Bandwidth-Need Driven Energy Efficiency Improvement of MPTCP Users in Wireless Networks

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***Abstract*—Multipath TCP (MPTCP) enables mobile devices to aggregate bandwidth from multiple wireless connections and own better mobility resilience but incurs additional energy consumption. Such a fact drives the research to find the energy-efficient access manner under MPTCP-based multipath access in wireless networks. However, existing work largely focuses on energy efficiency only and is agnostic to the bandwidth need of mobile devices. Therefore, in this paper, we propose to handle this gap by integrating the improvement of energy efficiency into the process of satisfying the bandwidth need. First, our approach keeps using a single connection if the bandwidth need is satisfied. A novel method is proposed based on TCP throughput modeling for monitoring bandwidth shortage when the client uses only a single connection. Second, when more bandwidth is needed, our approach does not turn to multipath access blindly but chooses the additional connection that has a potential in improving both energy efficiency and throughput. Third, when multipath is used, our approach keeps evaluating the necessity of switching back to using a single path based on the bandwidth need and energy efficiency. The three steps form a loop to continually assist mobile devices to balance bandwidth need and energy efficiency. Intensive experiments show that compared with using MPTCP on mobile devices directly, this method greatly improves energy efficiency while keeping bandwidth needs satisfied.**

***Index Terms*—MPTCP, wireless networks, energy efficiency, bandwidth need.**

I. Introduction

THE RECENT development of wireless technologies has made it possible for mobile devices to use multiple wireless connections simultaneously. On one hand, current mobile devices (e.g., smartphones and laptops) often own multiple wireless interfaces such as LTE and WiFi. Meanwhile, overlapped network coverage has become a norm under the fast development of LTE and WiFi networks (e.g., the entire city may be covered by WiFi [1], [2]). The emergence of multipath TCP (MPTCP) [3] enables a device to operate over multiple wireless connections simultaneously at the TCP level. A number of benefits can be attained with such a multipath access manner. Mobile devices can aggregate the bandwidth from multiple connections and improve mobility resilience by switching between connections seamlessly. Consequently, MPTCP based multipath access in wireless networks has attracted much attention recently [4]–[12].

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TABLE I
General Format of the MPTCP Energy Efficiency Model in LTE-WiFi Network

LTE (Mbps)	WiFi (Mbps)	
	LTE Only	WiFi Only
T_1	$< Th_{11}$	$\geq Th_{12}$
T_2	$< Th_{21}$	$\geq Th_{22}$
T_3	$< Th_{31}$	$\geq Th_{32}$
...	...	...

However, such a multipath based network access easily leads to concerns on energy consumption due to the concurrent use of multiple wireless interfaces. The work in [7] experimentally shows that the average radio power of an MPTCP device is 2.08 times of that of a single-path TCP (SPTCP) device. Even if we adopt the energy efficiency (i.e., energy per MB data or J/MB) instead of absolute energy consumption as the evaluation metric, MPTCP is not always beneficial. It is true that existing researches have shown that MPTCP can improve energy efficiency due to the synergy among engaged wireless interfaces [13]–[15]. However, the enhancement holds only when all connections attain a high throughput. When the throughput of a connection is low, the overall energy efficiency drops significantly. We demonstrate this point through both tests and analysis later in Section III.

Therefore, it is necessary to identify the access manner (i.e., which connections to use) that is energy efficient when adopting MPTCP in wireless networks. The intuitive idea is to study the MPTCP energy efficiency model in wireless networks [13]–[15]. As shown in Table I, the model shows the most energy efficient access manner upon different throughput of engaged wireless interfaces. We see that such a model can guide mobile devices to improve the energy efficiency under MPTCP based multipath access in wireless networks.

While the model is informative, it depends purely on the throughput achieved over engaged paths and is agnostic to the bandwidth need. Since network access is driven by bandwidth need, the aforementioned fact leads to two gaps.

- First, the throughput over a wireless connection is throttled by the bandwidth need of the device and the bandwidth availability of the connection, both of which are not known beforehand. Thus, mobile devices cannot apply the model before using all connections, which wastes energy if using a single connection is preferred.
- Second, even when the throughput of engaged interfaces is learned, simply following the model may deteriorate the bandwidth need of mobile devices. For example, suppose the bandwidth need of a device is 1 Mbps, and LTE and WiFi each can provide 0.5 Mbps each. In this case, the client can get the needed bandwidth by using both interfaces. However, the model may suggest using WiFi only for better energy efficiency, which makes the device get only half of its bandwidth need satisfied.

Existing researches either fail to handle the above two issues comprehensively or present limited energy efficiency improvement options. The work in [16] simply ignores the influence of throughput on energy efficiency and only considers energy efficiency at the interface level. Both eMPTCP [14] and MDP [17] adopt a "try and decide" model to find the most energy efficient access manner. Besides, eMPTCP is agonistic to bandwidth need, while MDP simply treats past throughput as the bandwidth need. E-MICE [18] adapts the use of multiple WiFi interfaces by monitoring network utilization and predicting their capacities, which is similar to our work. However, it limits the scope to WiFi network only. Optimum-rate based algorithms [19]–[21] deduce the optimal rate of each path that can maximize an energy efficiency related utility. They fail to consider the bandwidth availability of paths and/or the bandwidth needs of hosts. Congestion control based algorithms [22]–[24] steer traffic towards the path that is more energy efficient. This improves energy efficiency under the drive of bandwidth need. However, they are limited to multipath access and cannot further improve energy efficiency by turning to only using a single path.

The above limitations make mobile devices unable to satisfy both energy efficiency and bandwidth need while employing MPTCP based multipath access. In this work, we handle this problem by exploiting two key observations from our experiments and analysis. First, network access is driven by bandwidth need. Second, the energy efficiency of a wireless interface generally is inversely proportional to its throughput. Thus, instead of merely relying on the energy model, our method tries to embed energy efficiency improvement into the process of satisfying bandwidth need directly. The high-level principle is to avoid a low throughput on any wireless connection as much as possible, as this would decrease the overall energy efficiency and brings little to the overall throughput. In practice, the low throughput can be caused by either the low bandwidth need or the low bandwidth availability. We handle these causes in different steps.

First, when network access is initialized, our approach uses only one wireless interface unless it fails to satisfy the bandwidth need (i.e., causes bandwidth shortage). The initial interface is selected by either a user policy or a system policy. We novelly detect bandwidth shortage through the modeling of TCP throughput (note that each MPTCP subflow is a TCP flow). The rationale is that when using one connection is sufficient, turning to multipath access would decrease the energy efficiency without benefiting the bandwidth.

Second, when additional wireless connections are needed to provide more bandwidth to the device, our approach evaluates the potential of available connections in improving both energy efficiency and throughput. It is hard, if not impossible, to check whether a connection can provide enough bandwidth before actually accessing it. Thus, our approach turns to identifying and excluding connections that are not likely to achieve this goal based on the signal quality, i.e., non-qualified connections. This is because accessing these connections blindly would only slightly improve the throughput but could severely lower the energy efficiency.

Third, when multiple wireless connections are employed simultaneously, our approach keeps monitoring the throughput. Such information is further used to check the change of bandwidth need and energy efficiency. Then, a comprehensive evaluation is made to decide the necessity of turning back to single-path access. This design enables mobile devices to improve energy efficiency continuously under the bandwidth need. For example, after switching to single-path access, our approach owns the ability to return to multipath access in an energy efficient manner by following the first step, while current methods can only try blindly.

Our contributions in this paper are summarized as the following.

(1) We shed light on the possibility and benefits of bandwidth-need driven energy efficiency improvement for MPTCP users in wireless networks.
(2) We proposed novel methods to detect bandwidth shortage and evaluate the potential of a connection in improving the throughput and energy efficiency.
(3) We designed and implemented an approach that can effectively guide MPTCP users to improve energy efficiency while satisfying their bandwidth needs.

We have conducted extensive real implementation based experiments to demonstrate the efficiency and effectiveness of the proposed scheme. We focus on WiFi and LTE in this paper due to their prevalence. We focus on the downlink of wireless networks, as it accounts for the majority of mobile traffic. The uplink can be handled similarly.

