Research Article

Comprehensive Analysis on Heterogeneous Wireless Network in High-Speed Scenarios

Yuyang Zhang,¹ Tao Zheng ,¹ Ping Dong ,¹ Hongbin Luo,¹ and Zhibo Pang ²

¹Beijing Jiaotong University, China

²ABB Corporate Research, Sweden

Correspondence should be addressed to Tao Zheng; zhengtao@bjtu.edu.cn

Received 4 November 2017; Accepted 16 April 2018; Published 22 May 2018

Academic Editor: Richard Yu

Copyright © 2018 Yuyang Zhang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Greater demands are being placed on the access bandwidth, stability, and delay of network because of the quickening rhythm of life and work, especially in mobile scenario. In order to obtain a stable network with low latency and high bandwidth in mobile scenario, taking advantage of the wireless heterogeneous network in parallel is a good choice. Nowadays, people are increasingly concerned about the network quality under the mobile scenario. Some scholars have done the relevant measurements. However, all of those measurements mainly investigate part of the network parameters or part of mobile scenarios. In this paper, we make the following contributions. Firstly, in high-speed mobile scenario, the wireless network qualities of different vendors are measured synthetically. Secondly, we analyze the benefits of taking advantage of the different vendors. Thirdly, we deploy the replication link mechanism in high-speed mobile scenario and propose an algorithm to remove the duplicate packet in high-speed mobile scenario. And the algorithm can also be used in another multipath schedule algorithm to improve the reliability.

1. Introduction

With the rapid development of high-speed rail technologies, high-speed rails have become the main way of daily short or medium distance travels [1]. In China, there are 1.713 billion trips made in 2017 bringing the total cumulative number of trips to 7 billion. Followed by the tremendous passenger flow, greater demands are being placed on mobile scenario [2, 3].

Nowadays, cellular network has become the main way for people to access the Internet [4]. With the development of cellular network, many researchers measure the performance of cellular networks from different aspects in different scenarios. Tan et al. [5] did the research about multiple commercial 3G UMTS networks. They analyzed their latency, throughput, and the performance of different applications. Tso et al. [6] analyze the HSPA network in low-speed mobile scenario. However, all of those measurements mainly investigate the network layer parameters and transport layer parameters. And they miss SNR, an important network parameter in network access layer. Rodriguez-Pineiro J and Martin-Vega pointed out that SNR is an important network parameter

for analyzing the cellular networks in high-speed mobile scenario [7, 8].

In addition, there are some literatures studying the performance of wireless network in high-speed mobile scenario [9, 10]. However, these literatures only focus on the network performance of single vendor in high-speed mobile scenario, and they do not analyze the performance of heterogeneous networks that are created by different vendors. We analyze the relationship for heterogeneous networks at the same time and place in high-speed scenario.

In this paper, we carry out a measurement to study heterogeneous wireless networks performance in high-speed mobile scenarios. We define the high-speed mobile scenario that the speed of receiver relative to base station is 300 Km/h or above. 300 Km/h is the typical velocity of the China Railway High-Speed (CRH), which is the largest commercial high-speed railway network. We did our measurement in the Beijing-Tianjin Intercity Railway. In our experiments, we develop a special measurement tool, which is called Heterogeneous Network Measurement Instrument (HNMI). HNMI can access three heterogeneous wireless networks. In our measurement, we made the HNMI access to the three greatest

vendors CMCC, China Unicom (CU), and China Telecom (CT) at the same time. We choose Iperf [11] as the TCP packet generator and Ali cloud server as the TCP receiver, which is the Chinese biggest cloud service provider. In order to investigate the influence of moving speed on wireless network, we design the measurement in static scenario and low-speed mobile scenario as the reference. Beijing Metro Line 13 is selected as the low-speed mobile scenario, where the running speed of the train is about 50 Km/h. And a playground in Beijing Jiaotong University is selected as the static scenario, where the signal strength of three vendors is excellent. The results show that, in high-speed scenario, a single wireless network is too poor to satisfy the user's demand. And the network is not stabilized in high-speed scenario.

