center (RCt)

The RCt implements the control logic by dynamically adjusting the allocation of bandwidths for data flows.

1) Regulation Rules: The solution strategy in Section IV-A can be interpreted as the following rules.

- For each multipath user, the connection with the maximal achievable bandwidth is selected as its primary connection, and all others as secondary. Similarly, MPTCP subflows over the primary (secondary) connection are regarded as primary (secondary).
- When congestion happens on an AP, the amount of bandwidth allocated to secondary subflows should be dynamically adjusted until either 1) the congestion resolves or 2) they reach the minimal value.
- Flows from single-path users and primary subflows from multipath users are not intervened.

With those rules, single-path users' ability to obtain resources is not affected under multipath users, as each multipath user only competes for bandwidth through the primary connection. This also ensures the fairness to multipath users. Thus, the

solution strategy is achieved. The above rules are enforced through two algorithms named flow categorization algorithm and bandwidth regulation algorithm.

Algorithm 1: Flow Categorization.

```
1   for ∀ user u ∈ Ū do
2       if u.multipath == true then
3           c_um := maxbandwidth(u.connections) //find the max one.
4           for ∀ connection c ∈ u.connections do
5               for ∀ flow f ∈ c.flows do
6                   if c==c_um then
7                       f.primary = true;
8                       f.tier = 1;
9                   end
10                  else
11                      f.primary = false;
12                      f.tier = 2;
13                  end
14              end
15          end
16      end
17      else
18          for ∀ flow f ∈ u.connections.flows do
19              f.tier = 1;
20          end
21      end
22  end
```

---

2) Flow Categorization Algorithm: Algorithm 1 shows the flow categorization algorithm. This algorithm has two functions: 1) select the primary connection/path for multipath users and 2) categorize flows into the following two tiers.

- Tier 1: flows from single-path users and primary subflows from multipath users.
- Tier 2: secondary subflows from multipath users.

The primary connection of a multipath user is the one that owns the maximal achievable throughput. All other connections are regarded as secondary. Then, subflows on the primary and non-primary connections are categorized as Tier 1 and Tier 2, respectively. Note that we treat non-TCP flows such as UDP and QUIC flows as Tier 1, which requires UEs to send them through the primary connection. The two categories of flows are handled differently in the bandwidth regulation algorithm introduced in the next subsection.

The major challenge of the algorithm is to find the achievable throughput of a connection. Intuitively, we can follow Equations (2) and (3) to calculate the achievable throughput of a wireless connection in WiFi or LTE, respectively. However, such a method is inaccurate when our system is applied. This is because, as shown later in Section V-A3, our system suppresses non-primary connections over an AP when congestion happens on the AP. Thus, when calculating the achievable throughput of a connection over an AP, only primary connections on the AP should be considered. In other words, the estimation of achievable throughput for primary connection selection depends on the outcomes of the selection. This essentially forms a deadlock.

We provide two solutions to solve this problem.

Baseline Solution: The baseline solution has two steps: 1) exclude connections that are unlikely to be selected as the primary ones and 2) regard all remaining connections as active for achievable throughput estimation. Particularly, we process APs sequentially. For each AP, a percentage of connections with the lowest signal quality are excluded from

considerations directly, i.e., connection filtering. We use B_f to denote this percentage. In this process, each device should have at least one connection left after the filtering. Thus, if a connection is the only one left for a device, it is exempt from the filtering. The rationale for the filtering is that the lower radio signal strength indicator (RSSI) a connection has, the lower throughput it can achieve (i.e., as discussed in Section III-C), and the more unlikely it is a primary connection. After the filtering, we estimate the achievable throughput of the remaining connections. Such information is then used to decide actual primary connections.

The value of B_f is decided by the average percentage of primary connections out of all connections. Specifically, suppose there are N_d devices and N_c connections in a WNS. This means that on average, only $100*N_d/N_c\%$ of connections will be selected as the primary ones (i.e., a client can only have one primary connection). We assume that all APs follow this percentage on average. Consequently, the value of B_f is decided by: $B_f = 100 - 100 * N_d/N_c$.

Priority-based Solution: We further provide an enhanced solution that breaks the deadlock by prioritizing connections. It evaluates connections in decreasing order of the physical rate resulted from the RSSI (i.e., when the connection uses the AP exclusively). The rationale is that a connection with a higher physical rate is more likely to be the primary one. Specifically, this solution follows the following steps.

- Step 1: Sort all connections in decreasing order of the physical rate. Then, check all connections sequentially.
- Step 2: For each connection, if its user has already decided the primary connection, skip to the next connection and repeat from Step 2. Otherwise, go to Step 3.
- Step 3: Find the user of the connection and all its connections. Then, calculate the achievable throughput of each connection based on primary connections that are already identified and select the one with the maximal throughput as the primary connection.
- Step 4: Repeat from Step 2 with the next connection.

Since the proposed system resides on the network side, it can easily collect information needed by the above two solutions such as RSSI of all connections. The flow information needed in this algorithm is provided by the SDN system that will be introduced in Section V-B.

3) Bandwidth Regulation Algorithm: This algorithm implements the regulation rules proposed in Section V-A1. It checks the congestion status of each AP. Based on the congestion status, regulation commands are issued to adjust the bandwidth allocated to Tier 2 flows on the AP. To respond to the change of congestion status timely, this adjustment follows the additive increase and multiplicative decrease (AIMD) concept in TCP congestion control [49].