The remainder of this paper is arranged as follows. Related work is introduced in Section II. Section III shows the measurement study and theoretical analysis that drive the technical design. Section IV presents the details of the proposed scheme. System efficiency and effectiveness are evaluated in Section V. Finally, Section VI concludes the paper.

II. Related Work

A. Benefits of MPTCP in Wireless Networks

The works in [6]–[8] and [25]–[27] have systematically measured the performance of MPTCP based multipath access over cellular and WiFi networks. These works have confirmed such an access paradigm's benefit on bandwidth and the availability of concurrent wireless paths. They also have identified some limits, such as performance degrading under path heterogeneity in terms of bandwidth and delay [25], delay variation [6], not helpful to small flows [7], [8], and interactions with CDN [7] and upper-layer Web protocols [26]. The work in [28] analyzes the issue of buffer-bloat when using MPTCP over WiFi and cellular networks.

Employing MPTCP in wireless networks also enables transparent flow mobility/offloading [4], [9], [29]–[32]. Raiciu *et al.* [29] exploited MPTCP to achieve seamless flow mobility in wireless networks. The work in [30] summarizes key points in offloading cellular data to WiFi using MPTCP. Paasch *et al.* [9] demonstrated the feasibility of employing MPTCP to achieve transparent handover between different access points. Hampel *et al.* [31] proposed to build a lightweight MPTCP proxy to support flow mobility across different networks. In the work of [32] and [33], MPTCP is used to optimize resource allocation and load balancing in wireless networks, respectively. A recent work [4] exploits MPTCP to enable WiFi mobility without handoff by letting device connect and use multiple APs simultaneously.

B. Energy Concern of MPTCP in Wireless Networks

Energy consumption is the major concern of using MPTCP in wireless networks [9], [13], [15]. Paasch *et al.* [9] studied energy consumption of MPTCP on Nokia N950 in large file download and Web browsing. Their experiments show that using WiFi alone is more energy efficient than using MPTCP over both WiFi and cellular 3G. The work in [13] systematically measures and models the energy consumption of MPTCP in wireless networks and summarizes conditions under which MPTCP is more energy efficient. The work in [15] studies the energy cost of using MPTCP for constant bitrate mobile streaming. It finds that MPTCP is more energy efficient than single-path TCP only in certain scenarios. It also claims that MPTCP should be used only if the requested data rate can't be provided by a single interface.

To this end, a number of researches have been conducted to improve the energy efficiency of MPTCP devices in wireless networks. The first group of methods follows the energy efficiency model of MPTCP in wireless networks [14], [16]–[18]. The work in [17] improves the energy efficiency by modeling the scheduling of bandwidth need over available connections as a Markov decision process. However, they simply treat the throughput in previous slots as the bandwidth need. Chen *et al.* [16] simply offloaded traffic to interfaces that are more energy efficient statically. eMPTCP [14] determines the most energy efficient network access manner by mapping the measured path rates to the energy efficiency model in [13]. It also delays the addition of subflows. E-MICE [18] enables/disables WiFi interfaces by monitoring network utilization and predicting the capacity of available interfaces. This is in the same direction as in our work. However, it only works in WiFi networks.

The second group of methods deduces the appropriate rate of each path by optimizing an energy efficiency related utility. The researches in [19] and [20] jointly optimize the video quality and energy efficiency in MPTCP based video transfer in wireless networks with an energy-distortion analytic framework. EEMPTCP [21] models the energy efficiency maximization problem and exploits congestion control to enforce optimal rates. These methods fail to consider the bandwidth availability of paths and/or the bandwidth need of the host.

There are also researches that improve the energy efficiency of MPTCP through congestion control [22]–[24], [34]. ecMTCP [22] links the rate of subflows with the end-to-end energy cost by adding a linking function to the incremental part of congestion control. The work in [23] designs a delay related traffic-shifting parameter in the congestion control to shift traffic to low-delay paths, thus improving the energy efficiency of using MPTCP in datacenters. Zhao *et al.* [24] comprehensively studied key parameters in the congestion control that are related to energy efficiency. Peng *et al.* [34] proposed a two-timescale algorithm to improve the energy efficiency of MPTCP. The algorithm first selects paths and then adapts rates of subflows over these paths through congestion control. However, it improves the overall energy efficiency of all hosts in a network rather than individual hosts. A common issue for these algorithms is that they cannot further improve energy efficiency by using a single path only.

We see that existing approaches either are not efficient enough or are agonistic to the bandwidth need that is time-varying. This makes devices unable to improve energy efficiency and throughput at the same time. This research thus aims to better synergize the two goals.

III. FIELD MEASUREMENT AND ANALYSIS

We first try to understand the relationship between energy efficiency and throughput. We conduct measurements and analysis to show key factors affecting energy efficiency under different bandwidth needs. We define an **MPTCP device/user** as one that accesses multiple wireless connections concurrently through MPTCP. We also define **energy efficiency** as the amount of energy per MB data transmission, i.e., J/MB, rather than the absolute amount of energy. The lower this metric is, the more energy efficient a device is. We believe this is a fair metric under the context of MPTCP as it integrates the amount of data transmitted.

We consider scenarios with both limited and unlimited bandwidth needs. We used FTP downloading with and without a rate limit to implement the two cases. For multipath network access, we consider both WiFi-WiFi network (i.e., uses two WiFi APs) and WiFi-LTE network (i.e., uses one WiFi AP and one LTE BS). The WiFi-WiFi network is adopted for two reasons. First, in this case, the two wireless paths are homogeneous (i.e., both are WiFi) and can better show how multipath access influences energy efficiency. Second, MPTCP based multipath access has been proven to improve the bandwidth and mobility performance of devices in WiFi networks [4]. The measurement setup is shown in Figure 1. The MPTCP server is a desktop, and the MPTCP client is a laptop. Both are installed with Ubuntu 14.04 with MPTCP v0.90 (Linux kernel 3.18.43+) [35]. In the experiment, AP1 is a TPlink WiFi access point (802.11n), while AP2 is either another TPlink WiFi access point or a Lemko EZ LTE base

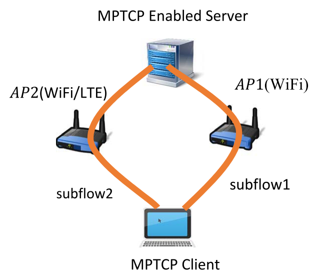
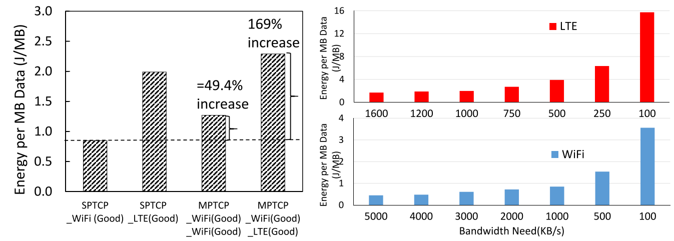
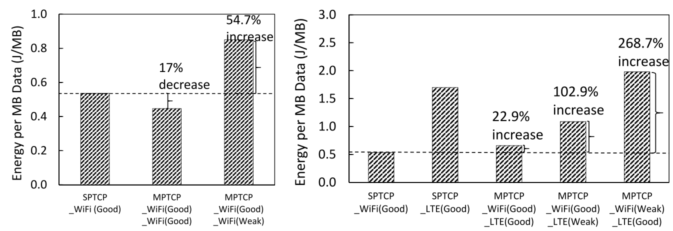


Fig. 1. Setup of the energy efficiency measurement.



(a) Multipath user at 1000 KB/s. (b) Single-path user.

Fig. 2. The energy efficiency under limited bandwidth need.



(a) WiFi-WiFi network. (b) WiFi-LTE network.

Fig. 3. Energy efficiency under unlimited bandwidth need (note that the "good" and "weak" in the figures represent the signal quality of the corresponding wireless connection).

station [36] running over the 3.65 GHz CBRS band. For energy measurement, we developed a tool using the laptop's inherent "current_now" and "voltage_now" variables stored inside "sys/class/power_supply/BAT" and the formula $P = V * I$. We measured background energy consumption beforehand and subtracted it from the measured value to get the energy consumption incurred by wireless data transmission.

