A Measurement Study on TCP Behaviors in HSPA+ Networks on High-speed Rails

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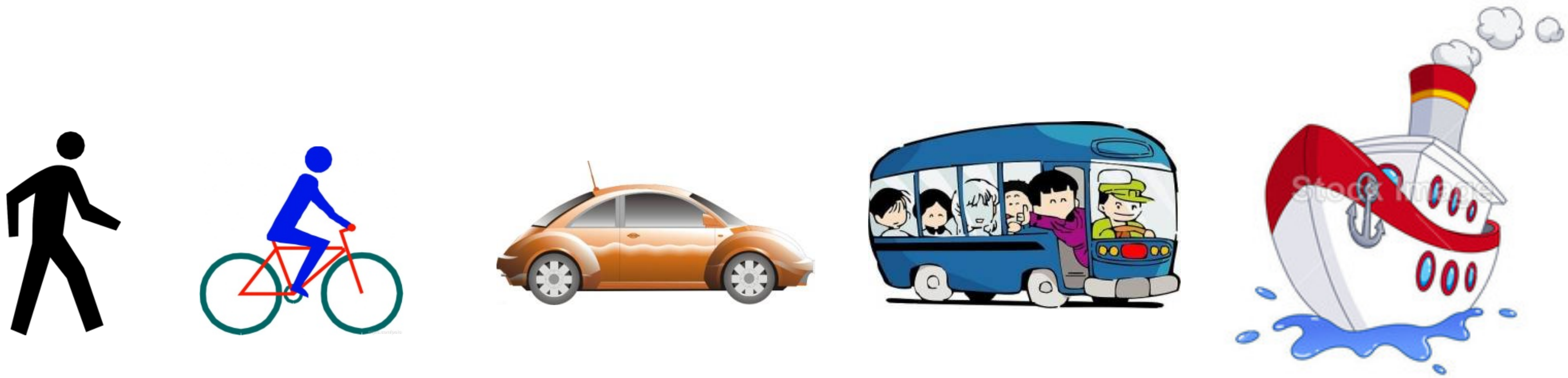
I' m one of the authors of this paper!

Motivation



While TCP has been extensively studied in a static and slowly moving scenarios, it has not been well explored in high-speed (**> 200 km/h**) mobility cases.

Motivation

In the past few years, we have witnessed a significant worldwide development of high-speed rail (HSR), reaching **22,000 km** at end of 2013.

Motivation

China contributes more than **a half** of the world's HSR network and the speed reaches **310 km/h.**

Purpose

1) What is the main challenge brought by HSR to TCP?

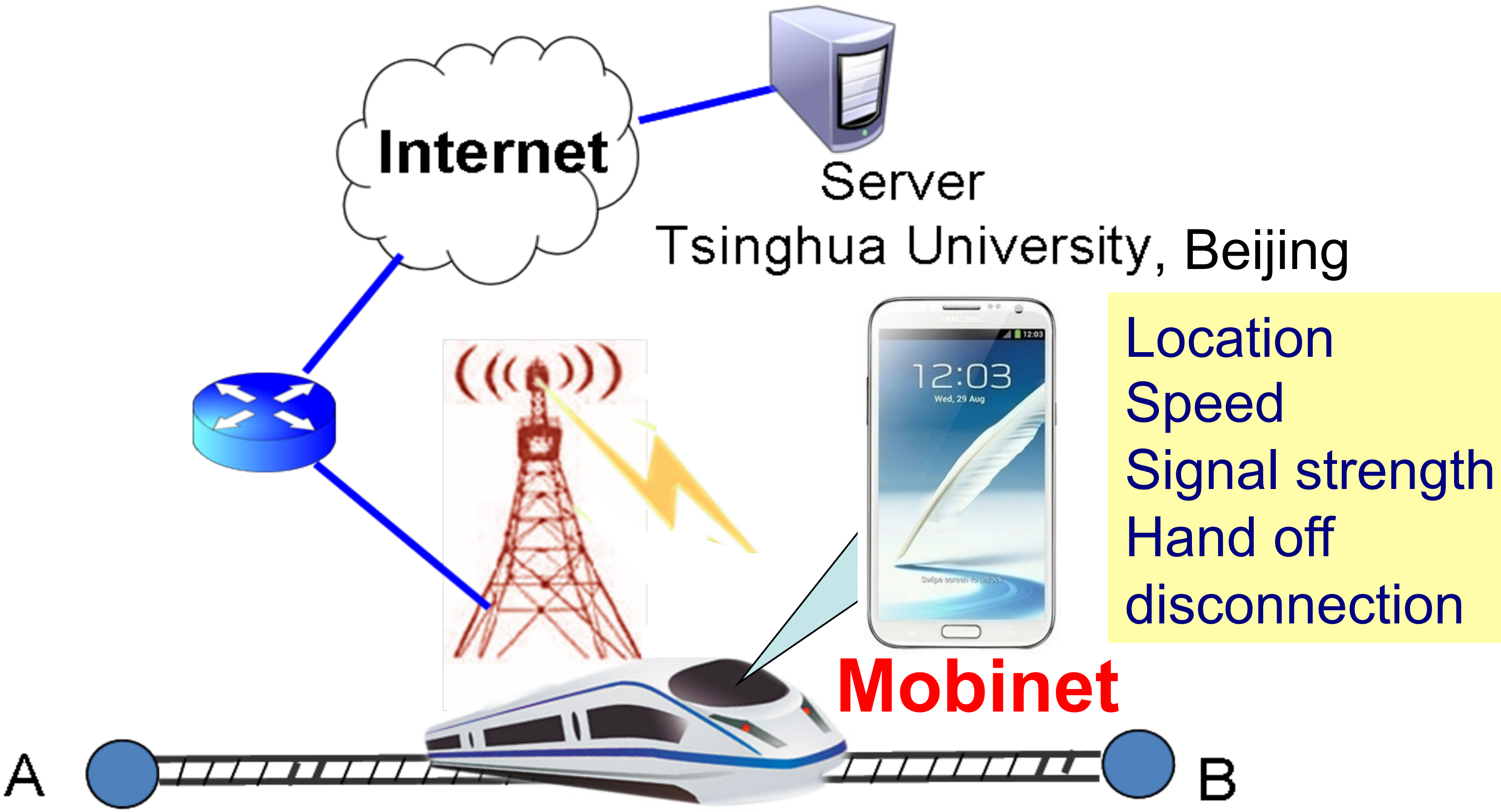
While the impact of mobility has been studied in prior works, but most are based on slowly moving of end devices. Another deficiency is that these studies do not analyze the independent effects of mobility and hand off on TCP

Purpose

2) Can TCP adapt well to the challenge? If not, what abnormal behaviors does it show?

