Energy Efficient Based Splitting for MPTCP in Heterogeneous Networks

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Abstract. This paper models a theoretical framework of energy efficiency concurrent multipath transfer based on MPTCP. An optimal energy efficient splitting way was proposed. By exploring the theoretical relationship between transmission rate and energy efficiency, a multi-network concurrent multipath transmission energy efficiency optimization model is developed. For downlink and concurrent transmission scenarios in heterogeneous wireless networks, the relationship between different network channel states, energy consumption and transmission rate is studied. In order to ensure that the data leave the send queue within a limited time, the Lyapunov optimization method is used in this paper, and then obtained an optimal splitting strategy.

Keywords: Energy efficiency · Lyapunov optimization
Concurrent multi-path transfer · MPTCP

1 Introduction

With the rise of various high-speed transmission business, the demand for transmission rate is increasing, and the fifth generation mobile communication system has proposed the grand goal of increasing the network capacity by 1000 times. To solve these problems, the concurrent transmission was proposed. The multi-path transmite control protocol (MPTCP) [6] and stream control transport protocol (SCTP) [7], [8] based concurrent multi-path transfer (CMT-SCTP) [8] support communication between datacenter and users with a variety of sub-flows under a single connection session. But, MPTCP is easy to be deployed with its readily to TCP. Now, these works mainly care for the problem and some schemes such as retransmission mechanism [9], path management schemes [10], subflow assigning

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algorithms [11], NC based deliver decision [12,13] and rate control algorithms [14] have been discussed.

Neverthless, concurrent multi-path transfer familiarly consumes more energy to remain these interfaces alive. Therefore, an optimal energy efficiency splitting scheme was proposed.

The next, this context is stated as follows. In Sect. 2, the system model was described. We present the problem formulation in Sect. 3. In Sect. 4, We derive the energy-efficiency maximum algorithm via Lyapunov optimization. Section 5, we study the performance of the algorithm. In Sect. 6, we run a simulation of the algorihm. We conclude this context and present later study directions in Sect. 7.

2 System Model Describetion and Derivation

The destination of the presentation scheme is to ensure high quality multipath deliver in a manner that maximizes energy efficient on the downlink side of the network. In the section, w'll present an overview of multipath communication systems MPTCP-based and transmitter energy models.

We consider multi-connection transmission based on MPTCP. Figure 1 shows the communication model. The request data from the internet are forwarded to many wireless networks through many paths. The user equipped with MPTCP are connected to the Internet via HetNets consisting of a lot of radio access technologies (RATs) such as IEEE802.16, 4G, 3G, WiMAX, and the like. The path can access the RAT and be out of line with other paths. The channel bandwidth, channel gain, noise power and transmit power was expressed by $B = \{B_1, B, \ldots, B_N\}$, $G = \{g_1, g_2, \ldots, g_N\}$, $\sigma^2 = \{N_0, N_0, \ldots, N_0\}$,$P = \{P_1, P_2, \ldots, P_N\}$, respectively.

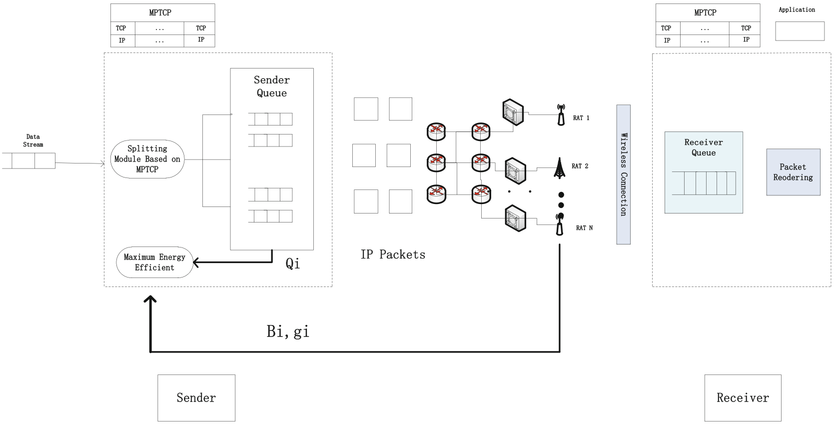

Fig. 1. System model

According to the Shannon formula, the capacity of any access network is:

$$R_i = B_i log_2(1 + \frac{g_i P_i}{B_i N_0}) \tag{1}$$

Consequently, we can obtain the transmite power.

