3G and 3.5G Wireless Network Performance Measured from Moving Cars and High-Speed Trains

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ABSTRACT

In recent years, the world has witnessed the deployment of several 3G and 3.5G wireless networks based on technologies such as CDMA 1x EVolution Data-Only (EVDO), High-Speed Downlink Packet Access (HSDPA), and mobile WiMax (e.g., WiBro). Although 3G and 3.5G wireless networks support enough bandwidth for typical Internet applications, their performance varies greatly due to the wireless link characteristics.

We present a measurement analysis of the performance of UDP and TCP over 3G and 3.5G wireless networks. The novelty of our measurement experiments lies in that we took our measurements in a fast moving car on a highway and in a high-speed train running at 300 km/h. Our results show that mobile nodes experience far worse performance than stationary nodes over the same network.

Categories and Subject Descriptors:
C.2.3 [Computer-communication networks]: Network Operations — *Network Monitoring*

General Terms: Measurement

Keywords: Measurement, HSDPA, CDMA-EVDO, Wireless, Mobility

1. INTRODUCTION

In recent years, the world has witnessed the deployment of several 3G and 3.5G wireless networks based on technologies such as CDMA 1x EVolution Data-Only (EVDO), High-Speed Downlink Packet Access (HSDPA), and mobile WiMax (e.g., WiBro). CDMA 1xEV-DO was standardized by Third Generation Partnership Project 2 (3GPP2) [2] and it allows cell phone users to connect to the Internet with speed of up to 2.4 Mbps for downlink operations. The HSDPA technology is considered a 3.5G technology and currently supports a downlink bandwidth of up to 7.2 Mbps [1]. Although 3G and 3.5G wireless networks support enough bandwidth for typical Internet applications, performance varies greatly due to the wireless link characteristics.

In a cellular network, mobile terminals are equipped with wireless link specific features, such as Forward Error Correction (FEC) and interleaving latencies which dynamically change the data rates due to interference and mobility. The performance of Internet applications over cellular networks may be significantly degraded because of non-optimized behaviors of transport protocols over the wireless links. The well-known effects of wireless links on the transport protocol performance are burst loss, spurious timeouts, data and ACK compression, and occasional short or long outages.

Many enhancements have been proposed as a means of overcoming the negative effects on the TCP performance. Elaarag surveyed research on improvements to TCP performance over mobile wireless networks [5]. We note that most solutions are based on theoretical modeling and simulation with limited mobility. Experimental research into mobility is daunting because of the difficulty of creating a mobile environment for experiments and because the task of recreating the same environment for verification is not always feasible.

In this paper, we analyze the measurements of UDP and TCP performance over 3G and 3.5G wireless networks. The novelty of our measurement experiments lies in that we took measurements in a fast moving car on a highway and in a high-speed train running at 300 km/h. Previous studies that measure the performance of the 3G network depend on stationary end hosts and do not include the mobile end hosts [4, 11]. Predictably, our results show that mobile nodes experience far worse performance than stationary nodes over the same network, indicating difficulties that are specific to this type of measurement.

The rest of this paper is organized as follows: Section 2 describes the measurement methodology. We then present the results of the UDP and TCP measurements in Section 3. We describe related work in Section 4. Finally we summarize our work and discuss our future directions in Section 5.

2. MEASUREMENT METHODOLOGY

2.1 Mobility Scenarios

Data communication over cellular networks has opened up new opportunities for users to stay connected while in motion and new services tailored to the mobility of users. We consider stationary and moile scenarios for our experiment. The upper limit of mobility support in cellular networks is 250 km/h. However, users are not constrained to exploit connectivity only under the specified speed and often attempt to get online while moving at a higher speed. One example involves users on board the Korea Train eXpress (KTX), which runs the entire 450 km across the southern Korean peninsula from Seoul to Busan at a maximum speed of 300 km/h. Since its opening in May 2004, the KTX has become a popular means of transport for people taking a day trip between any two cities on the line. We include two scenarios for mobility: typical vehicular moblity and high-speed train. At the time of our measurement experiments, there was no 3.5G HSDPA network coverage along the KTX line, and we limited the experiment on the KTX to the 3G network. Table 1 shows the date of each measurement experiment.