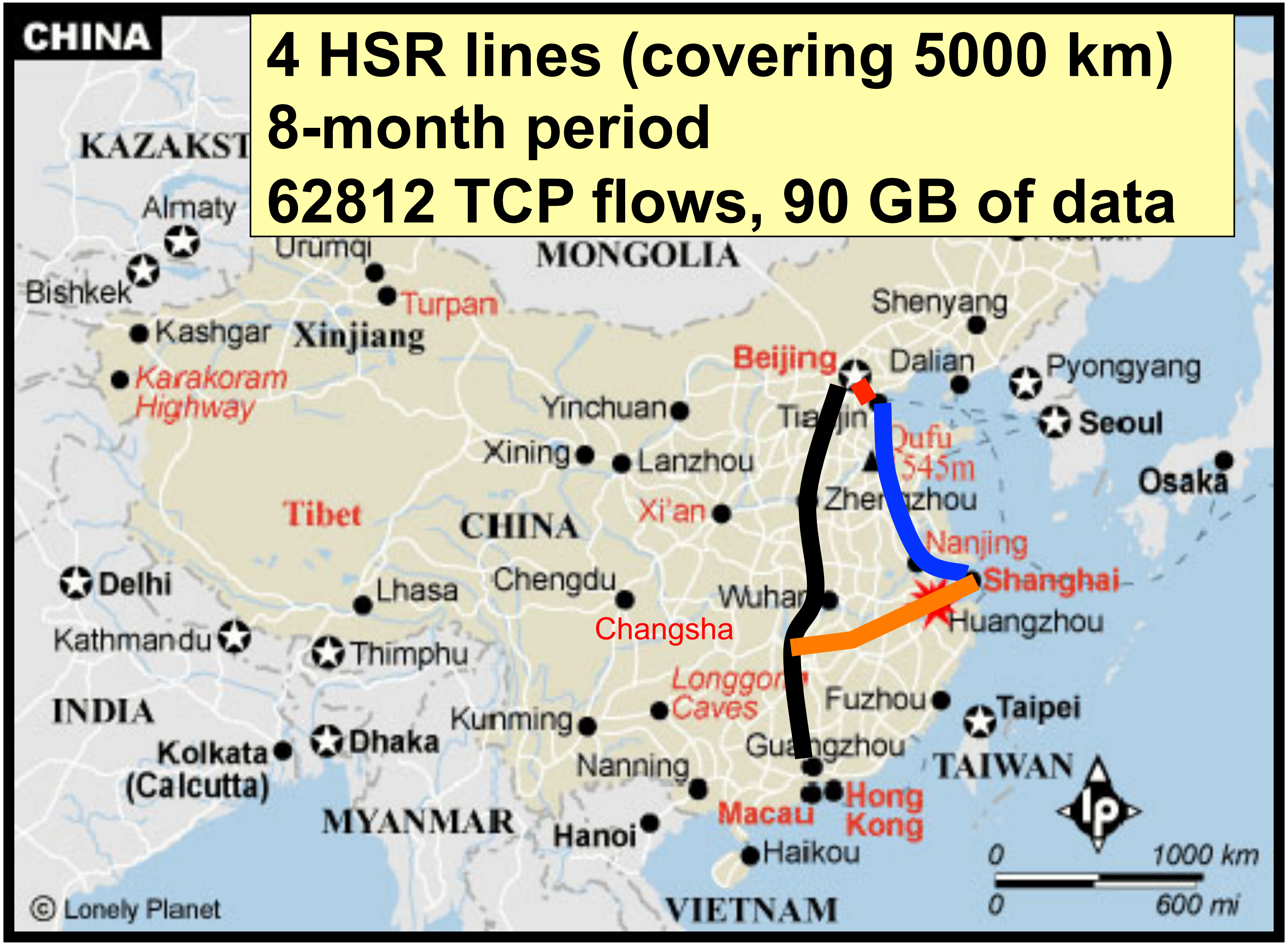
The adaptability has never been fully studied for all TCP aspects including connection establishment, transmission, congestion control and connection closure even in slowly moving mobile cases, not to mention high speed motion cases.

Measurement setup



Measurement setup

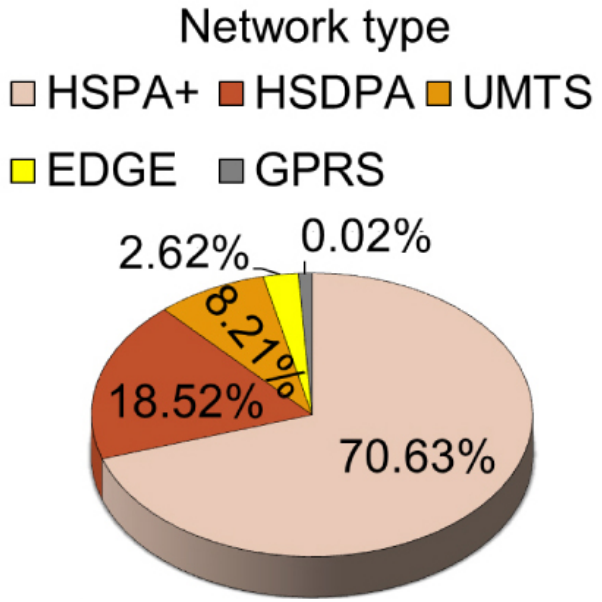
4 HSR lines (covering 5000 km)
8-month period
62812 TCP flows, 90 GB of data



Challenge

1) Network type

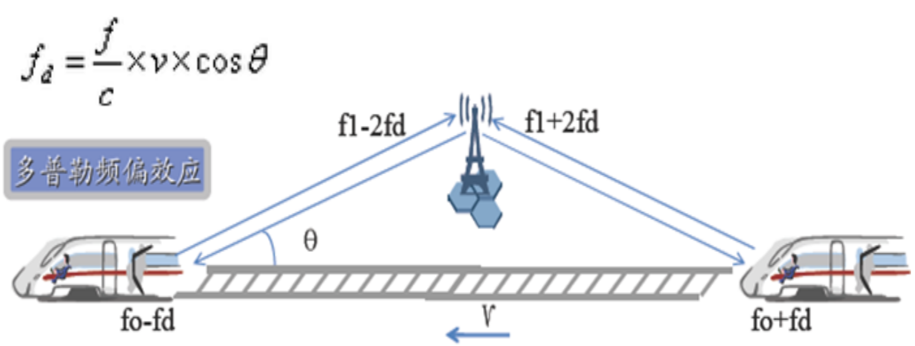
Various types of network belonging to the carrier we measure coexist along the railway, including HSPA+ (3.75G), HSDPA (3.5G), UMTS (3G), EDGE (2.75G), and GPRS (2.5G). Network type can highly affect TCP performance due to difference in bandwidth, network delay and packet loss rate.



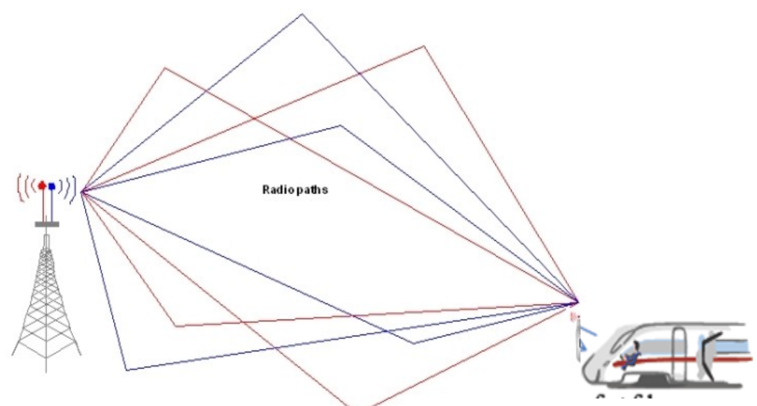
Challenge

2) Mobility

For Doppler frequency shift and fast multi-path fading, movement itself can cause fast signal fading, which can lead to bit error rate (BER) variation and bandwidth change. Therefore mobility can also affect TCP performance.



Doppler frequency shift

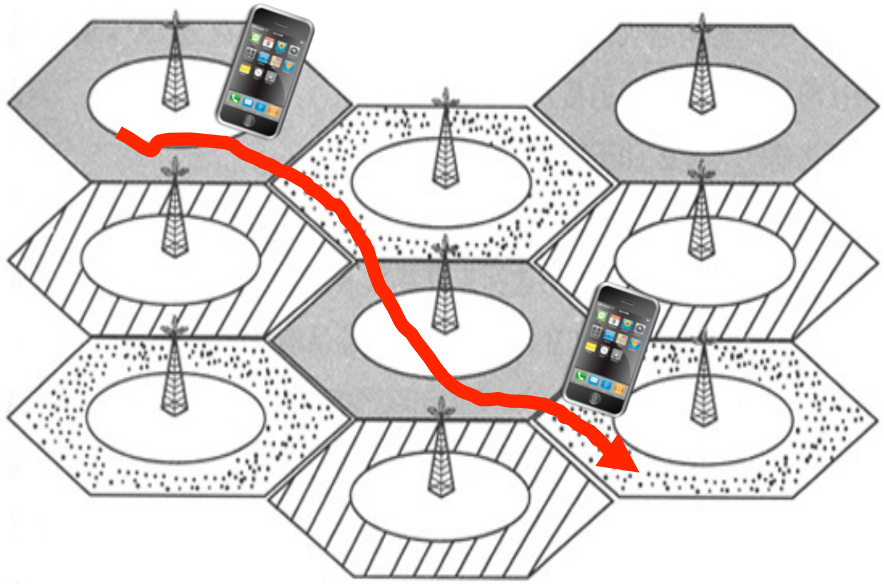


fast multi-path fading

Challenge

3) Handoff

high-speed motion causes more frequent handoffs, resulting in sharp delays, heavy packet losses, and network disconnections, hurting TCP performance badly.