$$P_i = \frac{N_0 B_i}{g_i}(2^{\frac{R_i}{B_i}} - 1) \tag{2}$$

The energy efficiency maximization goal can be derivated as

$$max \qquad \eta_e = \frac{\sum_i^N R_i}{\sum_j^N P_j(R_j)} = \frac{R_{req}}{\sum_i^N \frac{N_0 B_i}{g_i}(2^{\frac{R_i}{B_i}} - 1) + P_i^{cst}} \tag{3}$$

$$s.t. \qquad C1 : R_i \geq 0 \tag{4}$$

$$C2 : \sum_i^N R_i = R_{req}, \tag{5}$$

where P_i^{cst} is the static power, and R_{req} is the request data rate. However, this is a non-convex problem (see proof in [5]). The method of convex optimization can not be used directly. The Genetic Algorithm(GA) was used to search for the optimal solution in [5], but the complexity is too high. Consequently, we will simplify this issue.

When the request rate is constant, maximizing energy efficiency can be equivalent to minimizing power consumption. We consider the concurrent transmission of the downlink, and the static power consumption is not what we care about. In this paper, we treat it as a constant, so the original optimization problem can be equivalent to be write the following problem.

$$P1 : \qquad \min \qquad \sum_i^N \frac{N_0 B_i}{g_i}(2^{\frac{R_i}{B_i}} - 1) \tag{6}$$

$$s.t. \qquad C1 : R_i \geq 0 \tag{7}$$

$$C2 : \sum_i^N R_i = R_{req} \tag{8}$$

3 Probelm Formulation

To ensure that all arriving data leave the buffer for a limited time, we introduced the idea of queue-steady. In order to maximize energy-efficient transmission, the system tends to assign more link and energy to users with better link state. However, for users with poor link states, the queue size may increase indefinitely, resulting in a large number of packet delays, which may cause severe data out-of-order. In fact, this is a trade-off between latency and power. The data queue is expressed as follows.

$$Q_i(t+1) = max\{Q_i(t) - R_i(t) + A_i(t), 0\} \tag{9}$$

The $Q_i(t)$, $A_i(t)$, $R_i(t)$ are the queue size, arrival rate, and service rate, respectively. The strong stability of the queue [5] satisfies the following relationship.

$$\overline{Q_i(t)} = \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \{|Q_i(\tau)|\} < \infty \tag{10}$$

The original optimization problem can be derived from P1 as follows.

$$P2: \quad min \quad \sum_i^N \frac{N_0 B_i}{g_i}(2^{\frac{R_i}{B_i}} - 1) \tag{11}$$

$$s.t. \quad C1: R_i \geq 0 \tag{12}$$

$$C2: \sum_i^N R_i = R_{req} \tag{13}$$

$$C3: \overline{Q_i(t)} = \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \{|Q_i(\tau)|\} < \infty \tag{14}$$

4 An Energy-Efficiency Maximum Algorithm via Lyapunov Optimazation

This paper use the drift-plus-penalty (DPP) algorithm proposed in [1] to solve this optimization problem. According to [1], we can write the Lyapunov function as follows.

$$L(\boldsymbol{Q}(t)) = \sum_i Q_i^2(t) \tag{15}$$

where, the $\boldsymbol{Q}(t) = \{Q_1(t), Q_2(t), \ldots, Q_N(t)\}$. The conditional Lyapunov offset in unit time can be written as follows.