A. Limited Bandwidth Need

In this test, we limit the bandwidth need of the client to 1000 KB/s, which is enough for most mobile applications including 1080p video streaming. Besides, all wireless connections own a good signal strength and can provide enough bandwidth to the client. Figure 2(a) shows the energy efficiency of the multipath user in both WiFi-WiFi and WiFi-LTE networks. It shows that multipath access has a lower energy efficiency than using SPTCP in WiFi. The tests with other bandwidth needs present similar results (the reasons are explained later).

Since Figure 2(a) shows the combined energy efficiency under MPTCP, we further measured the energy efficiency of SPTCP over WiFi and LTE under different bandwidth needs. The results are shown in Figure 2(b). We see from the figure that the lower the bandwidth need (i.e., measured throughput) is, the lower the energy efficiency the client has. The energy efficiency does not decrease linearly when the bandwidth need decreases. It decreases faster when the bandwidth need is small. We explain the root cause of such a result in Section III-C.

The above results suggest that when a mobile device has a limited bandwidth need that can be satisfied through a single path, turning to multipath access is not favorable for energy efficiency. This because it leads to a smaller throughput over engaged wireless interfaces (i.e., the bandwidth need is split over multiple interfaces) and consequently lowers the energy efficiency. Due to this reason, tests with different bandwidth needs present a similar result as in Figure 2(a) (i.e., they all get a reduced energy efficiency after turning to multipath access).

B. Unlimited Bandwidth Need

In this case, the client saturates the capacity of wireless APs due to the unlimited bandwidth need. Thus, we evaluate the energy efficiency under different bandwidth availabilities that are implemented by varying the link quality. By following the work in [37], we used −55 dBm (−85 dBm) as the RSSI value for a good (weak) WiFi connection, and −65 dBm (−95 dBm) for a good (weak) LTE connection. We have tested with different RSSI values for a good/weak WiFi/LTE connection. The results are consistent with those using the above configuration (we explain the reasons later in Section III-C). The measurement results for both single-path access (through SPTCP) and multipath network access (through MPTCP) in the WiFi-WiFi and WiFi-LTE networks are shown in Figures 3(a) and 3(b), respectively.

Figure 3(a) shows that when both WiFi connections own a good signal, using both connections leads to better energy efficiency than using only one WiFi connection (i.e., 17% less energy per MB data). This is caused by the synergy of the two WiFi interfaces, as reported in [13]–[15]. However, when the signal quality of one connection turns to be weak, the energy efficiency decreases significantly (i.e., the energy per MB data increases by 54.7%).

Figure 3(b) shows the results of the same test in the WiFi-LTE network. It shows that LTE presents a higher energy per MB data than WiFi when they both own a good signal quality, which has also been confirmed in [13], [14], and [38]. After turning to multipath access with a good LTE connection and a good WiFi connection, the client's energy efficiency is mildly higher than that of using a good WiFi connection alone. But when either LTE or WiFi connection turns to be weak, the energy efficiency reduces dramatically.

The above results show that when there is unlimited bandwidth need, turning to multipath access with a weak connection reduces the energy efficiency. This is because the weak connection can only offer a low throughput, which makes the wireless interface own low energy efficiency. Such a result is consistent with that in the test with limited bandwidth need.

C. Cause Analysis

We further explain the reasons behind the above measurement results by modeling the energy consumption of wireless data transmission in both WiFi and LTE networks.

As presented in [14] and [38], a wireless interface experiences three states in transferring data: promote to active (i.e., promotion), data transmission, and staying on active after transmission is completed (i.e., tail). We use P_{prom}, P_{tx}, and P_{tail} to denote the power level in the three states, respectively, and T_{prom}, T_{tx}, and T_{tail} to represent the duration of the three states, respectively. Then, the energy consumption of a wireless interface can be modeled as:

$$E_{total} = P_{prom} * T_{prom} + P_{tx} * T_{tx} + P_{tail} * T_{tail} \quad (1)$$

Generally, the total amount of energy consumption during the promotion and tail status is fixed. It is about 2.91 *J* and 0.149 *J* for LTE and WiFi, respectively. We use $E_{overhead}$ to denote such an energy consumption, i.e., $E_{overhead} = P_{prom} * T_{prom} + P_{tail} * T_{tail}$. Therefore, Formula (1) can be written as $E_{total} = P_{tx} * T_{tx} + E_{overhead}$. By following the work in [38], we model P_{tx} as $P_{tx} = \alpha * s + \beta$, where s denotes the throughput of the wireless interface in MBps and α and β are two parameters of the power level model. Finally, the energy efficiency, denoted *EF*, of a wireless interface (i.e., energy consumption per MB data, J/MB) can be modeled as the amount of energy consumption (i.e., E_{total}) divided by the amount of data transferred (i.e., $s * T_{tx}$, note that s is the throughput). That is

$$\begin{aligned} EF &= E_{total}/(s * T_{tx}) \\ &= (P_{tx} * T_{tx} + E_{overhead})/(s * T_{tx}) \\ &= ((\alpha * s + \beta) * T_{tx} + E_{overhead})/(s * T_{tx}) \\ &= \alpha + \beta/s + E_{overhead}/(s * T_{tx}) \end{aligned}$$

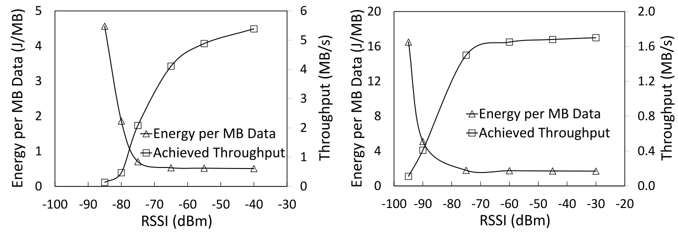
In the above formula, $s * T_{tx}$ denotes the amount of data transferred. Therefore, since we mainly consider the energy efficiency of transferring a fixed amount of data, $s * T_{tx}$ can be regarded as a constant. Thus, we let $\alpha^* = \alpha + E_{overhead}/s * T_{tx}$. We then get the following:

$$EF = \alpha^* + \beta/s \quad (2)$$

The above model indicates that the energy consumption per MB data is inversely proportional to the throughput. It is easy to find that our measurement results for WiFi and LTE, which are plotted in Figure 2(b), match with this model well.

This model explains the conclusions of our measurement study. First, this model confirms our conclusion in Section III-A regarding the scenario with a limited bandwidth need. Specifically, turning from single-path access to multipath access would reduce energy efficiency since it distributes the constant bandwidth need to multiple interfaces.

Second, in the scenario with an unlimited bandwidth need, adding a weak connection would decrease the overall energy efficiency. This is because a weak connection has a low throughput and consequently low energy efficiency. To better show this point, we measured the throughput and energy efficiency under different RSSI values for both WiFi and LTE.



(a) WiFi. (b) LTE.

Fig. 4. Data rate and energy efficiency at different RSSI values.

The results are shown in Figures 4(a) and 4(b). We see that the energy efficiency remains stable when the signal strength is good (i.e., when RSSI is higher than −80 dBm for WiFi and −90 dBm for LTE) and decreases rapidly when RSSI decreases. This is the reason why adopting different RSSI values for a good/weak connection presents similar results in the measurement in Section III-B.

This model also explains the MPTCP energy efficiency model in wireless networks proposed in [13] and [14]. In the model, using a single connection is recommended when the other connection presents a much lower throughput. This can be explained by Formula (2). The low-throughput connection owns a low energy efficiency and thus could drag the overall energy efficiency down if it is employed.

IV. System Design

In this section, we exploit the findings from the previous section to improve the energy efficiency of MPTCP in wireless networks under the context of bandwidth need.

A. Overview

Our measurement and analysis reveal that

- The energy efficiency and throughput of a wireless interface (i.e., WiFi and LTE) are not conflicting with each other. According to Formula (2), the higher the throughput is, the higher the energy efficiency is (i.e., the fewer energy consumed per MB data transmission).
- The strategy to improve energy efficiency is different when the end device has limited or unlimited bandwidth need. The former requires to concentrate on one connection, while the latter requires to avoid connections with a low bandwidth availability.