Challenge

Network type

Mobility

Handoff

TCP performance and behaviors

How to analyze effect of each factor independently?

Solution

To make analysis feasible, we don’t study the impact of network type change. We only analyze TCP flows transmitted in pure HSPA+ networks.

Long-lived flows ✗

Short-lived flows ✓

Solution

We use the total number of handoffs that a flow experiences during transmission to quantify the degree of handoff that a flow suffers.

Flows suffer more frequent handoffs in urban areas than in suburban and rural areas due to difference in base station distribution density.

Solution

(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.

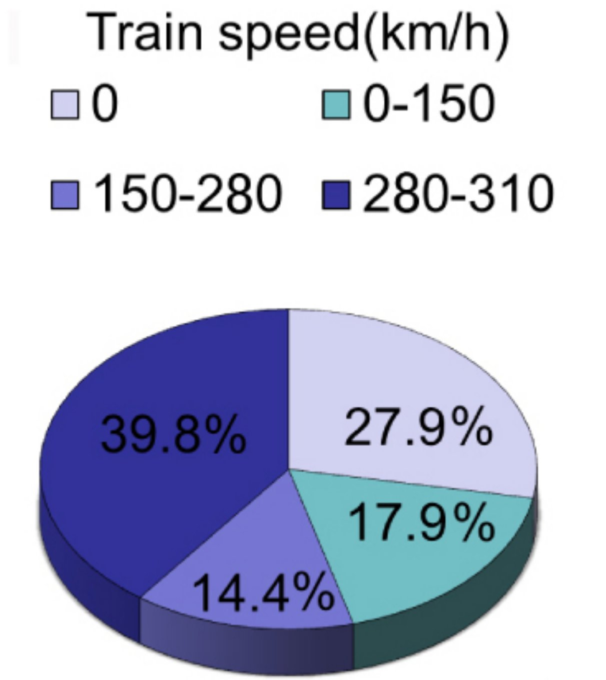


Fig. 1. Train speed

Solution

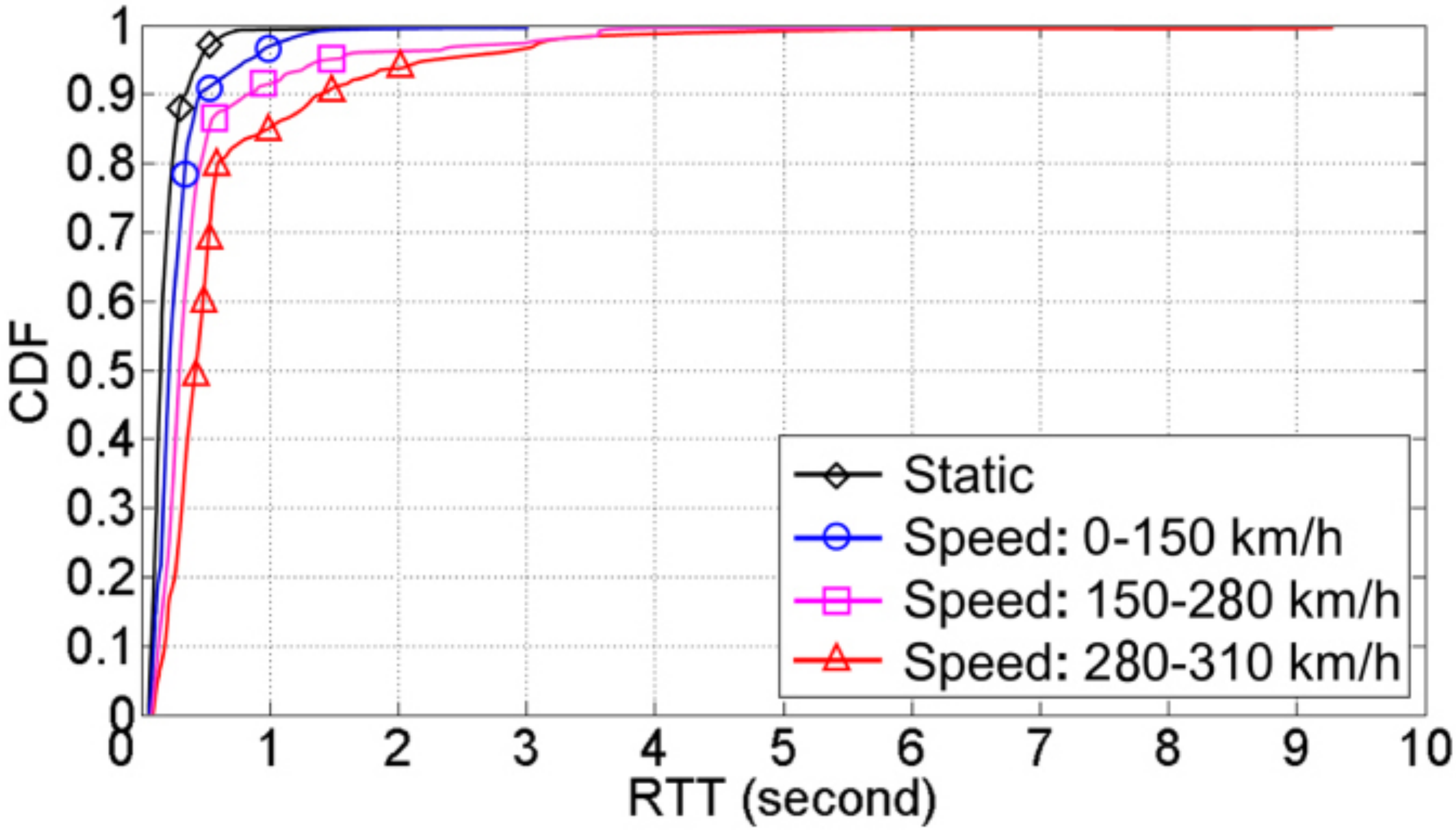
(2)We make a comparison in TCP performance among flows that suffer different number of handoffs when the train runs at a relatively stable high speed to quantitatively analyze the impacts of handoff.

Challenges posed to TCP

1) **Wide RTT variations**
2) **Heavy packet losses**
3) **Frequent network disconnections**

