

A Longitudinal Measurement Study of TCP Performance and Behavior in 3G/4G Networks Over High Speed Rails

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Abstract—While TCP has been extensively studied in static and low speed mobility situations, it has not yet been well explored in high speed mobility scenarios. Given the increasing deployment of high speed transport systems (such as high speed rails), there is an urgent need to understand the performance and behavior of TCP in such high speed mobility environments. In this paper, we conduct a comprehensive study to investigate the performance and behavior of TCP in a high speed environment with a peak speed of 310 km/h. Over a 16-month period spanning four years, we collect 500 GB of performance data on 3/4G networks in high speed trains in China, covering a distance of 108,490 km. We start by analyzing performance metrics, such as RTT, packet loss rate, and throughput. We then evaluate the challenges posed on the main TCP operations (establishment, transmission, congestion control, flow control, and termination) by such high speed mobility. This paper shows that RTT and packet loss rate increase significantly and throughput drops considerably in high speed situations. Moreover, TCP fails to

adapt well to such extremely high speed leading to abnormal behavior, such as high spurious retransmission time out rate, aggressive congestion window reduction, long delays during connection establishment and closure, and transmission interruption. As we prepare to move into the era of 5G, and as the need for high speed travel continues to increase, our findings indicate a critical need for efforts to develop more adaptive transport protocols for such high speed environments.

Index Terms—TCP, measurement, high speed mobility.

I. INTRODUCTION

MANY studies have been done on evaluating TCP in different scenarios, and various improvements have been proposed [1]–[12]. However, most previous work only consider either static or low speed mobile scenarios. The performance and behavior of TCP in high speed (>200 km/h) mobility cases has not yet been well studied. In the last few years, we have seen a significant worldwide progress in the development of high speed rail (HSR), reaching about 32,000 km at end of 2015. With much higher speeds, it will be more challenging for networks to adapt to highly varying mobile environments. Therefore, it is important to have a comprehensive study on the effect of HSR on TCP.

We make a contribution in this area by performing a comprehensive measurement to investigate TCP performance and behavior on Chinese HSRs with a peak speed of 310km/h. We conducted extensive measurements on various types of 3/4G networks of three large commercial cellular carriers with a combined number of users of about 1.3 Billion nationwide. We refer to these as Carrier A, Carrier B and Carrier C. The main difference between our work and previous studies lies in not only the very high speed scenarios we study and the large scale (covering a long distance and time) nature of our measurements, but also on our focus. Specifically, our main objective is to answer the following questions:

1) What are challenges brought by HSRs to TCP that do not exist (or are not so serious) in static and low speed mobile scenarios? The particular influence factors in high speed mobility, and the challenges they pose to TCP have never been systematically studied in previous works.

2) Can TCP adapt well to these challenges? If not, does its performance degrade significantly on HSRs? Does TCP show any abnormal behavior in its operations? With regard to TCP performance, while the impact of mobility on performance metrics such as RTT, packet drop and throughput has been

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studied in prior works [7]–[12], most of these studies are in low speed mobile cases. Another limitation is that these studies do not quantitatively analyze the independent (i.e. considered separately) effects of moving speed and handoff on these metrics. With regard to TCP behavior, this issue has never been fully studied for all aspects including connection establishment, transmission, congestion control, flow control and connection closure even in low speed mobile cases, not to mention high speed mobile scenarios.

To the best of our knowledge, our work is the first comprehensive study on the above two questions based on a real, largescale measurement in high speed mobile cases. This article is a significant extension of our previous paper [13], which analyzes TCP performance and behavior in HSPA+ networks of Carrier A. The conference paper finds that TCP cannot adapt well to extremely high speeds and shows significant performance degradation and severe abnormal behaviors in HSPA+ networks. However, there are two important questions which were not explored in the previous paper, which strongly motivated this extended article:

1) Are the results in the prior work affected or biased by anything specific to one network type of one carrier? Is the negative impact of HSRs on TCP performance and operations in HSPA+ networks also prevalent in various 3/4G networks of different carriers?

2) If the negative impact of HSRs on TCP is also common in various 3/4G networks, what lessons have we learned from the inadaptability of TCP? What suggestions can we provide to either enhance TCP for high speed environments, or to develop new more adaptive protocols?

To address above issues, we put significant efforts in extensive measurements on TCP performance and behavior in 3/4G networks with various network types (including FDD-LTE, TD-LTE, HSPA+, HSDPA, UMTS, and EVDOA) of three carriers. It is worth noting that we pay little attention to low layer technical details of various 3/4G networks, but treat low layer networks as a black box and conduct an end-to-end measurement study. This is because the purpose of measuring various 3/4G networks of different carriers is to investigate prevalent problems of TCP in high speed environments, which also have significant reference value for 5G and later networks. Therefore, it is necessary to treat low layer networks as a black box. However, for the differences in low layer networks, there might be some quantitative differences in these prevalent problems among various networks. Therefore, we do not only investigate what is common for various types of networks, but also show quantitative differences among them. Moreover, by evaluating TCP adaptability in high speed environments, we summarize the lessons in key operations of TCP and provide suggestions to develop more adaptive transport protocols.

We confirmed that most findings in HSPA+ networks of Carrier A in the prior work [13] were prevalent in both 3G and 4G networks of different carriers with various network types:

1) **Challenges brought by HSRs.** High speed trains mainly bring three challenges: i) high speed movement leads to serious Doppler frequency shift and fast multipath fading, ii) frequent handoffs result in sharp delays and consecutive

packet losses, and iii) repeated network disconnections lead to transmission interruption of TCP flows.

2) **TCP performance.** With an increase in train speed and number of handoffs that a flow suffers, RTT and packet loss rate rise sharply, while throughput drops significantly. Moreover, these three metrics all vary in much wider ranges than in static and low speed mobile cases. Compared with high speed mobility, frequent handoff brought by fast motion contributes more to TCP performance degradation. We observe that dense base station deployment in urban areas is a double-edged sword, which reduces the range of cells, improves network coverage and capability for stationary and slowly moving mobile users, but increases handoff frequency for fast moving mobile users, significantly hurting TCP performance.

3) **TCP behavior.** TCP operations (including connection establishment, transmission, congestion control, flow control, and connection termination) show serious inadaptability on HSRs. Due to wide RTT variations, the spurious retransmission timeout (RTO) rate is rather high, leading to many undesirable slow starts. Affected by frequent packet losses, TCP suffers aggressive congestion window reductions. Furthermore, TCP spends a longer time to establish or close a connection. In addition, a considerable portion of connections are even closed before a file is completely transmitted due to disconnections.

4) **Effects of flow size.** On HSR, big flows encounter more serious performance degradation than small flows. Big flows face a much higher risk of transmission failures, and suffer much significant congestion window reduction and throughput decrease than small flows.

Although these aforementioned common issues are qualitatively consistent for both 3G and 4G networks, there are quantitative differences between 3G and 4G networks:

1) **TCP performance.** TCP performs much better in 4G networks than in 3G networks on HSRs, with much shorter RTT, lower packet loss rate and higher throughput. It is worth noting that handoff is fatal for TCP in 3G networks, but is only harmful in 4G networks. When handoff occurs in 3G networks, throughput drops to 0 Mbps with a very high probability. Although throughput drops significantly, it rarely drops to 0 Mbps in 4G networks during handoffs.

2) **TCP behavior.** First, with a lower packet loss rate, the retransmission rate reduces on HSRs after the network is upgraded from 3G to 4G. However, the proportion of spurious RTOs in retransmissions does not decrease, remaining almost as high as that in 3G networks. Secondly, the issue of full advertised window and zero advertised window is prevalent in 4G networks, but is rare in 3G networks. Besides, network upgrades from 3G to 4G shift the bottleneck of TCP slide window growth from congestion window to advertised window sometimes in high speed trains. Finally, connection establishment and closure time significantly reduce in 4G networks.

3) **Effects of flow size.** Transmission failure rate of big and small flows both decrease and the difference between them becomes smaller in 4G networks, compared with 3G networks. Big flows can maintain an obvious advantage in congestion window over small flows in 4G networks on HSRs, similar

with static cases. However, big flows no longer maintain the advantage in 3G networks.

Although 4G networks show significant advantages over 3G networks even in high speed trains, the passive impact of HSRs on TCP performance and operations in 4G networks is still considerable. We finally summarize lessons in key operations of current TCP and provide valuable suggestions from the aspects of protocol design in both transport and application layers.