Table 1: Experiment Scenarios

Service	CDMA-EVDO		HSDPA	
Provider	SKT	KTF	SKT	KTF
Stationary	Aug 2006	Oct 2006	Nov 2006	May 2007
Car (100 km/h)	Jul 2007	Oct 2006	Nov 2006	Jun 2007
KTX (300 km/h)	Oct 2006	Oct 2006	N/A	N/A

We include the stationary scenario in order to capture the baseline or the best possible performance of the cellular networks. For the second scenario of mobility in a car at 100 km/h, we carried the *mobile node (MN)* in a car on a highway around the city of Daejeon. To drive the car at a constant speed of 100 km/h during the experiments, we chose the ring road around Daejeon as it is not congested and we could maintain the speed between 80 km/h to 120 km/h at all times. For the last scenario of mobility on the KTX, we rode the KTX train from Seoul to Busan with the MN and conducted our experiments.

2.2 Experimental Setup

As the main goal of this work is to measure and analyze the performance of commercially deployed 3G and 3.5G networks, it is imperative that we setup the experiment such that we measure the cellular network performance, not that of the wired Internet. In all our measurement experiments, we directly connect a PC, called *Correponding Node (CN)*, to a router on KOrea advanced REsearch Network (KOREN), which is a research network that interconnects research institutes and universities in Korea. KOREN and gateways to all the cellular networks are directly connected at KIX (KT Internet Exchange) and offers the close access to the commercial cellular networks in terms of the number of hops. Another advantage is that KOREN is lightly loaded. Hence, the performance degradation from cross-traffic is expected to be minimal. We use a laptop, called the *Mobile Node (MN)*, which is equipped with cellular modems. We then measure the performance between the MN and the CN.

In our measurement experiments, we generate two types of traffic: UDP constant bit rate (CBR) and TCP long-lived bulk traffic. We use the UDP CBR traffic to investigate the maximum feasible throughput over the cellular link and its variability. In addition, we look into the delay jitter and loss of UDP traffic. The variability in delay and loss from the cellular links affect the TCP behavior significantly. We analyze the variability in the TCP throughput and investigate the types of retransmission for the impact of variability on TCP behavior.

We use *iperf* to generate both UDP and TCP traffic [7]. Each measurement is conducted for 300 seconds and repeated 10 to 21 times. Gateways to 3G and 3.5G networks use the Network Address Translation (NAT), but *iperf* cannot initiate a connection to a node behind NAT. We modified the source code of *iperf* to traverse NATs. To collect packet traces at the CN and the MN, we use *tcpdump* and *windump*, respectively.

2.3 Target Networks

In Korea, the number one mobile service provider is SK Telecom (SKT) and the number two is Korea Telecom Freetel (KTF). Together, they control about 80% of the domestic mobile service market. As the two leaders in the market, they are the first ones to roll out the latest new technology and offer comparable services and rates. In this work, we target our measurement study on those two networks or, more specifically, on their 3G and 3.5G networks. For each network and mobility scenario, we use the following abbreviations: EVDO-S stands for the 3G CDMA 1xEVDO network of SKT and EVDO-K of KTF. Similarly, HSDPA-S and HSDPA-K stand for the 3.5G HSDPA networks of SKT and KTF, respectively.

3. ANALYSIS

We begin this section with an overview of the measurement experiments. Table 2 shows the number of 300s measurement sessions conduct along with other options. Although each cellular network has a predefined theoretical maximum throughput, the actual throughput a user experiences at a time can vary depending on the network service provider's configuration, the distance from the base station, and even the mobile device's computing resources. We conducted preliminary measurement experiments to determine the maximum throughput of each network, and set the transmission rates of the UDP traffic as listed in the right most column of Table 2(a). The data rates that we choose to saturate the links are not the maximum throughput, but what we consider to be *sustainable*. Beyond the sustainable rate, the loss rate falls precipitously and becomes intractable. However, our methodology in choosing the sustainable sending rate has not been thoroughly examined and we leave it for future work.

The frame size for CDMA 1xEVDO and HSDPA networks is a multiple of 1024 and varies depending on the data rates. This variation poses a challenge because we could not saturate the cellular link without knowing the exact data rate offered at the time of each experiment. The network service providers, SKT and KTF, constantly upgraded their networks in 2006 and 2007. Another challenge is the match with the Ethernet frame size. For the performance evaluation of the downlink, the CN sends traffic over the Ethernet segment and the Ethernet frame payload is limited to the well-known size of 1500 bytes. For our experiments, we chose 1498 bytes as our packet size (which, unfortunately, is 2 bytes short of the maximum Ethernet payload). We discuss the consequences of our choice later in this section.