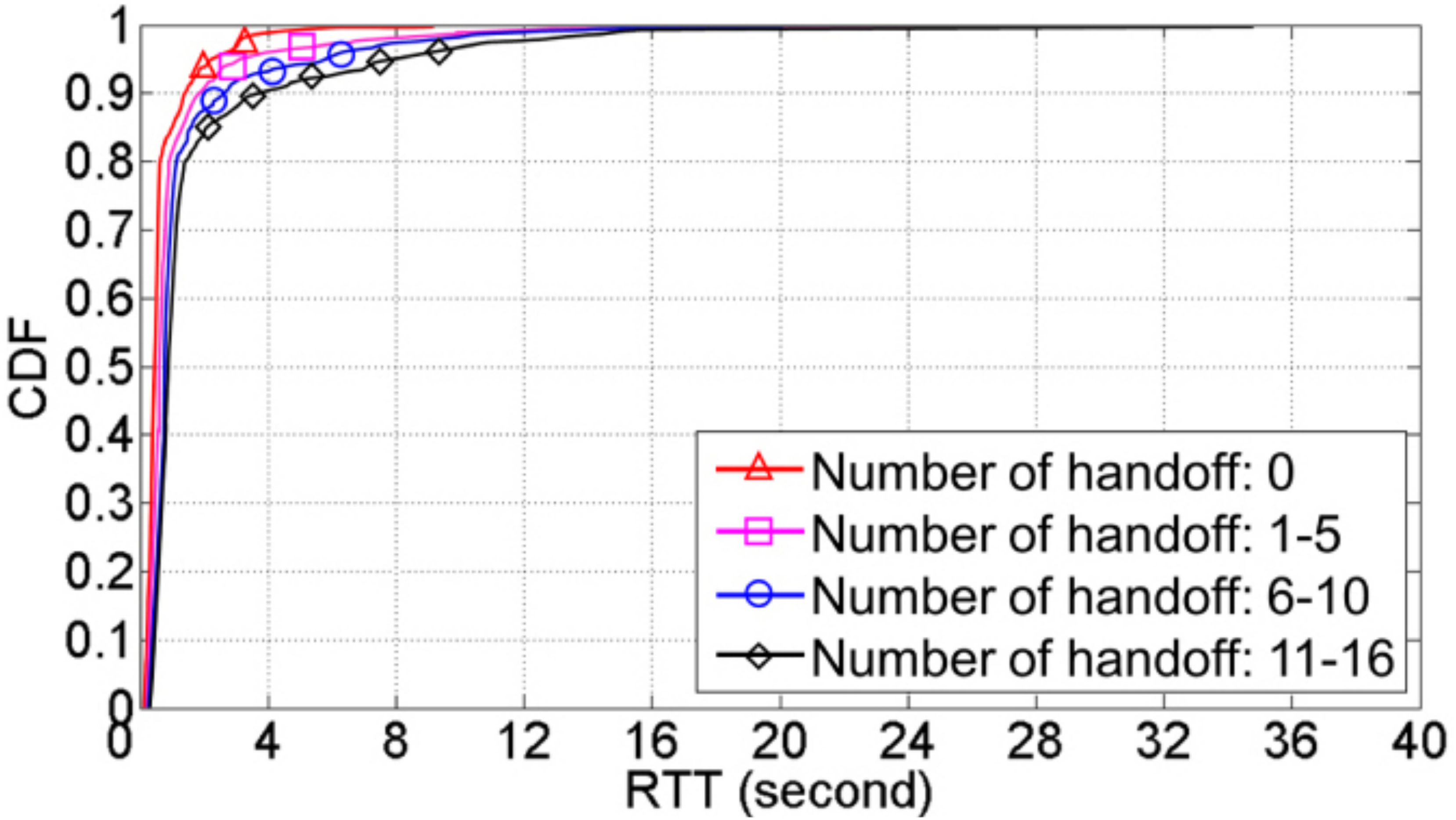
Challenges posed to TCP

1) Wide RTT variations



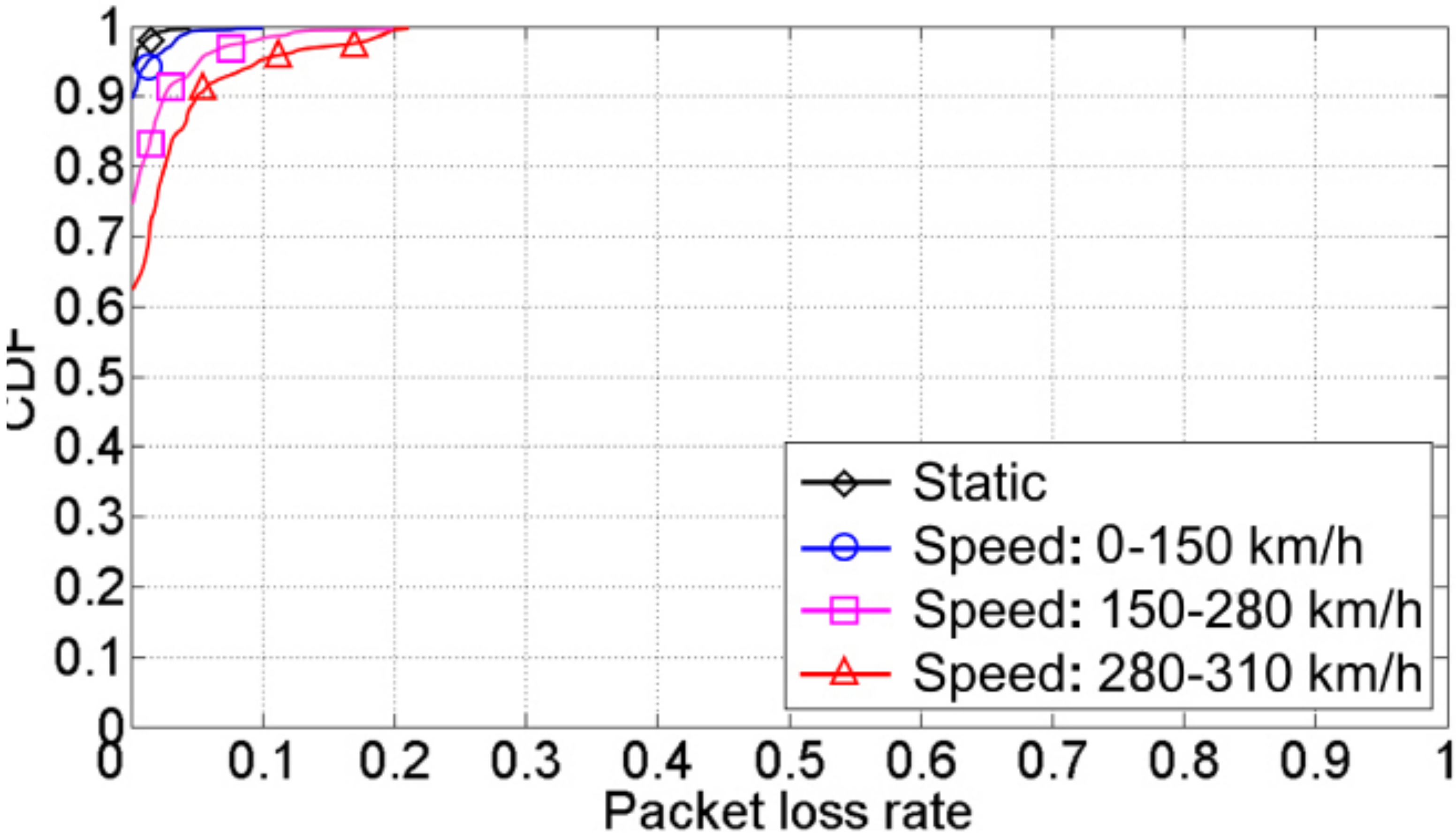
Challenges posed to TCP

1) Wide RTT variations



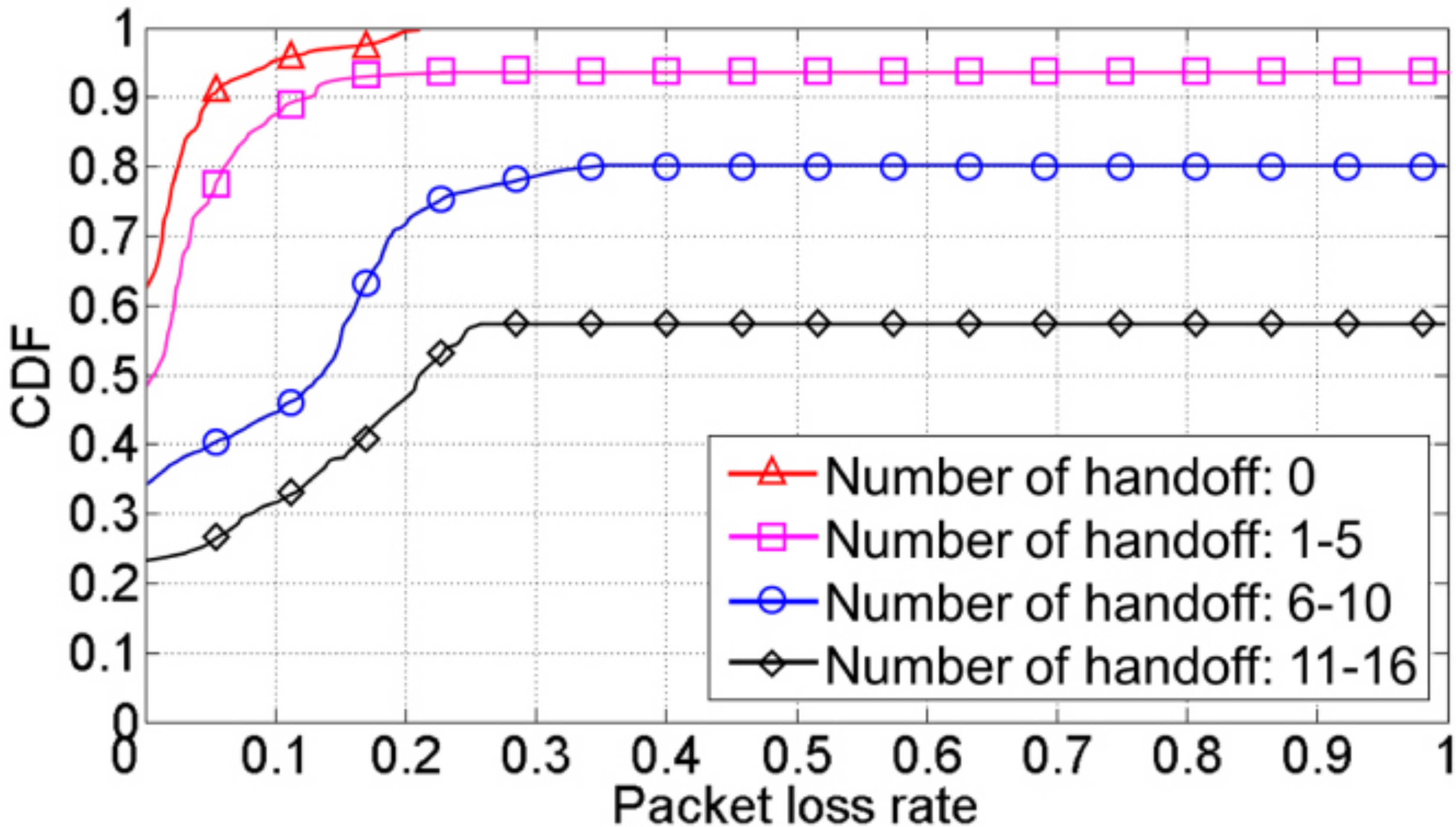
Challenges posed to TCP

2) Heavy packet losses



Challenges posed to TCP

2) Heavy packet losses



Challenges posed to TCP

3) Frequent network disconnections

1) Lack of a better choice. If signal quality of the current base station reaches the threshold to trigger a handoff yet no near base station can provide better signal quality, handoff failure will happen.
2) Small cells. If the cell of current base station is very small, the train may run out of range of the cell before completion of the handoff, leading to handoff failure.

TCP Behaviors

- **Retransmission**
