Improving Wireless Network Performance under MPTCP based Multipath Access

Kang Chen*, Xin Xing*, Mijanur Rahaman Palash*, Jianwei Liu†, and James Martin†
*Department of Electrical and Computer Engineering, Southern Illinois University, Carbondale, IL 62901
Email: {kchen, xin.xing, mijanur.palash}@siu.edu
†School of Computing, Clemson University, Clemson, SC 29634
Email: {jianwel, jmarty}@clemson.edu

***Abstract*—The emergence of multipath TCP (MPTCP) has made it much easier for mobile devices to use multiple wireless network access paths simultaneously. However, we find that a large amount of multipath users could negatively impact the performance of wireless networks in terms of throughput and fairness due to increased amount of wireless connections. Therefore, in this paper, we aim to mitigate such a problem while retaining the benefits of multipath access in wireless networks from the perspective of network owner. We solve the challenge by 1) identifying a solution principle that can effectively balance the two goals and 2) implementing the principle through an SDN based bandwidth usage management system on the network side. When there is congestion on an AP, our method enforces necessary suppressions on non-primary subflows from multipath users to protect the network performance, while keeping the multipath benefits as much as possible. When an AP owns idled capacity, no intervention is imposed, thus offering the maximal benefits to multipath users without substantially affecting the network performance. Thus, the multipath access is dynamically scaled to achieve a balance of the two goals. Extensive NS3 experiment with Linux Kernel MPTCP implementation demonstrates our findings as well as the effectiveness of the proposed system.**

I. Introduction

Multipath TCP (MPTCP) [1], [2] enables a TCP connection to exploit multiple paths transparently through parallel subflows. Such a feature makes it a useful tool to improve mobile devices' quality of services (QoS) in wireless networks by using multiple access points (APs) that belong to the same or different networks at the same time. For easy description, we use AP to uniformly represent a network access point such as WiFi AP and LTE eNodeB. Obvious benefits of the MPTCP based multipath access include higher bandwidth (by aggregating bandwidths of multiple APs) and transparent mobility resilience (by transparently switching away from poor/disconnected APs). More importantly, those benefits are provided at the TCP level, which makes them applicable to mobile applications directly.

We define mobile devices that access multiple wireless APs simultaneously through MPTCP as multipath users. We also define a **wireless network set (WNS)** as the set of wireless networks available to users in an area. In this paper, we focus on the WNS consisting of WiFi and LTE due to their prevalence, though our research can be directly extended to include other wireless networks. We further define the maximal throughput that a WNS/AP/device can achieve when there is backlogged traffic as its **achievable throughput**. This metric practically and fairly reflects the capacity of a WNS/AP as well as a device's ability to obtain bandwidth. It has been widely used in relevant research on scheduling and resource allocation in wireless networks [3]–[6]. Thus, we also use it as the major performance metric in this paper.

While state-of-art research focuses more on individual mobile devices' benefits from MPTCP based parallel multipath access in wireless networks [7]–[12], we realize that how the performance of WNSs might be affected by this new wireless network access manner has not been sufficiently studied so far. Without sufficient understanding on this side, the overall benefits of multipath based access in wireless networks would remain incomplete and obscure. This concern actually is motivated by two observations. First, multipath users do not add additional capacity to wireless networks. They just try to access multiple networks in parallel. Second, the MAC layer fairness strategy of wireless communication (which decides the allocation of resources on the AP to UEs) often makes the achievable throughput of a wireless AP non-static and be easily affected by the quantity and qualities of associated connections [13]. That is, the more connections (especially the more connections with a low link quality), the lower achievable throughput a wireless AP has.

Following this direction, we demonstrate that the achievable throughput of the WNS and the fairness to single-path users (i.e., only use one access path) are jeopardized when mobile devices turn to multipath through both measurements and theoretical analysis (details in Section III). First, the achievable throughput of associated APs (and that of the whole WNS) can be easily reduced due to the additionally-created and actively-used connections from multipath users. The reduction is caused by 1) the increased contention among users and 2) the low data rate on poor connections from multipath users. Second, single-path users' achievable throughput will be unfairly reduced. This is because 1) the achievable throughput of the associated APs now are shared among more connections and 2) the APs' achievable throughput itself may has already been reduced due to multipath users.

Therefore, we aim to protect the WNS performance under multipath users by thwarting the above two issues. An intuitive solution is to suppress multipath access directly, which, however, would lose all its benefits. As a result, it is desirable to allow the multipath access in wireless networks as much as possible. This makes the task much more challenging as the two goals are conflicting with each other. On one hand, as aforementioned, multipath users' adverse impacts originate from the additional connections they create, which indicates the necessity of some suppression. But, on the other hand, individual mobile devices rely on maintaining multiple paths (connections) to gain the benefits.