For the TCP experiments, we vary the buffer size and list our choices in the right-hand column of Table 2(b). In the rest of this section, we present only the results from the downlink measurement experiment.

3.1 UDP Traffic Analysis

We begin our analysis with the average throughput of the UDP CBR traffic and, due to limited space, we present a time-series plot only from the HSDPA-S data set in Figure 1(a) as a representative instance. We concatenate the results of sessions lasting 300s each and plot them as one long experiment along the x-axis of time. The throughput is calculated every 5 seconds.

Because we have 10 data sets from the stationary case and 15 from the car case, the gray plot for the stationary case finishes before that of the car case. When the MN is stationary, the throughput is visibly more stable than when the MN is mobile in a car. When the MN is mobile, the throughput fluctuates significantly.

To visualize this difference in variability, we plot in Figure 1(b) the interquartile dispersion of the throughput of all scenarios. All the data points that lie outside the interquartile range are individually plotted. The results show that our choice of the sustainable

Table 2: Summary of UDP and TCP experiments

(a) Data sets of UDP experiments

Service	# of Sessions (Upload/Download)			Option
	Stationary	Car	KTX	UDP CBR (kbps)
EVDO-S	9/9	16/16	17/17	120/500
EVDO-K	10/10	4/4	14/14	120/500
HSDPA-S	10/10	15/15	-	350/1300
HSDPA-K	15/15	13/13	-	120/1200

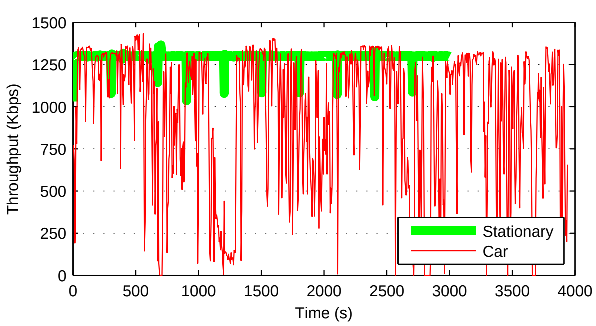
(a) Data sets of TCP experiments

Service	# of Sessions (Upload/Download)			Option
	Stationary	Car	KTX	TCP buffer size (KByte)
EVDO-S	20/20	16/16	15/15	20/64
EVDO-K	21/21	9/9	28/28	20/64
HSDPA-S	12/12	15/15	-	45/200
HSDPA-K	10/10	12/12	-	32/512

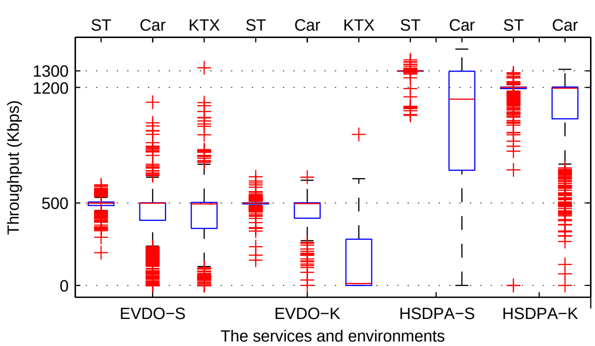
rate is rightly justified because the interquartile range falls right on the rate or right below, inclusive of the sustainable rate. The few data points above the sustainable rate represent packets sent at rates near the theoretical maximum rates.

Within a single network, the stationary case has the least variability, followed by the car mobile case and finally the KTX case. In EVDO-K, the performance degradation is more severe in the KTX than in the car. We suspect, but not confirm, that the limited deployment of base stations along the KTX line is the cause.