Moreover, it is possible to comprehensively utilize the heterogeneous wireless networks because of abundant wireless network resources along the railway [12]. In this paper, we try to deploy the replication link mechanism in high-speed mobile scenario. The actual measurement results show that the replication link mechanism effectively reduces the network volatility, reduces the overall packet loss rate, and significantly improves the network throughput.

The structure of the paper is organized as follows. Section 2 reviews some related works about wireless network measurement. In Section 3, we describe the measurement methodology of our measurement. In Section 4, we describe our result and analyze the influence of moving speed on network performance for each vendor. In Section 5, we deploy the packet replication mechanism in high-speed mobile scenario.

2. Related Work

Research on the vehicle-ground communication is a hot topic [13]. Studying the performance of wireless networks under different mobile speeds is an important direction of vehicle-ground communication. Many researchers do a lot of measurement for wireless mobile network. These works can be divided into two categories:

(1) Limited Scenarios.

Tso et al. [6] investigated the performance of HSPA networks. They analyze not only the static scenario but also many mobile scenarios including subway, trains, and city bus. However, limited by the commercial network deployment, they only analyze the 3G networks, instead of the 4G networks. Jang et al. [14] measured 3G and 3.5G networks with different vendors in different moving scenarios. References [8, 15] proposed different network channel models of high-speed mobile scenarios. Huang et al. [16] measured low-speed mobile scenario. They find that, in low-speed mobile scenario, the RTT remains stable with small volatility. As their analysis SNR is an important parameter that affects the network throughput, Li et al. [17] investigated the TCP behavior in high-speed mobile scenario. They find that current TCP is not adapted to high-speed mobile scenario. However,

the measurement scenarios for these literatures are limited and there is no comprehensive analysis of the network performance in high-speed mobile scenario.

(2) limited Network Parameters.

Xiao et al. [18] carried out extensive measurements on the 4G LTE networks performance in high-speed scenario. They investigate their RSRP, RTT, jitter, and TCP throughput. However, they do not measure the SNR, which is an important parameter for wireless network. Tan et al. do the research about multiple commercial 3G UMTS networks [5]. They analyze their latency, throughput, and the performance of different applications. Liu et al. [19] measured three different LTE networks in high-speed scenarios. They focus on the parameter of transport layer and they do not analyze the parameters of network access layer. However, these literatures only focus on the network performance of single vendor in high-speed mobile scenario and do not analyze the performance of heterogeneous networks that are created by different vendors.

In this paper, we carry out a measurement to study heterogeneous wireless networks performance in different mobile scenarios. We analyze the influence of high-speed mobile scenario on wireless network. And we explore the method of utilizing the heterogeneous networks along the high-speed rails.

3. Measurement Methodology

In order to explore the actual network quality, we design a set of experiments to measure the network quality in different scenarios. In this section, we describe the contents of our network measurements including the tools, scenarios, and measurement methods. And we analyze the measurement result of network quality in detail.

3.1. Measurement Scenario. In order to measure the impact on the wireless network at different moving speeds, we choose three typical scenarios, namely, static scenario, low-speed mobile scenario, and high-speed mobile scenario.

We select an open area of Beijing Jiaotong University as the static scenario, where the network signals of all the vendors are well. The Beijing Metro Line 13 is selected as the low-speed mobile scenario, where the running speed of the train is about 70 Km/h. We select the Beijing-Tianjin intercity high-speed rail as high-speed mobile scenario, where the running speed of the train is around 300 Km/h.

In China, the wireless cellular network is mainly operated by China Telecom (CT), China Unicom (CU), and China Mobile. We select these top three vendors in China to study the relationship between heterogeneous cellular networks at the same place and time. The names and frequency bands of the three major vendors are shown in the Table 1.

3.2. Measurement Parameters. With reference to the previous works, the network parameters are presented in the Table 2.

FIGURE 1: Measurement topology.