To solve this challenge, we identify a unified solution principle that can practically balance the two goals, i.e., preserving multipath benefits and protecting the WNS performance, by dynamically scaling the multipath access. Consequently, both multipath users' and single-path users' ability to obtain bandwidth from the wireless network remain the same as that when they all are single-path users. When the principle is implemented, the problems on overall throughput and fairness can be well controlled under multipath access. Section IV-1 explains the rationale behind this.

The next challenge is how to efficiently monitor and control the network access as required by the solution principle. We exploit the software-defined networking (SDN) [14] to develop a flow management system on the network side for this purpose in Section V. Our system places an SDN switch next to each AP to monitor and control flows going through it. It also contains a regulation center (RCt) responsible for making regulation decisions for flows from multipath users periodically based on AP congestion information and flow statistics. Those decisions are enforced through the SDN controller that controls deployed SDN switches. Each implementation of the SDN system serves a local area with several wireless APs independently. Therefore, our design can easily scale up for a large area through multiple parallel implementations.

In summary, our major contributions include

- We find that multipath users could adversely affect the performance of a WNS in terms of achievable throughput and fairness to single-path users, due to their additionally created and used wireless connections.
- We propose a solution principle that can effectively mitigate such adverse impacts, thus balancing the WNS performance and the multipath access.
- We exploit the features of SDN to implement an agile and efficient flow management system on the network side that can achieve the solution principle.

We focus on downlink of the wireless network in this paper, as it accounts for the majority of wireless traffic. The uplink traffic can be handled similarly following the method and rationale in this paper. For simplicity, we interchangeably use user, device, and UE in this paper.

In the remaining of this paper, related work is discussed in Section II. Section III shows the preliminary experiments and analysis that motivate this paper. Section IV introduces the solution thoughts. Section V presents the SDN based solution system. System effectiveness is evaluated in Section VI. Finally, Section VII concludes the paper.

II. Related Work

Accessing multiple wireless network connections simultaneously has attracted much attention under the concept of heterogeneous wireless networks (HetNets).

The first group of work focuses on client side radio access technology (RAT) selection in HetNets [3], [4], [15]–[17]. MOTA [3] designs a service model to allow an UE to associate interfaces to operators and application traffic to interfaces, based on operator signaling information. Aryafar *et al* [4] model the RAT selection in HetNets as a game among UEs and proves its ability to converge. Orsino *et al* [15] integrate multiple BS and UE parameters into the RAT selection process in 5G Multi-RAT network, thus improving the system performance. Similarly, two recent studies (i.e., [16] and [17]) exploit network side information (e.g., cost and QoS) and context information (e.g. network parameters and user preferences), respectively, to synergize individuals' NAT selection with the network performance. However, those algorithms cannot adapt to network load dynamism and thus cannot exploit multiple access paths for network level performance optimization.

To solve this drawback, researchers have proposed dynamic resource allocation or flow scheduling methods in HetNets [5], [6], [18], [19]. Choi *et al* [6] model the network resource allocation problem in accessing multi-radio networks in parallel for overall throughput maximization. ATOM [18] proposes a practical flow scheduling system for integrated LTE-WiFi network that can maximize the overall network utility. Sivchenko *et al* [5] propose an integrated mobility and resource management framework for HetNets. Kang *et al* [19] adopt SDN to instruct forwarding rules and resource allocation rules for optimal overall network resource usage. However, the improvement headroom in those work is quite limited as it is not easy to seamlessly migrate or split a data flow over different access networks.

MPTCP solves this barrier by allowing a mobile device to simultaneously use multiple access paths seamlessly [7]–[12]. Chen *et al* [7] first systematically measure the performance of MPTCP in HetNets and concludes that MPTCP improves the transport performance. Deng *et al* [8] conduct a similar research and found that MPTCP presents little or no improvement to short flows, and the benefits for long flows depend on configuration. The work in [9] categorizes the energy cost of using MPTCP in wireless networks for an energy efficient MPTCP. Croitoru*et al* [10] exploit MPTCP for improved mobility resilience in WiFi by letting a device connect to and use multiple WiFi APs simultaneously. In the work of [11], MPTCP is adopted to provide seamless flow migration in scheduling flows in HetNets for improved system capacity. Nikravesh *et al* [12] further reveal some limits of MPTCP in HetNets through field measurement and proposed a proxy based improvement method.

We can see that those work focuses on the benefits of individual multipath users in wireless networks. How multipath users affect the overall network performance has not been well discussed, which drives this research.

III. PRELIMINARY TESTS AND ANALYSIS

In this section, we present the measurement study and analysis that motivate this work.

