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Energy Efficient Congestion Control for Multipath TCP in Heterogeneous Networks

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ABSTRACT In this paper, we propose a receiver energy efficient congestion control algorithm based on multipath transmission control protocol (MPTCP) to enable the battery powered mobile devices receive more data than MPTCP with the same energy consumption. First, based on the receiver energy consumption model of wireless interface, a constrained optimization problem to maximize energy efficiency is formed. With genetic algorithm, a rate distribution vector is obtained as a near-optimal solution. Second, we adjust the congestion windows based on the acquired vector to schedule packets over each path directly. Jointly considering energy efficiency, round trip time and path loss rate, a novel congestion control algorithm is proposed to adjust the increment of congestion window when an acknowledgement is received in the congestion avoidance phase. The energy efficiency term is obtained by extending the energy efficient rate distribution vector into the window-based congestion control algorithm via fluid model. The simulation results demonstrate that the proposed algorithm shifts part of traffic from the higher energy consumption paths to the lower ones. It improves throughput greatly and achieves higher energy efficiency, almost twice the size of MPTCP.

INDEX TERMS Concurrent multipath transfer, multipath TCP, energy efficiency, congestion control, genetic algorithm, fluid model.

I. INTRODUCTION

Nowadays with advancements in network infrastructures and wireless devices, multi-mode terminals (MMT) equipped with multiple radio interfaces have access to ubiquitous access networks, e.g., cellular networks (UMTS, HSDPA, LTE), wireless local area networks (802.11 family), and broadband metropolitan area network (WiMAX) [1]. These advantages make it possible to make use of multiple radio interfaces concurrently which has been equipped with Apple's iOS [2] and Samsung's Galaxy [3]. On the other hand, the explosive growth in multimedia service (e.g., Youtube, online gaming, video conference, live sports etc.) exerts heavy loads on the resource restricted and capacity limited single wireless platforms [4]. To address this concern, concurrent multipath transfer (CMT) with higher throughput and resilience by utilizing multiple network interfaces simultaneously becomes widely studied [5].

For medical streams, the reliability of data is an essential requirement. To implement reliable concurrent transmission, Multipath protocols at the transport layer play an essential role in flow control, congestion control and ensuring fairness. Valuable progress has been made in standardization by Internet Engineering Task Force (IETF). Among all the research works, Multipath TCP (MPTCP) [6] and Stream Control Transport Protocol (SCTP) [7], [8] based concurrent multipath transfer (CMT-SCTP) [9] are in an advanced stage and have aroused tremendous interest. Both MPTCP and CMT-SCTP support communication between source and destination through multiple flows under a single connection session. However, MPTCP is easy to be implemented for its compatibility to TCP. MPTCP is a set of extensions to regular TCP that exploits multiple paths to transmit data simultaneously, providing improved throughput and resilience. In multicast scenarios, MPTCP can be implemented in the cluster head to improve its throughput, which can improve the performance of the multicast group. The congestion control algorithm of MPTCP aims to improve throughput, do no harm to other network users and balance congestion. But the round-robin scheduling scheme causes packet reordering issue due to the heterogeneous paths' dynamic nature and quality dissimilarities in delay, bandwidth and path loss rate. The current works mainly focus on this problem and many solutions such as retransmission policy [10], path management schemes [11], packet scheduling algorithms [12], network coding based schemes [13], [14] and congestion control algorithms [15] have been proposed.

However, multipath transfer generally consumes more energy to maintain multiple active interfaces, which is a great challenge for battery powered mobile wireless devices [16]. The limited battery capacity of the multi-mode devices determines the lifetime and reliability of a MPTCP connection. Thus optimizing energy efficiency of wireless clients should also be considered when utilizing MPTCP for concurrent transfer. Current methods mainly focus on reducing energy consumption by means of traffic shaping [17] and offloading [18]. With traffic shaping, the incoming traffic are shaped into periodic bursts to avoid the receiver staying in the active mode consistently. This method can be applied with other methods such as encoding to reduce energy consumption further [19]. By scheduling packets according to the real-time channel status or rate allocation schemes [20], the traffic can be offloaded from higher energy-consuming interfaces to others. In this case, a path with lower energy consumption undertakes more traffic, even all of the traffic in an extreme case. The aggregation benefit of MPTCP cannot be totally realized, which may degrade the transmission performance greatly in terms of throughput and transmission duration.

In this paper, we propose an energy efficient congestion control algorithm, named EEMPTCP, to enable receiver receive more bits per joule than the linked increase algorithm (LIA) of MPTCP. The algorithm adjusts the congestion window of each subflow jointly considering energy efficient rate distribution and path characteristics. As the rate adjustment of a TCP flow is performed by changing the size of congestion window, congestion control algorithms can achieve optimal data distribution directly and effectively. The traffic shifting parameters are designed to maximize the energy efficiency of receiver while guaranteeing the throughput and network load-balancing. Firstly we introduce the energy consumption model at the receiver side with the assumption that the receiver device stays in the active state. Then the model is applied to form a constrained optimization problem to maximize energy efficiency of the receiver. With genetic algorithm, we obtain a rate distribution vector as the near-optimal solution. After that, the congestion control algorithm EEMPTCP is proposed by extending the rate-based distribution scheme to a window-based one using the fluid model and taking paths characteristics into consideration as well. The effectiveness of EEMPTCP is proved by simulation results.