The rest of this article is structured as follows. Section II covers related work. Section III describes the measurement method and data set. We discuss influence factors and design analysis methods in Section IV. Section V analyzes TCP performance and Section VI discusses abnormal behavior in almost all TCP operations. We study the effects of flow size on TCP performance in Section VII, and summarize lessons and provide suggestions in Section VIII before concluding the article in Section IX.

II. RELATED WORK

There are some theoretical studies on TCP in mobile scenarios. Pacifico *et al.* [7] determine that intra-handoff in 4G networks during motion can hurt TCP performance significantly and propose an improvement mechanism. Wang *et al.* [8] design a fast adaptive congestion control scheme for improving TCP performance in soft vertical handoff between WLAN and 3G networks during the mobility of users. However, in real mobile environments, these theoretical studies are hard to apply. For example, handover is very hard to predict in high speed mobility cases, which makes the handover prediction scheme [7] infeasible. In the same way, the congestion control algorithm in work [8] is not able to quickly adapt to the serious variations in bandwidth and delay in high speed mobility scenarios.

There are multiple measurements in low speed mobile cases at speeds below 100 km/h. Litjens [9] evaluates data transfer performance in a UMTS/HSDPA network, with a principal focus on the impact of terminal mobility. Yao *et al.* [10] measure bandwidth and Derksen *et al.* [11] measure average downlink throughput in HSDPA networks in mobile vehicles. Tso *et al.* [12] conduct extensive measurements in HSDPA networks on trains, subways, self-driving vehicles, buses and ferries in Hong Kong, focusing on RTT and throughput performance, and on the impact of mobility and handoff.

Merz *et al.* [14] measure 4G networks in trains with a peak speed of 200 km/h, finding that such a high speed causes significant negative effects on network performance.

Considering speeds up to 300 km/h, only a few short-distanced measurements have been performed. Xiao *et al.* [15] measure 4G networks along a 115 km high speed railway, finding that TCP throughput and RTT are not only worse, but also have a large variance compared to the stationary and driving (100 km/h) scenarios. Jang *et al.* [16] analyze spurious retransmissions and ACK compression rate of TCP flows in CDMA-EVDO networks in 300 km/h trains, covering 450 km railway. Liu *et al.* [17] measure TCP performance in 3/4G networks along a 120 km HSR line. They find that HSRs introduce significant challenges to the TCP retransmission process

after timeouts, and ACKs are more likely to trigger spurious retransmission timeouts in high speed mobile environments.

All of these measurements in slow and high speed mobility cases mainly show statistics of metrics such as throughput, RTT and packet loss rate. Consistent with these prior studies, we also find that low speed (<100km/h) mobility only has a slight impact, but high speed mobility (>280km/h) has a significant impact on these metrics in various 3/4G networks of various carriers on HSRs.

Prior studies have the following limitations: i) The effects of mobility and handoff on TCP performance have not yet been quantitatively analyzed independently and clearly. ii) These studies neither fully study the behavior of TCP in all aspects including connection establishment, transmission, congestion control, flow control and connection closure, nor compare performance among flows with various sizes.

To summarize, the main difference between our work and all these studies lies not only in the high speed motion scenarios we focus on and the large scale nature of our measurements, but also in our contributions towards exposing the challenges posed by HSR to TCP, our quantitative analysis about the effects of mobility and handoff on TCP performance, as well as our evaluation of the adaptability of all aspects of TCP and our study on the impact of flow size on the performance of TCP.

III. MEASUREMENT AND DATA SET

In this Section, we first analyze challenges in measurement, then design the measurement method, and finally present the data set in detail.

A. Measurement Setup

Measurement on TCP in high speed trains is not only effort consuming, but also technically challenging for the following reasons:

1) It requires many people to put in a significant amount of time and effort to collect massive data traces on various HSR routes, covering long distance and time. To this end, we conducted an 8-month measurement on 3G cellular networks of Carrier A and Carrier B from December 2013 to July 2014, when there was no long distance deployment of 4G network along HSR lines in China. Thereafter, the carriers considered upgrading their networks from 3G to 4G along most HSR lines, providing us with a chance to compare TCP performance and behavior in 3G and 4G networks. Therefore, we performed another 8-month measurement on 4G networks of Carrier A and Carrier C from October 2015 to May 2016. Over the two periods spanning 4 years, we collected more than 500 GB of performance data and covered a distance of 108,490 km, almost three times the equatorial circumference of the earth.

2) It is technically very challenging, because too many influence factors are intertwined together. First, terrain along long distance HSR routes is diverse, including plains, hills and tunnels, which highly affects characteristics of signal fading [18], [19]. Secondly, trains experience 4 phases of motion: parking at stations, acceleration, full speed running and deceleration. The variation in speed also affects measurement results. Third, network conditions are highly varying.

TABLE I
TYPES OF SMARTPHONES

Phone	Version (model)	OS (Android)	Carrier	RAT
Samsung Galaxy S4	GT-I9500	Android 4.2	Carrier A	WCDMA (3G), GSM (2G)
Samsung Galaxy S4	GT-I959	Android 4.2	Carrier B	CDMA EVDO (3G), CDMA 1x (2G)
Samsung Galaxy S4	GT-I9507V	Android 4.3	Carrier A	FDD-LTE (4G), WCDMA (3G), GSM (2G)
Samsung Galaxy Note3	SM-N9008V	Android 4.3	Carrier C	TD-LTE (4G), TD-SCDMA (3G), GSM (2G)

Mobile users on trains experience varying handoff frequency, diverse network type (ranging from 2G to 4G) and varying disconnection rate in travel time. The variation in number of passengers in a train may have an impact on the load to the cellular network, which also has a significant impact on our measurement results. Finally, measurement setup schemes also have a significant impact, including choice of mobile devices, configuration of static servers and characteristics of test flows: i) differences in mobile devices may bring significant interference in analyzing the impacts of various networks of different carriers on TCP, ii) results may be affected or biased by anything specific to the server and the path to it, and iii) performance of TCP varies significantly among flows with various size and duration.

To overcome these technical challenges, we carefully design the measurement method:

First, to collect information of multiple factors, we have developed a measurement tool, *MobiNet* [15], which consists of a client and a server program. The client program can run on mobile devices with Android OS and the server program can run on computers with either Windows or Linux OS. The client and server transmit TCP traffic in a client/server mode. Moreover, the client program can get geographical location and speed of the train via GPS, read signal strength, network type, Location Area Code (LAC) and Cell ID (CID) of base stations from the Android OS, and record all of above information in log files. Besides, to make packet level analysis, we capture all the packets on both the phones and the servers with *tcpdump* and *wireshark* respectively.

Secondly, we record the number of passengers in trains and analyze its impact on measurement results. We find that when the number of passengers surpasses a certain threshold (For instance, when the ratio between the total number of passengers and seats on a train is over 1.1 on Beijing-Tianjin line), TCP performance degrades significantly. We find that there is a higher number of passengers on weekends (Saturday and Sunday) than workdays (Monday to Friday). Moreover, there are more passengers around 9:00 am, and around 6:30 pm than during other periods of time on workdays. Therefore, we do not perform measurements at these passenger volume peak times, to reduce the impact of network load resulting from increased access.

Thirdly, as shown in Table I, we use four similar phones with the same brand and series (Samsung Galaxy) to minimize the difference among phones. This can help us significantly reduce the interference from phone difference in analyzing the impacts of various 3/4G networks of different carriers on TCP in high speed trains. The four smartphones support various radio access technologies (RATs) of different carriers. We use the first two phones to measure 3G networks in the first 8-month period, and the last two to measure 4G networks in the second 8-month period.

We deploy servers in two different ways to ensure the results will not be affected or biased by anything specific to one server and the path to it. On one hand, we deploy a server in the same way with the prior work [13]. This server is hosted in the backbone of CERNET [20], which is a dedicated education and research network that interconnects research institutes and universities in China. On the other hand, we deploy an additional dedicated server that has the same configurations with the one in CERNET, which is rented from Alibaba's Aliyun Elastic Compute Service (ECS). The two servers both have sufficient upload/download capacity for our measurements on HSRs. A phone does not communicate with the two servers simultaneously to avoid cross-flow dependencies. The two servers are used alternately: a phone connects with a server in a one-way trip, and then with the other server in the next one-way trip on the same HSR line.