A. Measurement Study

*1) **NS3 Simulation based Measurement**:* We conducted NS3 simulation based test in a 200mX200m area with 30 UEs and a WNS (including three WiFi APs and one LTE eNodeB), as shown in Figure 1. The WiFi APs are on different channels to avoid interference, as commonly do in practice. This also rules out the influence from interferences. Every wireless AP also connects to a FTP server which is not shown in the figure. We used DCE [20] to integrate Linux Kernel MPTCP implementation v0.89 into the test. Both TCP Reno [21] and OLIA [22] were tested as the congestion control for MPTCP.

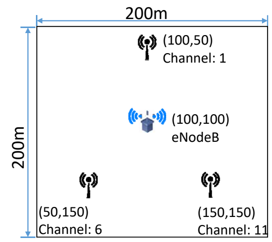


Fig. 1: NS3 measurement setup.

We randomly placed 30 devices in the simulation area. Nodes with the distance to the closest WiFi AP larger than a value (i.e., $\geq$50m) have an equal chance to be set as a multipath user or a single-path user on LTE. Nodes with a distance to the closest WiFi AP shorter than 50m have the same chance to be set as a multipath user or a single-path user on WiFi. We limit the percentage of multipath users to $Th_m\%$ and varied it from 0% to 80%. In the test, every device downloaded a 2GB file from the FTP server without a rate limit, thus creating backlogged traffic for every device. We measured the achieved throughput of each device.

The average measurement result from 10 runs is shown in Figures 2(a) and 2(b), in which "Reno" and "OLIA" represent the results when multipath users adopt Reno and OLIA as the congestion control algorithm, respectively. We can see that when the amount of multipath mobile devices increases, the achievable throughput of the whole WNS and that of single-path users keep decreasing. Also, Reno and OLIA lead to similar throughput degrading.

We have also done experiments with other topologies (including the scenarios with node mobility). The results show that the problem persists. This is because the causes are pervasive in all scenarios (as explained in the next subsection). Such results show that direct usage of multipath access in wireless networks adversely impacts the network performance.

B. Cause Analysis

We further explain the reasons for the issues identified above (i.e., throughput degrading and fairness) through the modeling of the throughput of WiFi and LTE.

1) Throughput Degrading: WiFi adopts a packet-level fairness resource allocation strategy and a distributed MAC scheme [18], [23]. The packet-level fairness indicates that the AP aims to transmit the same amount of packets for all associated devices, if they all have backlogged traffic. Then, the throughput of an AP with N devices can be represented as $T_w = \frac{N*S_p}{\sum_{i=0}^{N-1} t_i}$, where S_p is the maximal packet size (we can assume that devices generate max-sized packets under backlogged traffic) and t_i denotes the amount of time needed to transmit a packet for client c_i. t_i is influenced by two factors: retransmission incurred by collision (i.e., $\overline{k}$ retransmissions on average) and physical layer data rate (i.e., r_i). Thus, it is represented by $t_i = \overline{k} * \frac{S_p}{r_i}$. Then, we can transform T_w to the following

$$T_w = \frac{N}{\overline{k} * \sum_{i=0}^{N-1} \frac{1}{r_i}} = \frac{1}{\overline{k} * \overline{t}} \tag{1}$$

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

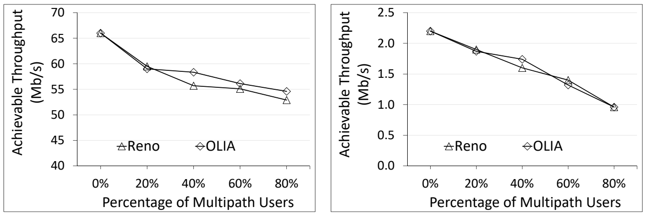
Eq (1) explains how multipath users affect the achievable throughput of a WiFi AP. Specifically, when some single-path users that rationally use the best wireless network turn to multipath on both WiFi and LTE, both $\overline{k}$ and $\overline{t}$ will increase. First, as WiFi MAC works in a distributed manner, $\overline{k}$ is positively related to the amount of associated active devices (more active devices indicates a higher collision probability). Thus, additional connections from multipath users would make $\overline{k}$ 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. As a result, multipath users that own a weak link to the WiFi AP (who may be single-path users over LTE previously) would cause $\overline{t}$ to increase. Those factors show that the achievable throughput of WiFi APs (and the WiFi network) can easily decrease under multipath users, due to additionally created and used connections.

LTE on the other side adopts a proportional fairness resource allocation strategy and a centralized MAC [18], [24]. The centralized MAC scheme schedules all transmissions, which indicates a very low chance of collision. The proportional fairness strategy allocates resources (i.e., air time and channel) to devices in proportion to the link quality. Thus, the throughput of a LTE BS with N associated devices can be represented as

$$T_l = \sum_{i=0}^{N-1} \frac{w_i * r_i}{\sum_{j=0}^{N-1} w_j} \tag{2}$$

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. Eq (2) indicates that additional low quality connections from multipath users also reduce the achievable throughput of the LTE BS, which, though, is less significant when compared with that in WiFi due to their small weights. This means that LTE is more resilient to the throughput loss under multipath access.