The rest of this paper is organized as follows. In Section II, related works are introduced and discussed. Then we present the system model and the receiver energy consumption model of wireless interfaces in Section III. In Section IV, we firstly form a constrained energy efficiency optimization problem. Secondly, a near-optimal solution is obtained by adopting genetic algorithm. Then the energy efficient congestion control algorithm is proposed based on the obtained solution. The simulation results and analysis are presented soon afterwards in Section V. Section VI concludes this paper and presents future work directions.

II. RELATED WORK

MPTCP has aroused great interest since it was proposed. With reliable transmission over multiple paths simultaneously, it improves resource usage and user experience in terms of throughput and resilience. However, due to the dynamic and dissimilar paths in heterogeneous networks, MPTCP equipped with round-robin scheduling scheme suffers from packet disordering, even receiver buffer blocking when the receiver buffer is not large enough. As mentioned before, many efforts [10]–[14] have been devoted to addressing this problem. Nevertheless, energy efficiency which is essential for battery powered mobile devices is not taken into account. To decrease energy consumption, some energy saving mechanisms such as video streaming shaping and traffic offloading are proposed.

Raja *et al.* [17] operates a shaping mechanism between the network layer and the data-link layer to shape incoming traffic into bursts and during the interval of two bursts the device turns into sleep state. In [19], raptor encoding as well as burst shaping is adopted to achieve energy efficiency. A video stream from application layer is firstly encoded with raptor code and then buffered for a specific interval waiting for composing a burst stream which is transmitted over wireless interfaces. The raptor encoding parameters are determined in real time with consideration of the energy consumption of on-the-fly raptor decoding at the receiver side. In addition, burst shaping enables the wireless network interfaces in a multi-mode device stay in the idle state longer, which reduces energy consumption further.

Another effective method to save energy is to offload traffic from the higher energy consumption wireless interfaces to the lower ones. It can be deployed via path selection [21] and data allocation [20]. Pluntke *et al.* [21] select a suitable path in the low congestion paths to maximize energy saving. Ghariani and Jouaber [22] select the most energy efficient technology among the networks that can offer required QoS for packet transmission. These two works both shift all traffic to the most energy efficient wireless interface, which may degrade the bandwidth aggregation benefit of MPTCP. Offloading schemes to make use of multiple paths are proposed as data allocation schemes. Chen *et al.* [18] propose an energy-aware MPTCP-based content delivery scheme named eMTCP which works at upper transport layer in mobile devices to increase the energy efficiency of devices. The scheme offloads part of traffic from the LTE subflow to the WiFi subflow which is in idle state according to the congestion control mechanism, the current congestion window size of the LTE subflow and information of channel state change. The authors extend eMTCP to eMTCP-BT [23] which offloads traffic based on traffic burstiness levels. When the delivered traffic are scheduled based on burstiness levels, eMTCP-BT achieves higher energy efficiency than eMTCP. Wu *et al.* [20] propose a video flow rate allocation algorithm to tradeoff energy and distortion while guaranteeing target video quality. Cao *et al.* [24] switch the transmission mode between partial MPTCP (WiFi only) and Full MPTCP (eMTCP proposed in [18]) according to the relationship between the application read rate of receiver and the sending rate of wireless interfaces to tradeoff throughput and energy consumption. An efficient SACK loss detection and recovery mechanism is also introduced to save energy further.

In a MPTCP connection, each subflow provides a regular TCP connection which uses a window-based mechanism to control the sending rate at the source [25]. As the congestion window increment of a subflow depends on ACK packets, the congestion windows for paths with short round trip time (RTT) and low path loss rate increase fast, vice verse. If these paths are with high energy consumption, they may not be fully utilized with offloading schemes. In addition, the traffic offloaded to low-energy long RTT subflows may spend more time in the queue as the transmission rate of a subflow is controlled by the size of congestion window. To modulate the transmission rate over each path directly, energy-efficient congestion control algorithms are proposed. Peng *et al.* [26] propose rate adjustment schemes on the selected paths based on network congestion and energy consumption for real-time applications and file transfer applications respectively. Le *et al.* [27] develop an energy-aware congestion control algorithm named ecMTCP by adding an energy related bound to MPTCP's linked increase algorithm. In [28], an energy-aware congestion control mechanism for mReno is proposed. The mechanism increases the congestion window inversely proportional to the energy cost, thus the path with higher cost increase the congestion window less aggressively. Zhao *et al.* [29] focus on the energy consumption of an end-to-end MPTCP connection. Based on the experiments of machine-to-machine data transfers over testbed, the authors summarize average throughput, path delay and network scenarios as the influencing parameters of energy efficiency. By applying the relationship into congestion control, a window increase factor is designed to improve the energy efficiency of the end-to-end connection.

In this paper, we focus on the energy efficiency of the receiver to enable the mobile device receive more packets with the same energy consumption. As congestion control mechanisms work well in guaranteeing throughput, fairness and load-balancing and they need little modification in servers and devices when to be implemented, the energy efficiency is realized by means of changing the increase patterns of each path's congestion window. In the scheme, we form an optimization problem to obtain an energy efficient rate distribution vector. Based on the acquired vector and path characteristics, an energy efficient congestion control algorithm is designed for MPTCP.

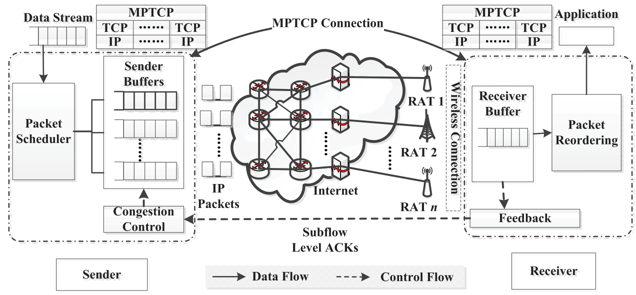

FIGURE 1. System model of multipath communication with MPTCP.