- **Congestion control**
- **Connection establishment and closure**
- **Effects of flow size**

TCP Behaviors

- **Retransmission**

RTO may not be estimated accurately for two reasons:

1) Estimation algorithm. In TCP, RTO is computed by the sender using smoothed RTT and RTT variation. The accuracy of the algorithm may decrease when RTT variation is high in high-speed trains.

RTTs=(1-a)*RTTs+a*RTTm， a=1/8，
RTTD = (1-b)*RTTD +b*|RTTm-RTTs|,b=1/4
RTO=RTTs+4RTTD

RTO Estimation algorithm

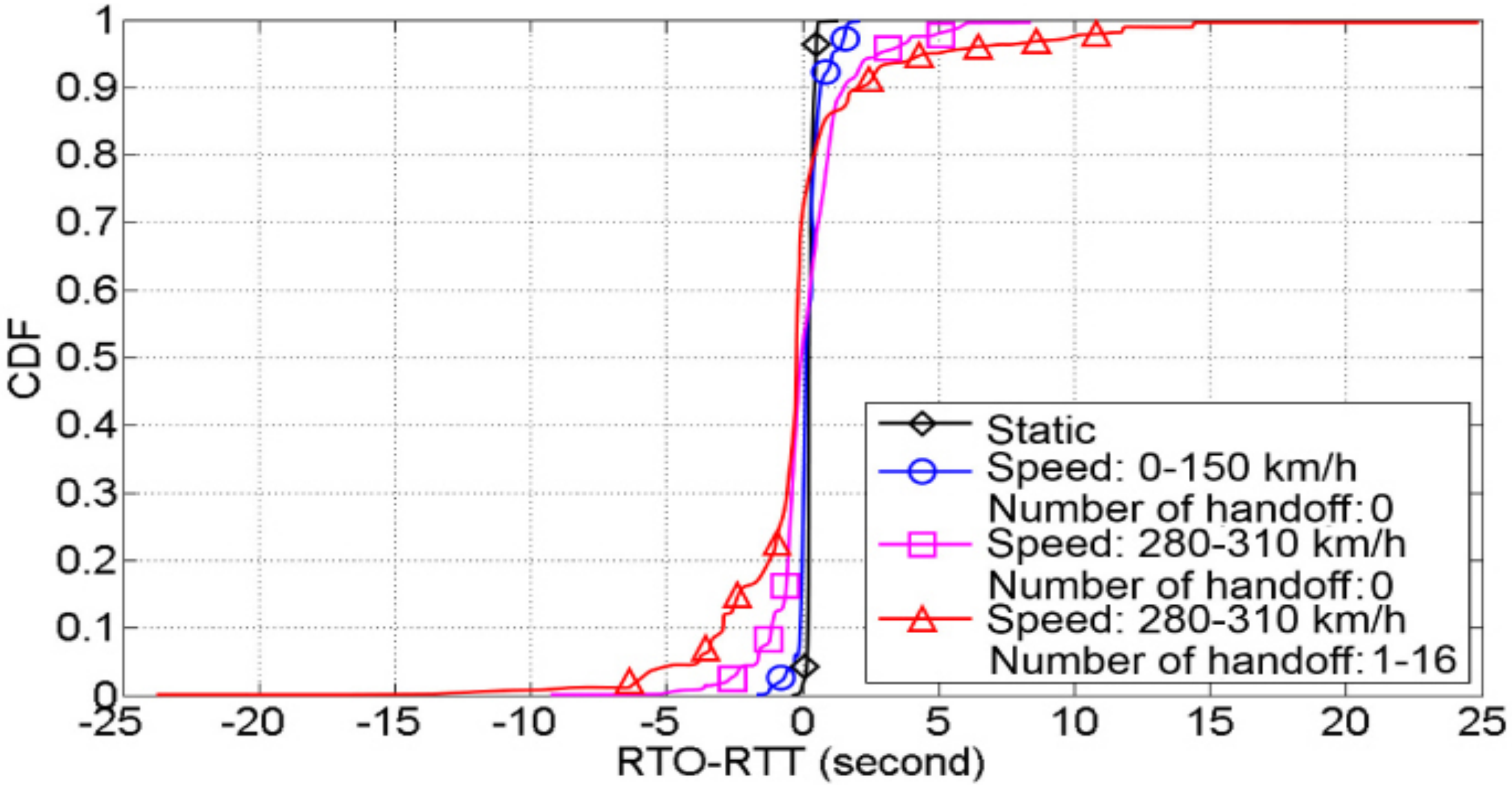
TCP Behaviors

- **Retransmission**

2) Duplicate ACKs. TCP does not use Duplicate ACKs to update RTT and RTO. In high-speed motion mobile scenarios, Duplicate ACKs account for a big proportion. When not using Duplicate ACKs, TCP may not update RTO timely and suffer estimation errors