In a summary, allowing multipath access in wireless network increases the amount of wireless connections served by the network. What worse, multipath users are more likely to bring in low-quality connections to the WNS as they usually



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

Fig. 2: Result of NS3 based measurement.

are aggressive in using all available links. Those factors would 1) increase the chance of collision in WiFi and 2) cause more AP/BS resources to be used by low-quality connections in both WiFi and LTE. As a result, the achievable throughput of the whole WNS will be reduced.

2) Fairness: The fairness issue is caused by two facts. First, as previously discussed, the achievable throughput of wireless APs would decrease upon the join in of multipath users. Second, wireless APs do not differentiate the connections from multipath or single-path users and treat them equally in resource allocation. This makes multipath users gain an unfair advantage of aggregating the bandwidth from both WiFi and LTE. 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. Obviously, single-path users obtain less bandwidth than before when there is no multipath users.

IV. Solution Thoughts

In this section, we present our thoughts on the principle to solve the problems identified above.

1) Solution Principle: We find that the following principle can well balance the MPTCP based multipath based wireless network access and the overall WNS performance.

Both multipath users' and single-path users' ability to obtain resource (bandwidth) from the WNS should remain the same as when all users are single-path users.

We explain how it is obtained and its indication below.

As explained in Section III-B1, the throughput degrading and fairness issue mainly are caused by the fact that additional connections created by multipath users join the competition for bandwidth over wireless APs. The competition favors multipath users' ability to gain bandwidth from APs and reduce that of single-path users. It also lowers the overall efficiency of wireless APs. Therefore, if all devices' ability of gaining bandwidth is not affected after the joining of additional connections from multipath users, the adverse impacts are controlled. Particularly, the wireless AP's achievable throughput is the same as when all devices are using a single path, and single-path users obtain the bandwidth fairly.

The principle indicates that multipath users should not unfairly gain a higher ability to obtain bandwidth from the WNS. This raises **a challenge of how to preserve the benefits of multipath based access under this requirement**. We exploit an observation to handle this challenge. That is, the adverse impact on achievable throughput is meaningful only when devices need that much throughput. Otherwise, their bandwidth demands are satisfied, which makes the impact not substantial. For example, suppose a weak connection from a multipath user lowers the achievable throughput of a WiFi AP. In this case, if the AP still is not fully loaded (i.e., the bandwidth demands of all users over it are satisfied), the lowering does not create any hurts to SPTCP users.

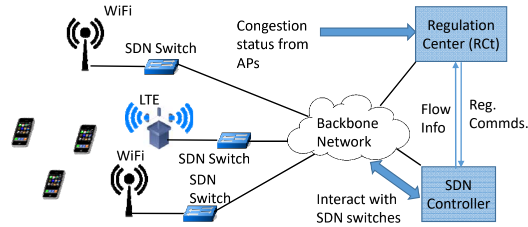


Fig. 3: Solution Overview.

The observation means that connections from multipath users can use the resources from APs as long as no congestion happens. Consequently, we design the following rules for handling multipath users, so the aforementioned principle can be attained while preserving the multipath benefits.

- Pick one connection as its primary connection.
- Use the primary connection freely and only take idled bandwidth on non-primary connections.

With the above rules, multipath users' adverse impact on AP's achievable throughput is prevented from turning to be substantial in a dynamic manner. This ensures that single-path users' ability to obtain bandwidth is not affected under the existence of multipath users. They just temporarily "lend" their bandwidth to multipath users when they do not need it. Meanwhile, multipath users' ability to obtain bandwidth is also guaranteed through the primary connection.

V. System Design

Considering that network administrator would like to be able to directly control the aforementioned negative impacts from multipath users, we propose an SDN based scheme on the infrastructure side to implement the solution principle. As shown in Figure 3, the scheme contains two major components: a Regulation Center (RCt) and an SDN system.

Scalability is one important requirement for such a network usage management system. The proposed system guarantees this requirement by letting one deployment (as shown in Figure 3) serve a local area independently. Thus, we can divide the whole network into many *control domains*, and each of which is served by one deployment of the proposed system in parallel. The granularity of the *control domain* can vary based on the network operator's mission.

A. Regulation Center (RCt)

The RCt implements the solution principle by dynamically adjusting the amount of bandwidth for data flows. We present its regulation rules and algorithms in this subsection.

1) Regulation Rules: The regulation rules abstracted from the solution principle in Section IV-1 include the following

- 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 used by secondary subflows is gradually reduced until either 1) the congestion resolves or 2) it reaches the minimal value.
- Flows from single-path users and primary subflows from multipath users will not be intervened.