The first finding indicates that it is possible to synergize the goals of achieving high energy efficiency and satisfying the bandwidth need. However, applying the second finding to attain this synergy faces two challenges. First, it is hard to detect whether the client has a limited or unlimited bandwidth need. Second, even when we can detect the bandwidth need, the bandwidth availability of a connection is basically unknown before accessing it.

Fortunately, we find that the strategies for the two types of bandwidth need can be unified as one principle: avoid causing a small throughput on any connection. This alleviates the need to predict bandwidth availability. Instead, we can embed the energy improvement strategy into the process of satisfying bandwidth need. Specifically, when network access starts, there is no need to turn to multipath access when a single connection can cover the bandwidth need. In other words, the device should consider multipath access only when bandwidth shortage is detected. In the process of turning to multipath access, we should avoid connections with no potentials in meaningfully contributing more bandwidth. This can be done by taking advantage of some side information. When multiple connections are used, connections that present a low throughput should be avoided. This helps us decide when to turn back to using a single path.

Thus, our bandwidth-need driven energy efficiency improvement approach for MPTCP users contains three components:

- Policy-based Network Access Initialization: When network access is needed, MPTCP starts over one connection only by following a certain user/system policy.
- Bandwidth Shortage Monitoring: Bandwidth shortage (i.e., failing to satisfy the bandwidth need of the application) is continuously monitored.
- Energy- and Throughput-Efficient Multipath Strategy: This strategy contains efforts in three folds. 1) MPTCP turns to multipath access only when bandwidth shortage is detected. 2) When multipath access is needed, non-qualified connections that can hardly contribute substantial bandwidth are filtered directly. 3) Multipath access is then started over qualified connections. After this, active connections are monitored to evaluate the necessity of turning back to single-path access.

The details of those components are presented in the following.

B. Policy-Based Network Access Initialization

As proved earlier, turning to multipath access would decrease the energy efficiency if a single interface can provide the needed bandwidth. Therefore, when network access is initiated, the new MPTCP connection should only start a subflow over one of the available wireless interfaces. The next question then is which interface to choose. Since there is very limited information regarding the bandwidth availability of available interfaces at this stage, we propose that this selection should follow either a user policy or a system policy.

The user policy reflects the preference of the device owner. For example, he/she may set up a policy to prefer WiFi over LTE. On the other hand, the system policy aims to optimize a certain system level metric. For example, in order to improve the energy efficiency, the system policy can be made to set the following preference order: Good WiFi $>$ Good LTE $>$ Weak WiFi $>$ Weak LTE. The rationale is that 1) a good-quality connection owns a higher energy efficiency than a weak one due to its high data rate, and 2) WiFi is preferred over LTE when they own a similar link quality due to its low power level. We adopted this policy in this paper. We further took -80 dBm and -90 dBm as the threshold for deciding a good or bad quality connection in WiFi and LTE networks, respectively. The two values were selected based on our measurement in Section III and the recommendation in the work of [37].

However, either user policy or system policy cannot guarantee that the selected interface can provide the needed bandwidth. Therefore, we further design a three-step multipath strategy to adaptively find the most energy efficient access manner while satisfying the bandwidth need. The details of the strategy are presented in Section IV-D.

C. Bandwidth Shortage Monitoring

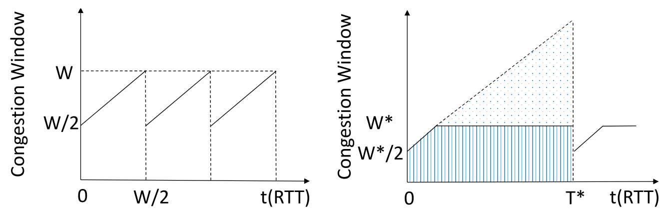
A key component in our approach is to detect whether the bandwidth need of the application has been satisfied by the current connection. Obviously, it is impractical to require the application to notify the MPTCP layer its bandwidth need. We solve this problem by novelly exploiting the Mathis Equation that models TCP throughput [39]. The equation is expressed by $BW = \frac{C*MSS}{\sqrt{p}*RTT}$, where *MSS* is the maximal segment size of a TCP packet, *p* is the loss rate of the path, *RTT* is the round trip time, and *C* is a constant value (i.e., 0.93 with delayed ACK). Specifically, we first define Gap Ratio as:

$$GapRatio(\%) = \frac{(PredictedTh - AchievedTh)}{AchievedTh} * 100 \qquad (3)$$

where *PredictedTh* and *AchievedTh* denote the throughput calculated from the Mathis Equation (i.e., with the measured loss rate and *RTT*) and that directly measured (i.e., based on the amount of packets sent in each measurement cycle), respectively. Then, the detection logic is that there is bandwidth shortage if the Gap Ratio is smaller than a threshold.

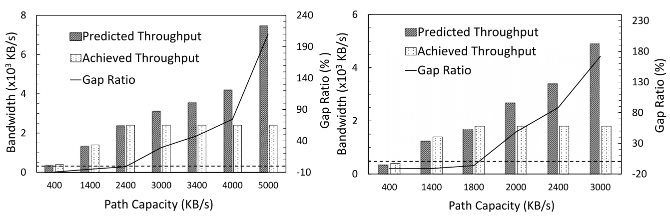
To prove this model, we first explain how the Mathis Equation is deduced. It estimates the throughput of a TCP flow under the assumption that the flow's throughput is throttled by the path's capacity. We assume that this indicates bandwidth shortage. Based on the design of TCP congestion control, the congestion window increases by 1 every RTT and halves when the sending rate surpasses the available bandwidth and causes a packet loss. We use *W* to denote the size of the congestion window that causes a packet loss. Thus, in case there is bandwidth shortage, the congestion window increases from *W*/2 to *W* in *RTT***W*/2 amount of time periodically, as shown in Figure 5(a). The amount of packets transmitted in each period is $\frac{W}{2} * \frac{W}{2} + \frac{1}{2} * \frac{W}{2} * \frac{W}{2} = \frac{3*W^2}{8}$. As a result, the loss rate p is $p = 1/\frac{3*W^2}{8}$. We then can get $W = \sqrt{\frac{8}{3*p}}$. Consequently, the flow's throughput $Th = \frac{MSS*3*W^2/8}{RTT*W/2} = \frac{MSS}{RTT} * \sqrt{\frac{8/3}{p}} = \frac{C^* * MSS}{\sqrt{p}*RTT}$, where $C^* = \sqrt{\frac{3}{2}}$.

However, on the other hand, when a TCP flow's bandwidth need can be satisfied by the bandwidth availability (i.e., there is no bandwidth shortage), its congestion window stops increasing and keeps stable after reaching the needed throughput, as shown in Figure 5(b). We assume that the window size corresponding to the bandwidth need is W^*, and it takes $T^* * RTT$ for a loss to happen on average. Then, the amount of packets transmitted in $T^* * RTT$, denoted N^*, is $N^* = T^* * W^* - \frac{W^{*2}}{8}$, i.e., the area of the shape marked with vertical bars in Figure 5(b). Thus, the loss rate can be denoted as $\frac{1}{T^* * W^* - \frac{W^{*2}}{8}}$. In this case, if we still apply the loss rate and RTT to the Mathis Equation, the resultant throughput (i.e., *PredictTh*) will be much larger than the actual throughput of the flow (i.e., *AchievedTh*). This is because the Mathis



(a) Bandwidth need is throttled by bandwidth availability. (b) Bandwidth need is satisfied by bandwidth availability.

Fig. 5. Congestion window size under different bandwidth availabilities of the path.



(a) 2400 KB/s demand. (b) 1800 KB/s demand.

Fig. 6. Effectiveness of the bandwidth shortage monitoring method (the dot line in the two figures denotes the zero line).

Equation assumes that the flow's congestion window continues increasing until the time of packet loss (i.e., $T^* * RTT$), as illustrated in Figure 5(b). In other words, the result from the equation assumes $N^* + \frac{(T^* - W^*/2)^2}{2}$ packets are transmitted in $T^* * RTT$, where $\frac{(T^* - W^*/2)^2}{2}$ is the area of dotted triangle in Figure 5(b). Consequently, the Gap Ratio will be quite large in this case. Besides, the looser the path is, the longer for a loss to happen (i.e., the larger T^* is), the larger the doted triangle in Figure 5(b) is, and the larger the Gap Ratio will be.

