

Study on Characteristics of Metric-aware Multipath Algorithms in Real Heterogeneous Networks

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Abstract—Multipath transmission is considered one of the promising solutions to improve wireless resource utilization where there are many kinds of heterogeneous networks around. Most scheduling algorithms rely on real-time network metrics, including delay, packet loss, and arrival rates, and achieve satisfying results in simulation or wired environments. However, the implicit premise of a scheduling algorithm may conflict with the characteristics of real heterogeneous wireless networks, which has been ignored before. This paper analyzes the real network metrics of three Chinese heterogeneous wireless networks under different transmission rates. To make the results more convincing, we conduct experiments in various scenarios, including different locations, different times of the day, different numbers of users, and different motion speeds. Further, we verify the suitability of a typical delay-aware multipath scheduling algorithm, Lowest Round Trip Time, in heterogeneous networks based on the actual data measured above. Finally, we conclude the characteristics of heterogeneous wireless networks, which need to be considered in a well-designed multipath scheduling algorithm.

Index Terms—Measurement, Heterogeneous Wireless Network, Multipath, Metrics-aware

I. INTRODUCTION

With the appearance of multi-interface devices, terminals have the ability to access heterogeneous networks at the same time, such as WiFi [1], 3G, 4G, 5G. However, most terminals can only provide network services for users using a single link, rather than coordinated transmission using heterogeneous networks. It is difficult for a single link to provide satisfying quality of experience (QoE) at anytime and anywhere, especially in the dense urban area and the remote mountain area. Meanwhile, the load imbalance among heterogeneous links happens frequently. Some links have amounts of users but a few resources available, while others are the opposite.

Multipath transmission [2] utilizes heterogeneous links simultaneously, increasing resource utilization and providing users with satisfying QoE. It is a typical thought to select the most optimal path for different data flows in heterogeneous networks [3]–[5]. Scheduling algorithms play a key role in the process of selection because they decide whether multipath transmission can achieve good results. Most scheduling algorithms determine the proportion and order of each link based

on real-time metrics, such as delay [6], packet loss [7], and the combination of several metrics [8].

As shown in Fig.1, a typical multipath transmission usually conducts between a sender and a receiver. The sender sends data through different links, while the receiver aggregates the separation data, forwarding them to the next hop. The sender can obtain some network metrics, including the Round Trip Time (RTT), transmission rate (TR), packet loss rate (PLR), and the reported arrival rate (AR) from the receiver. However, the detailed real-time information of intermediate nodes, such as the length of the queue and the volume of traffic, is unavailable. Insufficient information and dynamic metrics bring significant challenges to scheduling algorithms. Although these algorithms have achieved perfect results in simulation or wired environments, their performance in wireless networks is still dissatisfaction [9]. However, the reasons for poor performance have not been analyzed in detail.

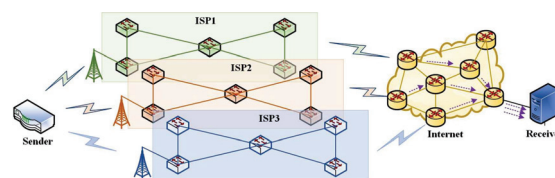


Fig. 1: A typical multipath transmission process.

It is essential to understand the performance of wireless networks in the real world. Researchers conduct related experiments about the latency an Internet Service Provider (ISP) can provide around the world, including China Unicom [10], China Mobile, China Telecom, Telecom of Kosovo (TK) [11], etc. Other measurements focus on different aspects of wireless networks, such as throughput [12], energy efficient [13], and the Transmission Control Protocol (TCP) performance in the high-speed environment [14]. However, most experiments do not pay much attention to the different performance among heterogeneous networks at different transmission rates, which is essential for multipath algorithms to optimize scheduling. The experiments in this paper mainly focus on the similarities and differences among heterogeneous wireless networks to provide a data foundation for future analysis.

