Multipath TCP for User Cooperation in LTE Networks

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Abstract

User cooperation exploits nearby mobile devices as relays and offers an opportunity to enable multipath transmission for multi-homed mobile devices, even when there is no multiple access coverage. Multipath transport control protocol (MPTCP) by Internet Engineering Task Force (IETF) is a promising solution to support simultaneous delivery of transport control protocol (TCP) packets over multiple paths. One key component of MPTCP is the coupled congestion control algorithm, which aims to aggregate available bandwidths of multiple paths while avoiding aggressive behavior to regular single-path TCP traffic sharing the paths. However, we find out that, in a user cooperation scenario, the throughput of local single-path traffic of relays can be severely degraded by forwarding subflows of MPTCP, which can jeopardize the motivation for user cooperation. In this paper, we propose extensions to the congestion control of MPTCP for a user cooperation scenario in the Long Term Evolution (LTE) network. The local traffic at relays can be controlled by regular TCP and more generic additive-increase and multiplicative-decrease (AIMD) protocols. Simulation results demonstrate that our extensions do not degrade performance for adding MPTCP subflows to local traffic, and thus better promote user cooperation.

Index Terms

User cooperation, multipath transmission, multipath TCP, congestion control, AIMD, LTE.

I. INTRODUCTION

In recent years, user cooperation has become an important research topic in both academia and industry as it can effectively address various performance limitations of highly dynamic wireless networks [1]. Fig. 1 shows a user cooperation model in the Long Term Evolution (LTE) network, which takes advantage of the multi-radio capability of user equipment (UE). In this case, a number of nearby UEs associated with an Evolved Node B (eNB) can form a cooperative community [2]. The *relay UEs* can receive packets on behalf of the *root UE* via the LTE interfaces and then forward the packets to the root UE via the Wi-Fi interfaces. Such user cooperation offers a good solution to fully exploit multiple radio interfaces even when there is not simultaneous multi-access coverage. As a result, multiple transmission paths in the wireless access domain can be engaged so as to aggregate the scarce bandwidths of cooperative users.

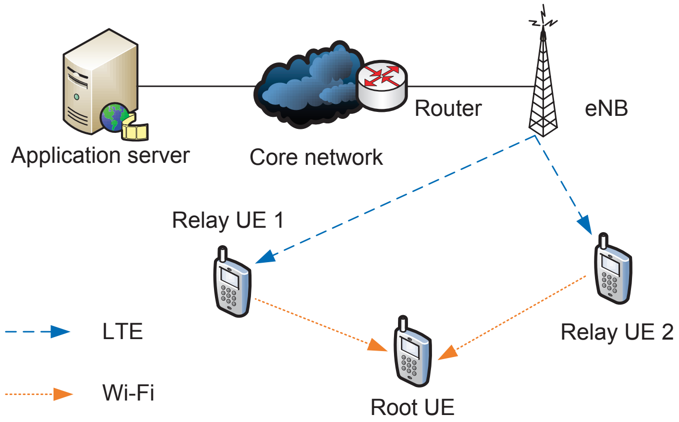


Fig. 1. User cooperation in the LTE network.

To enable multipath transmission at the transport layer, the dominant transport control protocol (TCP) needs to be extended to accommodate multiple simultaneous subflows. Many TCP-based multipath transmission protocols have been proposed. In particular, the multipath transport control protocol (MPTCP) specified in RFC6182 [3] by Internet Engineering Task Force (IETF) became an Internet draft in 2011. MPTCP can run at multi-homed devices to simultaneously deliver TCP packets over multiple interfaces. One subflow TCP connection is maintained for each path. For the user cooperation scenario in Fig. 1, MPTCP can run between the application server (source) and the root UE (sink) through multiple relay UEs. However, since only one IP address is usually allocated to one network interface card (NIC), there is a potential problem when the root is required to have multiple IP addresses for its Wi-Fi interface to establish multiple TCP subflows. Fortunately, this can be solved by the virtual interface technique to configure multiple IP addresses to one NIC [4].

To support multipath transmission in the user cooperation scenario, MPTCP needs to address another critical challenge, which is to ensure that the MPTCP flow does not harm the local traffic of relay UEs. In other words, even when MPTCP engages the relay UEs for forwarding packets to the root UE, the relay UEs should be guaranteed the same throughput for the local traffic as that when they do not help forward traffic. Otherwise, the relay UEs would not be motivated to provide any relay service. Unfortunately, we find out in this study that MPTCP may not meet this requirement when the sending rates of some local flows at the relay UEs are greater than an expected even share. This is mainly because the design objectives of MPTCP for congestion control do not consider the special scenario of user cooperation. As a result, the MPTCP subflows for the root UE can be too aggressive, taking more than the remaining bandwidths unused by the local flows of relay UEs.

In this paper, we aim to extend MPTCP for the user cooperation scenario in the LTE network. Specifically, we extend the coupled congestion control algorithm of MPTCP so as to avoid throughput degradation to the local traffic of relay UEs. The local traffic can be controlled by TCP or more generic additive-increase and multiplicative-decrease (AIMD) protocols. The general AIMD-based congestion control is more flexible to accommodate diverse quality-of-service (QoS) requirements of multimedia traffic [5]. Our proposed MPTCP extensions protect the throughput of relay UEs no matter the local traffic control is TCP-based or more generic AIMD-based.

The remainder of this paper is organized as follows. In Section II, we review MPTCP and related work. Our extended congestion control algorithms for MPTCP are presented in Section III. Simulation results are given in Section IV. Section V summarizes this research and identifies open issues.