III. SYSTEM MODEL

The goal of the proposed scheme is to support a high-quality multipath transmission in a receiver energy-efficient way. As MPTCP is compatible with TCP and easy to be implemented, MPTCP is adopted as the transport layer protocol. The system overview of multipath communication based on MPTCP and the receiver energy consumption model are presented in this section.

A. SYSTEM OVERVIEW

We consider a multipath communication based on MPTCP. Fig.1 presents the system model. Application streams from the content server are transmitted to a wireless device via multiple paths. The multimode mobile device connects to the Internet via heterogeneous networks which consist of multiple radio access technologies (RATs) such as WiFi, LTE, HSPA, WiMAX and so on. A path has access to a RAT and is disjoint with others.

The sender and receiver are both equipped with MPTCP [30] to support parallel transmission. A MPTCP connection utilizes multiple standard TCP sessions named subflows to provide underlying transport. The protocol stack of MPTCP is depicted in Fig.1. It decomposes regular transport layer into two sections, MPTCP and TCP. To distinguish from the overall transport protocol MPTCP, we mention the layer over TCP as MPTCP extension below. The MPTCP extension implements functions of path management, packet scheduling, subflow interface and congestion control, while TCP provides reliable delivery as regular TCP does. As reliable delivery only delivers in-order packets to the upper layer, the out-of-order packets must stay in the receiver buffer until all the packets are in the right sequence. When the packets arrive at the receiver, the receiver sends feedback information to the sender for path quality estimation, congestion control and packet scheduling functions. It is assumed that middleboxes such as NATs, firewalls and proxies are MPTCP-aware and do no harm to the transmission performance.

A MPTCP connection initiates connection setup between a source address and a destination address similar to a regular TCP connection. Additional subflows exchange packets with the MP_JOIN option in the same way as initiating a normal TCP connection to join in the MPTCP connection. Then data can be transferred over the subflows that compose the MPTCP connection for concurrent multipath transfer. MPTCP's implementation uses the linked increase algorithm (LIA) [31] to provide a compromise between optimal resource pooling and friendliness. LIA couples the additive increase function of subflows when receiving an ACK in the congestion avoidance phase and follows TCP in case of a drop and in the slow-start phase. Let w_r and rtt_r be the congestion window size and the round-trip time of subflow r in the MPTCP connection, respectively. LIA works as follows.

- For each ACK on subflow r, increase w_r by $\triangle w_r$ which is calculated as (1).

$$\triangle w_r = \min\left(\frac{\max_i \frac{w_i}{rtt_i^2}}{\left(\sum_i \frac{w_i}{rtt_i}\right)^2}, \frac{1}{w_r}\right) \tag{1}$$

- For each loss on subflow r, decrease w_r by $w_r/2$.

The congestion control algorithm of MPTCP aims to satisfy the goals of throughput improvement, fairness and load-balancing. But it pays no attention to energy efficiency. As wireless devices are usually powered by battery, it is necessary to make use of multiple paths in an energy efficient way to enable mobile receivers receive more packets with the same energy consumption. Based on the system model in Fig. 1, we introduce a receiver energy efficient congestion control algorithm as an alternative for MPTCP's LIA. To deploy the proposed algorithm, modifications located in the congestion control function of the MPTCP extension should be made.

B. RECEIVER ENERGY CONSUMPTION MODEL

In a MPTCP session, the receiver receives data packets and sends ACK packets. The improvement in energy consumption and efficiency caused by modifications in ACK processing is limited, as demonstrated in [24]. To receive packets, the energy is mainly consumed by data copying and processing operations [32]. The former one is essential and cannot be scheduled. Thus in the receiver energy consumption model, we neglect the energy consumption of ACK and only consider the processing operations for data receiving in this paper.

According to [19], the receiver has at least two operating modes during the receiving process, e.g. receiving and waiting for traffic, which correspond to different power states respectively. Generally the device turns to a mode with lower power consumption if there is no more traffic waiting for receiving after a certain while. That is the reason why energy consumption can be decreased with traffic shaping. For a streaming service or a shaped service, the data is often delivered in regularly repeated bursts. If the time intervals between two bursts are less than the certain fixed duration, the receiver will not switch to the idle state during these intervals. Based on this, we assume that the wireless network interfaces (WNIs) of a receiver always stay in the receiving mode to receive the continuous flow of data packets during the duration of a connection.

The power consumption model in [33] is adopted to obtain the energy model for wireless devices. The model is suitable for most wireless interfaces such as 4G, 3G and WiFi. According to the model, the power consumption on path r denoted as $P_r(x_r)$, is direct proportional to the throughput x_r, represented as (2).

$$P_r\,(x_r) = b_r x_r + \theta_r 1_{\{x_r>0\}} \tag{2}$$

where $b_r, \theta_r > 0$ are the power consumed per bit for receiving data and the sunk power cost for being active, respectively.

Thus if the process lasts for a duration T, the energy consumption on path r can be obtained by multiplying $P_r(x_r)$ by T, represented as (3).

$$E_r\,(x_r) = b_r x_r T + \theta_r 1_{\{x_r>0\}} T \tag{3}$$

It is noted that a WNI may return to the idle mode in some cases such as long delay caused by packet losses. The measured value of E_r may be lower than the estimated value from the model. But this can be accepted as multimedia streaming for the transfer energy constitutes the majority of energy consumption [34].