$$\varDelta(\boldsymbol{Q}(t)) = L(\boldsymbol{Q}(t+1)) - L(\boldsymbol{Q}(t)) \tag{16}$$

The above problems can be described by

$$VP(t) + \varDelta(\boldsymbol{Q}(t)) \tag{17}$$

where $P(t) = \sum_i^N \frac{N_0 B_i}{g_i}(2^{\frac{R_i}{B_i}} - 1)$ and V is a control parameters

Lemma 1. *Suppose that the link is independently and equally distributed (i.i.d) in each time slot. Under any splitting algorithm, $\forall V \geq 0$, and $\forall Q(t) \geq 0$, the DPP subject to the following relationships.*

$$\begin{aligned} VP(t) + \varDelta(\boldsymbol{Q}(t)) \\ \leq \Im + VP(t) \\ + \sum_i^N Q_i(t)(A_i(t) - R_i(t)) \end{aligned} \tag{18}$$

where $\Im$ *is more than zero, subject to for all* t

$$\Im \geq \sum_{i}^{N}(A_i(t)^2 + R_i(t)^2). \tag{19}$$

Proof of Lemma 1 reference [4].

In order to minimize P2, a traffic offload scheme is presented to minimize DPP terms of P3. Therefore, we can minimize the upper bound in (18) subject to the same conditions of C1-C2 besides the C3 by the optimization theory. And then, the problem P3 can be exoressed by

$$\begin{aligned} P3: \qquad & min \qquad V\sum_{i}^{N} P_i - \sum_{i}^{N} Q_i R_i & (20)\\ & s.t. \qquad C1: R_i \geq 0 & (21)\\ & \qquad\qquad C2: \sum_{i}^{N} R_i = R_{req} & (22) \end{aligned}$$

Obviously, this problem is a convex optimization problem, which is proved as follows. The second order partial derivatives of $P3(R)$ can be written as (23) and (24).

$$\frac{\partial^2 P3(R)}{\partial R_i^2} = ln^2 2 \frac{N_0}{B_i g_i} 2^{\frac{R_i}{B_i}} \tag{23}$$

$$\frac{\partial^2 P3(R)}{\partial R_i R_j} = \frac{\partial^2 P3(R)}{\partial R_j R_i} = 0 \tag{24}$$

So, the Hessian Matrix of (20) that is constructed of the second order partial derivatives of $P3(R)$ could be written as (25).

$$\boldsymbol{H} = \begin{pmatrix} ln^2 2 \frac{N_0}{B_1 \cdot g_1} 2^{\frac{R_1}{B_1}} & 0 \ldots & 0 \\ 0 & ln^2 2 \frac{N_0}{B_2 \cdot g_2} 2^{\frac{R_2}{B_2}} & \ldots 0 \\ \ldots & & \\ 0 & 0 \ldots & ln^2 2 \frac{N_0}{B_N \cdot g_N} 2^{\frac{R_N}{B_N}} \end{pmatrix} \tag{25}$$

Letting the $\boldsymbol{x}$ is the non-zero vector, we can obtain the formula as follows.

$$\boldsymbol{x}^T \boldsymbol{H} \boldsymbol{x} > 0 \tag{26}$$

Its value is always greater than zero, and the convexity can be guaranteed. Here, the convex optimization theory can be used to resolve the object issue and the optimal rate of N networks joining the concurrent transmission network can be solved. Therefore, we can use the gradient descent algorithm to find the optimal solution. The raised algorithm can be detailly presented in Algorithm 1.