TABLE 1: Heterogeneous wireless networks for different vendors.

vendor	Uplink Freq	Downlink Freq	mode	
CMCC	890–909	935–954	GSM900	2G
	1710–1725	1805–1820	DCS1800	2G
	2010–2025	2010–2025	TD-SCDMA	3G
	1880–1890	1880–1890		
	2320–2370	2320–2370	TD-LTE	4G
	2575–2635	2575–2635		
CU	909–915	954–960	GSM900	2G
	1940–1955	2130–2145	WCDMA	3G
	1755–1765	1850–1860	FDD-LTE	4G
CT	825–840	870–885	CDMA	2G
	1920–1935	2110–2125	CDMA-2000	3G
	1765–1780	1860–1875	FDD-LTE	4G

We divide all the parameters into three parts according to the TCP/IP Stack. There are a couple of reasons for this: (1) a large number of applications exist on the Internet; (2) the vast majority of traffic is TCP traffic; (3) the throughput of TCP can well reflect the user's network experience. Therefore, we select TCP throughput as the breakthrough point of our measurement. The quality of the network layer impacts the quality of the transport layer. Hence, we analyze the network layer parameters. RTT and jitter are the most popular parameters. The network access layer guarantees the quality of network layer. As the 4G network is widely covered by vendors in China, RSRP is the most important parameter for indicating the strength of network signal. According to [7, 8], SNR is a significant parameter for network transmission model especially in high-speed scenario. The cell ID represent the cellular network base station that we access. The change of cell ID means that the access network has been switched. During the network switch, the mobile devices have to send a series of packets for reregistration, which is bad for transmission.

3.3. Measurement Tools. Most of the traditional measurement tools can only measure one kind of wireless network at the same time. In order to get further study about the network quality in the different mobile scenarios at the same time, we design the network transmission topology shown in Figure 1.

FIGURE 2: Heterogeneous Network Measurement Instrument.

Moreover, the network quality measurement tool we develop is shown in Figure 2.

The topology of the measurement is shown in Figure 1. We purchase Ali cloud services as our server. The reason why we choose Ali cloud is that it is the largest cloud service provider in China and it has enough access bandwidth to those three major mobile vendors. Last but not least, it can reduce the impact of the cable link in the measurement. The client is the dedicated network quality measurement tool shown in Figure 2. It consists of three identical cellular network adapters and a WLAN network adapter. Each cellular network adapter corresponds to a separate cellular network. Therefore, the device can support three major vendors simultaneously. The WLAN network adapter accommodates the control devices in the IEEE 802.11 b/g/n protocol.

As for software, we develop a network parameters monitoring module based on the Linux 3.2.0 kernel. The module can monitor information including RSRP, SNR, access base station information, network delay, TCP throughput, and so on.

3.4. Measurement Procedure. We did the measurement over three different network vendors simultaneously in three different scenarios. We group the parameters by characteristics of four layers of TCP/IP model. Aiming at the network access layer's parameters, we read the network adapter information every 100 ms. At the network layer, we get the information by the way of sending Ping command periodically. The transport layer information is obtained by Iperf that can make the best of the transport layer's resources. Then we calculate the results of transport layer's parameters from the network adapter every 100 ms.

TABLE 2: Measurement parameters.

parameters	division	introduction
RSRP	Network access Layer	Reference Signal Received Power (RSRP) is a measurement used to represent the received power level in an LTE cell network.
SNR		Signal-to-noise ratio is a measurement used in science and engineering that compares the level of a desired signal to the level of background noise.
Mode		Received signal network standard
Cell ID		The ID of cellular network base station. It means that a network switch has occurred when it changes.
RTT	Network Layer	Round-trip time is the length of time it takes for a signal to be sent plus the length of time it takes for an acknowledgment of that signal to be received.
Jitter		Jitter is the variation in packet delay at the receiver of the information.
TCP throughput	Transport Layer	The rate of TCP packets delivery over a transmission channel.

FIGURE 3: TCP throughput in different scenarios.

4. The Advantage of Heterogeneous Network

By actual measurement result, we find that the network performance is not good in high-speed mobile scenario that cannot meet people's demands of accessing the Internet. In this section, we analyze the factors that affect single vendor's network performance in high-speed mobile scenario layer by layer. In addition, we make a further discussion of the advantage of using heterogeneous networks.