We use one AP as an example to demonstrate this algorithm. Our algorithm checks the AP's average MAC queue occupancy ratio (i.e., the percentage of filled slots) in the past period, denoted $MacOcc$. If $MacOcc$ is larger than the congestion threshold, denoted CTh, the maximal bandwidth for Tier 2 flows will be decreased by half, thereby providing more bandwidth for single-path flows and primary MPTCP subflows. We also set the minimum bandwidth for all secondary MPTCP

subflows on an AP to R_m Mb/s. This is because, as proven in [1], the primary subflow of an MPTCP connection will be throttled due to head-of-line block if the secondary subflow presents a much lower rate. Generally, the value of R_m is correlated to the maximal size of the primary subflow. In this paper, based on the study in [1], we find that setting R_m to 0.1 Mb/s works well in our experiment.

On the other hand, if $MacOcc$ is smaller than the congestion threshold, we increase the bandwidth for Tier 2 flows by $BW_i * \frac{\alpha*(CTh-MacOcc)}{MacOcc}$, where BW_i is the current bandwidth allocated to Tier 2 flows and $\alpha \in (0,1)$ is an aggressiveness factor. This means that the less the AP is loaded, the more bandwidth can be allocated to Tier 2 flows. In summary, the bandwidth for Tier 2 flows is updated by

$$BW_{i+1} = \begin{cases} max(100kbps, BW_i/2) & : MacOcc \geq CTh \\ BW_i * \frac{\alpha*(CTh-MacOcc)}{MacOcc} & : MacOcc < CTh \end{cases} \tag{4}$$

Algorithm 2 summarizes the bandwidth regulation algorithm. Since non-TCP flows are treated as Tier 1 in our design, the proposed bandwidth regulation algorithm would not affect those flows. The bandwidth limit is enforced through the meter in SDN switches, which will be introduced in Section V-B. In this paper, CTh and α affect the aggressiveness of allocating bandwidth to Tier 2 flows. We empirically set them to 85% and 0.5, respectively. We have evaluated the influence of α later in Section VI-C.

Algorithm 2: Bandwidth Regulation Algorithm.

---
1 **for** $\forall\, ap \in \overline{AP}$ **do**
2     $ap.MacOcc = QueryMac(ap)$;
3   **if** $ap.MacOcc \geq CTh$ **then**
4        $ap.t2ratelimit = max(100kbps, ap.t2ratelimit/2)$;
5   **end**
6   **if** $ap.MacOcc < CTh$ **then**
7        $ap.t2ratelimit = ap.t2ratelimit * \frac{\alpha*(CTh-MacOcc)}{MacOcc}$;
8   **end**
9   Ratelimit(ap); //through meter in SDN switches
10 **end**

---

4) Handling User Dynamism: UEs present two types of dynamism in accessing the wireless network. The first one is mobility, which would change the link quality of associated wireless connections and incur handover between APs. The second is bandwidth demand, i.e., on-off network access pattern. Both types of dynamism interact with the flow categorization algorithm (i.e., Section V-A2) and the bandwidth regulation algorithm (i.e., Section V-A3). For example, when a UE moves away from the AP of its primary connection, the achievable throughput of the connection would reduce due to the decrease of link quality and/or handover. As a result, we may need to update its primary connection to another one. Further, when a UE increases or reduces its bandwidth demand, the congestion status of the associated AP would change. This may trigger the bandwidth regulation algorithm to adapt the bandwidth for Tier 2 flows over the AP.

Thus, the two algorithms need to be executed periodically to handle the dynamism. It is not hard to see that the more frequently they are repeated, the better the two types of

dynamism are handled. We find that this requirement can be satisfied due to the low complexity of the two algorithms. They both have a complexity of $O(N)$, where N is the number of flows/subflows. Furthermore, the data communication needed by the two algorithms is lightweight. They only need to 1) collect the congestion status (e.g., MAC queue occupancy ratio) from each AP and flow statistics from the SDN controller and 2) send new rate limits to the SDN controller. Consequently, the execution interval of the two algorithms can be quite small, e.g., 2s or 4s, for a refined control accuracy.

The ideal execution frequency of the two algorithms is decided by the level of the dynamism. Therefore, it is hard to decide an optimal frequency for all scenarios. The network administrator can decide the frequency based on its need. We use 2 seconds by default and find that it allows timely response to user dynamism. We have evaluated the influence of the execution frequency in the experiment (i.e., Section VI-C) and how different execution intervals affect the performance under mobility (i.e., Section VI-D). We can also dynamically adjust the execution frequency to provide a better balance on the overhead and control accuracy. For example, when congestion happens on an AP or when link qualities fluctuate severely due to fast mobility, the frequency can be increased to quickly respond to the change of AP/link status.

B. SDN System

Current wireless network infrastructures, especially LTE, are closed and thus may not provide the functionalities required by the RCt. As a result, we choose SDN [11] to support the development of the RCt.

SDN is an emerging networking paradigm that aims to improve network performance through flexible programmability. Different from the legacy architecture that couples the routing process (i.e., control plane) and packet forwarding (i.e., data plane) on each switch/router, SDN decouples them. Particularly, SDN centralizes the control plane in a controller and leaves switches as simple forwarding devices. A controller supervises a set of switches and can easily monitor and manipulate flows passing through these switches through programmable interfaces. We can see that SDN fits the needs of RCt by 1) providing a global view of flows and 2) realizing flexible control over flows. Furthermore, SDN can also be incrementally deployed over existing networks.