Algorithm 1. Optimal splitting stratergy base on Armijio Rute algorithm

```
Require:
  Initialize $P_i$, $N_0$ and $R_i$, $B_i$, $Q_i$.
  Initialize capacity, denoted as $C_i = \{C_1, C_2, \dots C_N\}$
  Initialize rate for RAT, $\left\{R_1^{(0)}, R_2^{(0)}, \dots R_N^{(0)}\right\}$. Initialize values of each dual variables, $\alpha_i^{(0)}, b_i^{(0)} \in \mathrm{dom}N$.
  while $\left|f_l^{(k+1)}\text{-}f_l^{(k)}\right| \leq \eta$ do
      for $i = 1 : N$ do
          Calculate the direction of dual variables. $\Delta\alpha_i^{(k)} = -\frac{\partial f_l}{\partial \alpha_i}, \Delta b_i^{(k)} = -\frac{\partial f_l}{\partial b_i}$
          Select the step size of dual varibles by gradient descent.
          The $f_l$ is calculated from (27) updated dual variables
      end for
  end while
Ensure:
  Output the optimal rate allocation set $\{R_1^*, R_2^*, \dots R_N^*\}$ and optimal splitting stratergy according to the (34).
```

For the aforementioned problem, the Lagrangian function can be presented by.

$$
\begin{aligned}
&f_l(R, \alpha, b) \\
&\quad = V \sum_i^N P_i - \sum_i^N Q_i R_i + \alpha' * g(R) + b * h(R) \\
&\quad = V \sum_i^N \frac{N_0 B_i}{g_i}\left(2^{\frac{R_i}{B_i}} - 1\right) - \sum_i^N Q_i R_i + \alpha' * g(R) + b * h(R)
\end{aligned}
\tag{27}
$$

where

$$g_i = -R_i \tag{28}$$

$$h(R) = \sum_i^N R_i - R_{req} \tag{29}$$

We can write Karush-Kuhn-Tucker (KKT) conditions as follows.

$$\frac{\partial f_l(R, \alpha, b)}{\partial R_i} = \frac{N_0}{g_i}\left(2^{\frac{R_i}{B_i}} - 1\right) ln2 - Q_i - \alpha_i + b = 0 \tag{30}$$

$$h(R) = 0 \tag{31}$$

$$\sum_i^N \alpha_i g(R_i) = 0 \tag{32}$$

So

$$\frac{\partial f_l(R)}{\partial R_1}\Big|_{R_1^*} = \frac{\partial f_l(R)}{\partial R_2}\Big|_{R_2^*} = \dots = \frac{\partial f_l(R)}{\partial R_N}\Big|_{R_N^*} \tag{33}$$

We can obtain the optimal rate R_i^* with the set $R^* = \{R_1^*, R_2^*, \ldots, R_N^*\}$.

For access network RAT_i, letting the splitting ratio as follows.

$$\phi_i = \frac{R_i^*}{\sum_i^N R_i^*} \tag{34}$$

The result of the object issue is the splitting vector consisting of the splitting factors of all sub-flows in R.

5 Performance Analysis

Theorem 1. *If the link state is i.i.d on each slot, then, we have the relationships about the average power and queue backlogg as follows.*

$$\overline{P} \leq \frac{\Im}{V} + \overline{P^*} \tag{35}$$

$$\overline{Q} \leq \frac{\Im + V\overline{P^*}}{\epsilon} \tag{36}$$

where ϵ is a small positive value.

Theorem 1 describes a trade-off of $[O(1/V), O(V)]$ between power consumption and data backlogg (i.e., latency). As increasing control parameter V, the power consumption can tend to the upper bound, however, the transmission latency remains increasing by (35) and (36). Proof sees the context [4].

6 Simulation

See (Table 1).

Table 1. The simulation parameters.

Network	RAT_1	RAT_2	RAT_3	RAT_4
Bandwidth (B/KHz)	220	240	280	320
Channel gain (g)	0.008	0.007	0.006	0.005
Queue length (Q, k = 1:50)	500*k	700*k	900*k	1000*k
Control parameters (V)	1–200	1–200	1–200	1–200

6.1 Impact of Request Rate (R_{req}) on Energy Efficiency ($V = 75$)

Figure 2 presents that the request rate is small, the energy efficiency of a single network operator is similar to the algorithm of this paper, and it will be higher under a certain threshold. With the increase of user request rate, the energy efficiency of single network operator declines rapidly. This is explained by the fact that the system has reached its ultimate capacity. Increasing the transmission power does not increase the transmission rate of the system. On the contrary, it will cause more interference to nearby users.