4.1. Transport Layer. First of all, let us intuitively observe the performance of the transport layer parameters in high-speed mobile scenario. Figure 3 illustrates the TCP performance in different scenarios. The changing trends of TCP throughput at different speeds are similar to each vendor. In all of three

scenarios, obviously, the performance of TCP throughput in high-speed scenario is the poorest. In high-speed scenario, the average of TCP throughput is the lowest and the TCP throughput's volatility is the most dramatic.

Next, we give the statistic analysis by boxplot and cumulative distribution function (CDF) figure. Figure 4 shows the boxplot of TCP throughput in different scenarios. The pattern that we name the horizontal axis is "vendor_scenario." S means static scenario, L means low-speed mobile scenario, and H means high-speed mobile scenario. For each cellular network, the median ratios of high-speed mobile scenario to static scenario are 33.32%, 6.25%, and 15.9%.

Furthermore, we study the volatility of TCP throughput. Figure 5 is the CDF of the volatility of TCP throughput in 100 ms. The horizontal axis is the ratio of the volatility

FIGURE 4: TCP throughput boxplot in different scenarios.

of TCP throughput within the 100 ms to the median of results. Vertical axis is the cumulative probability. In high-speed mobile scenario, it is only about 40% possible that the volatility is stable. However, in static scenario, the index is more than 60%. And in high-speed scenario, it is about 40% possible that the volatility of TCP throughput is over 20%. The same index in static scenario is about 20%. In high-speed scenario, such huge volatility in a single network has a great impact on user experience.

Based on the above analysis, we find that, in high-speed mobile scenario, it is difficult to satisfy people's demand for accessing the Internet by single wireless network. Maybe taking advantage of heterogeneous networks can satisfy the people's demand for accessing the Internet. From Figure 3, we find that there is little risk that all the wireless networks perform badly in throughput at the same time. Therefore, as shown in Figure 6, an appropriate algorithm that can utilize heterogeneous networks and achieve bandwidth aggregation can get a relatively reliable network.

4.2. Network Layer. Through the analysis of the transport layer, we can observe that, in high-speed mobile scenario, the network performance of a single wireless network is poor. However, with the heterogeneous networks, the performance of the entire network has a huge room for improvement. Next, we analyze the network layer to find out the advantages of using heterogeneous networks.

Figure 7 shows the RTT in different scenarios for single wireless network. Vertical axis is the RTT value. RTT equal to zero means that the probe packet is lost at this moment. We can observe that, with the increase of moving speed, the average RTT is increasing and sometimes the probe packet is lost.

Next, let us observe the effect of moving on RTT jitter [20]. From Figure 8, we can observe that the RTT jitter in high-speed scenarios is more dramatic. In the CMCC network, it is more than 40% possible that the RTT jitters over 50 ms in high-speed scenario. However, the median RTT is only 131 ms.

Through the above analysis, we find that the trend of RTT is similar. With the increase of moving speed, the packets need more time for delivery and are even lost. This may cause disaster to the applications that are very sensitive to packet delay, such as real-time games. Maybe taking advantage of heterogeneous networks can reduce the transmission delay.

TABLE 3: RSRP level.

level	RSRP (dBm)
Very Good	$\text{RSRP} > -85 \text{ dBm}$
Good	$-85 \text{ dBm} \geq \text{RSRP} > -95 \text{ dBm}$
Average	$-95 \text{ dBm} \geq \text{RSRP} > -105 \text{ dBm}$
Weak	$-105 \text{ dBm} \geq \text{RSRP} > -115 \text{ dBm}$
Bad	$-115 \text{ dBm} \geq \text{RSRP}$

TABLE 4: RSRP level in different scenarios.

	vendor	static	low-speed	high-speed
Very Good	CT	100%	8.0%	2.1%
	CU	100%	10.0%	2.2%
	CMCC	100%	28.0%	2.1%
Good	CT	0	28.2%	15.5%
	CU	0	20.8%	4.3%
	CMCC	0	56.5	3.4%
Average	CT	0	33.8%	39.1%
	CU	0	54.6%	37.2%
	CMCC	0	12.5%	19.2%
Weak	CT	0	22.9%	41.1%
	CU	0	9.0%	50.0
	CMCC	0	3.0%	61.6%
Bad	CT	0	7.1%	2.3%
	CU	0	5.6%	6.4%
	CMCC	0	0	13.8%

Therefore, as shown in Figure 9, an appropriate algorithm shows that each time network selects the fastest link it can get a relatively reliable network.