IV. ENERGY EFFICIENT MPTCP

The goal of the proposed scheme is to maximize the energy efficiency also named energy utility at the receiver side to enable the battery powered mobile devices receive more packets per joule energy. The details of the proposed algorithm are presented in this section. With limitations of the wireless interfaces in terms of capacity and energy, the optimization problem is formed and derived. To solve the problem, genetic algorithm is adopted to obtain a near-optimal solution. Finally, based on the aquired solution, an energy efficient congestion control algorithm is proposed.

A. PROBLEM FORMULATION

Energy efficiency is defined as the number of bits transmitted per joule energy, the ratio of total data size to the sum energy consumption during transmission. As the total data size can be represented as the product of average rate and duration of connection, the term can be simplified as the ratio of the average rate to the power which is in direct proportion to the rate. Thus energy efficiency is dependent of the transmission rate of each subflow and the maximum energy efficiency can be obtained with the optimal transmission rate distribution over each subflow.

For a multipath flow f with the subflow set $\Re$, the constrained energy efficiency maximization problem can be formulated as follows.

$$\text{maximize } ee = \frac{\sum_{r\in\Re} x_r}{\sum_{r\in\Re} (\theta_r + b_r x_r)} \tag{4}$$

$$\text{subject to } \sum_{r\in\Re} x_r \geq R \tag{5}$$

$$0 \leq x_r \leq C_r \tag{6}$$

$$\sum_{r\in\Re} (\theta_r + b_r x_r) \leq E_{\max} \tag{7}$$

A subflow r in $\Re$ with transmission rate x_r corresponds to a wireless network interface r with capacity C_r which is calculated according to the Mathis Model. To guarantee the aggregation benefit of CMT, a term R is defined as $R = \max(C_i)$. The sum rate of all active subflows in $\Re$ should be no less than R to achieve the goal of throughput improvement referred to [31]. The limiting condition (7) is to avoid the excessive increase in throughput for energy efficiency maximization at the expense of too much energy consumption, the power threshold is set as the power when all packets are transmitted over the maximum energy consumption subflow.

For subflow r, define the rate splitting ratio as

$$\alpha_r = \frac{x_r}{\sum\limits_{i \in S} x_i}.$$

The solution of the problem is the rate distribution vector composing of the splitting ratios of all subflows in $\Re$. It is noted that the formulation problem does not take fairness and out-of-order problems into account. These problems may be left for future work.

B. A NEAR-OPTIMAL SOLUTION

If there are two subflows in a flow, the problem can be derived with differential properties. But when the number of subflows increases, it is hard to obtain the optimum equilibrium by means of convex optimization theory as the goal function is non-convex (see proof in Appendix). Thus, genetic algorithm (GA) is adopted to pursue a sub-optimal solution with low computation complexity.

Genetic algorithm [35] is an adaptive heuristic search algorithm using directed random searches to locate optimal solutions. It is rooted in the mechanisms of revolution and natural genetics. In the natural evolutionary process, the fittest individuals in the gene pool survive and reproduce by means of natural selection and recombination, respectively. Similarly, in the genetic algorithm, better solutions are selected to survive in selection according to fitness value. The higher the fitness value of an individual, the higher its chance of survival and reproduction. These selected individuals form a new population. Then a crossover mechanism exchanges some bits between strings according to the crossover probability. The other operation, called mutation, regenerates lost genetic materials by altering bits of strings randomly. The details of the near-optimal solution based on GA are presented in Algorithm 1.

In the algorithm, the fitness metric is defined as the objective function (4). The transmission rate to be distributed over path r, x_r, is encoded into binary strings with the length of $\lceil \log_2(x_i) \rceil$. As there are n TCP subflows in a MPTCP flow, the length of an individual in the gene pool is represented as $N = \sum_{i=1}^{n} \lceil \log_2(x_i) \rceil$. Firstly generate an initial population of M individuals randomly. After selection, crossover, and mutation, a new population is produced. In the selection process, the roulette wheel selection scheme is adopted to implement proportionate selection. The crossover probability and the mutation probability are denoted as P_c and P_m, respectively. In the new population, remove the individuals which do not satisfy (5), (6) and (7), calculate the left individuals' fitness value and record the individual with the best fitness. Then the new produced population serves as the initial population for the succeeding iteration, steps 3 to 8 in Algorithm 1, until the repeat time reaches the maximum generation number gn_{max}. Thus far the best individuals in each generation are obtained. Select the best one with the maximum fitness value from the recorded individuals and decode it into decimal numeral system represented as $\overline{x} = (x_1, x_2, \cdots, x_i, \cdots, x_n)$. After the above procedure, the traffic distribution vector $\overline{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_i, \cdots, \alpha_n)$ can be finally obtained. At last, the distribution vector is output to design the energy efficient MPTCP scheme.