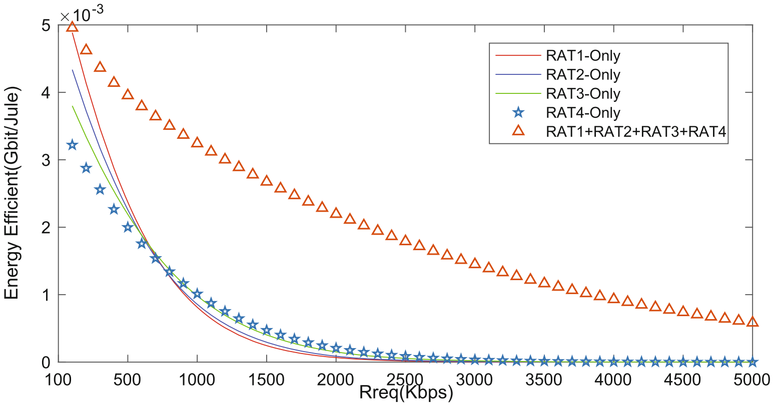

Fig. 2. Energy efficiency changes with the request rate

6.2 Effect of Control Parameter V on Energy Efficiency

Figure 3 shows that we can strike a balance between power and latency. For example, if the network controller selects $0\ leV\ le20$, the before algorithm is better than splitting. In particular, the proposed algorithm can increase the energy efficienct of our way with the same traffic latency.

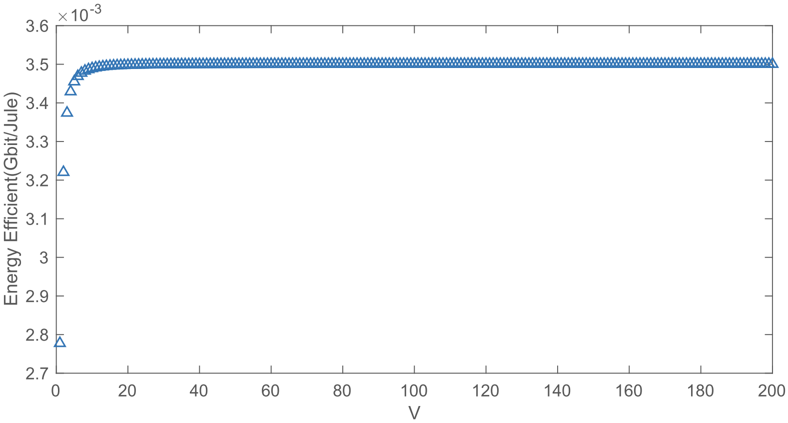

Fig. 3. Energy efficiency changes with the control parameters V

6.3 The Effect of Average Queue Length on Energy Efficiency

Figure 4 displays that the longer the queue, the lower the energy efficienct of the system will be. When the request capacity is a constant, the longer the queue,

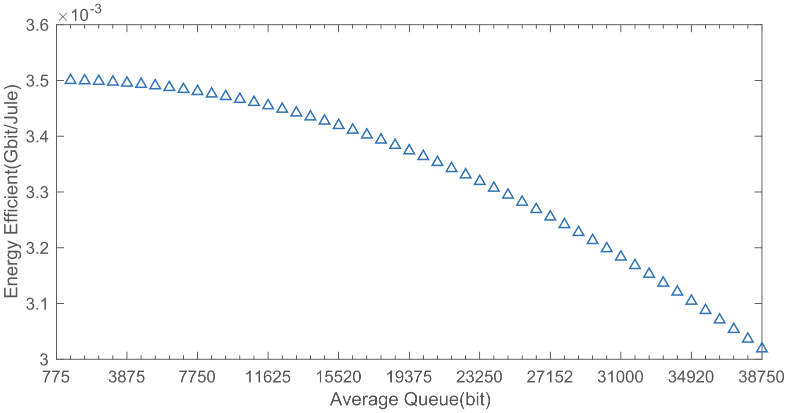

Fig. 4. Energy efficiency changes with the average queue

the longer the time of the packet will leave the send buffer. After the maximum time limit, packet loss and out-of-order will occur. At this time, the receiver will require retransmission, resulting in increasing energy consumption and reducing energy efficiency.