With those rules, single-path users' ability to obtain resources will not be affected as secondary subflows from multipath users will retreat when congestion happens. Also, a multipath user's primary subflow ensures at least the same ability to obtain bandwidth as if it was a single-path user. The above rules are enforced through the following two algorithms.

2) Flow Categorization Algorithm: This algorithm has two functions: 1) select the primary connection for multipath users and 2) categorize flows from all users into two tiers.

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

The two tiers of flows are handled differently in the bandwidth regulation algorithm introduced next.

Algorithm 1 shows the detail of the flow categorization algorithm. The key part of this algorithm is finding the path (connection) that owns the maximal achievable bandwidth. We follow Equations (1) and (2) to calculate the achievable throughput of a wireless connection in WiFi and LTE, respectively, based on existing connections on the AP. However, this may not be the optimal method as connections that are regarded as secondary later will be suppressed upon congestion in our system. Those connections should be excluded from the above calculation. Fully considering this factor will turn the primary path selection into NP-Hard, as a multipath user's achievable throughput on a path (connection) depends on the selection of primary/secondary path of others on the same AP. Therefore, the current algorithm is a heuristic method that estimates the achievable throughput under the worst case. We leave the optimal method to future work and adopt the heuristic method due to its practicality.

The flow information needed in this algorithm is provided by the SDN system that will be introduced in Section V-B. Besides, we also assume that the RSSI and IP address of each user's wireless connections are known to the RCt. The RCt also knows the amount of connections on each AP. Such information is not hard to obtain on the network infrastructure side where the RCt resides. Then, it can predict each user's achievable bandwidth on each of its wireless connections and identify the primary connection/subflows.

3) Bandwidth Regulation Algorithm: This algorithm regulates the bandwidth usage on an AP following the regulation rules mentioned in Section V-A1. It queries the average MAC queue occupancy ratio (which is defined as the percentage of filled slots in the queue) of each AP, denoted $MacOcc$, to check the congestion status. Based on the congestion status reflected by $MacOcc$, regulation commands are issued to adjust the maximal bandwidth allocated to Tier 2 flows on the AP. We follow the additive increase multiplicative decrease (AIMD) concept in TCP congestion control [25] to provide fast response to congestion change on an AP.

Algorithm 1: Flow Categorization.

```
for user u ∈ Ū do
    if u.multipath == true then
        c_um := maxsize(u.connections) //return the max one.
        for connection c ∈ u.connections do
            for flow f ∈ c.flows do
                if c==c_um then
                    f.primary = true;
                    f.tier = 1;
                end
                else
                    f.primary = false;
                    f.tier = 2;
                end
            end
        end
    end
    else
        for flow f ∈ u.connections.flows do
            f.tier = 1;
        end
    end
end
```

Specifically, first of all, Tier 1 flows are not intervened. For Tier 2 flows, our algorithm periodically checks the value of $MacOcc$. In each check, if $MacOcc$ is larger than the congestion threshold, denoted CTh, the maximal bandwidth allocated to Tier 2 flows will be decreased by half. This is because when the AP is likely to be congested, secondary MPTCP subflows should be throttled to provide more bandwidth for single-path flows and primary MPTCP subflows. Note that we set a minimal rate limit of 100 kbs for all secondary MPTCP subflows to avoid head of line block of primary subflows, as indicated in [1]. On the other hand, if $MacOcc$ is smaller than the congestion threshold, the maximal bandwidth allocated to Tier 2 flows will increase by $BW_i * \frac{\alpha*(CTh-MacOcc)}{MacOcc}$, where BW_i is the current allocated bandwidth and $\alpha \in (0,1)$ is an aggressiveness factor. This means that when the AP is idled, more bandwidth can be allocated to secondary MPTCP subflows. In summary, the maximal bandwidth for Tier 2 flows is updated by

$$BW_{i+1} = \begin{cases} max(100, BW_i/2) & : MacOcc \geq CTh \\ BW_i * \frac{\alpha*(CTh-MacOcc)}{MacOcc} & : MacOcc < CTh \end{cases} \quad (3)$$

Obviously, CTh and α affect the aggressiveness of allocating bandwidth to secondary MPTCP subflows. We empirically set them to 85% and 0.5, respectively. We have evaluated the influence of α in the experiment (Section VI-C). The bandwidth limit is enforced through the meter in SDN switches, which will be introduced in Section V-B.

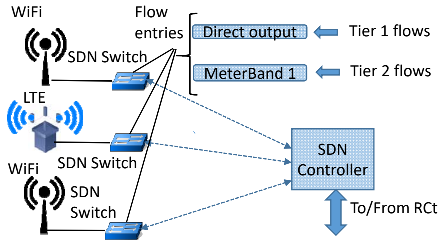


Fig. 4: SDN System Conceptive Overview.