Next, we analyze the jitter and loss rates of the CBR traffic. We could not achieve sub-millisecond clock synchronization between



(a) Time-series plot of UDP CBR traffic



(b) Inter-quartile range plot of UDP CBR traffic

Figure 1: UDP CBR traffic throughput in all scenarios

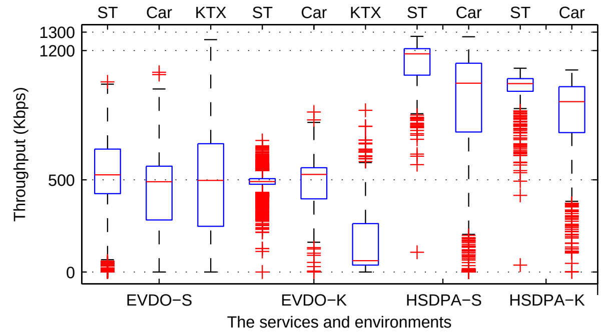


Figure 3: TCP download throughput

the CN and the MN and could not measure the absolute delay between them. Instead, we define jitter as the difference between the sending intervals and the arrival intervals at the CN and the MN; we than analyze the variability in the arrival intervals. Figure 2(a) depicts the cumulative distribution function (CDF) of the UDP CBR traffic jitter. As explained in Seection 2.1, the two plots on the right have no data from the KTX case. Except for the HSDPA-S case, all the graphs in Figure 2(a) have a rising step at about 7 ms. Because the HSDPA-S case has jitter less than 7 ms, the rising step is not due to clock timestamp granularity on the MN. Note also that the graphs with a rising step at 7 ms were taken in 2007. We suspect that this outcome is due to the multiple Ethernet-frame-sized packets that were sent to a single frame; the outcome may also depend on our choice of the 1498-byte packet size. Only after comparing different data sets, we realized that the frame size could be the reason, but could not go back in time and experiment with different packet sizes. We leave this question for future consideration.

Although mobile cases exhibit higher jitter than stationary cases, more than 90% of jitters are less than 100 milliseconds in both cases. Given that our traffic exceeds the sustainable bandwidth, this result is encouraging for real-time applications.

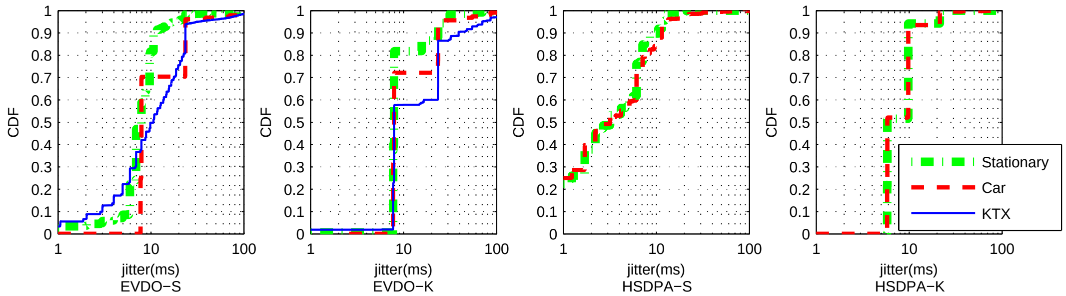
We now look at the loss rate of the UDP CBR traffic. In Figure 2(b) the loss rate in the mobile cases is much higher than the stationary case, reaching more than 50% for about 10% of the 5-second intervals. In 3G and 3.5G networks, a MAC layer retransmission mechanism called a Hybrid Auto Repeat reQuest (HARQ) is used to reduce the loss rate at the cost of increased delay. Even with the added loss recovery at the data link layer, the end-to-end loss is very high in the mobile cases.

3.2 TCP Traffic Analysis

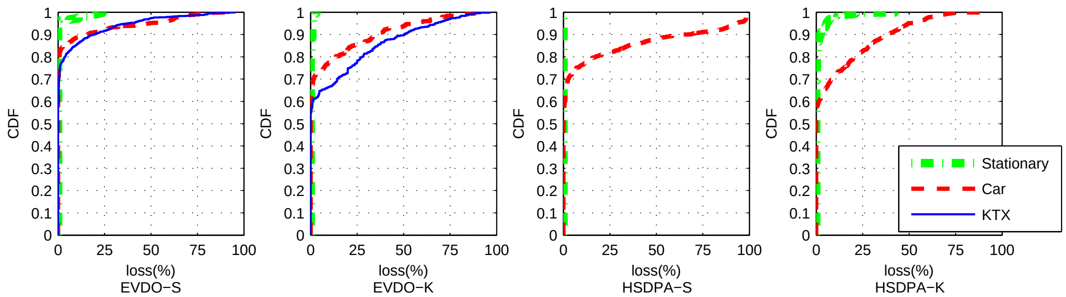
In the previous section, we observed that the link loss rate is much higher in the mobile cases than in the stationary case. High loss rates impacts the TCP performance severely, and problems such as spurious timeout and inaccurate estimation of the sending rate are aggravated.