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TABLE I: The description of measurement scenarios

Group	Scenes	China Telecom	China Unicom	China Mobile	Transmission Rates	t_1	t_2
1	Statics, Beijing, 2:00, week, 4G	✓	✓	✓	0.1Mbps, 0.2Mbps ..., 3Mbps, 3.5Mbps, 4Mbps, ..., 10Mbps, 11Mbps, 12Mbps, ..., 30Mbps, 40Mbps, 50Mbps, ..., 90Mbps.	5s	60s
2	Statics, Beijing, 5:00, week, 4G	✓	✓	✓			
3	Statics, Beijing, 8:00, week, 4G	✓	✓	✓			
4	Statics, Beijing, 11:00, week, 4G	✓	✓	✓			
5	Statics, Beijing, 14:00, week, 4G	✓	✓	✓			
6	Statics, Beijing, 17:00, week, 4G	✓	✓	✓			
7	Statics, Beijing, 20:00, week, 4G	✓	✓	✓			
8	Statics, Beijing, 23:00, week, 4G	✓	✓	✓			
9	Statics, Beijing, 8:00, weekend, 4G	✓	✓	✓			
10	Statics, Hebei, 11:00, week, 4G	✓	✓	✓			
11	Statics, Hebei, 23:00, week, 4G	✓	✓	✓			
12	Mobile environment, 4G	✓	✓	✓	0.1Mbps, ..., 90Mbps ¹	5s	120s

¹ TRs = {0.1Mbps, 0.5Mbps, 1Mbps, 1.5Mbps, 2Mbps, 2.5Mbps, ..., 9Mbps, 9.5Mbps, 10Mbps, 12Mbps, 14Mbps, 16Mbps, 20Mbps, 25Mbps, 30Mbps, 50Mbps, 70Mbps, 90Mbps}

In this paper, we mainly focus on the characteristics of heterogeneous wireless networks in the real world and their influence on typical multipath scheduling algorithms. Our contributions can be summarized as follows:

- We collect delay, arrival rates, and packet loss rates under different transmission rates between the sender and the receiver in wireless networks provided by three ISPs of China.
- We analyze the suitability of a typical thought in most multipath scheduling algorithms, Lowest Round Trip Time (LowRTT), in such heterogeneous networks.
- Based on the network metrics measured above, we summarize the characteristics that need to be considered in a multipath scheduling algorithm.

The rest of the paper is organized as follows. In Section II, we introduce the measurement setting and the performance of three ISPs' networks in varieties of scenes. The suitability of LowRTT in such heterogeneous networks and the summary of key characteristics are present in Section III. The paper is concluded in Section IV.

II. KEY CHARACTERISTICS ANALYSIS OF ISP NETWORKS IN VARIETIES OF SCENES.

A. measurement settings

The scenarios where experiments are conducted are shown in Table I. In each group, The sender sends User Datagram Protocol (UDP) packets to the receiver at TRs listed in Table I through three links, respectively. The length of each UDP packet is 1512 bytes, and each transmission lasts for t_2 seconds. At the same time, the sender sends an Internet Control Message Protocol (ICMP) packet with 98 bytes to the receiver every 10 ms. To ensure that the latency when sending UDP data is recorded accurately, we begin to send ICMP packets t_1 seconds before UDP packets and end sending t_1 seconds after UDP packets. In order to avoid unnecessary overhead and increase effectiveness, different transmission rates and t_2 are set in the mobile environment as shown in Group 12.

B. Characteristics analysis of ISP networks at different TRs

Due to the limitation of article length, only part of the delay at different transmission rates is displayed in Fig.2.

Delay: When the transmission rate is small (Fig.2(a)), the delay of three ISP networks is similar, ranging from 20ms to 100ms. With the increasing transmission rates, the delay of three ISP networks presents different trends:

- The delay of China Mobile increases at $TR = 4Mbps$ because of the lowest bandwidth and stays with about 800ms at last (yellow curves in Fig.2(b), Fig.2(c)).
- The delay of China Unicom increases gradually, from $TR = 9Mbps$ to $TR = 27Mbps$ (orange curves in Fig.2(c) ~ Fig.2(g)). Its delay stays with about 200ms.
- Similarly, The delay of China Telecom increases gradually from $TR = 17Mbps$ to $TR = 21Mbps$ (blue curves in Fig.2(e), Fig.2(f)), and stay with similar ranges with China Unicom.