Finally, we carefully choose test flows. We define flow size as the total number of payload bytes within the flow (excluding IP/transport layer headers). Duration is defined as the time span between the first and last packet of a flow. Three types of TCP downlink flows are measured, including flows of 3-minute duration as well as those of size 50 KB and 2 MB. Using short-lived rather than long-lived flows enables us to filter data and perform analysis. We explain the issue in detail in Section IV-A. It is worth noting that when a flow is established, if the user equipment (UE) is not in active mode, radio resource control (RRC) state transitions will significantly affect TCP performance [21]. Therefore, we measure flows in quick succession to avoid that UE becomes inactive after a pause. When a disconnection occurs, we wait until the phone re-connects to the server before resuming the measurements.

B. Data Set

Experiments were conducted on 3 routes: Beijing-Guangzhou (B-G) line, Shanghai-Beijing (S-B) line and Beijing-Tianjin (B-T) line. Table II shows the routes in detail. As an example, the length of the B-G line is 2,298 km, and the train stops at 17 stations along the line. The duration of each on-way trip is 9.7 hours (excluding the parking time at the originating and terminal stations). We accumulated a mileage of 57,450 km in 25 one-way trips (2,298 km in each trip) on the line. Trains experience 4 phases of motion: parking at stations, acceleration, full speed running and deceleration. As shown in Table II, in 25 trips on the B-G line, the train parks at 17 stations (including the originating and terminal station) along the line for 42.2 hours, and the train runs at a speed between 0 and 150 km/h, between 150 and 280 km/h, and between 280 and 310 km/h for 61.3, 48.8 and 115.7 hours respectively. In each one-way trip, we get on the train and start the measurement about 30 minutes before the train leaves the originating station, and stay on the train for about 30 minutes after the train arrives at the terminal to continue

TABLE II
HSR LINES

HSR line	Length (km)	Number of stations	Duration (h)	Number of trips	Mileage (km)	Static (h)	0-150km/h (h)	150-280km/h (h)	280-310km/h (h)
B-G	2,298	17	9.7	25	57,450	42.2	61.3	48.8	115.7
S-B	1,318	10	5.8	30	39,540	41.9	37.5	31.5	91.5
B-T	115	2	0.6	100	11,500	85.6	13.1	10.0	31.9

TABLE III
DATA SET I (DECEMBER 2013 TO JULY 2014)

HSR line	Sub-data Set: A-2014-3G						Sub-data Set: B-2014-3G					
	3-minute		50 KB-sized		2 MB-sized		3-minute		50 KB-sized		2 MB-sized	
	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)
B-G	1,397	17.3	17,410	1.6	3,722	12.5	1,209	12.9	16,618	1.5	3,626	12.2
S-B	1,161	15.3	14,254	1.4	3,142	10.5	1,068	11.2	13,212	1.3	2,937	9.8
B-T	803	8.8	7,475	0.7	1,492	5.3	792	6.7	7,370	0.7	1,459	5.2
U-rate	50.5%		56.7%		54.1%		43.4%		50.9%		47.3%	

TABLE IV
DATA SET II (OCTOBER 2015 TO MAY 2016)

HSR line	Sub-data Set: A-2016-4G						Sub-data Set: C-2016-4G					
	3-minute		50 KB-sized		2 MB-sized		3-minute		50 KB-sized		2 MB-sized	
	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)	number of flows	size (GB)
B-G	608	81.6	12,175	1.2	2,072	7.9	554	65.2	9,265	0.9	1,808	7.0
S-B	479	62.1	10,085	1.0	1,757	6.7	341	38.7	8,187	0.8	1,489	5.6
B-T	461	49.4	5,116	0.5	1,019	3.9	401	40.3	6,090	0.6	896	3.4
U-rate	93.9%		96.2%		95.5%		94.8%		97.1%		95.2%	

the measurement. Therefore, we have enough time to perform static measurements.

Tables III and IV show details of data set collected in the two 8-month periods respectively. According to the carrier, measurement period, and network, we divide data set I into two sub-data sets: A-2014-3G and B-2014-3G, and divide data set II into another two sub-data sets: A-2016-4G and C-2016-4G. As an example, sub-data set A-2014-3G contains data measured on 3G networks of Carrier A in the period from December 2013 to July 2014. It consists of data collected along three different HSR routes. For instance, the number of the 3 types of flows measured on B-G line are 1,397, 17,410, and 3,722. The total size of packets captured on both the server and the phones, and log files of *MobiNet* when testing each type of flow is 17.3, 1.6 and 12.5 GB respectively.

IV. INFLUENCE FACTORS AND ANALYSIS METHOD

In this Section, we first discuss the various factors that may influence TCP in high speed mobility scenarios, and then design an analysis method to quantitatively study the impact of these factors.

A. Influence Factors

Analyzing TCP performance and behavior in high speed environment is challenging because many influence factors are intertwined together (terrain along the rails, train speed, network type, handoff, disconnections, etc.), making it nearly infeasible to analyze how each factor affects TCP clearly.

With the information on geographical location (longitude and latitude) collected by *MobiNet*, we can know the terrain of areas crossed by the train through Google Earth. We find that terrain along HSR routes in China is diverse. It includes plains, hills, valleys and tunnels, all of which affect cellular signal

quality and shadow fading characteristics [18]. Therefore, users on HSRs may experience highly varying signal quality when the train crosses different terrain types, which may impact the performance of TCP.

Through analysis of log files from *MobiNet*, we observe variations in network type. Tables V and VI depict the average proportion of time that the phones connect to each type of network for the same carrier in the two 8-month periods respectively. Due to the diversity of network types along HSR lines, a TCP flow may experience network type variations, which posed a big challenge to our analysis. For example, if the network type changes from LTE to GPRS suddenly during the transmission of a TCP flow, it is necessary to decide on whether to attribute the performance degradation to a change in the network type, or to high speed motion.

To make analysis feasible, we do not consider the impact of changes in terrain and network type. Specifically, we discard flows measured when the train passes through hills, valleys, and tunnels, only using flows measured in large areas of open plains. We also discard flows transmitted during network type changes to avoid its interference on the analysis, only using those transmitted in a single HSPA+, HSDPA, UMTS or EVDOA network in sub-data sets A-2014-3G and B-2014-3G, and those in a single FDD-LTE or TD-LTE network in sub-data sets A-2016-4G and C-2016-4G. By using short-lived flows, we are able to use on those flows that are transmitted in open plains and without changes in network type. This would have been difficult with longer-lived flows.

Since flows measured in complicated terrain or experiencing network type variations cannot be used, we show the utilization rate (U-rate) of flows in four sub-data sets respectively in Table III and IV. We explain the significant difference in number of flows and utilization rate between data sets I and II

TABLE V
PROPORTIONS OF VARIOUS NETWORK TYPES (DECEMBER 2013 TO JULY 2014)

Carrier A						Carrier B		
Network type	HSPA+ (3.75G)	HSDPA (3.5G)	UMTS (3G)	EDGE (2.75G)	GPRS (2.5G)	Network type	CDMA EVDOA (3G)	CDMA 1x (2G)
Proportion	69.69%	20.16%	7.23%	2.89%	0.03%	Proportion	75.28%	24.72%

TABLE VI
PROPORTIONS OF VARIOUS NETWORK TYPES (OCTOBER 2015 TO MAY 2016)

Carrier A							Carrier C				
Network type	FDD-LTE (4G)	HSPA+ (3.75G)	HSDPA (3.5G)	UMTS (3G)	EDGE (2.75G)	GPRS (2.5G)	Network type	TD-LTE (4G)	TD-SCDMA (3G)	EDGE (2.75G)	GPRS (2.5G)
Proportion	75.23%	10.18%	9.21%	4.08%	1.29%	0.01%	Proportion	71.32%	11.01%	8.39%	9.28%

as follows: In the first 8-month period, we originally planned to also analyze the flows collected in complicated terrain areas and experiencing network type variations, so the data covers most of the travel time. However, we realized that this was infeasible after making analysis on this data set. Therefore, we reduced the measurement time in the second period. To this end, we pause the measurements temporarily, when passing through complicated terrain areas, or accessing 2G/3G networks. As a result, we collect fewer flows in the second period. However, with much higher utilization rate, the number of available flows collected in the two periods are comparable.