1) Overview: Fig. 8 shows the conceptive overview of the proposed SDN system. We deploy an SDN switch before each AP to collect flow statistics and control the bandwidth used by flows. Note that each SDN switch does not need to be placed immediately next to the AP. It can be placed after other network entities, e.g., EPC for LTE, as long as it can see all flows going to/from mobile devices. This is because the AP may connect to the next entity through a tunnel, e.g., the tunnel between the eNodeB and EPC in LTE.

The SDN switches in one *control domain* are controlled by a controller. The controller receives commands from the RCt through its northbound APIs. In other words, the RCt is an application that interacts with the SDN controller through the Network Services Abstraction Layer (NSAL) interfaces.
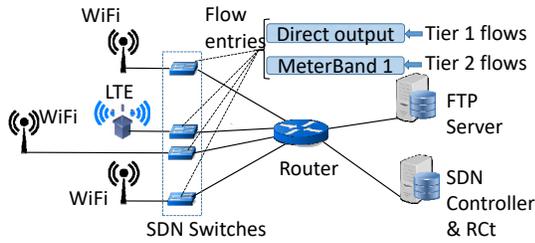
Fig. 8: SDN System Conceptive Overview (note that this is also the architecture of the network in NS3 simulation).

In this way, the RCt can be united with the SDN system by following the SDN framework, i.e., RFC 7426 [50].

2) Flow Statistics: Every SDN switch is initialized with one meter that limits the total bandwidth for Tier 2 flows. Meter is a feature of SDN that can provide the rate-limiting function. When the first packet of a flow arrives at the switch, it will be forwarded to the controller due to miss match. The controller then creates a flow entry that forwards the flow's packets to the correct output port. The controller further attaches the flow entry to the meter if the flow is Tier 2. Tier 1 flows are not attached to a meter as they are not intervened. Those steps are guided by the RCt, which knows whether a flow is primary or secondary and its tier.

Consequently, each SDN switch contains one flow entry for every data flow going through it and one meter for all Tier 2 flows, as shown in Fig. 8. The built-in functions of SDN switch directly record the information needed by the flow regulation system (RCt) efficiently. Such data can be queried by the SDN controller and be provided to the RCt through standard interfaces. Thus, no additional overhead is incurred other than what already provided by SDN, which helps us control the complexity of the proposed solution.

3) Flow Control: The SDN system can easily enforce flow categorization and bandwidth regulation decisions. When the tier of a flow changes, the controller just needs to change its meter association, i.e., no meter for Tier 1 flows and meter 1 for Tier 2 flows. When the maximal bandwidth for Tier 2 flows changes, the controller only needs to modify the rate limit of meter 1. The RCt communicates with the SDN controller through its northbound APIs to achieve these functions.

4) SDN System Practicality: Though the SDN system has to see and label all flows, we believe that it can be practically deployed. Currently, SDN switches can support up to 40 Gbps throughput with all the functions needed in our design (e.g., PICA8 SDN switches [51]). The labeling and measuring of flows can be done quite efficiently on SDN switches. Our solution just needs to label flows one time (i.e., when the flow first shows up). It also only query the meter on SDN switches. The regulation process just changes the throughput limit of the meter and the association of individual subflows with the meter when needed.

C. Application to Uplink

The solution system can solve the adverse impacts in the uplink after a slight adaptation. This is because the solution strategy in the uplink is the same as that in the downlink,

which can be summarized as: 1) select primary and non-primary uplink flows/subflows and 2) suppress non-primary ones adaptively based on the congestion status at the AP.

The solution system, i.e., RCt in Section V-A and SDN system in Section V-B, can implement the solution strategy for uplink. Particularly, SDN switches placed near wireless APs (as shown in Fig. 8) can monitor and control all uplink flows from UEs too. The RCt can collect such statistics through the SDN controller. The RCt then can start an agent running the flow categorization and bandwidth management algorithms for uplink flows, in addition to that for downlink flows. Afterward, the management decisions regarding uplink flows are sent to the SDN controller for enforcement. The enforcement is implemented in the same way as for downlink flows, i.e., through a meterband for Tier 2 flows.

Furthermore, when both downlink and uplink flows are regulated by the proposed system, ACK packets need to be exempted from the regulation (i.e., be treated as Tier 1 flows). Otherwise, dropping ACK packets would severely reduce the rate of data flows. We evaluate the performance of our solution system in uplink in Section VI-E.

VI. PERFORMANCE EVALUATION

We denote the proposed solution system as "MP-SDN". To provide a direct comparison between the network performance with and without our solution, we used the two network scenarios in the measurement study (i.e., Section III-B) as default evaluation scenarios. Since the proposed solution system targets the causes of identified issues and is independent of network scenarios, we believe that the evaluation results are representative. We first focus on the downlink in Sections VI-A, VI-B, VI-C and VI-D. We then evaluate the performance of MP-SDN in uplink in Section VI-E.