When the transmission rate continues to increase as far beyond the bandwidth of links, their delay does not increase endlessly (Fig.2(h), Fig.2(o)). The steady delay of China Mobile is much higher than that of China Telecom and China Unicom. It means that the latency of heterogeneous links has a big difference with one another when overloading happens.

To prove whether the upper limit of delay in heterogeneous wireless networks is significantly different, we conduct detailed experiments in various scenes. The statistical consequences are shown in subsection C.

Packet loss: In Fig.3, the packet loss rate of each link is plotted on the left axis using a dashed curve. To obtain the continuous change of packet loss, we calculate the sliding packet loss rate as

$$loss_{i \rightarrow limit+i} = 1 - \frac{num_{arrival< i \rightarrow limit+i >}}{limit} \quad (1)$$

where $i = 1, 1+s, \dots, 1 + \lfloor \frac{Max_{ID} - limit - s}{s} \rfloor * s$ represents packet sequences, $limit = 200$ denotes the size of window, $s = 100$ denotes the sliding steps, $num_{arrival< i \rightarrow limit+i >}$ denotes the number of packets whose sequences is in $< i, limit + i >$, and Max_{ID} is the sequence of the last packet.

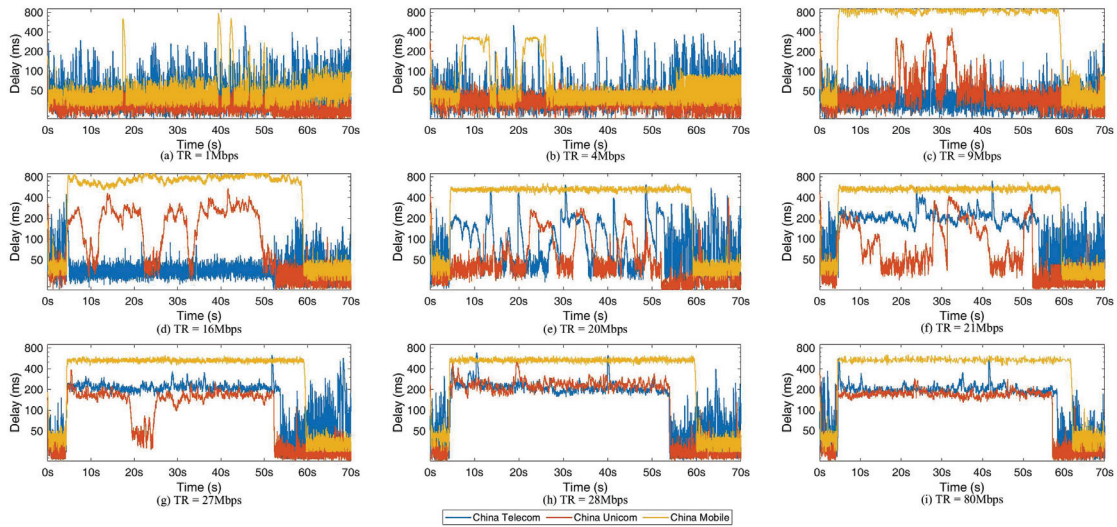


Fig. 2: Delay of different ISP networks in different transmission rates.