4) Executing Algorithms: Both the above two algorithms are executed periodically inside the RCt to offer dynamic adaptation. The complexity of the two algorithms is quite small, i.e., roughly $O(N)$, where N is the total number of flows. The data communication needed for RCt is also small. It only needs to 1) collect the MAC queue occupancy ratio from each AP and flow statistics from SDN controller and 2) send new rate limits to the SDN controller. Thus, the RCt can be easily implemented on the infrastructure side.

Due to the same reason, the execution interval of the two algorithms can be quite small, e.g., every 1s or 2s, for refined control accuracy. We use 2 seconds by default. We have evaluated the influence of the execution frequency in the experiment (Section VI-C). It is also possible to dynamically adjust the execution interval to provide a better control. For example, when congestion (or resource idle) happens on an AP, the frequency can be increased to quickly adjust the bandwidth for Tier 2 subflows.

B. SDN System

A critical issue regarding the success of the proposed RCt is how to implement its functions in an easy and incremental manner. Current wireless network infrastructures, especially LTE, are quite closed and thus may not provide the functionalities required by the RCt. For this consideration, we choose SDN in this paper to effectively support the RCt for three reasons: it can easily 1) provide a global view of all flows, 2) realize flexible control over flows, and 3) be incrementally deployed over existing networks.

Figure 4 shows the conceptive overview of the proposed SDN system. We deploy an SDN switch before each wireless network 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 after other network entities, e.g., EPC for LTE, as long as it can see all flows going to 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 following introduces how the SDN system works.

1) Flow Statistics: Every SDN switch is initialized with one meter that has a rate limit that equals to the allocated maximal bandwidth for Tier 2 flows. When the first packet of a data flow arrives at the switch, it will be forwarded to the controller due to miss match. The controller then creates a flow entry that matches with the flow's subsequent packets and forwards them to the correct output port (uplink flows can be handled similarly and thus is not discussed in this paper). The controller will also attach the flow entry to the meter if it belongs to Tier 2, which limits the bandwidth that Tier 2 flows can obtain. Tier 1 flows are not attached to a meter as they are not intervened in the proposed solution. Meter is a SDN feature that can provide the rate-limiting function. Those steps are guided by the RCt, which knows whether a flow is primary or secondary and the tier that it belongs to.

Consequently, each SDN switch contains one flow entry for every data flow going through it, and one meter for Tier 2 flows, as shown in Figure 4. The SDN controller can query an SDN switch to learn the matching fields and size of each flow, as well as the accumulated bandwidth of Tier 2 flows, which will be provided to the RCt.

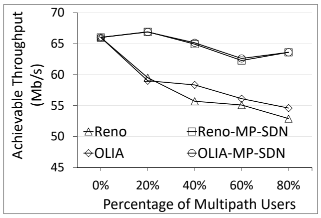
2) Flow Control: The SDN system can easily enforce the flow categorization and bandwidth regulation decisions. When the tier of a flow changes, the controller just needs to change its meter association, i.e., no meter for Tier 1 flows and meter 1 for Tier 2 flows. When the maximal bandwidth for Tier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

3) System Practicality: Though the SDN system has to see and label all flows, we believe it can be practically deployed. Currently, SDN switches can support 10 Gbps and even 40 Gbps throughput with all the functions needed in our design (e.g., PICA8 SDN switches [26]). 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) and then just queries the measured statistics. The regulation process mainly just changes the throughput limit of the meter and only touches the association of individual subflows with the meter when it is needed.

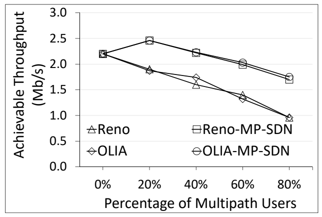
VI. Performance Evaluation

We conducted NS3 [20] based experiments to evaluate the performance of the proposed system. We denote the proposed system as "MP-SDN". We use NS3 DCE to integrate MPTCP Linux Kernel implementation v0.89 in the experiment. The basic setup is the same as in Section III-A1 (Figure 1). We further added a SDN switch between each wireless AP and the FTP server, as required by the design of the SDN system (i.e., Figure 4). The SDN system is developed based on NS3 OpenFlow 1.3 module [27]. We developed the RCt inside the SDN controller. Unless explicitly indicated, mobile devices download a 2GB file without a rate limit in the experiment. We set the execution interval of the regulation algorithms, congestion threshold CTh, and aggressiveness factor α to 2 seconds, 85%, and 0.5 by default.

Since this paper illustrates the issue of performance degrading under uncontrolled multipath access in wireless networks, we mainly evaluate whether the problem is solved by comparing the WNS performance with and without our solution. We first evaluate MP-SDN's performance in protecting WNS performance and reserving the multipath benefits in



(a) Overall achievable throughput of the WNS.