We have further conducted an experiment to verify the effectiveness of this idea. We set up a single WiFi AP, through which a client connects to a server on our campus network. We throttle the capacity of the WiFi AP to simulate different path capacities between the client and the server. We set the bandwidth demand to 2400 KB/s and 1800 KB/s, respectively, in two tests. The calculated Gap Ratios are plotted in Figure 6. We see that our method presents a very good accuracy in both experiments. The Gap Ratio is close to or smaller than 0 as long as the bandwidth need is larger than the path capacity, i.e., bandwidth shortage. When the path capacity increases above the bandwidth need, the Gap Ratio is considerably high, i.e., $\geq$ 10% even under a small amount of idled bandwidth. This demonstrates the effectiveness of our method.

We are aware that advanced MPTCP congestion control (CC) algorithms, such as LIA [12], OLIA [5], and BALIA [10], correlate the CC of parallel subflows and make them behave differently than a standard TCP flow. However, when there is only one subflow, these algorithms all fall back to standard TCP CC. Therefore, since the proposed bandwidth shortage monitoring method is used to check whether the current single-path access can satisfy the bandwidth need, it works when these advanced CC algorithms are adopted.

D. Energy- and Throughput-Efficient Multipath Strategy

We adopt three steps to ensure that turning to multipath access is energy efficient and adaptive.

1) When to Turn to Multipath Access: Our approach starts a subflow over an additional connection only when the current one selected following the policy in Section IV-B fails to satisfy the bandwidth need. The bandwidth shortage is determined when the Gap Ratio is larger than a threshold Th_g. We empirically set Th_g to 10% based on our previous discussion, which is found to be able to detect bandwidth shortage effectively in our experiments.

2) Connection Qualification Assessing: When an additional connection is needed to provide more bandwidth, our approach does not do this blindly. Ideally, we should evaluate the potential of the candidate connection in providing substantial bandwidth, which is the key to satisfy bandwidth need and guarantee energy efficiency. However, predicting the bandwidth availability of a wireless connection is hard to be accurate. This is because the available bandwidth is affected by not only the link quality but also the congestion status of the wireless AP.

As a result, we turn to finding wireless connections that most likely are unable to provide substantial bandwidth, denoted non-qualified connections. One good indicator that can be used for this purpose is the link quality. As shown in Figures 4(a) and 4(b), the bandwidth of a wireless connection is quite low and drops fast after the RSSI falls below a threshold (i.e., -80 dBm for WiFi and -90 dBm for LTE). This low bandwidth often is shared with other users on the AP, which further reduces the available bandwidth on the connection. Therefore, we can reasonably think that a connection with RSSI below the threshold is not qualified and should be excluded from consideration. It is true that a qualified connection may not be able to provide substantial bandwidth. However, it is hard to predict this at the moment. We thus just start using the qualified connection and leave it to further examination in the next step.

3) Active Connection Monitoring: After the second step, our approach turns to multipath access by starting a subflow over the best qualified connection. However, a qualified connection may not be able to substantially alleviate the bandwidth shortage due to congestion at the AP. Even when the connection can provide sufficient bandwidth initially, changes on the end device or the AP may make it unable to provide the needed bandwidth. For example, the connection quality can deteriorate suddenly due to device mobility, and the wireless AP may become congested later on. Moreover, the bandwidth need of the device can also decrease to the point that using a single path is enough. Those factors make multipath access unnecessary. Therefore, it is necessary to actively monitor engaged wireless connections under the multipath access.

The goal of the monitoring is to check whether the network access should turn back to using a single connection. The decision depends on the answers to two questions: 1) whether the current throughput is Th_b% higher than that before turning to multipath access and 2) whether multipath is the current most energy-efficient access manner. Both answers can be found by

TABLE II
SUMMARY OF THE PROCESSING LOGIC OF ACTIVE CONNECTION MONITORING

		Energy Efficiency Improved?	
		Yes	No
Throughput Improved?	Yes	Stay on multipath access	Make a tradeoff on throughput (i.e., use multipath) and energy efficiency (i.e., use single-path)
	No	Turn to single-path access if current loss rate is no larger than before on a single path and stay on multipath access otherwise	Turn to single-path access

monitoring the throughput of engaged wireless connections. The first question can be answered by comparing the throughput before and after the multipath access. The second question can be answered by applying the existing MPTCP energy model, e.g., Table I. The answer is positive if the model suggests to keep on multipath and negative otherwise.

The handling policy upon different combinations of the two answers includes:

- Positive + Positive: In this case, the device should keep on the multipath access as it gets the bandwidth need better served and the energy efficiency improved.
- Positive + Negative: In this case, the multipath access better serves the bandwidth need but sacrifices the energy efficiency. Thus, the choice is left to user preference. A model can be proposed to make an appropriate tradeoff. We leave this task to future work.
- Negative + Positive: In this case, the achieved throughput is reduced, which can be caused by two reasons. First, if it is caused by the lowering of bandwidth need, it is possible that only using a single path is enough. Second, if the throughput reduction is caused by the lowering of link capacity, turning back to a single path would further reduce the throughput and energy efficiency. Therefore, we rely on the loss rate over the path to differentiate the two cases. If the current loss rate is higher than that before turning to multipath access, it indicates the second case (i.e., the link capacity reduces). Then, the device should stay on multipath access. Otherwise, the device rolls back to single-path access.
- Negative + Negative: In this case, the device should turn back to single-path access as multipath access is not favorable even in energy efficiency, though the cause for the throughput reduction may vary (as explained in the previous case).

A summary of the above processing logic is plotted in Table II. Note that when the decision of turning back to a single path is made, the one that can cover the bandwidth need will be selected. This is because the energy efficiency of a wireless interface is proportional to the achieved throughput, as shown in the previous section.

4) Advantages: An important advantage of our approach is that the three steps effectively form a closed enhancement loop. It enables the mobile device to improve the energy efficiency continuously under the drive of bandwidth need. The network access starts from one connection and is kept in this state if the bandwidth need is satisfied (step 1). In case more bandwidth is needed, the additional connection is added with a caution (step 2). Then, active connections are monitored for the most energy-efficient access manner that can satisfy the bandwidth need (step 3). In case the third step suggests using a single connection, the loop repeats from the first step for continuous energy efficiency enhancement.

Such a loop makes our approach resilient to inaccuracies in the initial network access and adaptive to the changes of connection status and/or bandwidth need. For example, in case the device chooses a heavily loaded good connection in the initial stage, our approach would quickly start an additional connection (step 1) and suggest turning away from the initial connection (step 3). Similarly, when the throughput over a connection decreases, the three-step approach is able to find the access manner that can improve the energy efficiency as much as possible while satisfying the bandwidth need.

E. Implementation Details

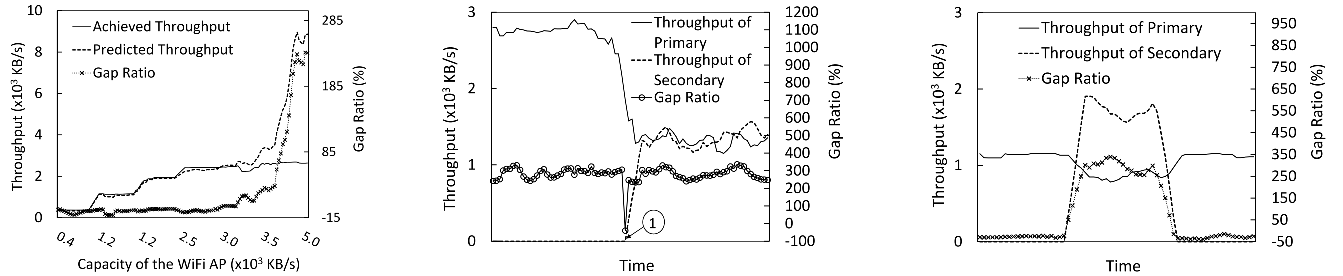
We have implemented our scheme along with Linux Kernel MPTCP v0.90 [35] for evaluation. The development includes around 500 lines of code written in C along with bash scripting. The policy-based network access initialization (Section IV-B) is implemented with efforts in both MPTCP and a bash script. The script stores the policy and calls the MPTCP configuration commands to set the preferred wireless interface as the default one for MPTCP. The code inside MPTCP limits the number of subflows to 1 initially.