Then we focus on three important influence factors: train speed, handoff frequency and network disconnection. The three factors pose big challenges to TCP on HSRs. First, due to Doppler frequency shift and fast multi-path fading, high speed movement can cause serious fast signal fading [18], [19], which may lead to bit error rate (BER) variation and bandwidth change. Second, high speed motion causes more frequent handoffs, resulting in sharp delays and consecutive packet losses, negatively impacting TCP performance. Finally, mobile devices suffer repeated network disconnections, resulting in TCP transmission interruptions. In the next subsection, we design a method to analyze the impact of these three factors.

B. Analysis Method

Train speed, handoff frequency, and network disconnection are three important factors that affect TCP performance and behavior in high speed trains. Since these factors are intertwined, it is very difficult to study the independent effect of each factor at the same time. This is a big challenge posed to our research. To overcome this, we design the following analysis methods.

Network disconnections will lead to transmission interruption of TCP. So we will study the effect of network disconnections alone when we discuss TCP transmission interruptions.

Since mobility and handoff are intertwined, it is difficult to analyze the effect of each factor at the same time. We design a method to quantitatively analyze the independent impact of mobility and handoff. We use the total number of handoffs that a flow experiences during transmission to quantify the degree of handoff that a flow suffers.

Through measurements, we observe that flows suffer more frequent handoffs in urban areas than in sub-urban and rural

areas. For example, when the train passes through Beijing, a 3-minute flow can experience 12 handoffs. However, as the train crosses large areas of farmland along the B-T line, sometimes a 3-minute flow suffers no handoff. This can be explained by variation in base station distribution density. Generally, due to difference in population and volume of network traffic, carriers deploy much denser base stations and smaller cells in urban areas than sub-urban and rural areas. Due to the variation of base station deployment along the railway lines, we are able to achieve variation in the number of handoffs suffered by flows.

In addition, we make use of variation in train speed as shown in Table II to perform measurements in static, low speed, and high speed motion mobile scenarios.

We use the following methods to independently analyze the effect of speed and handoff: (1) we compare the performance among TCP flows that suffer no handoff when the train runs at various speed to study the effects of speed change alone, (2) we make a comparison in TCP performance among flows that suffer different number of handoffs when the train runs at a relatively stable high speed to quantitatively analyze the impacts of handoff.

V. TCP PERFORMANCE

We analyze TCP performance in this Section. In addition to packet loss rate and RTT which were also studied for HSPA+ networks in our prior work [13], this article adds analysis on another important metric, throughput. We want to answer following questions:

1) Is the passive impact of HSRs on TCP performance in HSPA+ networks prevalent in various 3/4G networks of different carriers?

2) If the passive impact of HSRs is common in various networks, is there any quantitative difference among them?

We use the same methods to calculate packet loss rate and RTT as the prior work [13], and throughput is calculated as the number of payload bytes received by the phone per second.

It is worth noting that serial (multiple) retransmissions, which mean that a packet is retransmitted several times and suffers from exponential back-offs, often happen when a flow suffers multiple handoffs. Due to exponential back-offs, there are intervals during which the server sends out no packet. We cannot update packet loss rate and RTT, and throughput is calculated as zero in these intervals.

According to train speed and number of handoffs a flow experiences, we choose five types of 3-minute flows: a) The

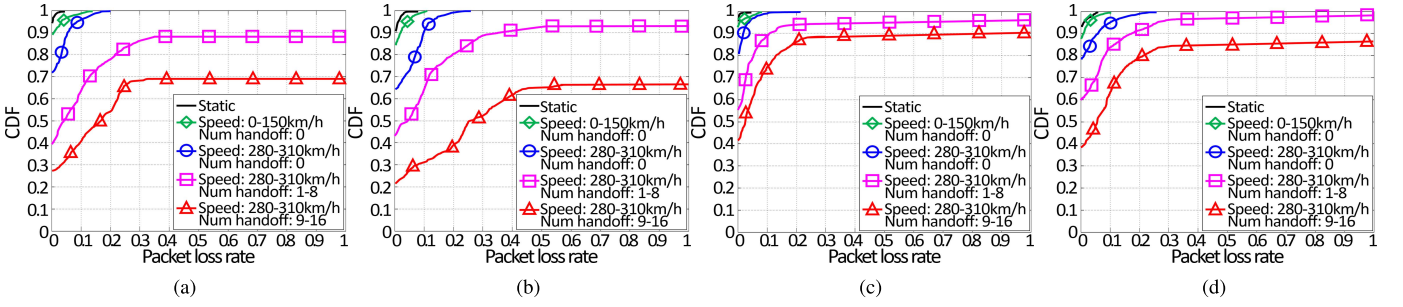


Fig. 1. CDF of packet loss rate. (a) (A-2014-3G). (b) (B-2014-3G). (c) (A-2016-4G). (d) (C-2016-4G).

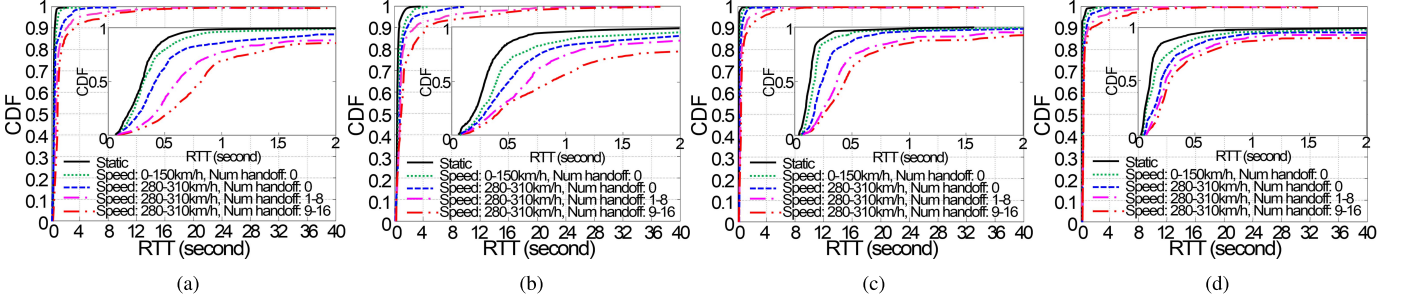


Fig. 2. CDF of RTT. (a) (A-2014-3G). (b) (B-2014-3G). (c) (A-2016-4G). (d) (C-2016-4G).

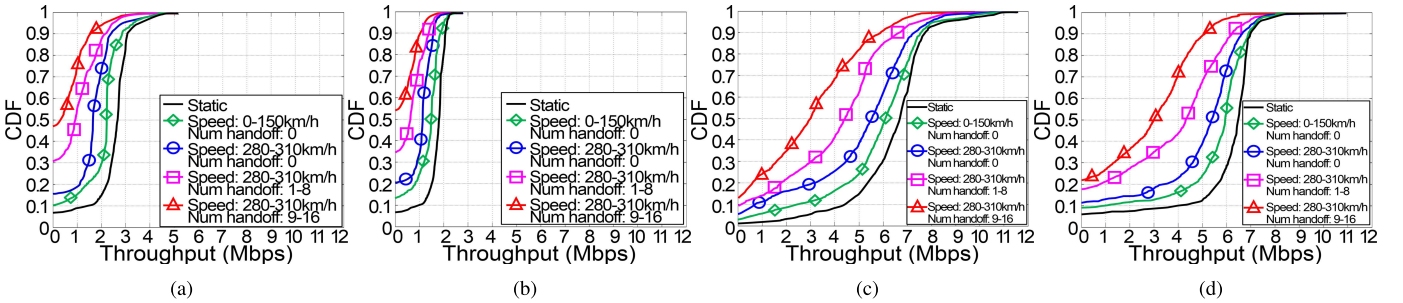


Fig. 3. CDF of throughput. (a) (A-2014-3G). (b) (B-2014-3G). (c) (A-2016-4G). (d) (C-2016-4G).

train is static and no handoff occurs. b) The train speed is below 150km/h and no handoff occurs. c) The train speed is over 280km/h and no handoff occurs. d) The train speed is over 280km/h and 1 to 8 handoffs occur. e) The train speed is over 280km/h and 9 to 16 handoffs occur. We use analytical methods described in Section IV-B to quantitatively analyze independent impacts of speed and handoff on the three metrics. For example, comparing TCP performance among the first three types of flows, we can learn the impact of speed alone. Comparing TCP performance among the last three types of flows, we can learn the impact of handoff alone. Figures 1(a) to 1(d), Figures 2(a) to 2(d), and Figures 3(a) to 3(d), show the CDF of packet loss rate, RTT and throughput, of flows measured in 3G and 4G networks of various carriers respectively.