Algorithm 1 Near-Optimal Solution Based on GA

1: Input: $M, N, C_r, b_r, \theta_r, gn_{max}, P_c, P_m$
2: Output: The rate distribution vector $\overline{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_n)$
3: Generate a $M * N$ matrix randomly as the initial population;
4: **for** $gn < gn_{max}$ **do**
5: Selection with the roulette wheel selection scheme;
6: Crossover with the probability P_c;
7: Mutation with the probability P_m;
8: Remove the individuals not satisfying the requirements (5), (6) and (7);
9: Calculate the object value according to (4) and record the best individuals;
10: $gn++$;
11: **end for**
12: Select the best individual $\overline{x} = (x_1, x_2, \cdots, x_i, \cdots, x_n)$ as the near-optimal solution;
13: Calculate and output the splitting vector $\overline{\alpha} = (\alpha_1, \alpha_2, \cdots, \alpha_i, \cdots, \alpha_n)$.

C. ENERGY EFFICIENT CONGESTION CONTROL ALGORITHM

With the fluid model, the rate-based distribution vector in Algorithm 1 can be applied into the window-based congestion control algorithm. Based on this, an energy-efficient congestion control algorithm named EEMPTCP is proposed to improve receiver's energy efficiency. EEMPTCP adds a term to MPTCP's congestion control algorithm LIA in the congestion avoidance phase and follows the same way as MPTCP in the slow-start phase and in case of a loss.

In the fluid model, rate x is an approximation of window size w divided by round trip time rtt, i.e. $x = w/rtt$. For path r, when taking path loss rate p_r into account, more packets should be sent at the sender side to reach rate x_r at the receiver side. Thus the congestion window of path r is the function of x_r, rtt_r and p_r, represented as $w_r = x_r * rtt_r/p_r$. The expected energy efficient distribution ratio of w_r is $\frac{rtt_r\alpha_r/p_r}{\sum_i rtt_i\alpha_i/p_i}$. Define β_r to indicate whether the current case is energy-efficient or not. With the definition of β_r, the algorithm can enlarge or decrease the size of congestion window of MPTCP's congestion control scheme. The EEMPTCP algorithm is implemented as follows.

- For each ACK on subflow r, increase w_r by $\triangle w_r$ which is calculated as (8).

$$\triangle w_r = \min\left(\frac{\max_i \frac{w_i}{rtt_i^2}}{\left(\sum_i \frac{w_i}{rtt_i}\right)^2}, \frac{1}{w_r}\right) + \frac{\beta_r}{w_r} \tag{8}$$

where $\beta_r = \frac{rtt_r\alpha_r/p_r}{\sum_i rtt_i\alpha_i/p_i} - \frac{w_r}{\sum_i w_i}$

- For each loss on subflow r, decrease w_r by $w_r/2$.

In (8), the first term is MPTCP's linked increase algorithm which guarantees throughput improvement, fairness and load-balancing. The second term aims to improve receiver's energy efficiency. If the current distribution ratio is less than the expected value, β_r is positive for path r in the multipath flow. Then the scheme enlarges the congestiom window to load traffic to path r. In the opposite situation, i.e. $\beta_r < 0$, the window size is decreased. If $\beta_r = 0$, EEMPTCP becomes MPTCP. With β_r, the scheme can shift traffic from the higher energy path to paths which consume less energy.

To illustrate the property of EEMPTCP, the fluid approximation of throughput rate is derived as (9).

$$\frac{dx_r}{dt} = \min\left(\frac{x_r \max_i \frac{w_i}{rtt_i^2}}{rtt_r\left(\sum_i \frac{w_i}{rtt_i}\right)^2}, \frac{1}{rtt_r^2}\right) + \frac{\beta_r}{rtt_r^2} - \frac{x_r^2 p_r}{2} \tag{9}$$

If the current state of congestion window is energy efficient, the defined indicator β_r is zero. Then the differential equation of EEMPTCP becomes same as MPTCP and the two congestion control algorithms have the same properties in throughput improvement, fairness and load-balancing. When β_r is positive, it means the congestion window size of path r is less than the expected value. To improve energy efficiency, the congestion window should be increased. Consequently, the maximum throughput over path r is larger than that of MPTCP, which is consistent with the extremum condition $\frac{dx_r}{dt} = 0$. The opposing case can be seen when β_r is negative. If $\beta_r < 0$, the congestion window should be decreased and the corresponding throughput becomes lower.

The control flowchart of a subflow in the multipath connection is depicted in Fig. 2 to illustrate how EEMPTCP works. As EEMPTCP provides an energy-efficient congestion control algorithm for MPTCP, the differences from MPTCP locate in the congestion control process. For subflow r, the congestion window increases when receiving an ACK that acknowledges a new packet and decreases when packet loss occurs. In Fig. 2, *cwnd*, *ssthresh*, *outs* and *ad_rbuf* represent the size of congestion window, the slow-start threshold, the size of outstanding bytes and the advertised receiver buffer size, respectively. In congestion avoidance phase, the congestion window increases according to (8). For other cases, the congestion window follows the same way as MPTCP. The sender sends data over a subflow if there is available space in the receiver buffer and the size of congestion window is larger than the number of outstanding bytes. Once there is no data waiting for transmission, the process is over and the connection will be shut down.