The detection of bandwidth shortage (Section IV-C) is mainly implemented in tcp_input.c and tcp_output.c. Particularly, whenever there is a packet loss event, the loss rate is updated with a moving window. The loss rate is further used to update the predicted throughput of the subflow based on the Mathis Equation, i.e., $BW_p = \frac{C*MSS}{\sqrt{p*RTT}}$. Note that the RTT is already maintained in kernel TCP stack, and *C* is set to 0.93. On the other hand, the actually achieved throughput BW_a is calculated by the following formula:

$$BW_a = \sum_{i=1}^{n}(M_i)/T \tag{4}$$

where *n* and *T* are the number of packets sent and the amount of time since last packet loss, respectively, and M_i stands for the size of the *ith* packet. The values of BW_a and BW_p are then used to update the Gap Ratio following Equation (3). Additional variables are added to the "mptcp_tcp_sock" structure of each MPTCP subflow to record its status data such as RSSI, throughput, loss rate, and Gap Ratio.

The energy- and throughput-efficient multipath strategy (Section IV-D) is implemented in the MPTCP layer. A variable is added to the MPTCP control block structure (i.e.,



(a) Evolvement of the Gap Ratio under different path capacities.

(b) Efficiency of detecting bandwidth shortage for starting a new subflow. At point 1, the capacity of the WiFi AP is reduced, which makes the Gap Ratio drop and triggers a new subflow over LTE.

(c) Evolvement of the Gap Ratio with intermittent LTE connection. The connection to the LTE BS is turned on only in the middle segment, which makes the Gap Ratio become high.

Fig. 7. Performance of the bandwidth shortage detection method.

"mptcp_cb") to denote whether the current MPTCP flow is on single-path access or multipath access. The logic of switching between multipath access and single-path access is developed as a new path manager module following existing ones such as fullmesh and ndiffports [35]. Besides, the value of Th_b (defined in Section IV-D3) is set to 15 in our implementation.

V. Performance Evaluation

The experiment configuration (i.e., testing device, network setup, and energy measurement method) is the same as that in the measurement study in Section III (i.e., Figure 1) unless otherwise specifically described. We use **primary** connection/subflow to denote the one established in the network access initialization stage. It is selected according to the policy mentioned in Section IV-B. Additional ones are regarded as secondary. In the experiment, we mainly measured two metrics, i.e., throughput (i.e., data rate) and instant power level. We also calculated the overall energy efficiency (i.e., energy per MB of data transfer) after each test.

We first compare the bandwidth and energy efficiency of our scheme with those resulted from using MPTCP directly. We evaluated the effectiveness of the bandwidth shortage detection method in Section V-A. Then we did experiments to show the performance of our scheme under various scenarios (i.e., bulk file download, video streaming, and Web browsing) in Sections V-B–V-D, which cover both unlimited and limited bandwidth need. Further, in Section V-E, we compare our method with two recent approaches: eMPTCP [14] and ecMTCP [22]. eMPTCP follows the MPTCP energy efficiency model, while ecMTCP exploits the congestion control to improve energy efficiency of MPTCP.

A. Evaluating the Bandwidth Shortage Detection Method

In this experiment, we evaluate the effectiveness of the bandwidth shortage detection method (which is presented in Section IV-C) in a real scenario.

We first check the effectiveness in responding to the change of bandwidth availability. We let the testing device only connect to WiFi to download a file with a maximal rate of 2800 Kbps. During this process, we varied the available bandwidth of the WiFi AP. We measured the actual throughput of the device and plotted it along with the throughput predicted from the Mathis Equation and the Gap Ratio (i.e., Eq. (3)) in Figure 7(a). We see that when the WiFi AP could not provide enough bandwidth, the Gap Ratio remains close to 0 or negative. However, as long as the available bandwidth of the WiFi AP increases above the bandwidth need, the Gap Ratio responds to the change timely and jumps above 10% immediately. The Gap Ratio grows further when the amount of available bandwidth keeps increasing.

We further evaluate how the bandwidth shortage detection performs in a dynamic environment. In this test, the mobile device connects to both WiFi and LTE but only uses WiFi initially. It requires 2800 KB/s for a video streaming, while the WiFi AP has a capacity of 5000 KB/s in the beginning. The results are shown in Figure 7(b). We see that the Gap Ratio is very high initially. After a while, we manually limited the capacity of the WiFi AP to 1400 KB/s. As a result, the Gap Ratio falls sharply to -20%, and our algorithm starts an additional subflow on LTE to provide the needed bandwidth. This makes the Gap Ratio become high again.

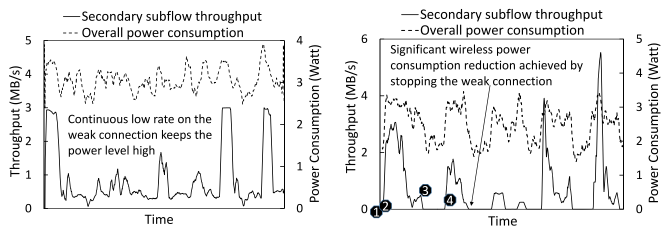
We also turned the LTE connection off and on when the WiFi AP alone cannot satisfy the bandwidth need. The results are shown in Figure 7(c). We see that our method can detect the bandwidth shortage dynamically. As long as the LTE connection is turned off, the Gap Ratio becomes quite low, which indicates a bandwidth shortage. When the LTE connection is turned on to resolve the bandwidth shortage, the Gap Ratio recovers to a high value.

The above results conclude that our method can detect bandwidth shortage effectively under dynamic bandwidth availability. This greatly supports the bandwidth-need driven energy efficiency improvement.

B. Unlimited Bandwidth Need: Bulk File Download

We then evaluate the performance of the proposed scheme under unlimited bandwidth need. In the experiment, the testing device downloaded a large file without a rate limit. The device moved in the experiment to vary the quality of the connection to the secondary wireless AP. The quality of the connection to the first (primary) wireless AP is always good. We tested with both WiFi-WiFi and WiFi-LTE networks.

The results of the tests in the WiFi-WiFi network are shown in Figure 8(a) and Figure 8(b). We see from Figure 8(a) that



(a) MPTCP: 3369 MB data downloaded in 888 seconds with an energy consumption of 2777.1 Joules. (b) Our scheme: 3308 MB data downloaded in 888 seconds with an energy consumption of 2195.4 Joules.

Fig. 8. Experiment with bulk file downloading (i.e., unlimited bandwidth need). The figures show the rate of the secondary subflow and the overall wireless power consumption (the throughput of the primary subflow is not plotted for a better visibility).

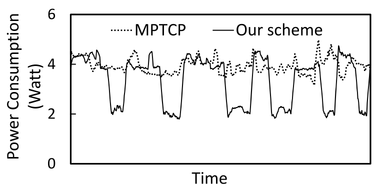
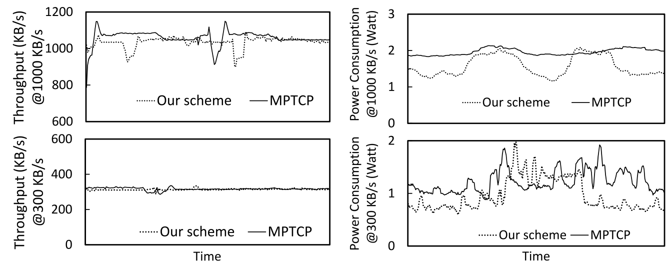


Fig. 9. Energy consumption in the test in WiFi-LTE network.

the power consumption is constantly high when MPTCP is adopted. This is because it always keeps the secondary WiFi connection active regardless of its link quality. The results in Figure 8(b) show that our scheme can effectively prevent such an energy waste. The novel multipath access strategy (Section IV-D) turns the secondary WiFi connection to backup when it fails to bring a substantial amount of bandwidth and brings it back when the link quality improves. Therefore, our scheme saves the energy with a marginal loss on the overall throughput. At the end of the test (i.e., after 888 seconds), our scheme downloaded 3308 MB data while MPTCP completed 3369 MB data. This means that the average throughput reduces by only 1.81% with our scheme. However, our scheme consumed total 2195.4 Joules of energy, while MPTCP consumed 2777.1 Joules. This reflects a significant improvement on the energy efficiency, i.e., 0.66 J/MB in our method vs. 0.82 J/MB in MPTCP.