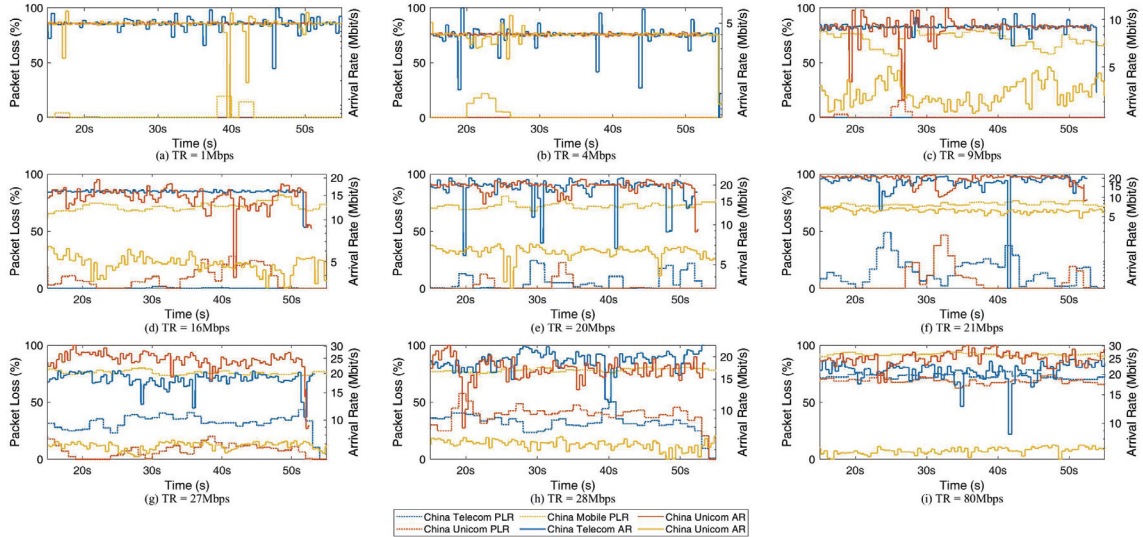


Fig. 3: Packet loss and arrival rate of different ISP networks in different transmission rates.

There is a positive correlation between the packet loss rate and delay of the same link. As shown in Fig.3(b), The packet loss rate of China Mobile (the dashed yellow curve) increases at $time = 20s$, and the corresponding delay (the continuous yellow curve in Fig.2(b)) increases in the meanwhile. The same pattern is found when packet loss happens on any link at anytime. Packet loss is more likely to occur when delay increases. Meanwhile, when the packet loss of a link is 0, its delay is also stable around $50ms$.

Arrival rate: In Fig.3, the arrival rate of each link is plotted on the right axis using continuous lines. A noticeable fluctuation at the receiver is observed. Even though $TR = 1Mbps$ is much lower than the bandwidth of China Unicom and

China Telecom, the corresponding arrival rates of the two links are still unstable (orange and yellow continuous curves in Fig.3(a)). The arrival rates at the receiver do not form a straight line but a curve that fluctuates around the average arrival rate. With the increasing transmission rate at the sender, the fluctuation of arrival rates becomes more severe at the receiver, which brings great difficulty to scheduling algorithms to achieve bandwidth aggregation.

Further, there is a feature worth mentioning. If there is a line parallel to the X-axis between the real-time packet loss rate and arrival rate of the same link, the packet loss rate and the arrival rate are symmetric about this line in most cases. It means that it is possible to evaluate the arrival rate using the

real-time transmission rate and packet loss rate.

C. Statics analysis on ISP networks in varieties scenarios

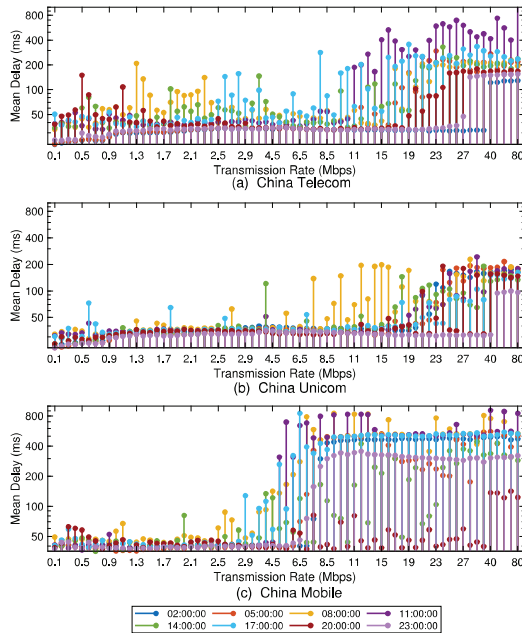


Fig. 4: Delay of different ISP networks at different times of the day.