TCP Behaviors

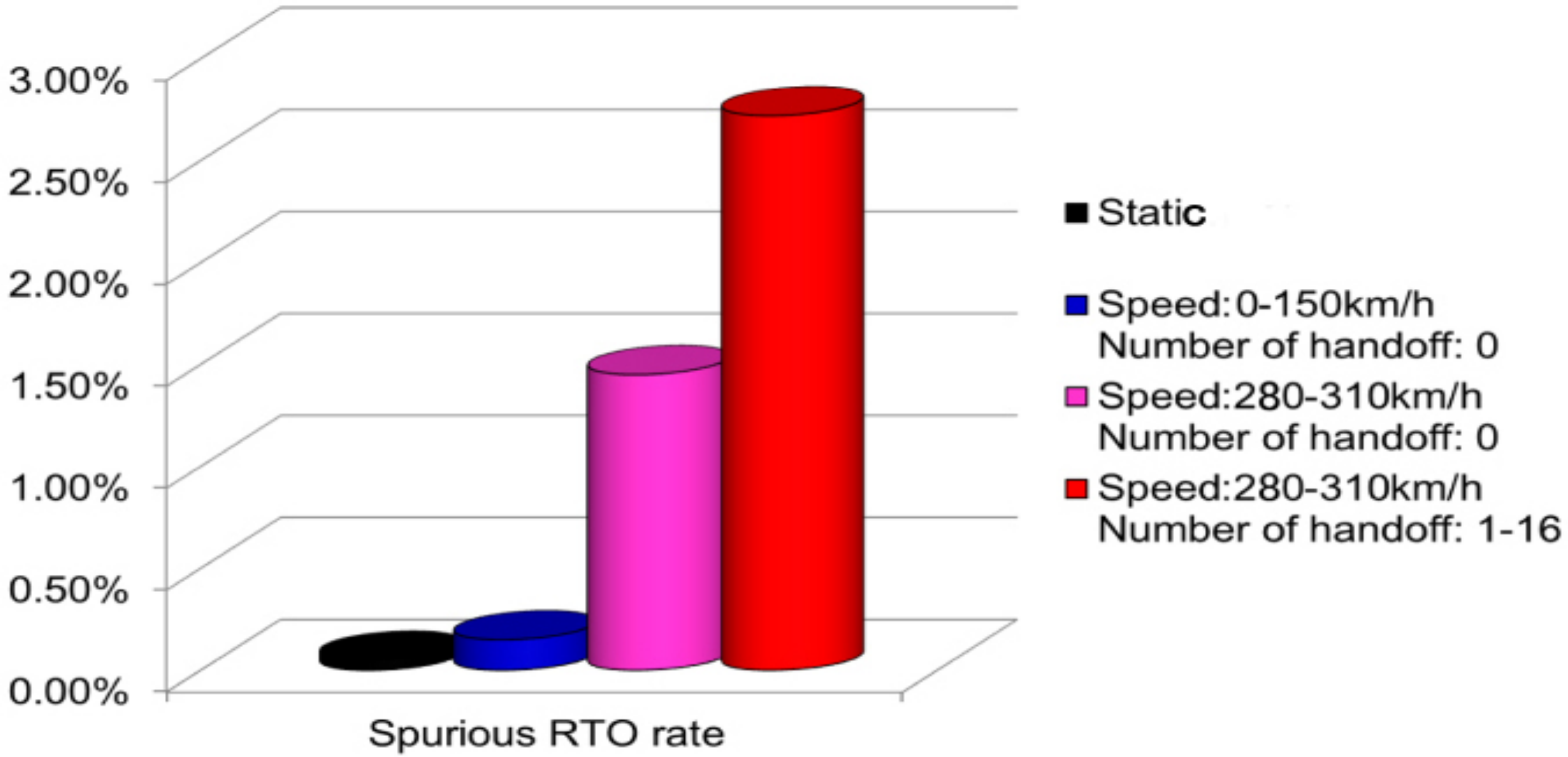
- **Retransmission**
  Both high speed mobility and handoff can lead to bigger differences between RTO and RTT.



TCP Behaviors

- **Retransmission**

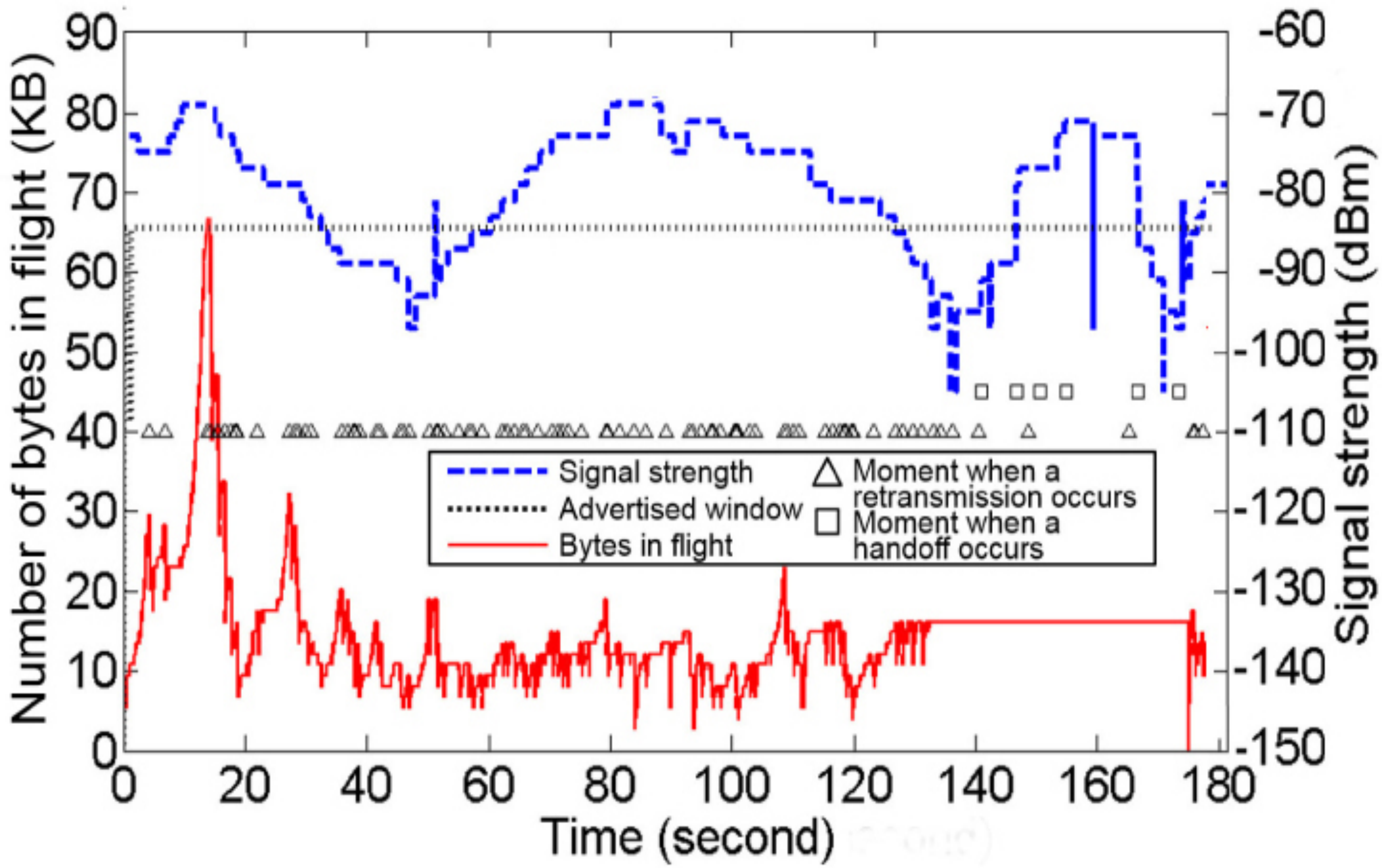
  Both high speed mobility and handoff can cause increase in spurious RTO rate.