Figure 8(b) also shows that our approach is adaptive. Our scheme starts with the primary subflow (point 1). When the bandwidth shortage is detected shortly, the secondary subflow is employed (point 2). At point 3, the device turns to using the primary connection only. This is because the change of the link quality of the secondary WiFi connection makes both checks in the active connection monitoring stage (i.e., step 3 in Section IV-D) return negative. After this, the secondary connection is not employed even under continuous bandwidth shortage. This is because the connection is regarded as a non-qualified one due to the low link quality. At point 4, the quality of the secondary connection recovers, which turns the secondary subflow back. This process repeats along with the movement of the device in the experiment.

We have performed the same test in the WiFi-LTE network. The results are consistent with those in the WiFi-WiFi network. We thus only plot the instantaneous power consumption in MPTCP and our scheme in Figure 9. We notice



(a) Overall throughput. (b) Overall power consumption.

Fig. 10. Experiments with video streaming in the WiFi-WiFi network (1000 KB/s and 300 KB/s bandwidth need).

from the figure that our scheme periodically turns the subflow over LTE to backup when the LTE connection presents a low RSSI, the energy consumption is obviously reduced. In the test (which lasts 741 seconds), our scheme reduces the energy consumption by 15.28% (2528 Joules vs. 2994 Joules) but only suffers less than 1% throughput loss (2885 MB data downloaded data in our scheme vs. 2907 MB in MPTCP).

C. Limited Bandwidth Need: Video Streaming

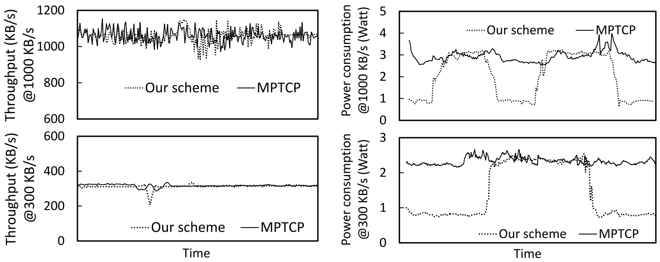
We further evaluate the performance of our scheme under limited bandwidth need. In this test, we also adopted both WiFi-WiFi and WiFi-LTE networks. We adopted video streaming that requires a data rate of 1000 KB/s and 300 KB/s as the showcase application. In the experiment, we varied the bandwidth availability by making the AP congested. Specifically, the device connects to a good WiFi AP that can offer enough bandwidth initially. We denote this connection as the primary one. After a while, the capacity of the primary connection reduces to half of the bandwidth need due to the join in of other clients accessing the WiFi AP.

The test results in the WiFi-WiFi network are shown in Figure 10. We see that the testing device receives the needed bandwidth with both MPTCP and our scheme. However, the power level is lower under our scheme for most of the time and stays the same with that under MPTCP only for a few periods of time. We found that the first AP's capacity is reduced to half of the bandwidth need during these time periods. This shows that our scheme uses the primary connection alone if it can satisfy the bandwidth need. However, when the primary connection's capacity reduces, our scheme can quickly detect the bandwidth shortage and start the second subflow over an additional connection. As a result, our scheme reduces the energy consumption (383.7 Joules vs. 481 Joules in the 1000 KB/s case and 340.57 Joules vs. 434.21 Joules in the 300 KB/s case) while keeping the bandwidth need satisfied.

We have also conducted the same experiments in the WiFi-LTE network. The results are shown in Figure 11. We see that the results are consistent with those in the WiFi-WiFi network. In a summary, our scheme saves around 20% energy than MPTCP while keeping the bandwidth need satisfied under both unlimited and limited bandwidth needs.

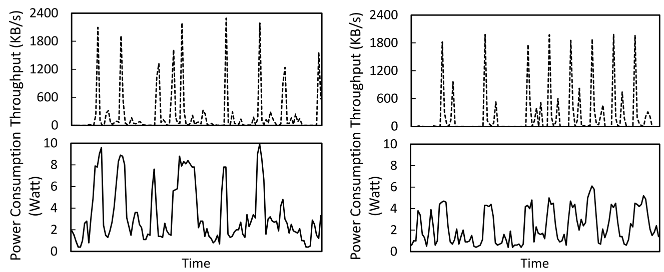
D. Limited Bandwidth Need: Web Browsing

We have also evaluated the performance of our scheme under Web browsing. In this test, we used the test device to browse a webpage of the Wikipedia USA site with a size



(a) Overall throughput. (b) Overall power consumption.

Fig. 11. Experiments with video streaming in the WiFi-LTE network (1000 KB/s and 300 KB/s bandwidth need).



(a) MPTCP (transmitted 26 MB web traffic with 415 Joules energy consumption). (b) Our scheme (transmitted 24 MB of web traffic with 273 Joules energy consumption).

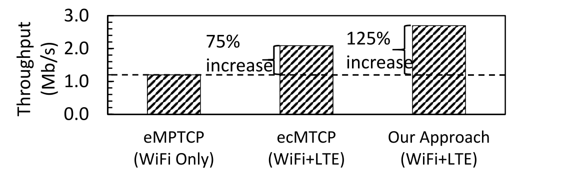
Fig. 12. Experiments with Web browsing in the WiFi-WiFi network.

of 1647 KB. We refreshed the webpage every 30-40 seconds for a period of 4 minutes. We measured the power consumption and throughput of the testing device and plotted the results Figures 12(a) and 12(b). We see that both our scheme and MPTCP can satisfy the bandwidth need when refreshing the webpage, i.e., periodic spikes in the throughput. However, our scheme leads to better energy efficiency. This is because our scheme starts with a single subflow and adds secondary subflow only when necessary. The short-lived webpage traffic in this experiment can be satisfied by the first connection. Therefore, our scheme always only uses the first connection in the test. But MPTCP uses the two connections blindly and thus suffers a significant energy efficiency degrading. Finally, our scheme transmitted 24 MB of Web traffic while MPTCP transmitted 26 MB. However, our scheme consumes 52% less energy than MPTCP (i.e., 273 J vs. 415 J). Such a result further shows the drawback of blind multipath access.

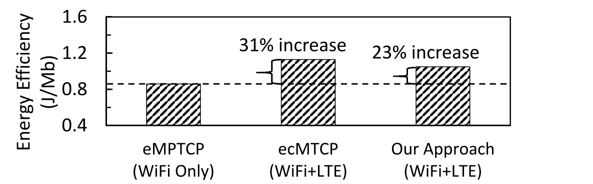
E. Comparing With eMPTCP and ecMTCP

The above experiments show that our approach improves the energy efficiency while attaining a similar throughput as MPTCP. We thus further compare our approach with eMPTCP [14] and ecMTCP [22]. eMPTCP primarily follows the energy efficiency model for network access, while ecMTCP steers traffic to the path that is more energy-efficient through congestion control. The testing setup is the same as in Figure 1 with both WiFi and LTE.

1) Performance Under Static Configuration: We first conduct a test in a static configuration to illustrate the differences of these methods. In the test, both WiFi and LTE connections



(a) Throughput.



(b) Energy Efficiency.

Fig. 13. Comparison of eMPTCP, ecMTCP, and our approach in a static scenario.

own good signal strength. Besides, the client presents a bandwidth need of 2.7 Mb/s, while the WiFi connection and LTE connection can provide 1.2 Mb/s and 1.5 Mb/s, respectively.

eMPTCP starts on WiFi alone for a fixed amount of time (i.e., delayed multipath access). Then, it applies the throughput on WiFi and a default high throughput on LTE to the energy efficiency model, which recommends keep using both connections. After obtaining the actual throughput on both connections, the model is applied again. Since the two connections present a rate of 1.5 Mb/s and 1.2 Mb/s, respectively, the model recommends to use WiFi only. As a result, the client would only use WiFi under eMPTCP.