In the downlink scenario, we first evaluate how MP-SDN protects WNS performance (Section VI-A) and reserve the multipath benefits (Section VI-B) and the influence of two key parameters (Section VI-C) in the static scenario. We then evaluate how MP-SDN performs under user mobility in Section VI-D. Since the issues on the uplink and the handling strategy are very similar to those in the downlink, we only show how MP-SDN protects WNS performance in uplink in a static network scenario in Section VI-E.

We used both prototyping and NS3 simulation in experiments. In the system prototype, we implemented the same setup as in the deployment based measurement (i.e., Fig. 2b). The SDN switch is implemented as an additional desktop running the Open vSwitch (OVS) [52]. Per the design of the SDN system (i.e., Fig. 8), this desktop is placed between the server and WiFi AP/LTE BS. We used Floodlight [53] as the SDN controller. It runs on the same desktop of the OVS. The RCt is implemented as a module of the controller.

Since the prototype based experiment cannot scale easily, we further conducted NS3 [43] based simulation for extensive evaluation. The default setup is the same as in Section III-B2 (i.e., Fig. 4). Fig. 8 shows how the proposed system is integrated into the NS3 simulation. In the simulation, we added an SDN switch between each wireless AP and the FTP server. The
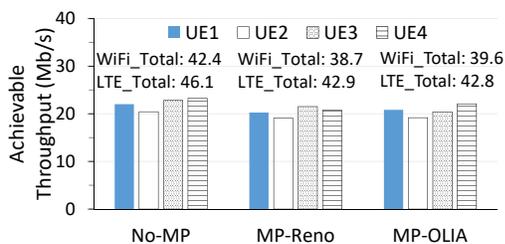
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Fig. 9: Prototype experiment: protecting WNS performance.

(a) Overall achievable throughput of the WNS. (b) Average achievable throughput of single-path users.

Fig. 10: NS3 simulation: protecting WNS performance in the default network scenario.

SDN functionalities are developed with the NS3 OpenFlow 1.3 module [54]. The RCt is developed inside the SDN controller. Further, we adopted NS3 DCE to integrate MPTCP Linux Kernel implementation [40] into the NS3 simulation.

Unless explicitly indicated, mobile devices download a 2GB file without a rate limit in the experiment. We set the execution interval of the bandwidth regulation algorithm, congestion threshold CTh, and aggressiveness factor α to 2 seconds, 85%, and 0.5 by default. We adopted the priority-based solution for the deadlock problem in the flow categorization algorithm (Section V-A2). This is because this solution is more efficient and also has low complexity.

A. Protecting WNS Performance

1) Prototype Experiment: We first conducted the same test as in the deployment based measurement in Section III-B1 but with the MP-SDN system enabled. The throughput of the four UEs is plotted in Fig. 9. In the figure, the results with MP-SDN enabled are labeled as MP-X where x denotes the adopted congestion control algorithm.

By comparing Fig. 9 with Fig. 3, we see that when MP-SDN is enabled, the throughput of WiFi AP and LTE BS only slightly decreases when UE2 and UE3 turn to multipath access (i.e., the reduction is about 3.5 Mb/s in WiFi and 3.1 Mb/s in LTE). The reduction is caused by the fact that weak connections from multipath users are not completely disconnected under MP-SDN. However, this shows that the overall performance of this small WNS is well protected. Further, the result shows that the throughput of the two SPTCP UEs (i.e., UE1 and UE4) remains stable after UE2 and UE3 turn to multipath access (i.e., 22 Mb/s to 20.5 Mb/s for UE1 and 23 Mb/s to 21.3 Mb/s for UE4). This means that SPTCP UEs are not suffering obvious throughput loss when UE2 and UE3 turn to multipath access. This suggests that the fairness to SPTCP UEs is improved under MP-SDN.

2) NS3 Simulation: We further conducted NS3 based simulation to verify whether the performance improvement holds in a larger topology. We first adopted the same test configuration as in Section III-B2. The achievable throughput of the whole WNS and the average achievable throughput of all single-path users under different percentages of multipath users are plotted in Fig. 10a and Fig. 10b, respectively. The results clearly show that with MP-SDN, the achievable throughput of the WNS remains relatively stable, while that without MP-SDN keeps decreasing when the percentage of multipath users increases. The improvement of MP-SDN over MPTCP is consistent over all test cases and can reach up to 20%. Such a result shows that
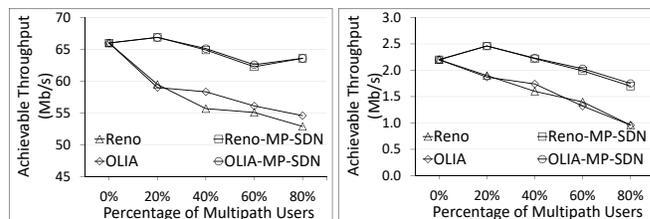
MP-SDN can effectively protect the achievable throughput of WNSs under multipath users.

Moreover, we see from Fig. 10b that when MP-SDN is enabled (i.e., Reno-MP-SDN or OLIA-MP-SDN), the average achievable throughput (AAT) of single-path users remains around 2 Mbps when there are up to 60% of multipath users. When there are more than 60% percentage of multipath users, the AAT of single-path users under MP-SDN further drops about 10%. This is because there are only a small number of single-path users (i.e., less than 12) in this case. However, even in this case, MP-SDN greatly improves the AAT of single-path users by up to 60%. Therefore, we believe that the fairness to single-path users is well improved by MP-SDN.