Different times of the day: The average delay of each link with changeable transmission rates at different times of day is plotted in Fig.4. The mean delay of China Telecom (Fig.4(a)) fluctuates obviously, even though the transmission rate is low. In contrast, the mean delay of China Unicom (Fig.4(b)) and China Mobile (Fig.4(c)) is relatively stable. When the transmission rate grows continuously to near the bandwidth, the average delay of each link increases quickly. The upper limit of China Telecom ranges from 150ms to 300ms, and the upper limit of China Unicom ranges from 100ms to 200ms. The upper limit of China Mobile ranges from 300ms to 800ms in most cases, while the average delay in the group beginning at 20:00 is only 180ms.

Different numbers of users: To ask for the considerable difference between the group beginning at 20:00 and other groups in terms of China Mobile, we conduct a contrast experiment at 8:00 on the weekend, when the number of users is small. The results are shown in Fig.5. The average delay at 8:00 on the weekend (the orange curve in Fig.5) is similar to that at 20:00 on the week (the yellow curve in Fig.5). It means that China Mobile is sensitive to the number of users. In other words, China Mobile has to decline the quality of service (QoS) to a certain extent because of a vast number of users in regular times.

Different places: In Fig.6, the trend of average delay belonging to three ISPs in Beijing and Hebei is similar. When the transmission rate is low, the delay is stable, and the

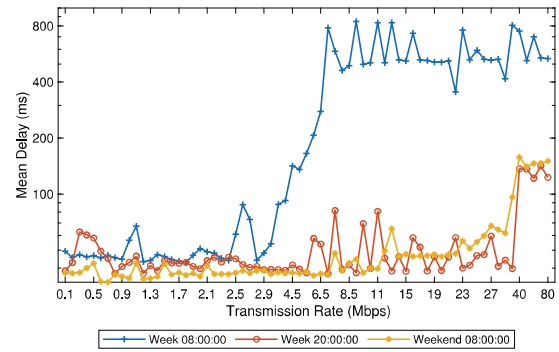


Fig. 5: The average delay of China Mobile in different number of users

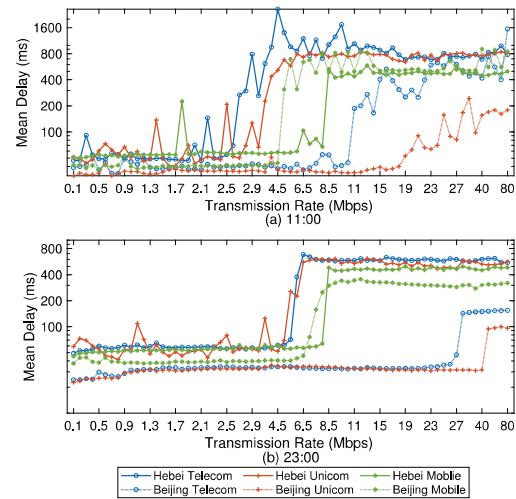


Fig. 6: The average delay in different places.

average delay increases rapidly and reaches the upper limit with the growing transmission rate. Although a significant difference exists about the upper limit of average delay between China Unicom and China Telecom in Beijing, there is no significant difference between them in Hebei. Meanwhile, links of different ISPs have apparent differences in the upper limit of average delay in different locations. There is a big difference between the upper limit of the average delay of China Unicom in Hebei and Beijing.

Mobile environment: There are two features different from the characteristics of wireless networks in the static environment. First, more severe fluctuations occur in the mobile environment (Fig.7(d), Fig.7(e), Fig.7(f)) than in static (Fig.7(a), Fig.7(b), Fig.7(c)). Second, the upper delay limit of China Mobile and China Telecom are larger than those for static environments. It means that the data is cached for a longer time in the ISP networks.

Due to the limited coverage of a single base station, handoff among base stations is inevitable in a mobile environment. User data is forwarded from the source BS to the target base station or Mobility Management Entity (MME) before the handoff.