II. BACKGROUND AND RELATED WORK

As a dominant transport protocol, TCP is widely deployed in wired and wireless networks. TCP adjusts a congestion window using an *increase-by-one* and *decrease-by-half* strategy to fairly and efficiently utilize the available bandwidth of an end-to-end path. The AIMD-based congestion control is a general extension to TCP. In AIMD, the source additively increases the congestion window by α units for each round trip time (RTT) and multiplicatively decreases the window size to a fraction β of its previous value

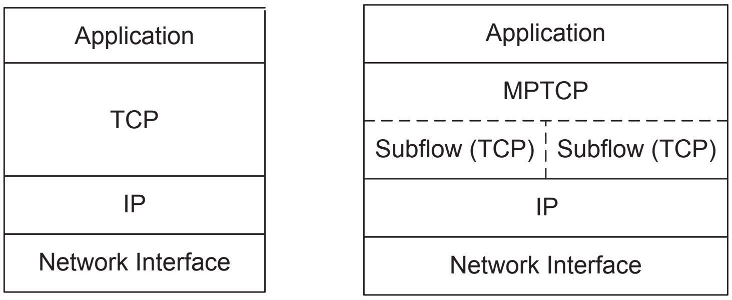


Fig. 2. Regular TCP and MPTCP protocol stacks.

whenever there is a congestion indication (e.g., triple duplicate acknowledgements). TCP is actually a special case of AIMD with $\alpha = 1$ and $\beta = 0.5$. On one hand, AIMD protocols are flexible to offer service differentiation by adapting the (α, β) pair. On the other hand, an AIMD flow can be ensured to be TCP-friendly if it satisfies $\alpha = \frac{3(1-\beta)}{1+\beta}$, where $0 < \alpha < 3$ and $0 < \beta < 1$ [5]. However, the single-path transport protocols such as TCP and AIMD may not be able to provide sufficient throughput to support bandwidth-intensive services, e.g., high-definition (HD) video streaming. In recent years, multipath transmission attracts substantial research attention given the benefits of bandwidth aggregation and fault tolerance.

A. Overview of MPTCP

As an IETF multipath solution, MPTCP [3] extends the regular TCP protocol to add the capability of using multiple paths simultaneously for an end-to-end connection. As shown in Fig. 2, MPTCP follows a layered structure similar to the standard TCP/IP protocol stack. The transport layer is loosely split into two sublayers, namely, MPTCP and subflow (TCP). As subflow (TCP) runs on each path independently and reuses most functions of TCP, MPTCP can be easily deployed within the existing network architecture.

A main difference between subflow (TCP) and regular TCP lies in that congestion control on each path is delegated to the MPTCP sublayer. Although each subflow maintains a congestion window at the source (sender), the coupled congestion control algorithm of MPTCP in [6] aims to ensure that a multipath flow should i) perform at least as well as a single-path flow on the best path available to it, and ii) take no more capacity than a single-path flow would obtain at maximum when experiencing the same loss rate. Basically, the objective i) motivates users to run MPTCP, while the objective ii) guarantees that an MPTCP flow gracefully shares the path bandwidth with regular single-path TCP flows. Specifically, the MPTCP congestion control algorithm works as follows:

- Once the source receives an acknowledgement (ACK) from path i, it increases the congestion window of path i by $\min(a/w_{total}, 1/w_i)$; and
- Once the source receives a congestion signal from path i, it decreases the congestion window w_i of path i to $w_i/2$.

Here, w_i is the current congestion window size of subflow on path i, w_{total} is the total congestion window size of all subflows, and a is an *aggressiveness* factor defined by

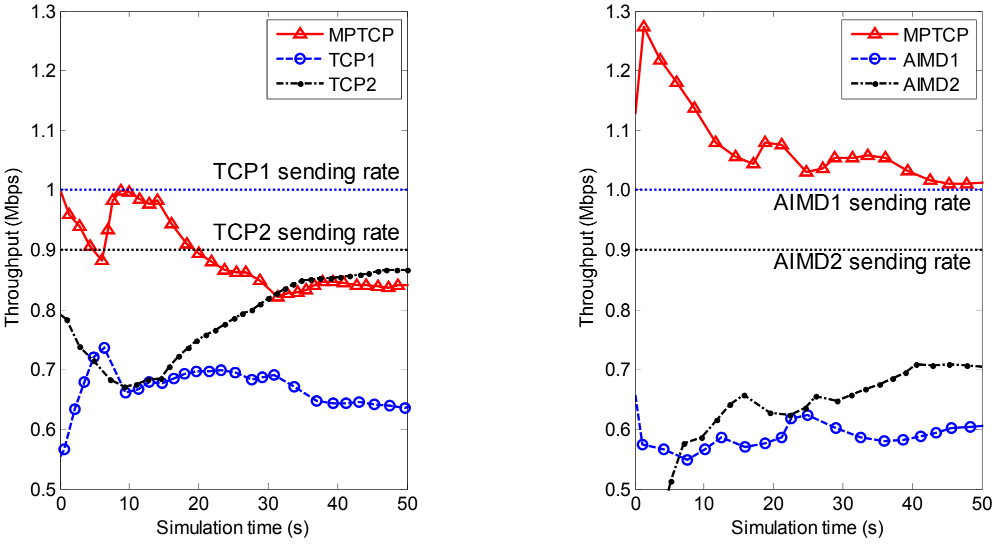
$$a = w_{total} \frac{\max_i w_i/RTT_i^2}{(\sum_i w_i/RTT_i)^2}. \tag{1}$$

In (1), RTT_i is the RTT of path i. The increment scale $\min(a/w_{total}, 1/w_i)$ for congestion window aims to ensure that each MPTCP subflow does not increase its congestion window faster than a single-path TCP flow with the same window size.