The above improvement is brought by the fact that MP-SDN can effectively throttle the bandwidth used by secondary MPTCP subflows (i.e., Tier 2 flows) on each AP. To show this point, we recorded the throughput of Tier 2 flows in all WiFi APs every 0.5 seconds in the experiment. The average throughput of Tier 2 flows on the three WiFi APs is 0.09 Mbps, 0.16 Mbps, and 0.15 Mbps, respectively, which demonstrates the suppression from MP-SDN.

3) Performance in Different Test Scenarios: The above results show the effectiveness of MP-SDN in the scenarios used in the measurement study. We further evaluate its performance in different scenarios through NS3 simulation. We only show the results on overall WNS throughput in this subsection.

We first reduced the number of UEs in the default network scenario (i.e., Fig. 4) to 15. The experiment result is shown in Fig. 11a. We see that the result is consistent with that in the experiment with the default network scenario. Particularly, when the percentage of multipath user increases, the throughput of the WNS decreases. However, when MP-SDN is applied, the throughput of the WNS remains relatively stable. We also see that the throughput reduction caused by multipath users (and the improvement from MP-SDN) is small in this test. This is because we have fewer multipath users (and thus less severe adverse impacts from them) in this test.

We also enlarged the simulation area to 300m by 300m. The result is shown in Fig. 11b. We again see that MP-SDN effectively keeps the overall throughput of the WNS stable when the percentage of multipath user increases. In addition, we find that the throughput reduction is more severe when the percentage of multipath user increases. This is because a larger simulation area increases the distance between UEs and APs and thus reduces the average link quality.
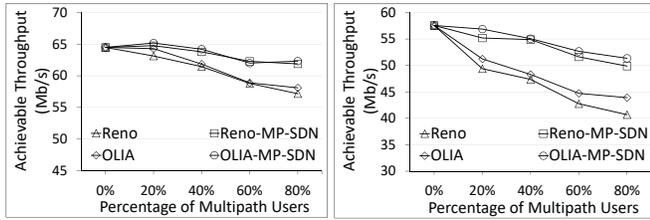
(a) Decrease the number of UEs to 15.
(b) Enlarge the simulation area to 300m by 300m.

Fig. 11: NS3 simulation: protecting WNS performance in different network scenarios (note that we only show the achievable throughput of the WNS).
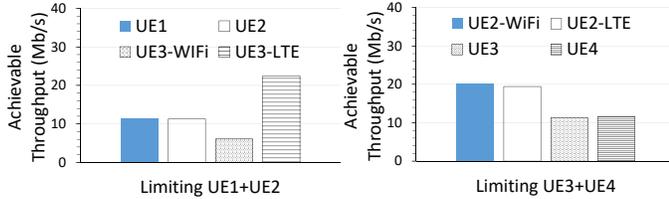
(a) Limit the demand of UE1 and UE2 to 12 Mb/s.
(b) Limit the demand of UE3 and UE4 to 12 Mb/s.

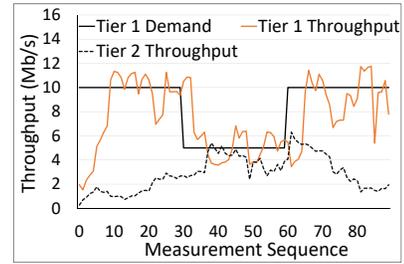Fig. 12: Prototype experiment: keeping the benefits for multipath users.

(a) Result of AP1.

(b) Result of AP2.

Fig. 13: NS3 simulation: keeping the benefits for multipath users.

The above results show the common existence of the adverse impacts of multipath users and the effectiveness of MP-SDN. This matches with our analysis of the causes of the problem and the design principle of MP-SDN. Such facts show that MP-SDN effectively handles the problem causes, which makes it able to protect the performance of WNS under multipath users in different scenarios. We thus focus on the two default network scenarios in the following experiments.

B. Preserving Multipath Benefits

In the previous experiments, the resource on each AP is saturated by Tier 1 flows. As a result, secondary MPTCP subflows on each AP are throttled to the minimal throughput. In this subsection, we thus evaluate whether the multipath benefits (i.e., obtaining additional bandwidth) could be attained when Tier 1 flows cannot take all bandwidth on the AP. The test configuration is the same as the previous prototype experiment and NS3 simulation.

1) Prototype Experiment: In this experiment, to test whether MPTCP users could take the idled resource on the WiFi AP (or LTE BS), we limit the bandwidth demand of UE1 and UE2 (or UE3 and UE4) to 12 Mb/s. We then measured the average throughput of relevant UEs and plotted the results in Fig. 12a and Fig. 12b. We see that when UE1 and UE2 are throttled, UE3 obtains 6 Mb/s from the WiFi AP. Similarly, UE2 obtains 19 Mb/s from the LTE BS when UE3 and UE4 are throttled. In the two cases, UE3 and UE2 receive much more bandwidth from the WiFi AP and the LTE BS, respectively, than before without throttling on demands. This is because the throttling creates idled capacity on the WiFi AP and LTE BS, and MP-SDN allows the two UEs to take it effectively.