We confirm that the negative impact of high speed mobility and handoff on packet loss rate and RTT in HSPA+ networks is prevalent in both 3G and 4G networks of multiple carriers with various network types. We also find that high speed mobility and handoff also show significant passive effects on throughput. To summarize, we make following common findings for both 3G and 4G networks:

1) Effects of Speed. Compared to stationary and low speed motion ($< 150\text{km/h}$) scenarios, packet loss rate and RTT

rise, throughput drops significantly, and the three metrics all vary within a wider range when the train runs at a speed over 280 km/h. This can be explained by big variation in BER and available bandwidth due to fast fading. With the fluctuation of BER and bandwidth, the rate of packet loss due to both bit error and congestion vary correspondingly. Then local retransmission rate at the link layer rises and drops correspondingly with the variation of packet loss rate, leading to more RTT spikes and wider RTT variation. Due to increase and variation in both packet loss rate and RTT, throughput declines significantly and fluctuates widely.

2) Effects of Handoff. Compared to high speed mobility itself, frequent handoffs that a flow suffers during the movement of the train contributes more to performance degradation of the three metrics. As the number of handoffs a flow suffers increases, packet loss rate and RTT rise drastically, and throughput drops significantly. For example, as shown in Figure 1(b), when the speed of the train is over 280km/h, packet loss rate never reaches 100% if no handoff occurs, but reaches 100% with a probability of 35% if 9 to 16 handoffs happen. The high packet loss rate can be explained by the large number of consecutive packet losses during the process of handoff. In the same way, the long RTT can be attributed to the long delay for smartphones to choose a new base station,

disconnect from the old one and reconnect to a new one. Since flows suffer much more handoffs in urban areas, we observe that dense base station deployment in urban areas is a double-edged sword. Although dense deployment of base stations and small cells improve network coverage and capability for stationary and low speed moving mobile users in big cities where network traffic volume is very high, it can lead to high handoff frequency for passengers on HSR, resulting in poor network performance.

Although the impact of HSRs on the three metrics is qualitatively consistent for various 3G and 4G networks belonging to different carriers, there are quantitative differences among them. With reference to 3G networks, we find that networks of Carrier A (including HSPA+, HSDPA and UMTS) outperform networks of Carrier B (EVDOA). As to 4G networks, we observe that networks of Carrier A (FDD-LTE) also outperform networks of Carrier C (TD-LTE). These differences can be explained by the difference in low layer technologies and the operational capability of various carriers. However, the difference between 3G and 4G networks is much bigger than that between different networks of the same generation, hence we mainly focus on the big quantitative differences between 3G and 4G networks.

First, similar to static scenarios, TCP performs much better in 4G networks than in 3G networks on HSRs, with much shorter RTT, higher throughput and lower packet loss rate.

Secondly, the advantage of 4G becomes more significant with the increase of the number of handoffs that a flow suffers under high speed mobility. It is worth noting that handoff is fatal for TCP in 3G networks, but is only harmful in 4G networks. As an example, if a 3-minute flow suffers 9 to 16 handoffs when the train is running at full speed, throughput drops to 0 Mbps with a probability of 47% in 3G networks of Carrier A, but the probability drops to 13% after Carrier A updates its networks to 4G.

To show the impact of handoff on throughput more clearly, Figures 4(a) and 4(b) show examples of two flows measured in 3G and 4G networks of Carrier A when the train is running at full speed on the B-T line respectively. The black dashed line shows the change in throughput over time, while moments when handoffs occur are marked by blue solid stems. We can see that throughput drops to 0 Mbps almost every time when suffering a handoff, and even keeps 0 Mbps for long durations ranging from several to dozens of seconds when encountering multiple successive handoffs in 3G networks. However, throughput unlikely drops to 0 Mbps, but only shows significant decrease during a handoff in 4G networks. Furthermore, even under multiple successive handoffs, the duration in which that throughput keeps 0 Mbps is much shorter.

This difference can be explained by the decrease of packet loss rate and delay during handoff in 4G networks. In 3G networks, for very high packet loss rate during handoffs, a packet is lost and retransmitted several times and suffers from exponential back-offs. Since RTT is long, intervals during which the server sends out no packet and throughput drops to 0 Mbps may reach as long as dozens of seconds after several exponential back-offs. In 4G networks, packet loss rate

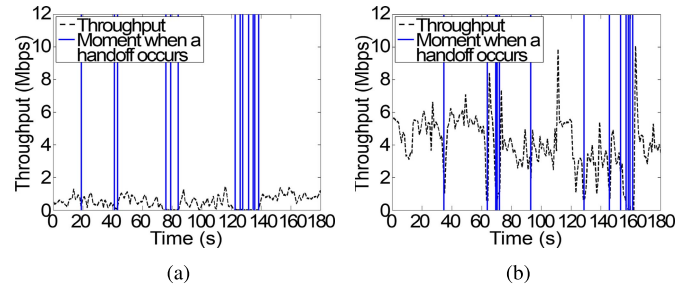


Fig. 4. Throughput change over time. (a) (A-2014-3G). (b) (A-2016-4G).

reduces significantly during handoffs, and hence the number of times a packet is retransmitted decreases correspondingly. Furthermore, RTT is much shorter in 4G networks. So, even if serial retransmissions occur, sending intervals hardly become very long after exponential back-offs. Therefore, throughput rarely drops to 0 Mbps under a single handoff, and improbably keeps 0 Mbps for a long time even under multiple successive handoffs in 4G networks.

VI. TCP BEHAVIOR

Similar to prior work [13], we also analyze TCP behavior in many aspects in this Section. Particularly, we make a much deeper analysis on retransmission in this article. We study the proportions of spurious RTO triggered by different causes, quantitatively analyze DupACK rates, and propose a more accurate method to evaluate RTO estimation bias. We want to answer following questions:

1) Are the abnormal TCP behaviors in HSPA+ networks of Carrier A prevalent in various 3/4G networks of different carriers?

2) If the abnormal TCP behaviors are common in various networks, is there any quantitative difference among them?

We use 3-minute TCP downlink flows to analyze abnormal behaviors in TCP operations including retransmission, congestion control and flow control, and use 50 KB-sized flows to study abnormal TCP connection establishment and closure. This is because the duration of 50 KB-sized flows is short, which allows us to observe more connection establishment and closure instances. Similar with Section V, we also divided flows into several groups according to the train speed and number of handoffs a flow experiences. Through analysis, we found that the quantitative difference in TCP behavior between 3G and 4G networks is much bigger than that between different carrier's networks of the same generation, hence we do not present the latter in this Section, but focus on the big quantitative differences between 3G and 4G networks.

A. Retransmission

If a sender neither receives the expected ACK, nor gets any indication of packet loss from 3 DupACKs or SACK, retransmission will be triggered by RTO. However, RTO sometimes occurs even when the packet is not lost at all, which is called as a spurious RTO. Spurious RTOs are very harmful to TCP performance, because they will lead to undesired slow starts. We define spurious RTO rate as the percentage of retransmitted packets triggered by spurious timeout in all retransmitted packets of a 3-minute flow. This definition is quite different

TABLE VII
SPURIOUS RTO RATE

Data Set	Static	Speed:280-310km/h Number of handoff:0	Speed:280-310km/h Number of handoff:1-16
A-2014-3G			
B-2014-3G	6.3%	20.68%	58.39%
A-2016-4G			
C-2016-4G	5.52%	17.21%	50.62%

TABLE VIII

PROPORTIONS OF SPURIOUS RTO TRIGGERED BY DIFFERENT CAUSES

Data Set	Static		Speed:280-310km/h Number of handoff:0		Speed:280-310km/h Number of handoff:1-16	
	RTOEI	ACKL	RTOEI	ACKL	RTOEI	ACKL
A-2014-3G						
B-2014-3G	98.62%	1.38%	96.79%	3.21%	91.88%	8.12%
A-2016-4G						
C-2016-4G	98.48%	1.52%	97.19%	2.81%	92.38%	7.62%

from that in the prior work [13], which calculates it as the proportion of spurious RTOs in all transmitted packets. Since there are quite big retransmission rate differences between 3G and 4G networks for the big differences in packet loss rate, It is more reasonable to compare the proportion of spurious RTOs in retransmissions. Table VII shows the spurious RTO rate in various scenarios. We confirm the finding that high speed mobility and handoff can lead to the increase in spurious RTO rate in HSPA+ networks is common for various 3/4G networks. Consistent with the prior work, we also observe that handoff leads to more significant increase of spurious RTO rate than high speed mobility itself in various 3/4G networks.