B. Limitations of MPTCP for User Cooperation

As seen in the congestion control algorithm of MPTCP, the objective ii) addresses bandwidth sharing between multipath and single-path TCP flows. There are more related studies in the literature. In [7], the authors extend the definition of fairness from single-path transport to multipath transport. They examine four congestion control approaches (including MPTCP) with respect to fairness. A multipath congestion control mechanism, dynamic window coupling (DWC), is proposed in [8], which aims to achieve both fair sharing and throughput maximization. In this paper, we consider a user cooperation scenario in the LTE network, which is different from the preceding works focusing on general wired networks with selected bottleneck. To demonstrate the effect of user cooperation on MPTCP performance, we test the example scenario in Fig. 1. An MPTCP source sends packets to the sink (receiver) at the root UE via two relay UEs. Each relay UE runs a local single-path TCP or AIMD ($\alpha = 0.7$, $\beta = 0.625$) flow, while acting as a relay for an MPTCP subflow to the root UE.

Fig. 3 shows the throughput of all single-path TCP or AIMD flows and MPTCP flows. The dotted lines represent the sending rates of single-path flows, which are greater than half of the capacity of the LTE link between eNB and each relay UE. As seen in Fig. 3(a), the aggregate throughput of MPTCP converges to the larger throughput of the two single-path TCP flows, which satisfies both objectives that



(a) With TCP local single-path flows.

(b) With AIMD local single-path flows.

Fig. 3. Throughput of MPTCP flows and local single-path flows.

the MPTCP congestion control algorithm claims [6]. Meanwhile, the throughput of single-path TCP flows becomes less than their corresponding sending rates, due to the bandwidth competition and sharing with the MPTCP subflows. Similar observations can be made from Fig. 3(b), where the relay UEs run single-path AIMD traffic flows locally. Moreover, the MPTCP aggregate throughput eventually converges to a level that significantly overwhelms the larger throughput of the two single-path AIMD flows, which violates the second objective of MPTCP. This is because the aggressiveness factor a in (1) for MPTCP cannot guarantee no throughput degradation for single-path AIMD flows.

In the user cooperation scenario, the performance objective of fair bandwidth sharing becomes more complex due to the mix of multipath and single-path flows, as well as the competition between local traffic and forwarding traffic. In a general case, it can be considered as best fairness when all connections sharing a path experience the same throughput, according to Jain's fairness index. However, it may not be reasonable in the user cooperation scenario, if the multipath subflow for the root UE achieves the same throughput as the local flows of the relay UE, which can be lower than the expected throughput when the relay UE does not help with the root UE. Ideally, even when a relay UE is forwarding packets to the root UE, the same throughput should be achieved for its local single-path flow as that when there were no MPTCP subflow sharing the relay path. Any possible performance degradation can jeopardize the motivation for user cooperation. As seen in Fig. 3, the MPTCP congestion control algorithm cannot accommodate this special requirement. In this work, we develop effective extensions to MPTCP so that the throughput of local TCP or AIMD traffic of relay UEs is not degraded while forwarding MPTCP subflows to the root UE.

III. MPTCP EXTENSIONS FOR USER COOPERATION

To address the problems observed from Fig. 3, we extend the MPTCP congestion control (MCC) algorithm discussed in Section II for the user cooperation scenario of Fig. 1. The first extension, referred to as *MCC-Coop*, aims to ensure that the MPTCP flow of the root UE runs gracefully with the local single-path TCP flows of relay UEs. To further protect local AIMD flows, another more generic extension, referred to as *GMCC-Coop* is developed.

A. MCC-Coop for MPTCP and Local TCP Flows

As illustrated in Fig. 1, there can be multiple transmission paths from the application server to the root UE through different relay UEs. The relay UEs forward packets to the root UE via Wi-Fi links, which have a higher transmission rate than the LTE links between eNB and the relay UEs. Hence, we assume that the LTE links are the bottleneck links of the paths. The *total bandwidth*, B_r, of an end-to-end path r via a relay UE U_r is then limited by the capacity of the bottleneck link between eNB and U_r. The *available bandwidth* of path r is defined as the unused bandwidth $B_r - C_r$, where C_r is the total traffic rate of flows over the bottleneck link [9]. Since the relay UE U_r knows the bandwidth allocated by eNB, it can thus estimate the total bandwidth of path r accordingly. Meanwhile, each relay UE periodically monitors its local traffic throughput and sends its available bandwidth to the root UE upon request. Given such knowledge, a key issue for congestion control is to ensure that an MPTCP subflow takes no more than the available bandwidth of a relay path.

Let N_r denote the number of local single-path TCP flows over path r, and $\lambda_{r,i}$ denote the sending rate of a single-path TCP flow i. Assume $\lambda_{r,i} \leq \lambda_{r,j}$ if $i < j$ and $1 \leq i, j \leq N_r$. Suppose that the sending rates of M_r ($M_r \leq N_r$) local flows are each less than $\gamma_r = \frac{B_r}{N_r+1}$, which is the even share of the total bandwidth of path r when the local TCP flows further share the path with an additional MPTCP subflow. Hence, if the standard TCP and MPTCP congestion control were followed, the expected throughput of the MPTCP subflow would be $(B_r - \sum_{i=1}^{M_r} \lambda_{r,i})/(N_r - M_r + 1)$, which is the same as the throughput of the $N_r - M_r$ TCP flows each having a sending rate greater than γ_r. As a result, these $N_r - M_r$ TCP flows cannot approach their sending rates for the throughput due to the competition of the MPTCP subflow. This is generally acceptable for applications where the MPTCP subflow and the TCP flows can be treated equally and do not need to be differentiated. However, in the user cooperation scenario, an essential motivation for cooperation is that the local flows of relay UEs are not affected adversely and the bandwidth demands of local traffic should be guaranteed first. In other words, the throughput that an additional MPTCP subflow can achieve over path r cannot exceed the available bandwidth unused by the local traffic, given by $B_r - \sum_{i=1}^{N_r} \lambda_{r,i}$. Hence, we define the ratio of the expected throughput of the MPTCP subflow based on the standard control to the maximum throughput without degrading local flows as

$$\rho_r = \frac{\Big(B_r - \sum_{i=1}^{M_r} \lambda_{r,i}\Big)\Big/\Big(N_r - M_r + 1\Big)}{B_r - \sum_{i=1}^{N_r} \lambda_{r,i}}. \tag{2}$$