4.3. Network Access Layer. After the analysis of transport layer and network access layer parameters, we find that the root cause of poor performance in high-speed scenarios is the poor performance of network access layer.

At first, we analyze the signal quality. In our whole measurement, each scenario is covered with 4G networks. RSRP is mainly used in 4G cellular network. Figure 10 shows the RSRP in different scenarios. In our measurement, we divide the RSRP into 5 levels as Table 3 shown. Table 4 is the measurement result. We can see that, in static scenarios, the RSRP is strong enough. However, when the receiver moves, the RSRP is not strong enough and most of the time the RSRP locates in the Average Level. What is more, the RSRP in high-speed scenario is lower than the low-speed scenario's. The SNR is another important parameter for cellular network. Figure 11 shows that SNR in high-speed scenario is lower than SNR in static scenario.

Next, we analyze the signal quality volatility. Figure 12 shows the volatility of RSRP in different scenarios. Figure 13 shows the volatility of SNR in different scenarios. We analyze these parameters together because they have similar characteristics. We can observe that, in static scenario, RSRP is stable and SNR is a little bit volatile. In mobile scenario, RSRP has a certain degree of volatility and the degrees of volatility

FIGURE 5: TCP throughput volatility CDF in different scenarios.

FIGURE 6: TCP throughput performance aggressive in high-speed scenario.

in high-speed scenario and low-speed scenario are closer. In my opinion, there are two reasons for this problem. For low-speed scenario, the measurement scenario is in urban area where the wireless environment is complex and the access to the base station often changes. In high-speed scenario, rapid movement of the receiver leads to changes in the RSRP and SNR. But the base station along the railway is more equally distributed. This is also proved by handoff duration CDF shown in Figure 14. The horizontal axis is the duration of receiver accessing in the same base station. Vertical axis is the cumulative probability. We can observe that although the receiver in high-speed scenario goes far in the same time, the receiver infrequently switched due to the distribution of base station.

Although the performance of the three vendors in high-speed mobile scenario is not very good, their network signals in high-speed mobile scenario are relatively independent. Table 5 is the result of correlation analysis of different vendors in high-speed mobile scenario. The data of the two groups are not correlated where the correlation coefficient is less than 0.3.

We give a further discussion about the handoff of each wireless cellular network under different scenarios. We measured these three wireless cellular networks simultaneously. Concrete analysis on the handoff is shown in one figure as

TABLE 5: Signal Correlation analysis.

	RSRP	SNR
CT vs CU	0.2807	0.1950
CT vs CMCC	0.0175	0.0559
CU vs CMCC	0.0248	0.1034

Figure 15. The horizontal axis is the time. Vertical axis is the different vendors in different scenarios. S means static scenario, L means low-speed scenario, and H means high-speed scenario. In Figure 15, the same color block means that the receiver is accessed to the same base station. In other words, the junction of different color blocks is the time when handoff occurs. We can clearly observe that, in the same scenario, it seldom happens that three cellular wireless network have handoff at the same time. In other word, even in the high-speed scenario, using multiple vendors' network with a suitable schedule algorithm can support a reliable network.

5. Comprehensive Utilization of Heterogeneous Network Resources in High-Speed Mobile Scenario

Section 4 points out that, in high-speed mobile scenario, due to the shielding of vehicle body and wireless cellular network volatility, a single wireless network is difficult to meet the needs of users. However, there are many different wireless networks resources along the railway. The comprehensive utilization of heterogeneous wireless networks along the railway has become an important method to solve the network access in high-speed mobile scenario.

For such a harsh network environment, a simple idea is to copy the data packets, respectively, from different links to send, taking the first arrival of the data packets as useful data packets. And the remaining packets are discarded. At first

FIGURE 7: RTT in different scenarios.