We find that although the retransmission rate decreases after the network is updated from 3G to 4G due to lighter packet drops in 4G networks, spurious RTO rate in 4G networks is almost as high as that in 3G networks. This unexpected finding reveals that spurious RTO is a serious problem in both 3G and 4G networks on HSRs. Therefore, we make a further study on spurious RTO in this article. We study the proportions of spurious RTO triggered by different causes, quantitatively analyze DupACK rates and propose a more accurate method to evaluate RTO estimation bias.

According to whether the expected ACK is lost or not, spurious RTOs can be classified into two types:

1) **Without ACK Loss.** Although the phone receives the original packet and the corresponding ACK arrives at the server finally, a spurious RTO occurs because RTO is estimated shorter than the real RTT.

2) **With ACK Loss.** Although the phone receives the original packet, the corresponding ACK is lost and a spurious RTO occurs.

To summarize, there are two causes of spurious RTO: RTO estimation inaccuracy and ACK loss. Table VIII shows the proportions of spurious RTOs caused by RTO estimation inaccuracy (denoted by RTOEI) and those caused by ACK losses (denoted by ACKL). We note that the percentage of spurious RTOs that are caused by ACK loss rises with the increase of train speed and the number of handoffs that a flow suffers. This can be explained by the increase in ACK loss rate for bad network conditions on HSRs. Nevertheless, RTO estimation inaccuracy is the dominant cause, accounting for over 90% in all scenarios. Then, it is important to further explore reasons for RTO estimation inaccuracy.

TABLE IX
DUPACK RATE

Data Set	Static	Speed:280-310km/h Number of handoff:0	Speed:280-310km/h Number of handoff:1-16
A-2014-3G			
B-2014-3G	2.52%	18.21%	50.69%
A-2016-4G			
C-2016-4G	1.08%	5.76%	12.16%

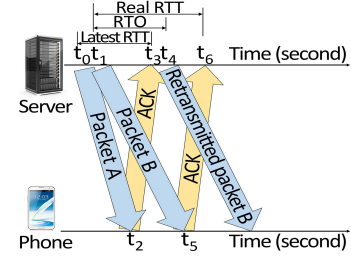


Fig. 5. RTO estimation bias calculation methods

We believe that there are two main reasons for RTO estimation inaccuracy:

Estimation Algorithm. In TCP, RTO is computed by the sender using smoothed RTT and RTT variation [22], which can work well in stationary and low speed motion scenarios since the variation of RTT is low. However, the accuracy of the algorithm may decrease when RTT variation is high. Because high speed mobility and frequent handoff can lead to high variation of RTT, the RTO estimation algorithm may not adapt fast enough to the change of RTT, leading to serious inaccuracy.

DupACKs. TCP does not use DupACKs to update RTT and RTO. In stationary scenarios, the percentage of DupACKs is low, and RTT is relatively stable, hence not using DupACKs to update RTT does not cause serious problems. However, as shown in Table IX, DupACKs account for a big proportion in high speed motion scenarios. Moreover, RTT fluctuates rapidly within a wide range, when not using large numbers of successive DupACKs to update RTT, TCP may not update RTO timely and suffer considerable estimation errors.

After analyzing the reasons for RTO estimation inaccuracy, we quantify the RTO estimation inaccuracy. We used the difference between RTO and the latest RTT to evaluate the inaccuracy of RTO estimation in prior work [13]. However, we use the difference between the spurious RTO and the real RTT in this article. Figure 5 shows the difference between the two methods. RTO is estimated as the interval between the moment when the original packet is sent out and the moment when the packet is retransmitted ($t_4 - t_1$), due to time out. We update RTT each time when receiving an ACK. The latest RTT is updated by the latest ACK ($t_3 - t_0$), while real RTT is estimated as the interval between the moment when the original packet is sent out and the moment when the corresponding ACK is received ($t_6 - t_1$). Since the difference between spurious RTO and real RTT can reflect the real RTO estimation bias, we use it instead of the difference between RTO and the latest RTT in this article. Figures 6(a) and 6(b) show the CDF of RTO estimation bias of flows measure in 3G and 4G networks respectively. As shown in the figures, when

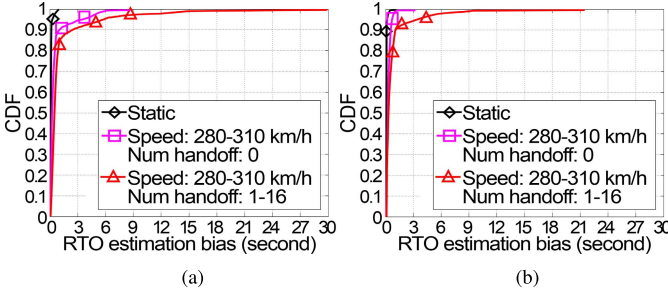


Fig. 6. CDF of RTO estimation bias. (a) (A-2014-3G, B-2014-3G). (b) (A-2016-4G, C-2016-4G).

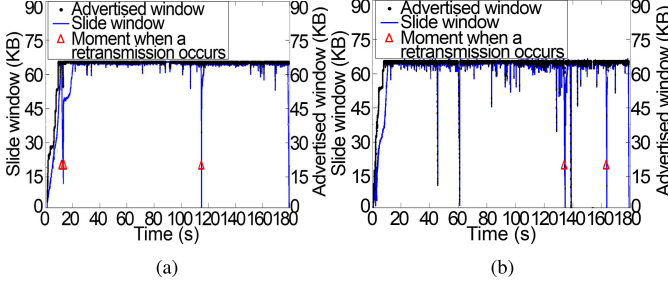


Fig. 7. Change of SWND and AWND over time (static). (a) (A-2014-3G). (b) (A-2016-4G).

the train is parking, RTO is very close to the real RTT with the difference within hundreds of milliseconds. However, with the increase in train speed and the number of handoffs a flow suffers, the difference becomes larger.

We note that RTO estimation bias is much smaller in 4G networks than in 3G networks. This is because RTT variation is much lower in 4G networks. However, spurious RTO occurs when RTO is estimated shorter than the real RTT, no matter how big the estimation bias is. We conclude that even RTT variation is much lower in 4G networks, the RTO estimation algorithm still cannot adapt fast enough to the variation of RTT on HSRs, leading to rather high spurious RTO rate.

B. Congestion and Flow Control

We use the number of bytes in flight and advertised widow (AWND) to analyze congestion and flow control. Bytes in flight are those bytes that have been sent out by the server, but not acknowledged yet by ACKs returned from the phone. AWND is carried by ACKs and it informs the server of the size of the phone's available receiving buffer. The number of bytes in flight can reflect the size of slide window (SWND), which is the minimum of congestion window (CWND) and AWND. Therefore, we use the number of bytes in flight to estimate SWND.

Figures 7(a) and 7(b), Figures 8(a) and 8(b), show the changes in SWND and AWND over time of four 3-minute flows measured in 3G and 4G networks when the train is parking and running at full speed respectively. The figures also mark moments when retransmissions occur.

We confirm that most findings in HSPA+ networks of Carrier A are common in various 3G and 4G networks of three carriers:

1) *Static Case.* Only a few retransmissions occur in the duration of the flow and SWND reaches the size of AWND

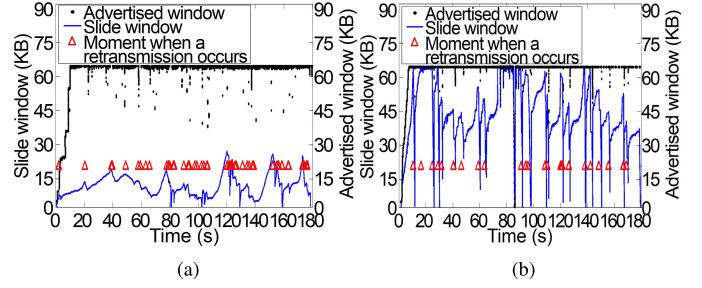


Fig. 8. Change of SWND and AWND over time (full speed). (a) (A-2014-3G). (b) (A-2016-4G).

most of the time. Even SWND drops suddenly when a retransmission occurs, it can rise to the size of AWND soon after.