For example, suppose that two local single-path TCP flows (A and B) run over a path r of a total bandwidth of 3 Mbps. The sending rates of A and B are 0.5 Mbps and 1.5 Mbps, respectively. If an MPTCP subflow of bulk data transfer further shares the path evenly with A and B, there should be a throughput of 1 Mbps each. Since the sending rate of B (1.5 Mbps) is greater than the even share (1 Mbps), the achieved throughput of B will be affected due to the bandwidth competition of the MPTCP subflow. The expected throughput of the TCP flow B and MPTCP subflow will be $\frac{3-0.5}{2-1+1}$ = 1.25 Mbps, while the maximum throughput that the MPTCP subflow can achieve without degrading the throughput of A and B is $3 - 0.5 - 1.5$ = 1 Mbps. Hence, $\rho_r = 1.25$. Here, $\rho_r > 1$ implies that the MPTCP subflow will take more than the unused bandwidth under the standard control and exceed the maximum throughput without degrading local traffic. Therefore, the increasing scale of the congestion window for the MPTCP subflow should be further constrained.

Thus, we have the following extension *MCC-Coop* for MPTCP in a user cooperation scenario:

- Once the source receives an ACK from path r, it increases the congestion window of path r by $\min(a/w_{total}, 1/w_r)$ if $\rho_r \leq 1$ or by $\min(1/w_r, 1/(\rho_r w_r))$ if $\rho_r > 1$; and
- Once the source receives a congestion signal from path r, it decreases the congestion window w_r of path r to $w_r/2$.

As seen, MCC-Coop differs from the original algorithm of MPTCP with respect to the increasing scale of congestion window when $\rho_r > 1$. The rationale behind this extension is based on our analysis in [10], which proves that the MPTCP subflow should satisfy the following condition to meet the ratio ρ_r:

$$\alpha_r = \frac{1}{\rho_r} \cdot \frac{3(1-\beta_r)}{1+\beta_r} \tag{3}$$

where (α_r, β_r) denote the general increasing and decreasing parameters of the MPTCP subflow on path r. In the MPTCP case, since $\beta_r = 0.5$, we have $\alpha_r = 1/\rho_r$. Hence, when $\rho_r > 1$, MCC-Coop further limits the increasing scale of the congestion window by the factor $1/\rho_r$, in the second parameter of $\min(1/w_r, 1/(\rho_r w_r))$. Without this constraint in the original MPTCP algorithm, the MPTCP subflow will have a larger congestion window and take more bandwidth from the path, which degrades the throughput of local flows at the relay UE and harms the motivation for cooperation.

B. GMCC-Coop for MPTCP and Local AIMD Flows

Let (α'_r, β'_r) denote the pair of increasing and decreasing parameters of the single-path AIMD flows sharing path r. As observed in Fig. 3(b), MPTCP cannot work well with local single-path AIMD flows because the MPTCP subflow is too aggressive and taking too much bandwidth of the LTE relay link. As a result, the throughput of local AIMD flows is significantly decreased. To address this problem, we consider a new aggressiveness factor derived in [10], given by

$$a_r = \alpha'_r w_{total} \frac{\max_i w_i/RTT_i^2}{(\sum_i w_i/RTT_i)^2}. \tag{4}$$

As such, it is guaranteed that the MPTCP subflow does not take more bandwidth than a single-path flow when experiencing the same loss rate. Accordingly, we develop the following generic extension *GMCC-Coop* for MPTCP congestion control with local single-path AIMD flows:

- Once the source receives an ACK message from path r, it increases its congestion window w_r for path r by $\min(a_r/w_{total}, \alpha'_r/w_r)$ if $\rho_r \le 1$, or by $\min(\alpha'_r/w_r, \alpha'_r/(\rho_r w_r))$ if $\rho_r > 1$; and
- Once the source receives a congestion signal from path r, it decreases its congestion window for path r to $w_r/2$.

Since $\rho_r > 1$ implies that the MPTCP subflow is taking more than the unused bandwidth and degrading local traffic, the increasing scale of the congestion window for the MPTCP subflow is limited by

$\min(\alpha'_r/w_r, \alpha'_r/(\rho_r w_r))$. The first parameter α'_r/w_r restricts that the MPTCP subflow does not increase its congestion window faster than the single-path AIMD flows. The second parameter $\alpha'_r/(\rho_r w_r)$ is extended from the constraint in (3). On the other hand, when $\rho_r \leq 1$, there is no bandwidth competition between the multipath subflow and local single-path traffic. In this case, the congestion window increasing parameter for the multipath subflow is defined as $\min(a_r/w_{total}, \alpha'_r/w_r)$. The first parameter a_r/w_{total} regulates the aggressive behavior of the multipath subflow, so that the multipath flow achieves an aggregate throughput no greater than that of the single-path flow. Here, a_r is the extended aggressiveness factor given in (4). The second parameter α'_r/w_r is similar to the case with $\rho_r > 1$.

GMCC-Coop requires that the MPTCP subflow obtain α'_r and β'_r through additional signalling. In practical implementation, a well-known fixed (α, β) pair is often defined for a specific scenario in advance [11]. Also, ρ_r can be measured by the MPTCP sink and signalled back to the source (e.g., for every 2 seconds in the experiments in Section IV).