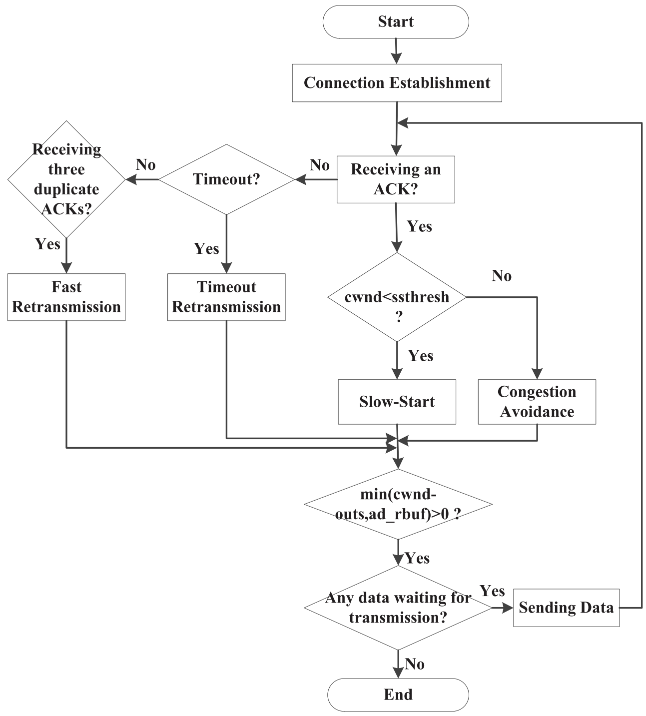

FIGURE 2. Control flowchart of a subflow in the MPTCP connection.

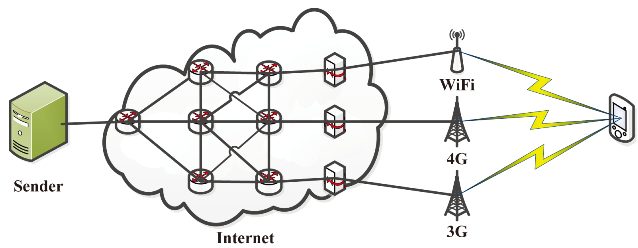

FIGURE 3. Simulation topology.

V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of EEMPTCP on the Network Simulator version 2 NS-2.35 with the MPTCP module developed by Nishida [36]. The simulation setup and performance analysis are presented.

A. SIMULATION SETUP

Consider a heterogeneous network consisting of 4G (LTE), 3G (WCDMA) and WiFi (802.11) which are generally equipped in a mobile device. As presented in Fig. 3, the sender communicates with the receiver via three disjoint paths. Both the sender and the receiver support concurrent multipath transfer by implementing MPTCP. Each path is

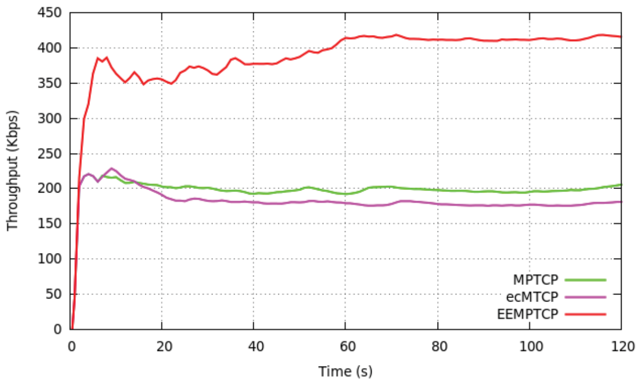

FIGURE 4. **Comparison of throughput.**

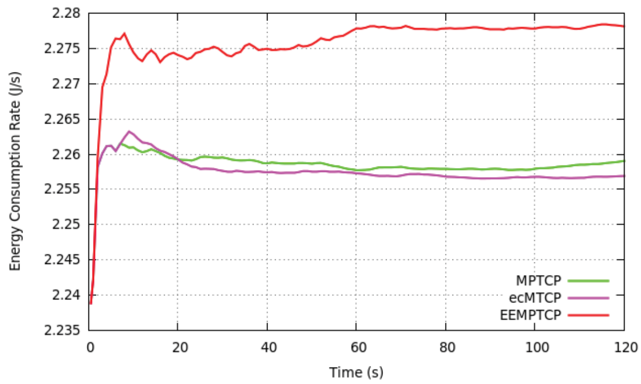

FIGURE 5. **Comparison of energy consumption rate.**

a subflow of a MPTCP connection. For easy representation, we name the paths as Path 1, Path 2 and Path 3 for WiFi, 4G and 3G respectively. Referred to [21], the energy consumption parameters are set to be 137mW/Mbps and 132.9mW, 52mW/Mbps and 1288mW, and 122.1mW/Mbps and 817.9mW for Path1, Path2 and Path 3 respectively. For each path, the former parameter represents for transmission power b_r, while the latter one is the sunk power θ_r. Path1's delay, path loss rate and access bandwidth are set to be 70ms, 0.1 and 10Mbps, respectively. For Path2, the parameters are 100ms, 0.02 and 4Mbps respectively. Path3 experiences 120ms delay, 0.02 path loss rate and 4Mbps access bandwidth. Note that the parameters are for end-to-end paths which consider properties of both wired and wireless links. The type of link queues is Droptail. Other parameters are set as MPTCP default values. The simulation lasts for 120 seconds.

B. SIMULATION RESULTS

In this subsection, the performance evaluation is presented. The near-optimal rate distribution vector of Algorithm 1 is obtained via Matlab. Then it performs as the input of the window-based congestion control algorithm which works in a multipath connection realized with NS-2.35. The transmission performance in terms of throughput, energy consumption rate and energy efficiency is presented and compared with regular MPTCP [31] and ecMTCP [27].