2) NS3 Simulation: We further use NS3 simulation to provide more details about how multipath benefits are kept under MP-SDN. We picked WiFi AP 1 (top one) and WiFi
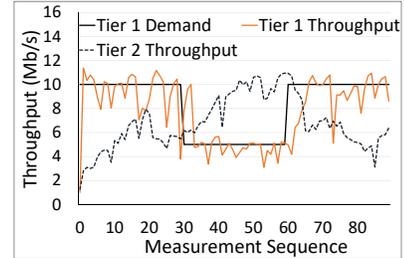
AP 2 (bottom left one) for illustration when there are 40% of multipath users. We swapped the bandwidth demand for Tier 1 flows between 10 Mbps and 5 Mbps every 15 seconds. We then measured the throughput of Tier 1 and Tier 2 flows every 0.5 second. The results are plotted in Fig. 13a and Fig. 13b. The "measurement sequence" in the two figures denotes the sequence number of measurement points.

We see from the two figures that, for both APs, when the bandwidth demand of Tier 1 flows reduces from 10 Mbps to 5Mbps at the 30s, the throughput of Tier 2 flows increases accordingly to take the released capacity of the AP. When the demand of Tier 1 flows increases back to 10 Mbps at the 60s, the throughput of Tier 2 flows is suppressed upon the detection of congestion on the AP. As a result, Tier 1 flows gain the throughput back quickly after one or two execution cycles (note that one cycle is 2 seconds).

Note that the response time (i.e., the time between the change of the bandwidth demand of Tier 1 flows and the adjustment of the bandwidth for Tier 2 flows) shown in the figure is larger than the actual value. This is because the bandwidth demand is implemented through the meter in the SDN switch associated with the AP (see Fig. 8). However, the software ofswitch used in the NS3 simulation seems to have a delay in enforcing the rate limit of the meter. As shown in the figure, the increase/decrease of the throughput of Tier 1 flows (i.e., orange line) always is delayed for a few measurement points when the rate limit changes (i.e., blue line). As long as the rate limit takes effect and changes the throughput of Tier 1 flows, our system could detect that quickly and adjust the throughput of Tier 2 flows accordingly.

The above results show that multipath users can use their non-primary subflows to take idled bandwidth. Meanwhile, multipath users keep all connections alive throughout the process. Therefore, we conclude that the proposed MP-SDN system can scale the multipath benefits dynamically and thus
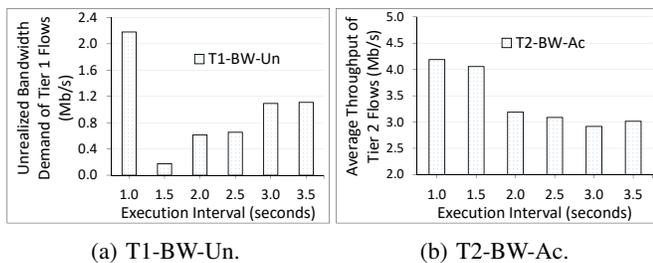
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(a) T1-BW-Un.   (b) T2-BW-Ac.

Fig. 14: Influence of the execution interval of the proposed system.

(a) T1-BW-Un.   (b) T2-BW-Ac.

Fig. 15: Influence of the aggressiveness factor α.

avoid causing substantial adverse impacts to the WNS, as required by our solution strategy.

C. Influences of Key Parameters

We further evaluate the influence of two key parameters: the execution interval of the bandwidth regulation algorithm (i.e., Section V-A3), denoted EI, and the aggressiveness factor α used in adjusting the bandwidth of Tier 2 flows (i.e., Eq. (4)). We used NS3 simulation in this evaluation. The test configuration is the same as in Section VI-B2 except that the bandwidth demand for Tier 1 flows swaps between 10 Mbps and 5 Mbps every 10 seconds. We measured the throughput of Tier 1 and Tier 2 flows every 0.5 second. As the measurement results of all wireless APs are similar, we only show that of the top WiFi AP in this subsection.

We further designed two metrics to assist the evaluation, denoted "T1-BW-Un" and "T2-BW-Ac". T1-BW-Un represents the average amount of unsatisfied bandwidth demand of Tier 1 flows. It is calculated by $\sum_{i=0}^{N} \frac{BWD_{1i}-BW_{1i}}{N}$, where BWD_{1i} and BW_{1i} denote the bandwidth demand and the throughput of Tier 1 flows at the i-th measurement point. T2-BW-Ac denotes the average throughput of Tier 2 flows. It is calculated by $\sum_{i=0}^{N} \frac{BW_{2i}}{N}$, where BW_{2i} is the throughput of Tier 2 flows at the i-th measurement point. The T1-BW-Un shows how the throughput of Tier 1 flows is affected by Tier 2 flows, while the T2-BW-Ac reflects how Tier 2 flows grab idled resources. Thus, the smaller the T1-BW-Un, the better our system protects the performance of the WNS, and the larger the T2-BW-Ac, the better our system ensures multipath benefits.