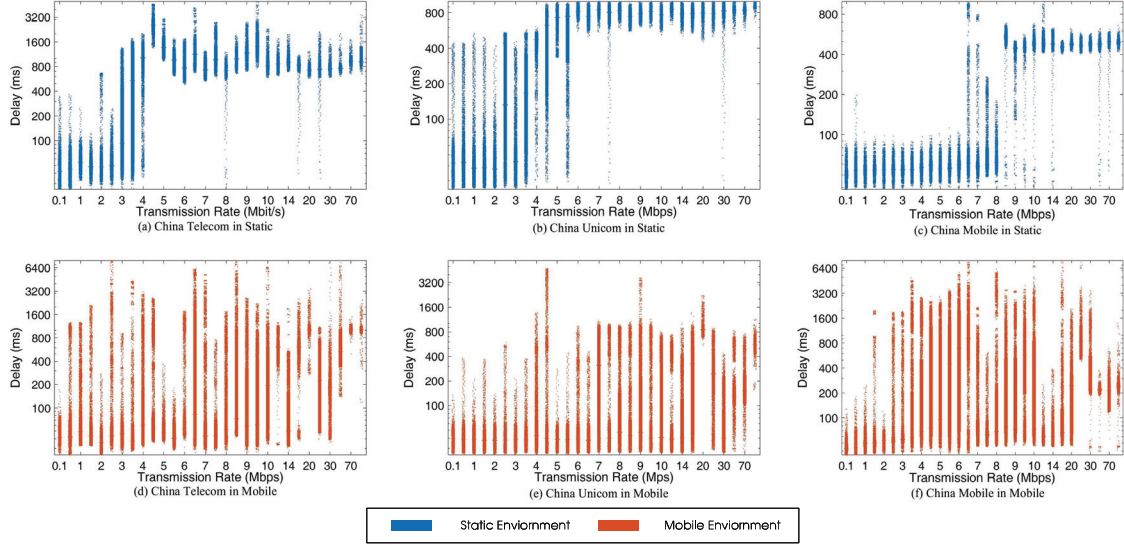


Fig. 7: Delay of different ISP networks in mobile environment.

The target base station or MME cache both the data user transferred to the receiver and the receiver's data replied to the user. Only when the handoff is complete will the target base station send the data cached during the handoff to the user. The cache in a target base station or MME is why the upper limit delay of China Unicom and China Mobile increases.

III. KEY CHARACTERISTICS FOR MULTIPATH ALGORITHMS IN HETEROGENEOUS WIRELESS NETWORK

A. Adaptability analysis of a typical multipath algorithm

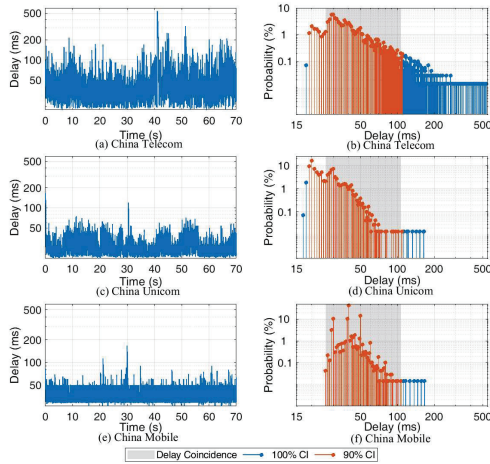


Fig. 8: Delay distribution different ISP networks under no load.

The main idea of LowRTT is that the link with the shortest delay is selected first, which influences most mainstream multipath scheduling algorithms, such as MultiPath Transmission

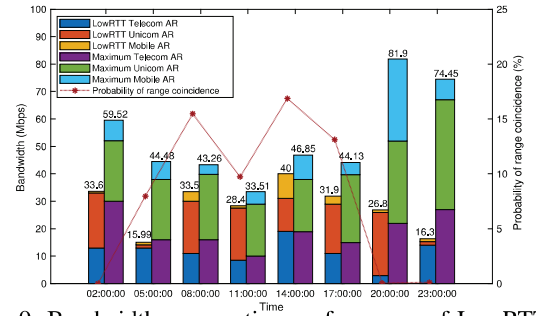


Fig. 9: Bandwidth aggregation performance of LowRTT.