In the test with ecMTCP, we set the RTT over LTE and WiFi the same and make them present different capacities through loss rates. Then, the congestion windows of the two subflows at the equilibrium point follow $\frac{w_t}{w_f} = \frac{p_f * e_f}{p_t * e_t}$, where w_t, p_t, and e_t represent the window size, loss rate, and energy level of the LTE path, respectively, and w_f, p_f, and e_f denote those on the WiFi path, respectively. In our configuration, $\frac{w_t}{w_f} \approx 0.75$. Thus, the LTE interface and WiFi interface attain a throughput of 0.9 Mb/s and 1.2 Mb/s, respectively.

Our approach also starts on WiFi first. It soon detects the bandwidth shortage and starts using LTE to gain more bandwidth. This alleviates the hassle of blindly delaying the addition of an additional subflow. After this, though the energy efficiency model recommends using WiFi alone (i.e., same as in eMPTCP), our approach detects that the bandwidth need is better served after turning to multipath access. Thus, our approach keeps using both LTE and WiFi.

The throughput and energy efficiency under the three methods are plotted in Figure 13(a) and Figure 13(b), respectively. We see that when compared with eMPTCP, both our approach and ecMTCP better serve the bandwidth need but have lower energy efficiency. This is because eMPTCP only uses WiFi, while the other two use both LTE and WiFi. Our approach performs better than ecMTCP on both throughput and energy efficiency. This is because ecMTCP limits the throughput on LTE. Most importantly, our approach fully satisfies the bandwidth need but only increases energy consumption per Mb data transfer by 23%.

2) Performance Under Dynamic Bandwidth Need: We further compare the three methods when the bandwidth need varies. Specifically, in the test, the bandwidth need of the MPTCP device is initialized as 2.7 Mbps and is lowered to 0.7 Mbps after 120 seconds. The bandwidth need restores back to 2.7 Mbps at 240s. The bandwidth of the WiFi and LTE connection is fixed at 1 Mbps and 2.5 Mbps, respectively. We recorded the throughput and energy consumption of the client in this test. The results are plotted in Figure 14(a).

From 0s to 120s (point 1), the device has a bandwidth need of 2.7 Mbps and thus uses both LTE and WiFi in all the three methods. When eMPTCP and our approach are applied, the throughput on LTE and WiFi is 1.9 Mbps and 0.8 Mbps, respectively. Thus, the two methods present identical throughput and energy consumption during this period of time. ecMTCP, on the other hand, limits the ratio of the rates over LTE and WiFi to around 2.98:1. Thus, the throughput on LTE and WiFi is 2.1 Mbps and 0.7 Mbps, respectively. As a result, ecMTCP presents slightly lower energy efficiency than eMPTCP and our approach.

At 120s, the bandwidth need is reduced to 0.7 Mbps. Thus, the client presents 0.52 Mbps and 0.18 Mbps throughput on LTE and WiFi, respectively, in the test with ecMTCP. In the tests with eMPTCP and our approach, the client's throughput over LTE and WiFi reduces to around 0.5 Mbps and 0.2 Mbps, respectively, at 120s. eMPTCP then keeps on multipath access based on the energy efficiency model. Our approach turns back to single-path access via WiFi, as the current loss rate is not obviously higher than that over WiFi before turning to multipath access. Therefore, all methods satisfy the bandwidth need between 120s and 240s. However, our approach owns the best energy efficiency since it only uses WiFi.

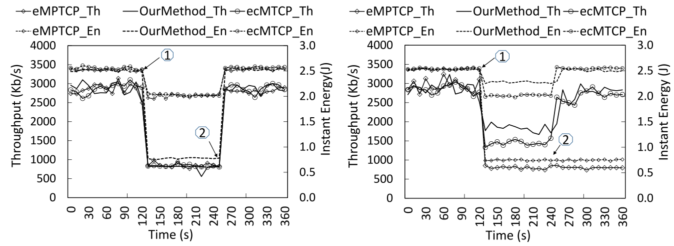
At 240s (point 2), the bandwidth need is restored to 2.7 Mbps. The throughput and energy efficiency of the three methods all restore to those between 0s and 120s. Note that our approach can quickly detect the bandwidth shortage and start a subflow over LTE accordingly.

The above results show that our approach can dynamically improve the energy efficiency while keeping the bandwidth need satisfied. It is worthwhile to note that the overall energy efficiency of the client is 1.13 J/Mb, 1.09 J/Mb, and 0.89 J/Mb in ecMTCP, eMPTCP, and our approach, respectively. This is because our approach can identify the scenario in which turning back to single-path access can improve energy efficiency without sacrificing the bandwidth need (i.e., the period of time between 120s to 240s in the test).

3) Performance With Dynamic Path Capacity: In this experiment, instead of changing bandwidth need, the capacity of the LTE connection is changed at 120s. The test results under the three methods are shown in Figure 14(b).

From 0s to 120s, the bandwidth need is 2.7 Mbps, and the WiFi and LTE connection provide 1 Mbps and 2.5 Mbps, respectively. Thus, the measurement results are the same as those in the previous test under dynamic bandwidth need.

At 120s (point 1), we reduce the capacity of the LTE connection to 1 Mbps. eMPTCP then suggests switching to using WiFi only as both WiFi and LTE connections present a throughput of 1 Mbps. ecMTCP changes the ratio of rates over LTE and WiFi to 0.49:1. Thus, the client presents 0.49 Mbps and 1 Mbps throughput over LTE and WiFi, respectively. Our approach keeps using both connections (i.e., we suppose the tradeoff in the active connection monitoring prefers bandwidth need over energy efficiency). As a result, the client presents roughly 1 Mbps, 1.5 Mbps, and 2 Mbps in eMPTCP, ecMTCP, and our approach, respectively.



(a) Dynamic bandwidth need. (b) Dynamic path capacity.

Fig. 14. Comparison of eMPTCP, ecMTCP, and our approach in dynamic scenarios.

At 240s (point 2), the capacity of the LTE connection is restored to 2.5 Mbps. However, eMPTCP is currently using WiFi only and is unaware of this change. It can only apply the last recorded throughput on LTE, i.e., 1 Mbps, to the energy efficiency model, which still recommends using WiFi only. Therefore, the client stays on WiFi even after the capacity of LTE has restored. On the other hand, our approach and ecMTCP can take advantage of the increased capacity on LTE and restore to the status between 0s and 120s.

In a summary, the above test shows that our approach can more efficiently respond to the change of path capacity than eMPTCP and ecMTCP. eMPTCP either assumes a static capacity for a never-accessed connection or relies on past recorded throughput that may be outdated. The capability of ecMTCP is throttled by the ratio of rates over engaged interfaces. Our approach, on the other hand, has a closed loop to adapt to the change of path capacity.

VI. Conclusion and Future Work

In this paper, we propose a bandwidth-need driven energy efficiency improvement scheme for MPTCP devices in wireless networks. Our study takes advantage of two key observations: 1) network access is driven by bandwidth need and 2) the energy efficiency of an interface is reversely proportional to the throughput. Both theoretical modeling and field measurement have been adopted to verify the second observation. With those observations, we systematically embed energy efficiency improvement into the process of network access. Specifically, we propose to let an MPTCP device stay on a single connection as long as the bandwidth need is satisfied and carefully choose additional connections when more bandwidth is needed. A strategy that allows the network access to turn back to single-path access is also developed. Consequently, a continuous energy efficiency enhancement loop is formed while satisfying the device's bandwidth need. Real implementation based experiments demonstrate the effectiveness of the proposed scheme. In the future, we plan to exploit more side information, e.g., network usage pattern and device mobility data, to better predict bandwidth need and use such information to further improve the multipath based wireless network access.

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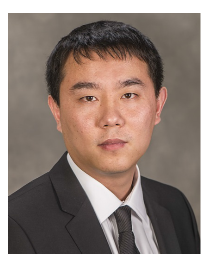

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