2) *Mobile Case.* When the train runs at full speed, packet losses and retransmissions happen frequently, so CWND repeatedly experiences additive increase and multiplicative decrease (AIMD) [23]. Hence, SWND decreases significantly, compared with static cases. Affected by bad network conditions in high speed trains, a big portion of packet losses may not be due to congestion, but bit error. However, TCP always attributes packet loss to network congestion, hence conducts very aggressive CWND reduction, which may lead to very low utilization rate of bandwidth. Besides, as spurious RTO rate increases on HSR, many undesired slow starts are triggered, hurting TCP performance significantly.

It is worth noting that network upgrades from 3G to 4G also bring a new problem, full or even zero AWND. Besides, 4G networks also shift the bottleneck of SWND growth to some extent, compared with 3G networks.

Full or even Zero AWND. In 3G networks, almost all of the decreases of SWND in both static and mobile cases are due to congestion controls for packet losses. However, in 4G networks, some reductions of SWND are due to full AWND or even zero AWND, but not congestion controls. For example, SWND decreases for the sharp reduction of AWND size, but not for congestion control due to packet losses at 48s, 61s, 139s in Figure 7(b), and at 87s in Figure 8(b), because no retransmission is observed at these moments. Huang et al. [2] also observed this full or even zero AWND problem in LTE networks. This is caused by many factors. The application is not reading the data fast enough from the receiving buffer at the TCP layer [2]. Besides, existing studies [24] have shown that smartphone vendors may have been reducing receive window sizes to mitigate the buffer bloat problem, resulting in TCP performance degradation. Since throughput is much lower in 3G networks, the application can read the data from the receiving buffer at the TCP layer timely. Therefore full or even zero AWND is prevalent in 4G networks but rare in 3G networks. We also observe that high speed mobility can relieve the problem to some extent. Since throughput drops significantly when the train is running at full speed, the risk that the phone suffers full buffer decreases correspondingly and the problem of full or even zero AWND is less serious.

Bottleneck of SWND Growth. When the train runs at full speed, due to aggressive congestion control for high loss rate and high spurious RTO rate, SWND can hardly reach the size of AWND in 3G networks. Therefore, the bottleneck

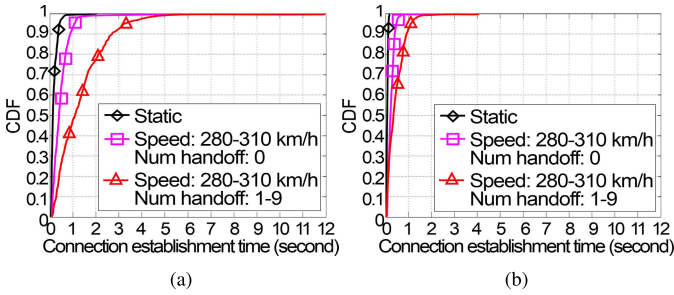


Fig. 9. CDF of connection establishment time. (a) (A-2014-3G, B-2014-3G). (b) (A-2016-4G, C-2016-4G).

of SWND growth is the limited CWND, but not AWND. However, since congestion control is less aggressive for lower packet loss rate in 4G networks, the number of bytes in flight can sometimes reach the size of the AWND even in high speed mobility. For example, the number of bytes in flight between 15s and 25s, between 75s and 92s reaches the maximum size of AMND. During these periods, the growth of SWND is mainly throttled by limited AWND. Therefore, CWND is not always the bottleneck of SWND growth, and AWND throttle the growth of SWND sometimes in 4G networks.

C. Connection Establishment and Closure

TCP uses three-way and four-way handshakes to establish and close a connection respectively. Due to high speed mobility and frequent handoff, loss rate of handshakes is higher on HSRs than static scenarios. Handshakes may be retransmitted multiple times and suffer from exponential back-offs, which leads to long delay in establishing or closing a connection. In our measurements, connection establishment and closure are initiated by the phone and the server respectively. We define connection establishment time as the time span from when the first SYN is sent out by the phone to when the last ACK is received by the server, which acknowledges the SYN-ACK sent out by the server. Connection closure time is defined as the time span from when the first FIN is sent out by the server to the last packet of the flow. Figures 9(a) and 9(b), and Figures 10(a) and 10(b) show the CDF of connection establishment and closure time in 3G and 4G networks respectively.

We observe that the findings in HSPA+ networks that connection establishment and closure time rise sharply on HSRs are prevalent in various 3G and 4G networks of different carriers. Moreover, we also observe that handoff leads to more significant increase of connection establishment and closure time, compared with high speed mobility itself. This is because handoff can lead to a very high packet loss rate even up to 100% with quite high probability, so handshakes may suffer multiple losses and serial retransmissions. The reason why connection closure time is much longer than establishment time is that RTO is much longer when the connection is to be closed than the initial RTO when connection is to be established, and the delay of closure becomes even much longer after exponential back-offs.

It is worth noting that there are quite big quantitative differences between 3G and 4G networks. TCP spends much

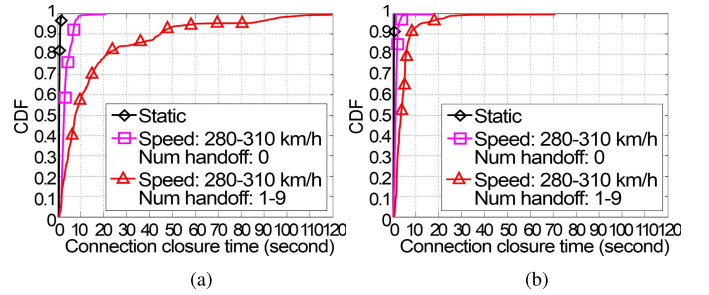


Fig. 10. CDF of connection closure time. (a) (A-2014-3G, B-2014-3G). (b) (A-2016-4G, C-2016-4G).

shorter time to establish or close a connection in 4G networks than in 3G networks, especially when a flow suffers multiple handoffs. The example of extremely long connection closure time (72.8 s) shown in Figure 8(a) in the prior work [13] is prevalent in 3G networks, but is rare in 4G networks. This difference can be explained by the decrease of packet loss rate and delay during handoff in 4G networks.

In addition to long connection establishment and closure time, another problem that TCP connections encounter is transmission interruption, which means that a TCP transmission is interrupted abnormally for network disconnections. We show an example of a TCP transmission interruption in Figure 8 (b) in the prior work [13]. Since transmission interruption rate is associated with flow size, we study the impacts of HSRs on transmission interruption rate, and make a comparison between 3G and 4G networks in the next Section.

VII. EFFECTS OF FLOW SIZE

In cellular networks, most flows are small. On the other hand, very small fraction of large flows, which are known as heavy-hitter flows, contribute to the majority of the traffic volume [3]. Big flows often show overwhelming advantage in congestion window size and throughput over small flows in stationary scenarios, because small flows often finish transmission before leaving slow start. We set 50 KB and 2 MB as typical sizes of small and big flows respectively and want to determine if big flows can maintain the advantage in high speed trains. We compare two characteristics between big and small flows: transmission failure rate and the number of bytes in flight. Transmission failure rate is the percentage of flows that suffer a transmission interruption, and are unusually closed before data transmission completion.

We use 50 KB-sized flows that suffer 0 to 9 handoffs, and 2 MB-sized flows that suffer handoff 0 to 12 times under various train speeds to study the impact of flow size. Figures 11(a) and 11(b) show transmission failure rate during the movement of the train on various routes. Excluding those failed flows, we compare the number of bytes in flight between successfully transmitted 50 KB-sized and 2 MB-sized flows. Figures 12(a) and 12(b) depict CDF of the number of bytes in flight. We confirm that the findings in HSPA+ networks are common in various 3G and 4G networks:

1) Transmission Failure Rate. Transmission failure rate of big flows is much higher than small flows. This can be explained by the difference in flow duration. Since the probability of network disconnection is much higher in a long

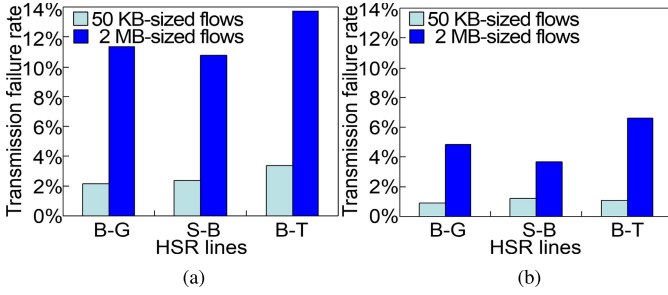


Fig. 11. Transmission failure rate. (a) (A-2014-3G, B-2014-3G). (b) (A-2016-4G, C-2016-4G).