Fig. 4 compares the average throughput of the multipath flow when EEMPTCP, MPTCP and ecMTCP are used, respectively. At the start of the connection, the curves rise fast and then vary moderately after a while. That is because of the specific congestion control mechanism which increases the congestion window exponentially in the slow-start phase and slightly in the congestion avoidance phase. As shown in Fig. 4, EEMPTCP attains higher throughput than MPTCP and MPTCP is better than ecMTCP. The average values of throughput during the total simulation time with the three congestion control algorithms are 415.66Kbps, 205.57Kbps and 181.07Kbps, respectively. There is appropriately twofold increase in throughput between EEMPTCP and MPTCP. The possible reason for the results is that EEMPTCP changes the number of packets over each path and influences the transmission sequence number of packets over each path. That may reduce the number of out-of-order packets. Therefore EEMPTCP can alleviate the consequent problems such as unnecessary retransmissions and congestion window decreases. The throughput of ecMTCP is lower than MPTCP. That is because ecMTCP adds a bound dependent of energy to MPTCP's linked increase algorithm to shift traffic from the higher energy consumption paths to the lower ones. As the algorithm increases the congestion window by the lower bound of the added item and LIA, the window increment of each subflow is less than the increment of MPTCP if the subflow is not energy saving. Therefore there is a dip in throughput compared to MPTCP.

Fig. 5 presents the average energy consumption rate with MPTCP, ecMTCP and EEMPTCP, respectively. We can observe that the trend of curves is similar to the curves of throughput. The reason is that the energy consumption rate is in direct proportional to throughput. However, the time of inflection points and cross points is different from that in the throughput curves. In addition, the gap between curves of different algorithms is not large during the connection. That is because the sunk power in the energy model to keep interfaces active accounts for a large proportion when the throughput is relatively low. Compared with MPTCP, the energy consumption rate of EEMPTCP climbs by 0.85 % while ecMTCP slides by 0.01% after 120s of simulation time. The high energy consumption rate of EEMPTCP is caused by the high throughput it attains. As more packets are received at the receiver side, more energy is consumed. The curves of ecMTCP and MPTCP intersect when the connection lasts for about 20s. Then ecMTCP becomes the most energy saving mechanism. One reason is that the receiver receives more packets with MPTCP. The other reason lies in the energy saving mechanism in ecMTCP which schedules some packets to the less energy consumption paths.

Fig. 6 shows comparison of energy efficiency among MPTCP, ecMTCP and EEMPTCP. As mentioned before, the energy efficiency in unit of Kbits/Joule is calculated by the ratio of throughput to energy consumption rate. For energy consumption rate varies slightly in the simulations, the

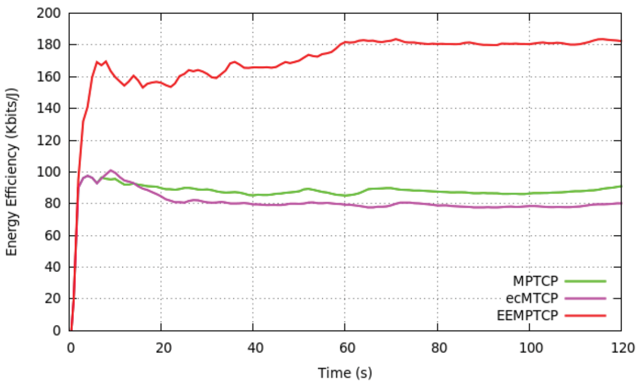

FIGURE 6. Comparison of energy efficiency.

TABLE 1. Performance comparison between MPTCP, ecMTCP and EEMPTCP.

	MPTCP	ecMTCP	EEMPTCP
Throughput (Kbps)	205.57	181.07	415.66
Energy Consumption Rate (Joule/Second)	2.26	2.26	2.28
Energy Efficiency (Kbits/Joule)	90.99	80.23	182.46

change of energy efficiency mainly depend on throughput. Thus the trend of curves for energy efficiency in Fig. 6 is similar to the trend of curves for throughput in Fig. 4. Specifically, EEMPTCP maintains the energy efficiency at a higher level than MPTCP and ecMTCP and MPTCP performs slightly better than ecMTCP. At the time of 120s, there is up to twofold increase in energy efficiency using EEMPTCP, compared with MPTCP. In conclusion, the proposed congestion control mechanism achieves the goal of improving energy efficiency at the receiver side through a tradeoff between throughput and energy consumption.

In order to better illustrate the comparison, the average values of performance metrics in terms of throughput, energy consumption rate and energy efficiency with the three algorithms are presented in Table I. From the tabular form, we can clearly see that although EEMPTCP consumes a little more energy per second, it improves energy efficiency of multipath transmission greatly compared with MPTCP and ecMTCP. To analyze the influence of EEMPTCP on transfer performance over each subflow, we calculate the normalized throughput of each subflow in the multipath flow by means of dividing throughput of a subflow by the overall throughput of the multipath flow. The normalized throughput when using EEMPTCP and MPTCP are presented in Fig. 7 and Fig. 8, respectively. In both cases, Path1 transfers the least traffic because of its high packet loss rate which directly leads to congestion window decrease and increases the number of out-of-order packets. Compared with MPTCP, EEMPTCP transmits less packets over Path1 for it moves some traffic to the lower energy consumption paths, Path2 and Path3. With EEMPTCP, more packets are transferred over Path3 ahead of 30s or so, but after that Path2 takes more responsibility.