Figure 3 shows the TCP throughput for all scenarios as in Figure 1(b). In EVDO-S, the stationary case has a slightly better median throughput than the mobile car case, and the interquartile of both types of cases is similar. Even the KTX case has a comparable interquartile range. In EVDO-K, the stationary case shows far better performance than the car and the KTX cases. Note that in the stationary case of EVDO-S, the car mobile case of EVDO-K, and the car mobile cases of both HSDPA-S and HSDP-K, the throughput is near zero at multiple points.

To investigate the cause of TCP performance degradation in the stationary case, we analyze the TCP behavior in more detail. We



(a) CDF of UDP CBR traffic jitter



(b) CDF of UDP CBR traffic loss rate

Figure 2: Delay jitter and loss of UDP CBR traffic

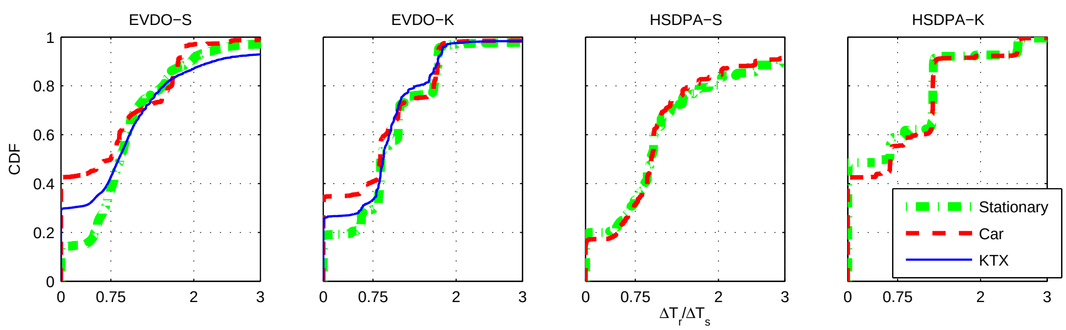


Figure 4: CDF of $\Delta T_r/\Delta T_s$

first look for the possibility of ACK compression. When a packet is delayed in the queue due to a poor link condition, the packets that subsequently arrive accumulate and are transferred altogether in a short period when the link condition improves. This phenomenon is called ACK compression, and causes the sending rate to increase beyond the available rate at the source [3]. We calculate the sending and receiving intervals of acknowledgment packets from the traces collected at both the CN and the MN, which we denote as ΔT_s and ΔT_r, respectively. If $\Delta T_r/\Delta T_s < 0.75$ in at least three consecutive packets, we consider this to be an ack compression event [12]. Ack compression events are reported to be rare on the Internet but significant in a wireless network such as 3G [3].

We show how often an ACK compression occurs in our measurement data. Figure 4 shows the CDF plots of $\Delta T_r/\Delta T_s$ between two consecutive ack packets. For all stationary cases except HSDPA-K, about 30% of ack packets arrive in a cluster. In the case of EVDO-S and EVDO-K, a high percentage (about 40%) of ACK packets actually arrive at the same time, signifying severe compression. If we consider the ACK compression of three packets or more, the ACK compressions are 10.8% in the stationary environment and 22.2% in the mobile environment. Many of ack compressions cause duplicate acks. Even for stationary hosts, the ack compression event is significant and causes TCP misbehavior.

Spurious retransmission is another problem that the TCP should deal with over a wireless link. Because TCP cannot distinguish congestion-induced from the loss over the wireless link or a sudden increase in delay, it retransmits a packet and reduces the sending rate unnecessarily. Varcica *et al.* have detected spurious retransmissions in the operational UMTS/GPRS network and concluded that spurious timeouts are infrequent [14]. However, they could not distinguish the TCP flows of mobile users from those without mobility. In this work, we analyze all retransmitted packets in TCP traces at both the sender and the receiver side and classify them into three types of retransmission: namely, normal retransmission (N-Rxt), which is due to the loss of a data packet, spurious retransmission (S-Rxt), which occurs when there is neither loss of an ACK nor loss of a data packet; and unavoidable retransmission (U-Rxt), which is due to the loss of an ACK packet. In addition, we analyze whether there are any serial (multiple) retransmissions (M-Rxt), which means that a packet is retransmitted several times