FIGURE 8: RTT jitter CDF in different scenarios.

glance the cost of this idea is very great. However, in such a harsh wireless network environment, due to the wireless link switching, network delay volatility, and packet loss, the TCP protocol designed for reliable wired network is difficult to make full use of the current network resource. In the case of link switching, we find that, in high-speed mobile scenario, the cellular base stations connected by the mobile devices are constantly switching. However, according to the analysis in the previous section, the possibility of the network switching of three vendors is almost no. In terms of network latency, the receiver only receives the first arriving packets.

In other words, this kind of multipath transmission idea can dynamically select the fastest link to transmit. And every choice it makes is absolutely accurate. Moreover, it can reduce the link delay volatility.

$$P_{\text{all}} = 1 - \prod_{i=1}^n P_i \quad (1)$$

In the packet loss, the probability analysis is shown in (1). We can find that the replication link mechanism greatly reduces the packet loss rate. In terms of throughput, the server

FIGURE 9: Minimum delay.

receives the first arriving packet in any one link. This ensures that, at any given time, throughput is the highest link of the currently available links. In high-speed mobile scenario, the real-time throughput of each link is rapidly fluctuating and the replication link mechanism can select the current optimal link in real-time to ensure the throughput. In addition, multipath transmission in heterogeneous network faces an important issue that is out-of-order packets. According to the design principle of TCP protocol, once the packet is out-of-order, it triggers the retransmission mechanism, which seriously affects the effective throughput of the link. In static scenario, the scholars design a lot of methods to prevent out-of-order packets. However, most of these methods are based on the precise measurement of the link quality based on the system or protocol. These methods, based on the measurement results, make accurate calculations to avoid out-of-order data packets. In high-speed mobile scenario, we find that the quality of the wireless link is very volatile. These methods have difficulty estimating the quality of accurate links and cannot make accurate scheduling decisions. However, the replication link mechanism effectively avoids the problem of out-of-order packet in multipath transmission because the problem of out-of-order packet can be neglected when the packets are transmitted on a single link.

The replication link mechanism is also faced with a lot of problems in design. Among them, removing the duplicate packet is a very important problem [17]. The problem for heterogeneous wireless networks in high-speed mobile scenario is particularly prominent. In the replication link mechanism, the same packets are copied into many copies and send from different links. In these same packets, any packet arrives as a valid packet and the rest of the packets are treated as duplicate packets are discarded. Duplicate ACKs in the packets trigger the congestion control mechanism of TCP, if these duplicate packets send to the receiver. The TCP throughput slows down and the link utilization drops. Therefore, we need to number the packets and remove the duplicate packets. We cannot record all the packet numbers because the computer's storage space is limited. At the same time, how to quickly determine whether a packet has been received is also an important problem. Moreover, in high-speed mobile scenario, the difference of packet sequence number is very large in a short time. Designing a deduplication algorithm in a high-speed mobile scenario faces enormous challenges.

We design a deduplication algorithm for high-speed mobile scenario. This algorithm can be not only deployed

```

(1)  $P_i = \text{AnalyzePacket}()$ 
(2) if  $P_i == 1$  then
(3)    $P_{\text{clear}} = 0$ 
(4)    $\text{Buffer.clear}(\text{all})$ 
(5)   return true
(6) end if
(7) if  $P_i < P_{\text{clear}}$  then
(8)   return true
(9) end if
(10) if  $\text{Buffer.find}(P_i)$  then
(11)   return true
(12) else
(13)    $\text{Buffer.Add}(P_i)$ 
(14)   if  $\text{Buffer.length}() > \text{MAX}$  then
(15)      $\text{Buffer.clear}(\text{threshold})$ 
(16)   end if
(17)   return false
(18) end if

```

ALGORITHM 1: Deduplication algorithm.

to the replication link mechanism but also used as a fault-tolerant mechanism in other multipath transmission mechanism. The deduplication algorithm is designed as shown in Algorithm 1.