IV. Simulation Results and Discussions

To evaluate the performance of the proposed extensions, we implement the core functions of MPTCP in NS-3 for the scenario of Fig. 1. Specifically, we consider an eNB connected to 11 UEs, among which there are one root UE and 10 relay UEs. These UEs are uniformly distributed within a rectangle area of a distance 800-1000m to eNB. Each UE has both LTE and Wi-Fi interfaces. The relay UEs and root UE can use their Wi-Fi interfaces to directly communicate in an ad hoc mode. The root UE receives packets from the application server through relay UEs. The simulation parameters are given in Table I. Here, the data rate of the Wi-Fi link is set to 54 Mbps, while that of the LTE link depends on the number of resource blocks allocated by eNB. The actual packet delays over both links also vary with the regulated traffic load and channel fading.

A. *Static Scenario*

We first evaluate the performance of MCC-Coop and GMCC-Coop in a static scenario, where the root UE is connected to two fixed relay UEs. Each relay UE forwards packets for one MPTCP subflow between the MPTCP source at the application server and the MPTCP sink at the root UE. Fig. 4 shows

TABLE I

SYSTEM PARAMETERS FOR EXPERIMENTS.

Parameter	Value	Parameter	Value
Transmit power of eNB and UE	eNB: 30 dBm, UE: 5dB	Noise figure at eNB and UE	eNB: 5 dB, UE: 5dB
eNB scheduler	Blind equal throughput	Transmission time interval (TTI)	1 ms
Radio link control (RLC) mode	Acknowledge mode (AM)	Adaptive modulation & coding (AMC)	PiroEW2010 [12]
Number of resource blocks (RBs)	50	Fading channel trace	Pedestrian at 3 km/h
Wi-Fi link	IEEE 802.11a	Wi-Fi transmission rate	54 Mbps
Wi-Fi Fragmentation threshold	2200 bytes	Wi-Fi RTS/CTS threshold	2200 bytes
Aggregate throughput target	3 Mbps	TCP type	New Reno

the aggregate throughput of the MPTCP flow for the root UE, and the individual throughput of local single-path flows of relay UEs. In Fig. 4(a), the sending rates of the two single-path TCP flows over the two relay UEs are 1.0 and 0.9 Mbps, respectively. Because the total bandwidth[1] of each relay UE is set to 1.2 Mbps, we have $\rho_1 = 5$ and $\rho_2 = 3$, both greater than 1. Hence, MCC-Coop is activated for both paths so as to protect the local traffic of relay UEs. As seen in Fig. 4(a), the throughput of the local TCP flows converges to their corresponding sending rates. This exactly achieves our design objective that the throughput of local TCP flows is not degraded by the MPTCP subflow sharing the same path. If the local traffic load is so high that the MPTCP flow cannot achieve the required aggregate throughput, the MPTCP flow should switch to relay UEs having more radio resources allocated from eNB and larger LTE link capacities. This is further discussed in Section IV-B for the dynamic scenario. A similar observation for MPTCP with GMCC-Coop can be made from Fig. 4(b), where the local traffic consists of two single-path AIMD flows with $\alpha'_r = 0.7$ and $\beta'_r = 0.625$.

B. Dynamic Scenario

We evaluate MCC-Coop and GMCC-Coop in a more dynamic scenario where the sending rates of the local traffic of relay UEs are time-varying during the simulation. To guarantee a stable aggregate throughput for the MPTCP flow of the root UE, the relays UEs connected to the root UE need to be

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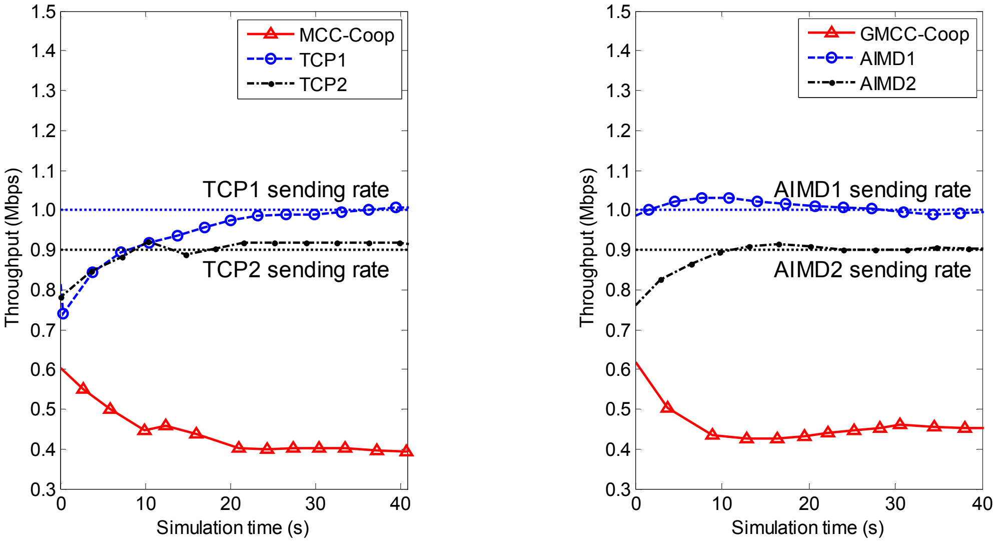
[1] The total bandwidth of a path from the application server to the root UE via a relay UE is actually bounded by the capacity of the LTE link between eNB and the relay UE. Hence, we control the total path bandwidth by limiting the radio resources allocated to each relay UE.



(a) With TCP local single-path flows.

(b) With AIMD local single-path flows.

Fig. 4. Throughput of MPTCP flows with MCC-Coop and GMCC-Coop and local single-path flows in a static scenario.

dynamically selected depending on the available bandwidths of the paths via the relays UEs. Considering channel and traffic variations, it is challenging to satisfy a strict throughput target. Hence, we consider a small margin and allow the aggregate throughput to fall into a range such as $[(1-\delta)\Upsilon, (1+\delta)\Upsilon]$, where Υ is the throughput target and δ is a small tolerable ratio, e.g., 0.1. Then, the problem of selecting a subset of relay UEs having a total available bandwidth within this range is the well-known subset-sum problem, which is NP-complete. To ensure timely adaptation to network dynamics, we developed a dynamic subset-sum based relay selection (SSRS) scheme [13] by extending an existing fully polynomial-time approximation algorithm [14]. The key idea is to have the root UE maintain multiple relay sets whose total available bandwidths are within the acceptable throughput range. Whenever the aggregate throughput is found out of this range, the root UE migrates to updated relay UEs.