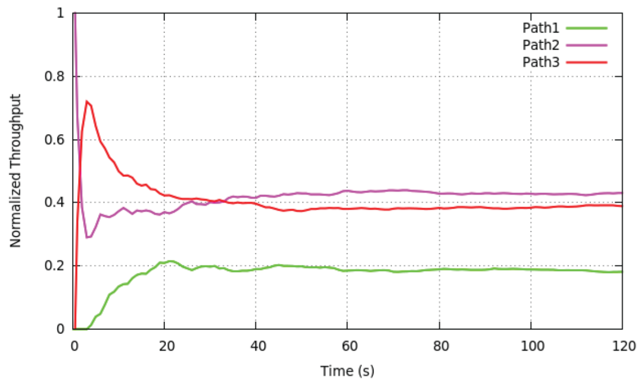

FIGURE 7. Normalized throughput with EEMPTCP.

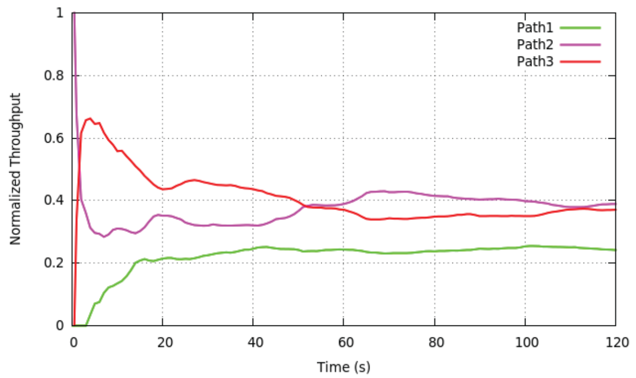

FIGURE 8. Normalized throughput with MPTCP.

When using MPTCP, the intersection occurs around 50s and the gap between Path2 and Path3 is larger than that with EEMPTCP. In general, the throughput gap between each subflow comes to be narrowing and stable along with simulation time. Here, we take the values at 120ms for example to see how solutions influence the size of congestion windows. The values of normalized throughput for the three subflows are 0.18, 0.43 and 0.39 with EEMPTCP, 0.24, 0.39 and 0.37 with MPTCP, respectively.

VI. CONCLUSION

This paper proposes an energy efficient congestion control algorithm for MPTCP by jointly considering throughput and energy consumption at the receiver side. EEMPTCP includes two major parts, the rate distribution and the congestion control. The former one is to find out the optimal rate distribution vector to maximize the energy efficiency of receiver by forming a constrained optimization problem and obtaining a near-optimal solution with genetic algorithm. Then the rate distribution vector is extended with fluid model and applied into the window-based congestion control algorithm of MPTCP to distribute traffic over each path in an energy efficient way. Simulation results show that the proposed algorithm can indeed shift traffic to lower energy consumption paths. In addition, it can increase throughput significantly which can decrease the transmission time in turn and reduce sum energy eventually. Future work will consider different kinds of service to improve the performance in terms of throughput and energy efficiency further. For loss tolerant media services, partial reliability may be adopted, while for reliable transmission, network coding may be adopted to alleviate the disorder problem. Furthermore, the performance evaluation will be carried out with hardware devices in real scenarios.

APPENDIX

The proof to illustrate the property of (4) is presented as follows. Assume there are $S(S > 2)$ elements in $\Re$. The first partial derivative of ee is derived as (10).

$$\frac{\partial ee}{\partial x_r} = \frac{\sum\limits_{i\in\Re}\theta_i + \sum\limits_{i\in\Re, i\neq r} b_i x_i - b_r \sum\limits_{i\in\Re, i\neq r} x_i}{\left[\sum\limits_{r\in\Re}(\theta_r + b_r x_r)\right]^2} \tag{10}$$

The second order partial derivatives of ee can be expressed as (11) and (12).

$$\frac{\partial^2 ee}{\partial {x_r}^2} = \frac{-2b_r\left(\sum\limits_{i\in\Re}\theta_i + \sum\limits_{i\in\Re, i\neq r} b_i x_i - b_r \sum\limits_{i\in\Re, i\neq r} x_i\right)}{\left[\sum\limits_{r\in\Re}(\theta_r + b_r x_r)\right]^3} \tag{11}$$

$$\frac{\partial^2 ee}{\partial x_r \partial x_s} = -\frac{(b_r + b_s)\sum\limits_{i\in\Re}(\theta_i + b_i x_i) + 2b_s b_r \sum\limits_{i\in\Re} x_i}{\left[\sum\limits_{r\in\Re}(\theta_r + b_r x_r)\right]^3} \tag{12}$$

Thus the Hessian Matrix of (4) which is composed by the second order partial derivatives of ee can be expressed as (13).

$$\mathbf{H} = \begin{pmatrix} \frac{\partial^2 ee}{\partial {x_1}^2} & \frac{\partial^2 ee}{\partial x_1 \partial x_2} \cdots & \frac{\partial^2 ee}{\partial x_1 \partial x_S} \\ \frac{\partial^2 ee}{\partial x_2 \partial x_1} & \frac{\partial^2 ee}{\partial {x_2}^2} \cdots & \frac{\partial^2 ee}{\partial x_2 \partial x_S} \\ \vdots & \vdots \quad \ddots & \vdots \\ \frac{\partial^2 ee}{\partial x_S \partial x_1} & \frac{\partial^2 ee}{\partial x_S \partial x_2} \cdots & \frac{\partial^2 ee}{\partial {x_S}^2} \end{pmatrix} \tag{13}$$

For a nonzero column vector $\mathbf{y}$ with S dimensions, the value of $\mathbf{y}^{\mathbf{T}}\mathbf{H}\mathbf{y}$ is determined by the values of b_r, θ_r and x_r. The convexity of (4) cannot be guaranteed. Thus convex optimization theory is not applicable.

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