1) Execution Interval: We varied the execution interval of the proposed system (EI) from 1s to 3.5s with a 0.5s increase each time. The results are shown in Fig. 14a and Fig. 14b. We see from Fig. 14a that the amount of unsatisfied bandwidth demand from Tier 1 flows is high (i.e., >1 Mb/s) when EI is small (i.e., 1s) or large (i.e., $\geq$3s) and reaches the minimal (i.e., 0.2 Mb/s) when $EI = 1.5s$. This is because a small EI indicates more frequent check of the queue occupancy on the AP. Since the queue occupancy fluctuates even under congestion, a small EI makes it more likely to detect a low occupancy ratio and allocate more bandwidth to Tier 2 flows. As a result, Tier 1 flows' bandwidth demand is undermined. On the other hand, when EI is large, the measurement of queue occupancy ratio becomes more accurate. However, the suppression of Tier 2 flows may not be executed timely, thus hurting the throughput of Tier 1 flows.
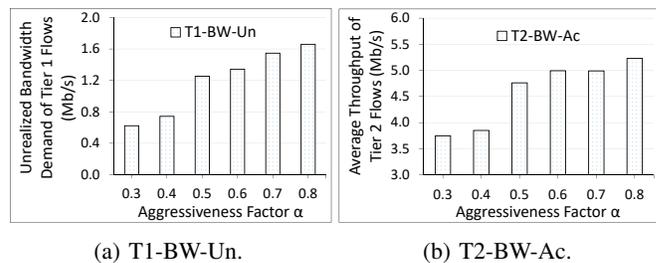
We see from Fig. 14b that the throughput of Tier 2 flows continuously decreases when EI increases. This is because a large EI indicates a delayed detection of idled resources on the AP. Thus, Tier 2 flows cannot obtain idled bandwidth timely. Combining the above two factors, a medium execution interval should be selected to keep a balance on the two metrics (e.g., 2s in our experiment).

2) Aggressiveness Factor α: In this test, we varied α from 0.3 to 0.8 with a 0.1 increase each time. The measurement results are shown in Fig. 15a and Fig. 15b. We find that when α increases, both the amount of unsatisfied bandwidth demand from Tier 1 flows (i.e., T1-BW-Un) and the average throughput of Tier 2 flows (i.e., T2-BW-Ac) increase. Recall that α controls the aggressiveness of allocating bandwidth to Tier 2 flows. Therefore, the larger α is, the more bandwidth is allocated to Tier 2 flows. This increases the average throughput of Tier 2 flows and the amount of unsatisfied bandwidth demand from Tier 1 flows (as the total bandwidth is limited). We also see from the two figures that the increase rate of both metrics is high when α is medium and low when α is small or large. Thus, since we want to have a small T1-BW-Un and a large T2-BW-Ac, it is more reasonable to choose a medium aggressiveness factor α (e.g., 0.5 in this test).

D. Handling User Mobility

In this experiment, we let UEs move in the NS3 simulation (i.e., Fig. 4). We adopted a random waypoint mobility model in which the mobility speed range is set to [1, 5] m/s. As introduced in Section V-A4, our system handles user mobility (and handover between APs) by executing the flow categorization algorithm periodically. We thus evaluate how it performs under different execution frequencies. We varied the interval between two executions from 2s to 45s. We measured the achievable throughput of the WNS when Reno and OLIA are adopted as the congestion control algorithm. The result is shown in Fig. 16. We have also recorded the throughput of one WiFi AP (i.e., WiFi AP1) every 0.5s under two representative execution intervals: 5s and 30s. The results under Reno and OLIA are presented in Fig. 17a and Fig. 17b.

We first see from Fig. 16 that in both experiments (i.e., with Reno and OLIA), the achievable throughput of the WNS decreases slightly in the beginning (i.e., from about 49 Mb/s to 45 Mb/s) and significantly when the interval goes beyond 25s (i.e., from about 45 Mb/s to 36 Mb/s). This is caused by two reasons. First, UE mobility changes the quality of wireless connections. Second, the proposed flow categorization
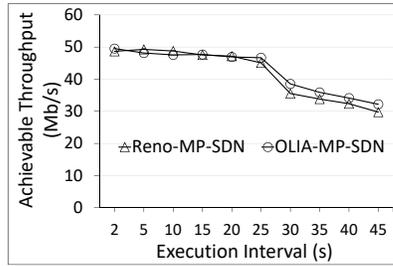
12

Fig. 16: Performance of MP-SDN under different execution intervals of the flow categorization algorithm in the mobility scenario.
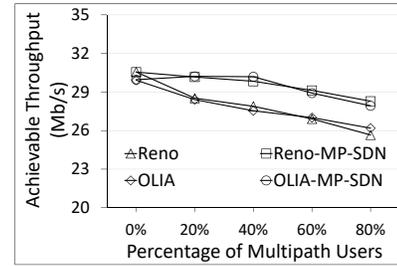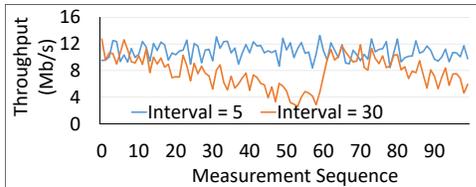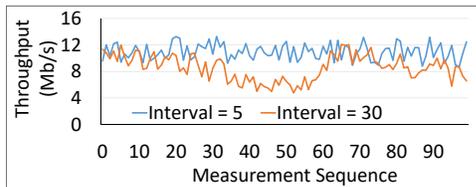

Fig. 18: Performance of MP-SDN in uplink.

(a) Using Reno.

(b) Using OLIA.

Fig. 17: Throughput of AP1 under UE mobility.

algorithm selects primary connections for each UE based on the instant connection quality at the time the algorithm is executed. As a result, UE mobility may make the quality of a primary connection becomes weak (i.e., even lower than the non-primary one). Recall that primary connections are exempted from suppression in MP-SDN. Therefore, when their link qualities decrease, the overall throughput of the WiFi AP/LTE BS decreases too, as modeled in Section III-C.