Consider a dynamic scenario where all the 10 relay UEs have dynamic sending rates for their local TCP or AIMD traffic. Due to the varying traffic load over the LTE links between eNB and relay UEs, the available bandwidths of the transmission paths via the relay UEs change dynamically. To ensure that an MPTCP flow of the root UE meets a target throughput of 3 Mbps, the SSRS algorithm adaptively updates the relay UEs that are selected to forward packets to the root UE. To examine different response behaviors of MPTCP and the proposed extensions, we include three special stages in the simulation:

- S_1 for the period from 10s to 20s: the sending rate of *each relay UE* in the active set is *less* than

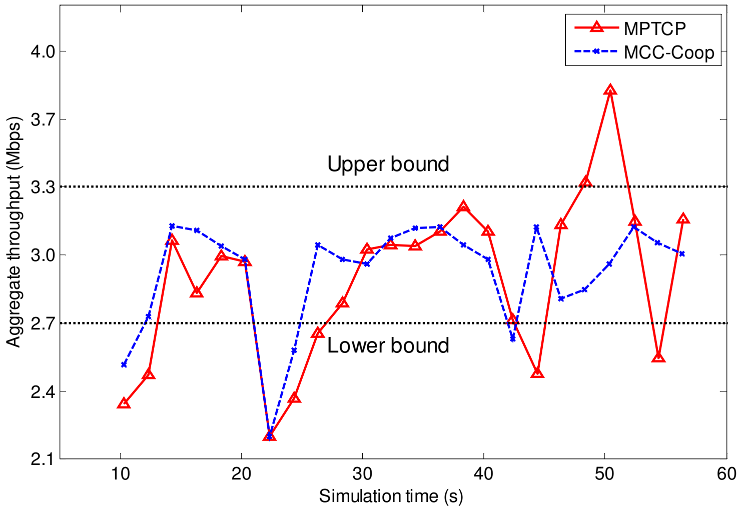


Fig. 5. Aggregate throughput of MPTCP and MCC-Coop in a dynamic scenario.

half of the total bandwidth on that path;

- S_2 for the period from 20s to 40s: the sending rates of *half of relay UEs* in the active set are *less* than half of the total bandwidth on that path, while the other half of relay UEs have sending rates *greater* than half of the total bandwidth on that path; and
- S_3 for the period from 40s to 60s: the sending rate of *each relay UE* in the active set is *greater* than half of the total bandwidth on that path.

Fig. 5 compares the throughput of MPTCP and the proposed extension MCC-Coop. In order to demonstrate performance variations with network dynamics, we use average throughput for every 2 seconds instead of long-term cumulative average. As seen in Fig. 5, because the sending rates of all active relay UEs in S_1 are so low, only the original MPTCP congestion control algorithm takes effect. Therefore, the aggregate throughput with MCC-Coop is very close to that of the original MPTCP. As the local traffic in some relay UEs is increased in S_2, a new active set with three relay UEs are selected to satisfy the throughput target. The sending rate of one particular relay UE is larger than half of the total bandwidth on that path. As already shown in Fig. 3(a), MPTCP tends to take more bandwidth aggressively and thus harms the local traffic in that relay UE. At the end of S_2, the aggregate throughput of MPTCP is greater than that of MCC-Coop. The aggressive behavior of MPTCP becomes more evident in S_3 when all active relay UEs are sending their local TCP traffic at rates greater than half of the path bandwidths. As a result, the aggregate throughput of MPTCP exceeds the target upper bound, which triggers SSRS to update the active relay set. Consequently, the aggregate throughput of MPTCP fluctuates at a much larger scale,

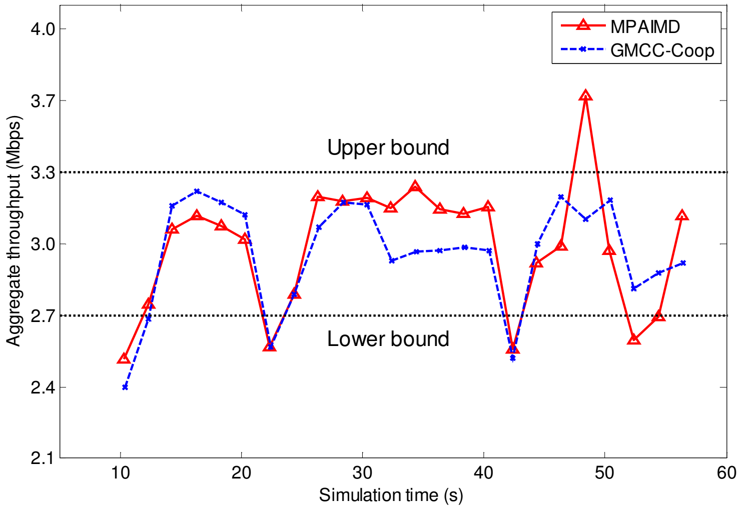


Fig. 6. Aggregate throughput of MPAIMD and GMCC-Coop in a dynamic scenario.

while the aggregate throughput of MCC-Coop is more stable and stays within the objective range.