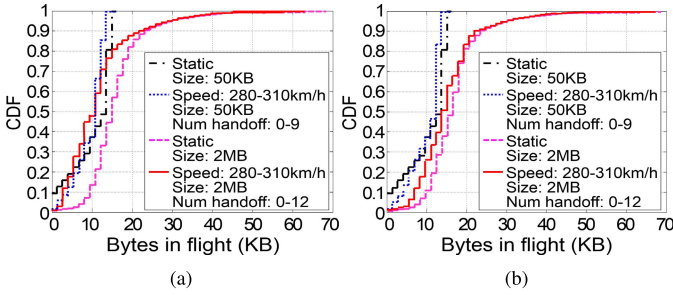


Fig. 12. CDF of the number of bytes in flight. (a) (A-2014-3G, B-2014-3G). (b) (A-2016-4G, C-2016-4G).

time duration than in a short time duration, big flows are more prone to transmission failures because its duration is much longer than small flows.

2) Bytes in Flight. For both big and small flows, the number of bytes in flight decreases in a fast running train. Big flows show much more significant decrease than small flows. This can be explained by aggressive congestion control as shown in Figures 8(a) and 8(b). Due to frequent packet drops, CWND experiences additive increase and multiplicative decrease repeatedly, even drops to one segment frequently when slow start is triggered by RTO. Therefore, in spite of longer durations, the CWND of big-sized flows is unlikely to reach and maintain a high level, and show more serious degradation than small flows.

Although the impacts of flow size are qualitatively consistent for both 3G and 4G networks, there are quite big quantitative differences between 3G and 4G networks:

1) Transmission Failure Rate. Transmission failure rate of big and small flows both decrease and the difference between big and small flows becomes smaller in 4G networks, compared with 3G networks. There are two causes for the change after network upgrades. On one hand, network disconnection is less frequent after network upgrades from 3G to 4G. On the other hand, the duration of 2MB-sized and 50KB-sized flows is much shorter in 4G networks due to a higher throughput, so the risk of suffering network disconnection during transmission decreases correspondingly.

2) Bytes in Flight. In 3G networks, when the train runs at a high speed, due to aggressive congestion control triggered by heavy packet drops, the overwhelming advantage of big flows on CWND over small flows cannot be maintained. However, for lower packet loss rates and less aggressive congestion control, big flows still show an obvious advantage over small flows in CWND in 4G networks, similar with static cases.

VIII. LESSONS AND SUGGESTIONS

All the above findings indicate that TCP cannot adapt well to high speed mobility, and there is an urgent need for more adaptive transport protocols that can effectively mask low layer problems brought by high speed environments, to the application layer. Hence, we summarize lessons in key operations of TCP and provide suggestions to either enhance TCP for such high speed environments, or to develop new transport protocols. Besides, we also give advice from the aspect of application protocols based on TCP, such as HTTP.

A. Transport Protocol

We have lessons and suggestions on TCP in three key operations, which we believe can also be generalized to other types of transport protocols. The existing protocols (such as TCP, Quick UDP Internet Connections (QUIC) [25], etc.) may be extended according to these suggestions, or a new transport protocol could be developed.

1) Retransmission. Spurious RTOs account for a big proportion of all retransmissions, resulting in many undesirable slow starts. On one hand, we should improve the RTO estimation algorithm to adapt fast enough to the variation in RTT in high speed mobility. In addition, it is necessary to make use of DupACKs to update the RTT, which can improve the accuracy of TCP RTO estimation. To reduce spurious RTO due to ACK loss, we suggest not using the ACK delay scheme, and bringing in active redundancy ACK. On the other hand, we should avoid undesirable slow starts. We suggest not triggering a slow start immediately when an RTO occurs, but wait for a while to see if the RTO is spurious. If the expected ACK arrives a short while after the RTO occurs, which indicates a spurious RTO, we should not perform the undesirable slow start in this case.

2) Congestion Control. TCP always attributes packet loss to congestion, hence conducting very aggressive congestion control on HSRs due to heavy packet drops. First, we should reduce packet loss rate by means such as the interweaves code technology in transport layer. Secondly, it is not enough to conduct congestion control only after packet losses are detected. We suggest monitoring of other parameters, such as available bandwidth and RTT, to estimate the network capability timely. Third, the additive increase and multiplicative decrease used by TCP cannot adapt fast enough to the serious network capability variation. We suggest a different congestion control scheme, which adjusts congestion window timely and accurately according to the real-time network capability, to make better use of network capability. Last but not least, since handoff is the major cause of TCP performance degradation, we should minimize its impact. For example, we can pause the timeout timer and freeze data transmission, but do not reduce congestion window even when packet drops occur during a handoff. This way, the congestion window just after the handoff is the same as that just before, and hence the negative impact of handoff can be reduced significantly.

3) Connection Closure. TCP spends much longer time to close a connection on HSRs. This is mainly caused by exponential back-offs during serial retransmissions of hand-

shakes when suffering multiple successive handoffs. The long tail time is energy-consuming for mobile devices. We suggest using a different mechanism to eliminate the long-time closure process timely, rather than exponential back-offs.

B. Application Protocol

We also provide some advice on how to improve the performance of application protocols based on TCP, such as HTTP.

1) Multiple Parallel TCP Connections. We suggest using multiple parallel TCP connections instead of a single one in application protocols, such as HTTP. Through measurement studies, we found that the combined congestion window of multiple parallel connections is much larger than that of a single connection in high speed trains, and we can achieve much higher network bandwidth utilization rate in this way.

2) Coping with Transmission Interruption. Due to repeated network disconnections, transmission interruption is a serious problem on HSRs. We provide two suggestions. First, it is unwise to put all eggs in one basket. Since transmission failure rate of big files is much higher than small files. It is better to send multiple small files rather than sending an aggregate big one. Secondly, it is strongly recommended to resume broken transfers caused by network disconnections to avoid waste of time and energy. Although it is not difficult to resume broken transfers technically, through measurements we found that most applications such as web page browsing and video playing do not resume broken transfers when reconnecting to the network after a period of network disconnection.

IX. CONCLUSION

In this article, we have, for the first time, presented a comprehensive measurement study of TCP performance and behavior in 3/4G networks on HSRs with speeds reaching 310 km/h in a 16 month period spanning 4 years. We have covered a distance of 108,490 km along various HSR routes in China and collected more than 500 GB of data.

This measurement study is very challenging because too many factors (terrain along the rails, train speed, network type, handoff, disconnections, etc.) are intertwined together, making it nearly infeasible to analyze how much each factor contributes to TCP performance degradation in high speed trains. We designed a measurement tool to collect information with multiple factors. We carefully design a measurement setup to minimize bias on the results brought by the measurement itself from four aspects: mobile devices, experiment time, servers, and test flows. We then focused on three important influence factors: train speed, handoff and disconnection. We designed a method to quantitatively analyze the independent impact of each factor on TCP.

We also studied TCP's performance (packet loss rate, RTT, throughput) and behavior in many aspects (establishment, transmission, congestion control, flow control and termination). We have found that RTT and packet loss rate rise sharply, and throughput drops significantly, compared with static or low speed scenarios. Moreover, we found that TCP cannot adapt well to high speed environments, showing serious

abnormal behaviors, such as high spurious RTO rate, aggressive congestion window reduction, a long delay of connection establishment and closure, and transmission interruption. We also studied the effect of flow size, and showed that big flows suffer higher performance degradation than small flows. Although 4G networks show significant advantages over their 3G predecessors, even in high speed trains, the passive impact of HSRs on TCP performance and operations in 3G and 4G networks is considerable.

As we prepare to move into the era of 5G, and as the need for high speed travel continues to increase, our findings indicate a critical need for more adaptive transport protocols that can effectively mask low layer problems brought by high speed environments, to the application layer. We summarize lessons in key operations of TCP and provide suggestions to either enhance TCP for such high speed environments, or to develop new transport protocols. Besides, we also give advice from the aspect of application protocols based on TCP, such as HTTP.

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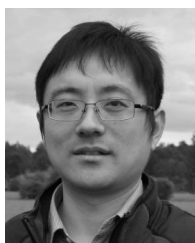
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