7 Conclusions

In this paper, a concurrent multipath transfer traffic splitting strategy based on energy efficiency maximum is proposed, and Lyapunov optimization method is utilized to obtain the optimal splitting ratio. Through simulation, we know that while guaranteeing the transmission rate requested by the user, it can effectively improve energy efficient of the system, reduce the power consumption of the system, and decrease the transmite delay of the data. The essence of the algorithm in this paper is to make a trade-off between delay and power. In line with the concept of green communication proposed by the fifth generation mobile communication. In the future, we will consider using random geometric methods to partition the interference. It is not necessary to ensure the QoS of the requesting user but also the QoS of the user under the access network that joins concurrent transmission network.

References

1. Cao, Y., et al.: A LDDoS-aware energy-efficient multipathing scheme for mobile cloud computing systems. IEEE Access **5**(99), 21862–21872 (2017)
2. Wang, W., et al.: Beamforming design for energy-constrained full-duplex two-way relaying system. J. Commun. (2018)
3. Ma, X., Sheng, M., Zhang, Y., Xijun, W., Chao, X.: Concurrent transmission for energy efficiency of user equipment in 5G wireless communication networks. Sci. China Inf. Sci. **59**, 1 (2016). https://doi.org/10.1007/s11432-015-5507-3d

4. Gu, Y., Wang, Y., Cui, Q.: A stochastic optimization framework for adaptive spectrum access and power allocation in licensed-assisted access networks. IEEE Access **5**, 16484–16494 (2017)
5. Wang, W., Wang, X., Wang, D.: Energy efficient congestion control for multipath TCP in heterogeneous networks. IEEE Access **6**, 2889–2898 (2018)
6. Peng, Q., et al.: Multipath TCP: analysis, design, and implementation. IEEE/ACM Trans. Netw. **24**(1), 596–609 (2016)
7. Sarwar, G., et al.: eCMT-SCTP: improving performance of multipath SCTP with erasure coding over lossy links, pp. 476–483 (2013)
8. Verma, L.P., Sharma, V.K., Kumar, M.: New delay-based fast retransmission policy for CMT-SCTP. Int. J. Intell. Syst. Appl. **10**, 3 (2018)
9. Xue, K., et al.: DPSAF: forward prediction based dynamic packet scheduling and adjusting with feedback for multipath TCP in lossy heterogeneous networks. IEEE Trans. Veh. Technol. **67**(2), 1521–1534 (2018)
10. Trivedi, P., Singh, A.: Stochastic multi-path routing problem with non-stationary rewards, pp. 1707–1712 (2018)
11. Low, S.H.: A duality model of TCP and queue management algorithms. IEEE/ACM Trans. Netw. **11**(4), 525–36 (2003)
12. Arianpoo, N., Aydin, I., Leung, V.C.M.: Network coding as a performance booster for concurrent multi-path transfer of data in multi-hop wireless networks. IEEE Trans. Mob. Comput. **16**(4), 1047–1058 (2017)
13. Aslam, M.A., Hassan, S.A.: Analysis of linear network coding in cooperative multi-hop networks. Wirel. Pers. Commun. **8**, 1–15 (2017)
14. Liu, J., et al.: Joint congestion control and routing optimization: an efficient second-order distributed approach. IEEE/ACM Trans. Netw. **24**(3), 1404–1420 (2016)