The GMCC-Coop extension in Section III-B addresses particularly the bandwidth sharing between MPTCP subflows and local AIMD flows at relay UEs. Depending on the projected throughput ratio ρ_r, the congestion window of the MPTCP subflow is increased in different manners. To illustrate the effect of this differentiation, we consider a reference algorithm, referred to as *MPAIMD* [10]. Following an ACK reception, MPAIMD always increases the congestion window w_r for path r by $\min(a_r/w_{total}, \alpha'_r/w_r)$. That is, MPAIMD does not distinguish different cases of ρ_r by always assuming $\rho_r \leq 1$ and thus neglects the bandwidth competition and potential harm to local single-path traffic. Fig. 6 compares the aggregate throughput of GMCC-Coop and MPAIMD with local AIMD flows. Similar to Fig. 5, it is observed that GMCC-Coop is not only less aggressive in S_2 and S_3 when there are higher local traffic demands, but also provides a more stable aggregate throughput than MPAIMD.

V. CONCLUSION AND FUTURE WORK

In this study, we extend the congestion control algorithm of MPTCP to a user cooperation scenario in the LTE network. Two types of local traffic at relay UEs are considered, including TCP and AIMD single-path flows. The proposed extensions, MCC-Coop and GMCC-Coop, aim to restrict the aggressive behavior of MPTCP and protect the local TCP and AIMD traffic at relays. Specifically, the multipath subflow on a path cannot exceed a maximum throughput, which is the unused bandwidth of the path so as not to degrade the local traffic. Depending on the ratio of the expected throughput under the standard

MPTCP control to the maximum throughput allowed for the multipath subflow, the congestion window of the MPTCP subflow, especially the increasing scale, is adapted in different manners. Simulation results demonstrate the effectiveness of the proposed solutions in both static or dynamic scenarios. Not only is the throughput of local single-path flows of relay UEs guaranteed, but also a stable aggregate throughput is achieved for the multipath flow to the root UE. An interesting issue worth further investigation is the impact of the bottleneck link between the relay UEs and a root UE, which is often based on Wi-Fi in an ad hoc mode. As the number of relay UEs increases, more collisions can happen among the relay UEs and thus affect the congestion control at the MPTCP source. In [15], we propose a reactive solution to mitigate the negative effect of such collisions on the source. Further studies are needed for proactive solutions that can effectively coordinate relay UEs and integrate the multipath transport protocol into the user cooperation scenario.

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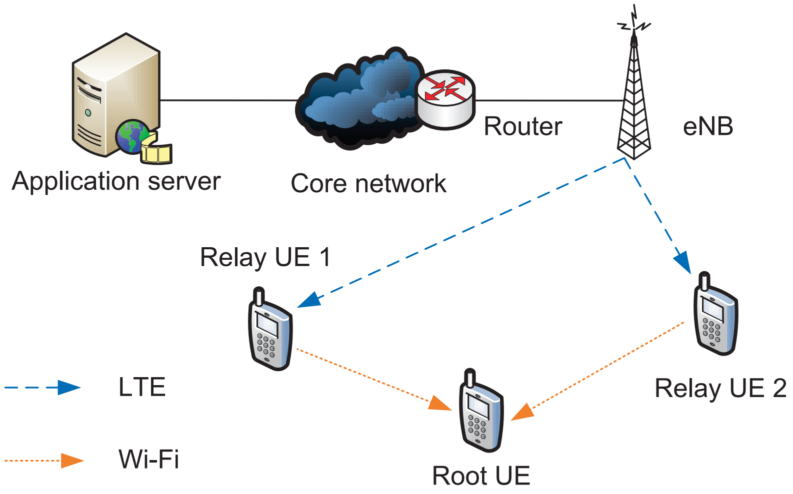


Fig. 1. User cooperation in the LTE network.

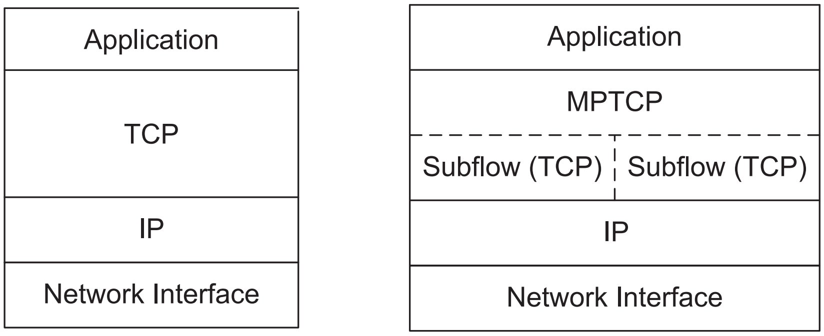
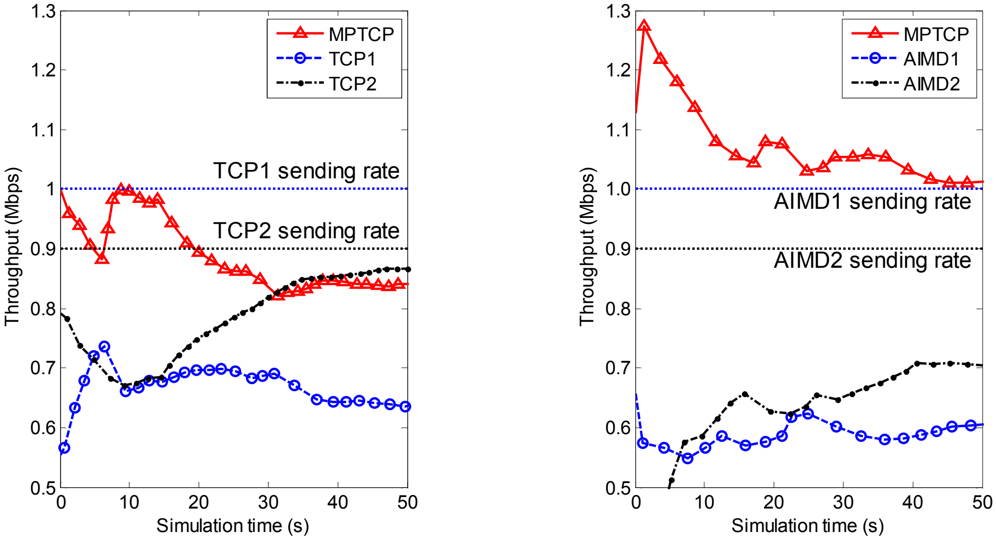