Table 3: Propotion of each retransmission type

Rate(%)	% Rxt.	N-Rxt.	S-Rxt.	U-Rxt.	M-Rxt.
Stationary					
EVDO-S	0.29	83.31	16.69	0.00	4.074
EVDO-K	0.42	12.09	86.32	1.59	0.469
HSDPA-S	0.54	12.52	87.48	0.00	0.062
HSDPA-K	0.02	23.81	76.19	0.00	0.000
Car					
EVDO-S	1.42	41.08	57.27	1.66	10.396
EVDO-K	0.98	15.85	82.45	1.70	3.585
HSDPA-S	0.47	4.95	94.97	0.08	7.889
HSDPA-K	0.17	7.75	92.25	0.00	6.295

and suffers from an exponential back-off. Table 3 summarizes the results of the three types of retransmission and serial retransmission.

As shown in Table 3, the overall retransmission rate for stationary cases is lower than for mobile cases, but the spurious retransmission rate is slightly higher. On the other hand, in the car mobile case, there is a high percenge of multiple retransmisions.

One particular observation we make across all of the analysis is that the stationary and the car mobile cases do not exhibit much difference in HSDPA-S. Possible explanations include: increased support for mobility in the 3.5G network and the small number of users in the early stage of deployment.

4. RELATED WORK

Kohlwes *et al.* measured two different UMTS networks in Germany[10]. Their results show that TCP throughput is stable at 350 Kbps which is close to theoretical maximum and TCP retransmission timer modification does not help to improve the performance. Jurvansuu *et al.* measured throughput over HSDPA and WCDMA networks[8]. Their result shows that TCP throughput on HSDPA is around 1 Mbps and that on WCDMA is 350 Kbps; both are close to corresponding ISPs advertised limits. Han *et al.* measured UDP throughput and VoIP quality over an WiBro network in a subway [6]. The UDP throughput is stable around 5.3 Mbps for downlink and 2 Mbps for uplink even in the subway moving at speed over 90 km/h. The VoIP quality over WiBro is as good as toll quality whether mobile or not. Kim *et al.* measured TCP performance over WiBro and reported that TCP throughput is around 4Mbps due to limited windows size of 64kB [9]. They indicate that reducing RTT or increasing receive window size would improve TCP throughput.

Jurvansuu *et al.* also measured over an HSDPA and WCDMA networks[8]. Lowest one-way delay in HSDPA network is 47 ms which is smaller than the WCDMA's 76 ms; in addition, WCDMA exhibits delay spikes of a few hundred miliseconds, while HSDPA rarely has delay spikes and the value is much smaller than that of WCDMA due to HARQ. Prokkola *et al.* measured delay in WCDMA and HSDPA networks[13]. They find that delay over an HSDPA network is smaller and more stable than that in a WCDMA network.

Most measurements over mobile wireless networks is conducted in a stationary manner due to difficulties of experimenting under mobile environment. The novelty of our work lies in that we took our measurement both mobile environments.

5. CONCLUSION AND FUTURE WORKS

In this paper, we have conducted a measurement study over commercial 3G and 3.5G networks. In the UDP CBR traffic analysis, we confirm that mobility significantly degrades the end-to-end performance. In the next TCP traffic analysis, we show that the ack compression is common and that spurious retransmissions represent more than half of all retransmissions.

During the course of this measurement study, we faced several challenges. First, we could not repeat certain experiments due to time constraints. To conduct measurement experiments in a car or on a KTX train, we had to drive around the town or ride the KTX ourselves to collect the data. Even though more experiments were needed or desirable, we could not conduct further experiments. In addition, the commercial networks constantly upgrade their services and change their billing policies. Because the details of the upgrades are not made public, we used the same parameters for all our experiments, even in cases where the circumstances had changed. All these problems pose a high threshold for those interested in measurement study of these networks.

In the future, we plan to investigate a feasible way of detecting the bottleneck capacity of the cellular network, taking into consideration the different frame sizes at different rates. We also hope to formulate a more rigorous definition of the "sustainable" rate to be used in the performance analysis.

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