(b) Average achievable throughput of single-path users.

Fig. 5: Performance of MP-SDN in NS3 experiment.

Sections VI-A and VI-B. We then evaluate the influence of the execution interval and aggressiveness factor α in Section VI-C.

A. Protecting WNS Performance

We first conducted the same measurement as in Section III-A1 but with the proposed MP-SDN system enabled. 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 Figures 5(a) and 5(b), respectively. We have incorporated the results in Figures 2(a) and 2(b) for better comparison here. The two figures clearly show that with MP-SDN, the achievable throughput of the WNS remains relatively stable, while that without our scheme keeps decreasing when the percentage of multipath users increases. The improvement of MP-SDN over MPTCP is consistent over all percentages of multipath users and over both Reno and OLIA. Such a result shows that the proposed MP-SDN can effectively protect the overall achievable throughput of WNSs under multipath users.

Moreover, we see from Figure 5(b) that when MP-SDN is enabled (i.e., series labeled as x-MP-SDN where x is Reno or OLIA), the average achievable throughput (AAT) of single-path users remain stably above 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 caused by the bias due to insufficient amount of single-path users (i.e., less than 12). 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 issue to single-path users is well controlled by MP-SDN.

The above improvement is brought by the fact that MP-SDN can effectively throttle the bandwidth used by secondary MPTCP subflows on each AP. To show this point, we record the achieved throughput of tiers 2 flows in all WiFi APs every 0.5 seconds in the experiment. The result is shown in Figure 6. We see from the figure that their values are constantly suppressed to be quite small, i.e., around 100 kbps. In this test, we do not limit the downloading rate for every mobile device. As a result, Tier 1 flows could take all resources on each AP and continuously cause congestion, which triggers the throttling on Tier 2 flows in MP-SDN.

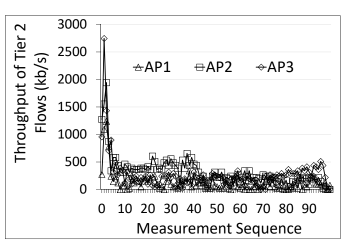
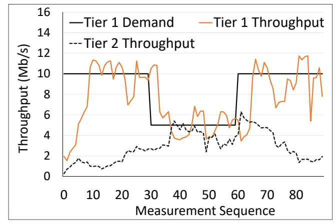
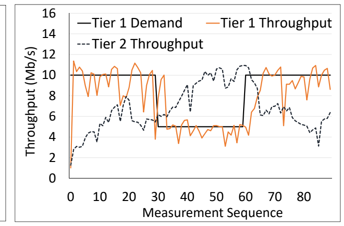


Fig. 6: Throughput of Tier 2 flows on the three WiFi APs.

With the above results, we conclude that MP-SDN can effectively thwart multipath users' adverse impact on achievable throughput and fairness to single-path users in WNSs.



(a) Result of AP1.



(b) Result of AP2.

Fig. 7: Keeping the benefits for multipath users.

B. Preserving Multipath Benefits

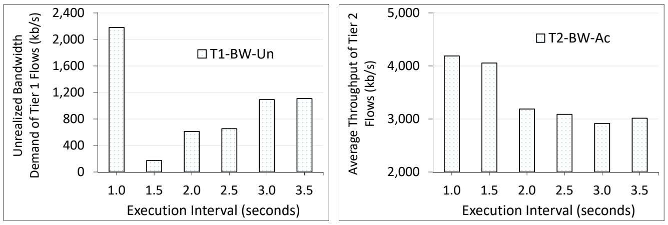
In the previous experiment, the resource on each AP is saturated by Tier 1 flows. As a result, secondary MPTCP subflows on each AP are throttled to gain a very low bandwidth. We further develop an experiment to show that the benefits of multipath users could be dynamically scaled when Tier 1 flows cannot take all bandwidth on the AP, as indicated in our solution principle. We picked WiFi AP 1 (top one) and WiFi AP 2 (bottom left one) for demonstration 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, and measured the throughput of Tier 1 and Tier 2 flows every 0.5 second. We plotted the results in Figures 7(a) and 7(b). The "measurement sequence" in the two figures denote the sequence number of measurement points.

We see from the two figures that in both APs, when the bandwidth demand of Tire 1 flows reduces from 10 Mbps to 5Mbps at 30s, the throughput of Tier 2 flows increases accordingly to take up the released AP resources. When it increases back to 10 Mbps at 60s, the throughput of tire 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 (one cycle is 2 seconds).

The above results show that multipath users can use their secondary subflows to dynamically obtain bandwidths from idled resources not taken by Tier 1 flows. Throughout the process, multipath users still keep all connections. Therefore, we conclude that the proposed MP-SDN system can scale the benefits to multipath users dynamically to avoid causing substantial adverse impacts to the WNS performance (i.e., Tier 1 flows can always get the right share of bandwidth as long as they have the demand), as required by our solution principle.