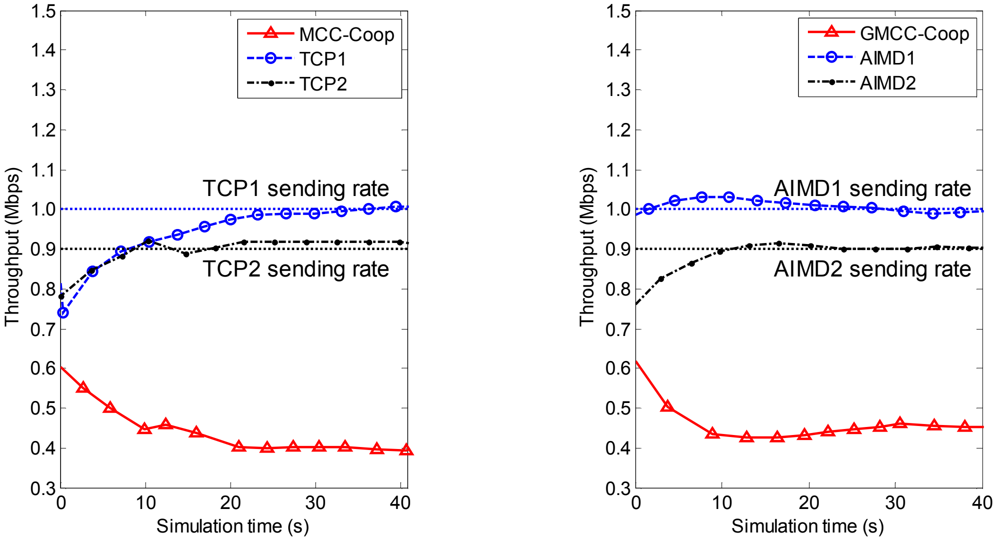
Fig. 2. Regular TCP and MPTCP protocol stacks.



(a) With TCP local single-path flows.

(b) With AIMD local single-path flows.

Fig. 3. Throughput of MPTCP flows and local single-path flows.



(a) With TCP local single-path flows.

(b) With AIMD local single-path flows.

Fig. 4. Throughput of MPTCP flows with MCC-Coop and GMCC-Coop and local single-path flows in a static scenario.

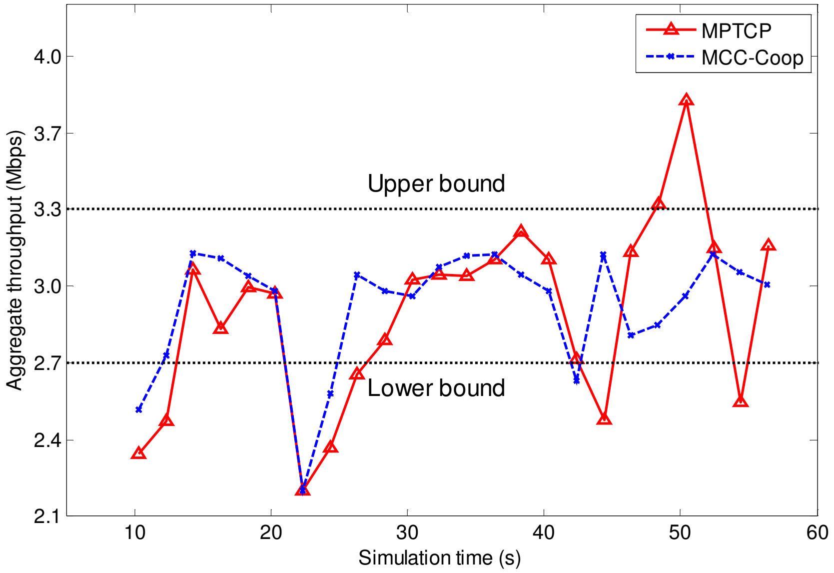


Fig. 5. Aggregate throughput of MPTCP and MCC-Coop in a dynamic scenario.

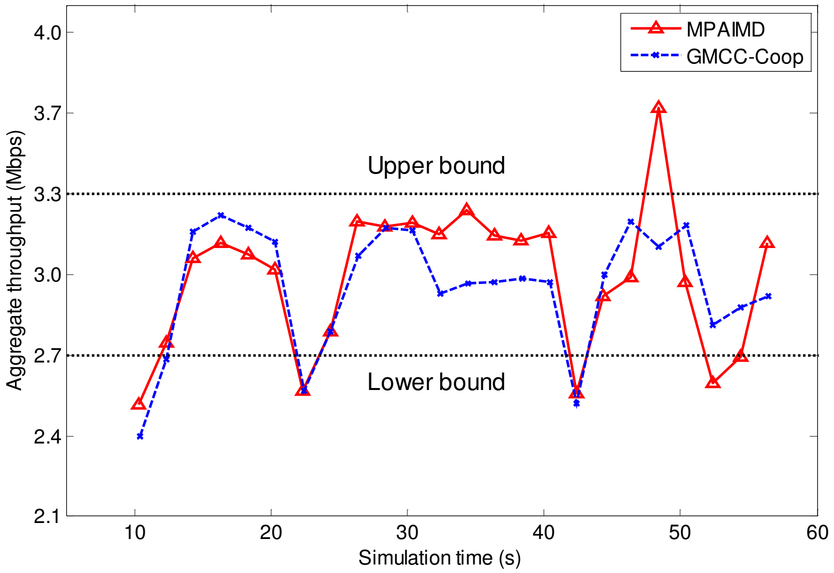


Fig. 6. Aggregate throughput of MPAIMD and GMCC-Coop in a dynamic scenario.