During the execution of the algorithm, the system stores two variables. One is that the last clear packet sequence number records the maximum sequence number of packets cleared each time. The other is a buffer to record the receive packet sequence number. And the received packet sequence number is stored in order and regularly cleaned. The algorithm is used to determine whether the packet is repeated. It indicates that the packet is a duplicate packet if the algorithm returns true. It indicates that the packet is not duplicated if the algorithm returns false. When packets arrive, step 1 analyzes the packet and obtains the packet sequence number. If the packet number is 1, as steps 3 and 4 showed, the algorithm clears the last clear packet sequence number and clears the received packet number buffer. In step 7, when the received packet number is less than the last clear packet number, which means that the same packet has already arrived, the packet is a duplicate packet. And the algorithm returns true. If the received packet number is greater than the last clear packet number, you need to search the received packet number buffer. In step 10, if the packet is found, it indicates that the same packet arrives. The algorithm returns true.

In step 12, if the packet is not found, it means that this packet is the first arrival of the data packet. In this case, the algorithm checks the length of the received packet number buffer. If the length exceeds the maximum length of the buffer. The algorithm clears a part of the buffer and return false. Here, out-of-order packet is a common phenomenon because the network in high-speed mobile scenario is very bad. Therefore, the received packet number buffer cannot be cleared. Otherwise, the out-of-order packets are mistaken for not receiving packets.

FIGURE 10: RSRP in different scenarios.

FIGURE 11: SNR in different scenarios.

FIGURE 12: RSRP volatility CDF in different scenarios.

FIGURE 13: SNR volatility CDF in different scenarios.

Figure 16 shows the results of our deployment of the replication link mechanism in high-speed mobile scenario. Compared with Figure 3, we can observe that, in high-speed mobile scenario, the effect of the replication link mechanism is much better than any single wireless network. Compared with Figure 6, we can observe that the replication link mechanism effectively reduces the volatility and packet loss of the network.

6. Conclusion

In this paper, with a lot of actual experimental results, we conduct a comprehensive analysis of heterogeneous wireless networks performance. We design the HNMI to measure different vendors' networks at the same time. We find that, in the high-speed mobile scenario, the single wireless network finds difficulty meeting the needs of accessing the Internet.

The comprehensive use of heterogeneous networks has many advantages. Moreover, we deploy a replication link mechanism in actual high-speed mobile scenario and propose an algorithm to remove the duplicate packet that can also be used in other multipath scheduling algorithms. From the measurement, we find that the replication link mechanism performs better than any single network because it effectively reduces the network volatility and packet loss. In the future, we will continue to explore how to use the heterogeneous networks in the high-speed mobile scenario, to provide users with better network services.

Disclosure

This manuscript was presented in the 5th International Conference on Enterprise Systems 2017 as slides, not a full manuscript.

FIGURE 14: Handoff CDF in different scenarios.

FIGURE 15: SNR in different scenarios.

FIGURE 16: Duplicate packet in high-speed mobile scenario.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities (Grant no. 2017JBM018) and the National Basic Research Program of China (973 Program, under Grant no. 2013CB329101).