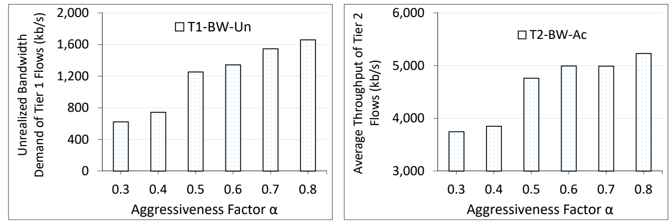
C. Influences of Key Parameters

We further evaluate the influence of two key parameters on the performance of our system: the execution interval of our bandwidth regulation algorithm (Section V-A3), denoted EI, and the aggressiveness factor α in increasing the bandwidth of Tier 2 subflows when there is no congestion (Eq (3)).



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

Fig. 8: Influence of the execution interval of the proposed system.



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

Fig. 9: Influence of the aggressiveness factor α.

The test configuration is the same as in Section VI-B except that the bandwidth demand for Tier 1 flows swaps between 10 Mbps and 5 Mbps every 10 seconds in this test. This is to create more bandwidth demand changes for the test. We again measured the throughput of Tier 1 and Tier 2 flows every 0.5 second. As the influence to all wireless APs is similar, we only show the results for the top WiFi AP in this section.

We further designed two metrics to assist evaluating the influence, denoted "T1-BW-Un" and "T2-BW-Ac". T1-BW-Un represents the average unsatisfied bandwidth demand of Tier 1 flows across all measurement points. 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 shows the average throughput of Tier 2 flows across all measurement points. It is calculated by $\sum_{i=0}^{N} \frac{BW_{2i}}{N}$, where BW_{2i} denotes the throughput of Tier 2 flows at the i-th measurement point. The two metrics show how well our system can avoid substantial decrease to the achievable throughput of Tier 1 flows and allow Tier 2 flows (i.e., secondary MPTCP subflows) to grab idled resources, respectively, under the up and down of the bandwidth demand of Tier 1 flows. Thus, the smaller the T1-BW-Un, the better our system can prevent degrading the performance of the WNS, and the larger the T2-BW-Ac, the better our system can provide multipath benefits.

1) Execution Interval: We varied the execution interval of the proposed system (i.e., EI) from 1s to 3.5s with a 0.5s increase each time. The results of the two metrics are shown in Figures 8(a) and 8(b). We see that the unsatisfied bandwidth demand for Tier 1 flows is high when EI is small (e.g., 1s) or large (e.g., $\geq$3s) and reaches the minimal when $EI = 1.5s$. This is because a small EI indicates a shorter period of time to evaluate the queue occupancy ratio. As the queue occupancy fluctuates dynamically even under congestion, a small EI makes it possible to detect a low occupancy ratio that does not reflect the congestion status and allocate more bandwidth to Tier 2 flows. As a result, Tier 1 flows' bandwidth demand is severely undermined. On the other hand, when EI is large, the queue occupancy ratio becomes more accurate. However, in this case, the suppression of Tier 2 flows may not be executed timely, thus hurting the throughput of Tier 1 flows.

We see from Figure 8(b) that the throughput of Tier 2 flows continuously decreases when EI increases. This is because a larger 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 configuration).

2) Aggressiveness Factor α: We varied the value of α from 0.3 to 0.8 with 0.1 increase each time. The results of the two designed metrics are shown in Figures 9(a) and 9(b). We find that when α increases, both the unsatisfied bandwidth demand of Tier 1 flows (T1-BW-Un) and the average throughput of Tier 2 flows (T2-BW-Ac) increase. Recall that α controls the aggressiveness of allocating bandwidth to Tier 2 flows. Therefore, the larger α is, the more likely that Tier 2 flows receive more bandwidth share. Consequently, the more increase on the average throughput of Tier 2 flows and the more unsatisfied bandwidth demand for Tier 1 flows (as the total available bandwidth is fixed).

We also see that the increase speed of both metrics is high when α is medium and low when α is small or large. Therefore, 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 our test configuration).

VII. Conclusion

In this paper, we found that multipath users could adversely impact the overall network achievable throughput and the fairness to single-path users in WNSs due to the creation of additional wireless connections. We thus propose an SDN based system on the infrastructure side to mitigate those impacts and protect the wireless network performance, 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, by selectively and dynamically suppressing additional subflows from multipath users. Extensive Linux Kernel MPTCP implementation based NS3 experiments demonstrate the effectiveness of the proposed system, as well as the influence of two key design parameters. In the future, we plan to investigate how to learn user needs and mobility parameters on the infrastructure side for more efficient multipath based wireless network access.

Acknowledgements

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