TCP Behaviors

- **Congestion control**

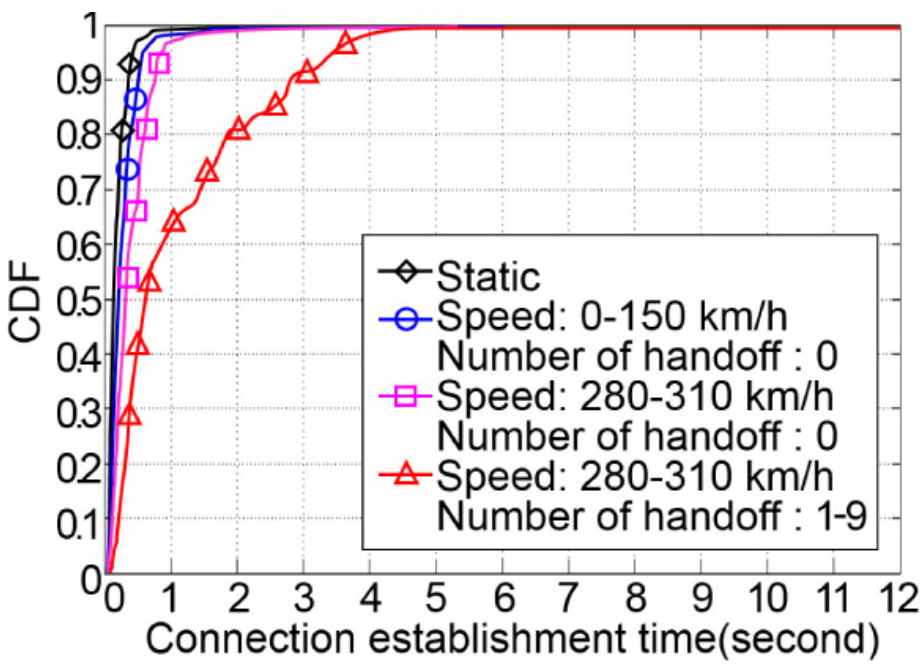
  TCP conducts very aggressive congestion control

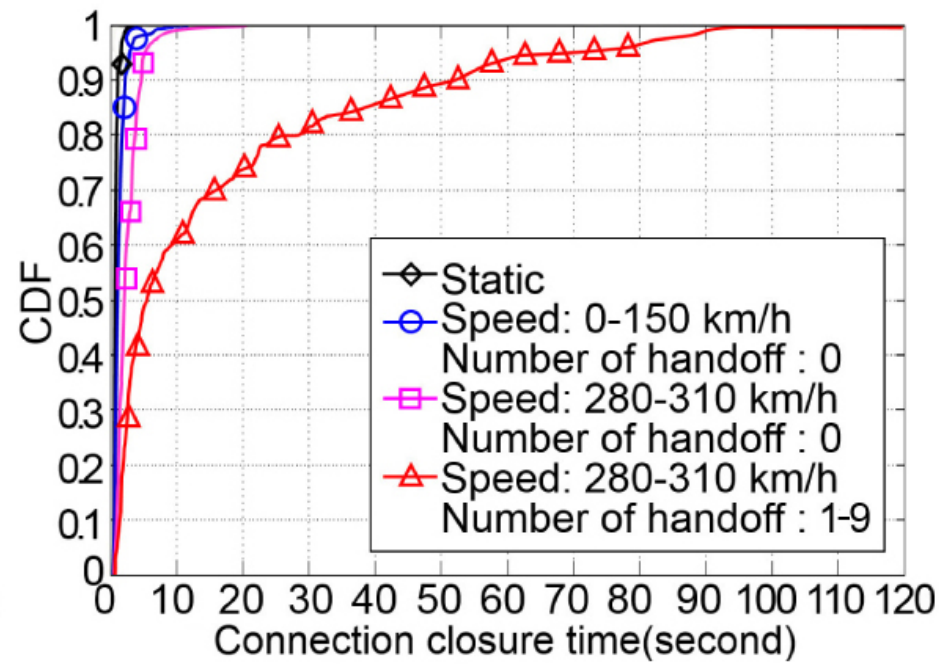


TCP Behaviors

- **Connection establishment and closure**

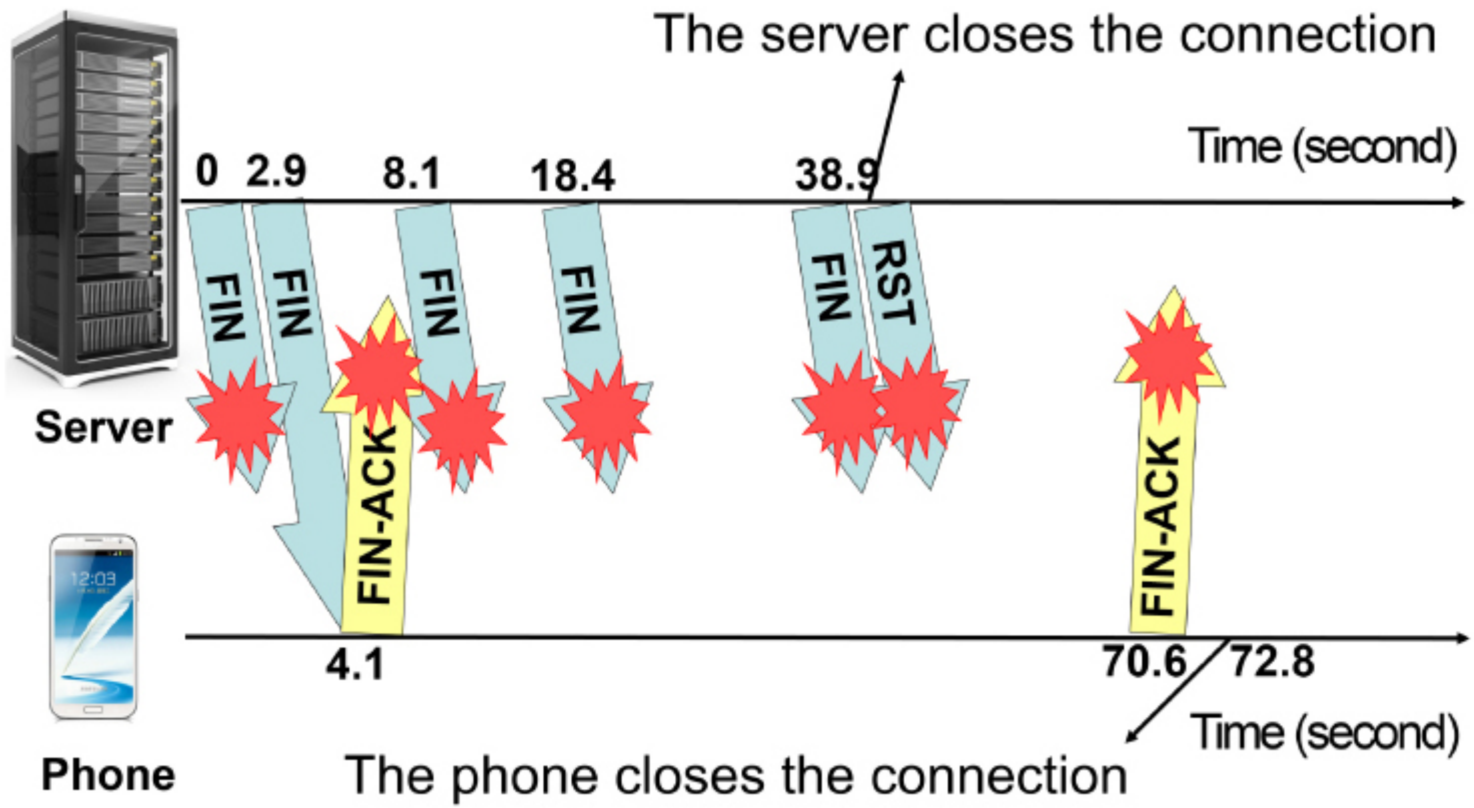
It takes a much longer time to set up or close a TCP connection on high-speed trains.





TCP Behaviors

- **Connection establishment and closure**



(a) Closure delay

TCP Behaviors

- **Connection establishment and closure**

A big portion of connections can not be properly closed by handshakes, but are closed abnormally by RST, network disconnection or timeout. Among these abnormally closed connections, most are closed before the phone completely receives the whole file, which is a waste of both time and energy.