References

- [1] H. Zhang, P. Dong, S. Yu, and J. Song, "A scalable and smart hierarchical wireless communication architecture based on network/user separation," *IEEE Wireless Communications Magazine*, vol. 24, no. 1, pp. 18–24, 2017.
- [2] L. Li, K. Xu, D. Wang et al., "A Longitudinal Measurement Study of TCP Performance and Behavior in 3G/4G Networks over High Speed Rails," *IEEE/ACM Transactions on Networking*, vol. 25, no. 4, pp. 2195–2208, 2017.
- [3] P. Dong, T. Zheng, S. Yu, H. Zhang, and X. Yan, "Enhancing Vehicular Communication Using 5G-Enabled Smart Collaborative Networking," *IEEE Wireless Communications Magazine*, vol. 24, no. 6, pp. 72–79, 2017.
- [4] P. Dong, B. Song, H. Zhang, and X. Du, "Improving Onboard Internet Services for High-Speed Vehicles by Multipath Transmission in Heterogeneous Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 12, pp. 9493–9507, 2016.
- [5] W. L. Tan, F. Lam, and W. C. Lau, "An Empirical Study on 3G Network Capacity and Performance," in *Proceedings of the IEEE INFOCOM 2007 - 26th IEEE International Conference on Computer Communications*, pp. 1514–1522, Anchorage, AK, USA, May 2007.
- [6] F. P. Tso, J. Teng, W. Jia, and D. Xuan, "Mobility: A double-edged sword for HSPA networks: A large-scale test on Hong Kong Mobile HSPA networks," in *Proceedings of the 11th ACM International Symposium on Mobile Ad Hoc Networking and Computing, MobiHoc 2010*, pp. 81–90, usa, September 2010.
- [7] P. Rodriguez, R. Chakravorty, J. Chesterfield, I. Pratt, and S. Banerjee, "MAR," in *Proceedings of the the 2nd international conference*, p. 217, Boston, MA, USA, June 2004.
- [8] J. Rodriguez-Pineiro, P. Suarez-Casal, M. Lerch et al., "LTE downlink performance in high speed trains," in *Proceedings of the 81st IEEE Vehicular Technology Conference, VTC Spring 2015*, gbr, May 2015.
- [9] G. Tingting and S. Bin, "A high-speed railway mobile communication system based on LTE," in *Proceedings of the 2010 International Conference on Electronics and Information Engineering (ICEIE 2010)*, pp. V1-414–V1-417, Kyoto, Japan, August 2010.
- [10] M.-S. Pan, T.-M. Lin, and W.-T. Chen, "An enhanced handover scheme for mobile relays in LTE-A high-speed rail networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 2, pp. 743–756, 2015.

- [11] L. M. Surhone, M. T. Tennoe, S. F. Henssonow, and P. Theorem, *Iperf*, Betascript Publishing, 2010.
- [12] M. Li, A. Lukyanenko, Z. Ou et al., "Multipath Transmission for the Internet: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2887–2925, 2016.
- [13] X. Yan, P. Dong, T. Zheng, and H. Zhang, "Fuzzy and utility based network selection for heterogeneous networks in high-speed railway," *Wireless Communications Mobile Computing*, vol. 2017, no. 4, p. 14, 2017.
- [14] K. Jang, M. Han, S. Cho et al., "3G and 3.5G wireless network performance measured from moving cars and high-speed trains," in *Proceedings of the 1st ACM workshop*, p. 19, Beijing, China, September 2009.
- [15] F. J. Martin-Vega, I. M. Delgado-Luque, F. Blaquez-Casado, G. Gomez, M. C. Aguayo-Torres, and J. T. Entrambasaguas, "LTE Performance over High Speed Railway Channel," in *Proceedings of the 2013 IEEE 78th Vehicular Technology Conference (VTC Fall)*, pp. 1–5, Las Vegas, NV, USA, September 2013.
- [16] J. Huang, F. Qian, A. Gerber, Z. M. Mao, S. Sen, and O. Spatscheck, "A close examination of performance and power characteristics of 4G LTE networks," in *Proceedings of the 10th International Conference on Mobile Systems, Applications, and Services (MobiSys '12)*, pp. 225–238, ACM, June 2012.
- [17] L. Li, K. Xu, D. Wang, C. Peng, Q. Xiao, and R. Mijumbi, "A measurement study on TCP behaviors in HSPA+ networks on high-speed rails," in *Proceedings of the 34th IEEE Annual Conference on Computer Communications and Networks, IEEE INFOCOM 2015*, pp. 2731–2739, Hong Kong, China, May 2015.
- [18] Q. Xiao, K. Xu, D. Wang, L. Li, and Y. Zhong, "TCP Performance over Mobile Networks in High-Speed Mobility Scenarios," in *Proceedings of the 2014 IEEE 22nd International Conference on Network Protocols (ICNP)*, pp. 281–286, October 2014.
- [19] Q. Liu, K. Xu, H. Wang, M. Shen, L. Li, and Q. Xiao, "Measurement, Modeling, and Analysis of TCP in High-Speed Mobility Scenarios," in *Proceedings of the 2016 IEEE 36th International Conference on Distributed Computing Systems (ICDCS)*, pp. 629–638, Nara, Japan, June 2016.
- [20] S. Paul, "Real-time transport protocol (rtp)," RFC1889, 1998.