Control Protocol (MPTCP). To analyze the idea of LowRTT in detail, we first test the delay distribution of three heterogeneous wireless links under no load, as shown in Fig.8(b), Fig.8(d), Fig.8(f). The blue curve represents the full delay range of each link, while the orange curve represents a 90% confidence interval (CI). The delay distributions of links need to coincide if LowRTT can use three links at the same time, which is displayed in the gray area in Fig.8(b), Fig.8(d), Fig.8(f). Similarly, we can calculate the delay distribution of each link at each transmission rate in each group based on the data measured before.

When the first packet is waiting to send, it selects the link with the shortest delay in real-time. In this case, LowRTT makes use of all links due to the delay range of three links overlapping. As data waiting to send increases to 100Kbps, the delay for the next packet comes to the delay distribution at $TR = 100Kbps$. In this way, as long as the delay distribution of these links at different transmission rates has a common range, these links are used simultaneously in multipath transmission.

We assume that the maximum packet loss rate of links is 1% because a larger packet loss rate provides poor QoE for users. The transmission rates with packet loss rate exceeding 1% are not evaluated next. The maximum transmission rate of a link is considered as its bandwidth. The maximum sum of transmission rates of three links on the promise of having a coincidence delay range is the performance limitation of LowRTT. The probability of range coincidence is defined as follows:

$$Pro_{(t_1, t_2)} = \prod_{m=1}^{m=\max} \left(\sum_{t=t_1}^{t=t_2} pro_m(t) \right) \quad (2)$$

where $pro_m(t)$ denotes the probability that the delay of $link_m$ in the common range.

The results are shown in Fig.9. LowRTT performs better during the period with many users because the delay fluctuation more severe, increasing the coincidence range of links. The delay fluctuation benefits the comprehensive utilization of heterogeneous links with different characteristics in a sense. However, unsatisfying results appear in the period with few users. The best bandwidth multiplexing reaches 85%, while the corresponding range coincidence rate is 17%.

However, the performance on bandwidth aggregation of LowRTT is unsatisfying in all. The root of the poor performance is the different delay upper limit of heterogeneous wireless links. When the delay of a link continues to be higher than other links, LowRTT sends packets through the link with the lowest delay even if packet loss has happened. On the other hand, If there is no packet loss in every link, LowRTT can not make full use of the links with higher delay. The former brings bad QoE to users due to packet loss, while the latter cannot make full use of multiple heterogeneous links, resulting in poor bandwidth aggregation performance, as shown in Fig.9.

B. Summary on key characteristics in heterogeneous networks

Based on experiments conducted above, key characteristics that can not be ignored when designing or optimizing multipath scheduling algorithms are summarized as follows:

- Limited upper delay. The biggest delay a link can reach is affected by the cache of intermediate nodes. The biggest delay of links is not under our control but must be considered. Well-designed algorithms need to avoid choosing the path filled with packets while its delay is still small.
- "High latency" when packets are lost. When packet loss happens due to unstable bandwidth, it is often accompanied by abnormally high latency. If the abnormal delay can predict packet loss, it is possible to schedule packets before congestion, obtaining good results.
- The similarity of packet loss rates and arrival rates. It is difficult to obtain real-time bandwidth when an algorithm schedules the number of packets to links. The evaluated bandwidth using transmission rate and packet loss rate may provide a good solution.

IV. CONCLUSION

In this paper, we conduct detailed experiments on the characteristics used in many scheduling algorithms in heterogeneous wireless networks. A noticeable phenomenon is the different upper limit of delay among heterogeneous networks, which brings trouble to multipath scheduling algorithms, such as LowRTT. Due to the different upper limit of delay, LowRTT cannot utilize links with high delay, resulting in poor performance on the bandwidth stack. Finally, we summarize network characteristics that need to be considered in scheduling algorithms, including the different upper limitation delays of links, the synchronously between high delay and packet loss, and the similarity between packet loss rates and arrival rate.

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