Therefore, if the flow categorization algorithm is repeated frequently, the conditions of all connections will be checked timely. During the check, weak primary connections will be re-classified as non-primary. Since non-primary connections will be suppressed to the minimal under MP-SDN in our testing configuration, they can only slightly lower the throughput of associated WiFi AP or LTE BS. This is the reason why the throughput of the WNS is not affected much under a low execution interval (i.e., less than 2s) in Fig. 16. However, if the execution interval is large (i.e., larger than 25s), weak primary connections will lower the throughput of associated WiFi AP and LTE BS for a long period of time.

The results in Fig. 17a and Fig. 17b further illustrate the above analysis. When the execution interval is 30s, the throughput of WiFi AP1 keeps decreasing until measurement sequence 60, due to the decrease of the link qualities of primary connections. At the measurement sequence 60, the flow categorization algorithm is executed, which re-selects the best connection of each UE as its primary connection. This improves the overall quality of primary connections served by

AP1 and thus increases its overall throughput. On the other hand, when the execution interval is 5s, the throughput of WiFi AP1 does not show the trend of continuous decreasing. This is because the flow categorization algorithm is timely repeated.

The above results show that a small execution interval is preferred for the proposed MP-SDN. Fortunately, as introduced in Section V-A4, MP-SDN can support a small execution interval since the proposed algorithms own a low complexity.

E. Uplink Performance

We have also tested the performance of MP-SDN in the uplink scenario through NS3 simulation. We adopted the same setup as in downlink experiments (i.e., Fig. 4). The only difference is that, in this test, UEs transfer a large file to servers behind wireless APs (i.e., uplink traffic) without a rate limit. We also varied the percentage of multipath users from 0% to 80%. We tested with both Reno and OLIA as the congestion control algorithm. The achievable throughput of the WNS without and with MP-SDN is measured.

The results are plotted in Fig. 18. It shows that the results under Reno and OLIA are very similar, as in the experiments in the downlink. We also see that without MP-SDN, the more multipath users, the lower achievable throughput the WNS has. Meanwhile, though not plotted, the average achievable throughput of single-path users also decreases when the percentage of multipath users increases. This confirms our conclusions in Section III-D that multipath access also adversely impacts the network performance in the uplink.

We further find that when MP-SDN is enabled, the achievable throughput of the WNS keeps relatively stable when the percentage of multipath users increases. This is because non-primary connections from multipath users are throttled by MP-SDN. Such a result shows that the proposed solution strategy and system apply to uplink effectively.

VII. CONCLUSION

In this paper, we found that multipath users could adversely impact the achievable throughput of the network and the fairness to single-path users due to their additional wireless connections. We thus propose an SDN based system on the infrastructure side to mitigate those impacts and protect the performance of the wireless networks, while keeping the benefits of multipath based wireless network access. The key idea is to keep all users' ability to obtain bandwidth from the wireless networks the same as when they all are single-path users. This goal is achieved by dynamically suppressing

non-primary subflows from multipath users. The proposed system can be applied to both downlink and uplink. It also handles user dynamism such as user mobility. Prototype-based experiment and NS3 simulation with Linux Kernel MPTCP demonstrate the effectiveness of the solution system, as well as the influence of two key parameters. In the future, we plan to learn user needs and mobility patterns to more efficiently manage multipath based wireless network access.

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James Martin received the PhD degree from North Carolina State University. He is an associate professor in the School of Computing, Clemson University. His research interests include broadband access, wireless networks, Internet protocols, and network performance analysis. His current research projects include heterogeneous wireless systems and DOCSIS 3.x cable access networks. He received funding from the US National Science Foundation (NSF), NASA, the Department of Justice, Cisco, IBM, CableLabs, and BMW. Prior to joining Clemson, he was a consultant for Gartner, and prior to that, a software engineer for IBM.

Kang Chen (S'13-M'15) received the BS degree in Electronics and Information Engineering from Huazhong University of Science and Technology, China in 2005, the MS in Communication and Information Systems from the Graduate University of Chinese Academy of Sciences, China in 2008, and the Ph.D. in Computer Engineering from Clemson University in 2014. He is currently an Assistant Professor in the Department of Electrical and Computer Engineering at Southern Illinois University. His research interests include emerging wireless networks, datacenter networks, and software defined networking.

Xin Xing received the BS degree in Communication Engineering from Shangdong University, China in 2011 and the MS in Communication Engineering and Media Technology from University of Stuttgart, Germany in 2016. He was a PhD student at Southern Illinois University Carbondale from 2016 to 2017. He is currently a PhD student in the Department of Computer Science at University of Kentucky. His research interests include Wireless Networks and Artificial Intelligence.

Mijanur Rahaman Palash received the BS degree in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology (BUET), Bangladesh in 2013. He earned his Master in Electrical and Computer Engineering from Southern Illinois University Carbondale in 2018. His research interests include Wireless Communication and Computer Networking.

Jianwei Liu received the BE in Software Engineering from Xidian University, China in 2007 and the MS in Information Systems from Xidian University, China in 2010. He is currently a PhD candidate in Computer Science at Clemson University. His current research focuses on the optimization of heterogeneous wireless networks.