TCP Behaviors

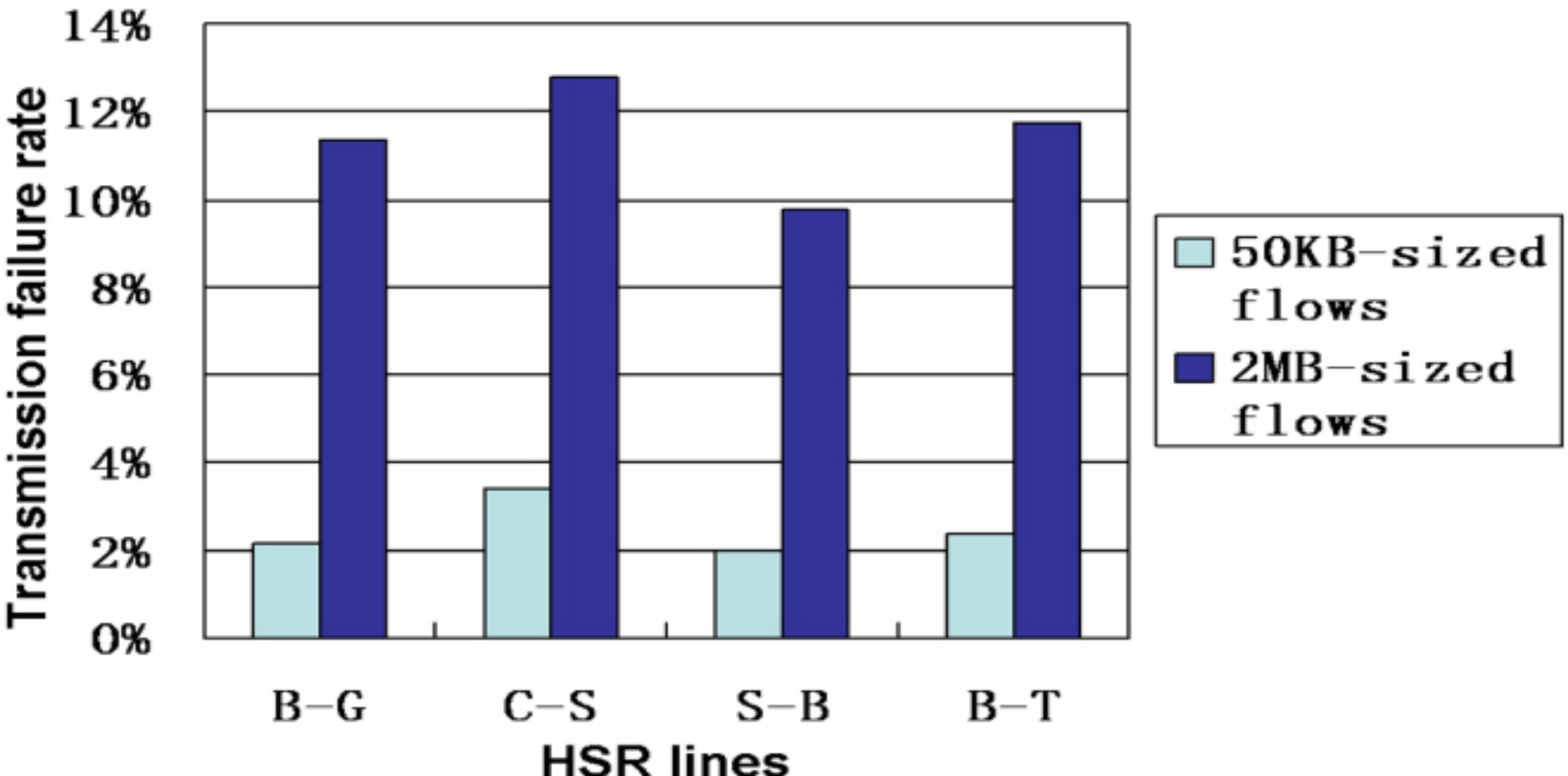
- **Effects of flow size**

We set 50 KB and 2 MB as typical sizes of small and big flows respectively.

TCP Behaviors

- **Effects of flow size**

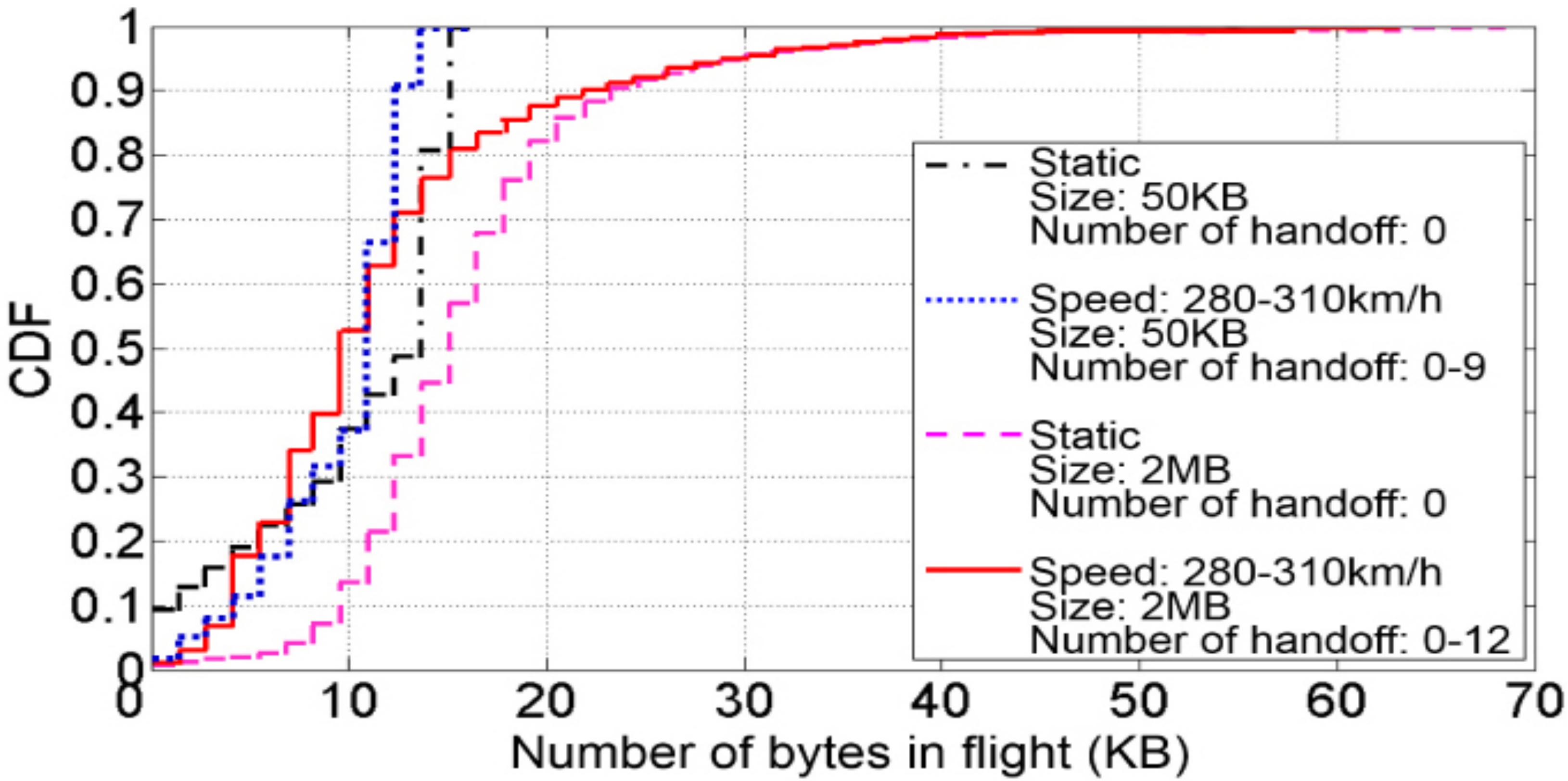
  Big flows are more prone to transmission failures than small flows



TCP Behaviors

- **Effects of flow size**

  Congestion window of big-sized flows decreases more significantly than small flows



Conclusion

Our study shows that performance greatly declines in HSR, where RTT spikes, packet drops and network disconnections are more significant and occur more frequently, compared with static, slowly moving or driving mobility cases.

Conclusion

Moreover, TCP fails to adapt well to such extremely high-speed and yields severely abnormal behaviors, such as high spurious RTO rate, aggressive congestion window reduction, long delay of connection establishment and closure, and transmission interruption. Big flows suffer higher performance degradation than small flows.

Conclusion

All these findings indicate that extremely high-speed indeed poses a big threat to today's TCP and it calls for urgent efforts to develop HSR-friendly protocols and wireless networks to address even more complicated challenges raised by faster trains in the foreseeable future.