# Measuring and Improving the Reliability of Wide-Area Cloud Paths

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## Abstract

Many popular cloud applications use inter-data center paths; yet, little is known about the characteristics of these “cloud paths”. Over an eighteen month period, we measure the inter-continental cloud paths of three providers (Amazon, Google, and Microsoft) using client side (VM-to-VM) measurements. We find that cloud paths are more predictable compared to public Internet paths, with an order of magnitude lower loss rate and jitter at the tail (95th percentile and beyond) compared to public Internet paths. We also investigate the nature of packet losses on these paths (e.g., random vs. bursty) and potential reasons why these paths may be better in quality. Based on our insights, we consider how we can further improve the quality of these paths with the help of existing loss mitigation techniques. We demonstrate that using the cloud path in conjunction with a detour path can mask most of the cloud losses, resulting in up to five 9’s of network availability for applications.

## 1. INTRODUCTION

To meet the performance and regulatory needs of customers, major cloud providers host data centers all around the world. Many cloud applications involve communication *between* these data centers; this include applications like wide area data analytics [44], distributed storage [45, 42], and user facing applications like search and video conferencing [16, 46]. Despite the active use of these inter-data center (cloud) paths, little is known about the characteristics of these cloud paths. For example, are these cloud paths similar to the public Internet paths, or different? Also, are there differences between cloud providers, and which provider should an application choose depending on its requirements?

To help answer these questions, we conduct a measurement study of cloud paths belonging to three major cloud providers: Google, Microsoft, and Amazon. All of our measurements are done between virtual machines (VM) located in different continents – it captures the expected performance received by a tenant who is running a geo-distributed cloud service. Our study spans a period of eighteen months and includes both a longitudinal analysis of important cloud path properties (e.g., loss rate, latency, etc) as well as an in-depth analysis of the nature of losses on these paths (bursty vs. random). We also compare cloud path characteristics with properties of public Internet paths, using inter-continental paths between PlanetLab [8] and Pinger [7] nodes.


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We find that in terms of cloud providers there is no clear winner – each cloud provider outperforms others on some metric (e.g., low loss rates on some paths but not on all paths). However, we do find that cloud path performance is more predictable compared to the public Internet paths. We find that:

- Cloud paths experience lower packet loss than an average Internet path; their loss rates are between 0.01% - 0.1% as compared to average public Internet loss rates of 0.1% - 1% [24, 18, 10, 38, 14, 41, 33]. The main difference arises because of the tail: even the worst cloud path has a loss rate lower than 0.07% whereas more than 5% of the public Internet paths had a loss rate of more than 2%.
- Cloud paths have lower tail jitter compared to Internet paths. We observed that latency on the cloud paths is quite predictable and the variation is mostly within 30% while Internet paths can have high jitter (>65%).
- Cloud paths have high inter-VM bandwidth, with high performance VMs of some providers getting up to 9Gbps bandwidth across their inter-continental paths. This performance is an order of magnitude higher than typical throughput achieved over the wide area public Internet paths [24, 1].

We also analyze the reasons behind these differences. Our autonomous system (AS) level path analysis confirms anecdotal evidence that cloud providers have “dedicated” paths between their data centers. Specifically, all cloud paths of Google and Microsoft, and most paths of Amazon, span only their own ASes. These dedicated cloud paths are therefore more likely to be well provisioned and better engineered than typical wide area paths, with cloud providers possibly using a logically centralized controller (e.g., B4 [31], SWAN [28]) for traffic engineering and reliability.

To illustrate the broader implications of our findings, we conduct a case study in which we investigate the following question: *can we further improve the availability of cloud paths, so they can offer near zero loss rate for wide area communication?* A positive answer to this question can improve the quality of today’s interactive applications (e.g., video conferencing, online gaming), facilitate the widespread use of emerging applications like tele-presence and remote surgery, and potentially be the driving force behind future, yet-to-be-known, real time applications.

Our results show that it is possible to offer such a WAN service that improves reliability of cloud paths. This observation is based on our finding that cloud paths experience two types of losses: *random*, isolated packet losses; and *degradation periods* that can last for several minutes, where most, if not all, packets are lost. Fortunately, both issues can be resolved using existing techniques. We show that forward error correction (FEC) can effectively mask random losses without incurring too much overhead, resulting in significant improvement for some cloud paths. More importantly, we show that one-hop detour routing [25] can avoid most degradation periods,

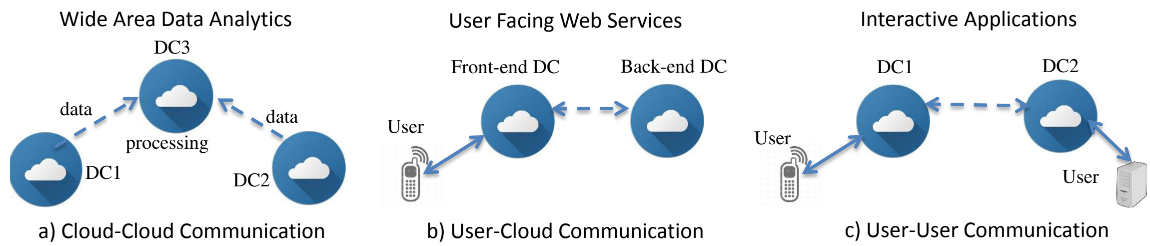



**Figure 1: Different applications using the inter-data center (DC) paths (cloud paths)**

resulting in very low loss rates for most cloud paths. We show that detour routing is more effective for cloud paths as compared to typical wide area Internet paths.

Overall, we make the following contributions in this paper:

- A longitudinal measurement study spanning one and a half years which investigates cloud path properties of three major cloud providers.
- An in-depth analysis of the nature of packet losses observed on the cloud paths (i.e. loss characterization).
- Evaluation of the benefits of using existing loss mitigation schemes (i.e., FEC, detour routing) to further improve the availability of cloud paths.

We believe that the cloud paths are increasingly becoming an integral part of the Internet ecosystem. Our findings are a first step towards understanding their path properties and their implications on application performance.[1]

# 2. BACKGROUND

We highlight scenarios that use cloud paths, and then contextualize our work in relation to prior measurement studies and other relevant proposals.

## 2.1 Application Scenarios

We categorize applications that use cloud paths into three categories, based on the underlying nature of their communication.

Fig 1a shows *cloud-cloud communication*, which includes applications like wide area data analytics [44, 43]. These applications typically only use the network of the cloud provider (both intra and inter data center network). Factors such as cost, throughput, and latency are important for these applications.

A wide range of online services (e.g., search, online social networking, geo-replicated cloud storage [45, 42], etc) fall in the category of *user-cloud communication* (Fig 1b). The typical use case for such applications is the following: client connects to a nearby front-end data center, which may need to retrieve data from a back-end data center, and the communication between the data centers uses the cloud path. This type of communication can benefit from the typical benefits of a split-transport approach [37, 23, 20, 22, 19], such as shorter RTTs, local retransmissions, customized transport for cloud paths, etc.

Finally, another growing use case of cloud paths is the *user-user communication* (Fig 1c), which includes traditional P2P applications, such as VoIP and online gaming. For example, in Google Hangout, each end-point communicates with a relay server (typically hosted in a nearby data center), and the relay servers communicate with each other using the cloud path [46]. Such cloud enabled end-to-end communication potentially provides several benefits, including deployment of in-network services (inside the cloud) [36, 26] and the benefits of a split-connection approach as discussed above.

[1] To facilitate reproducibility, we have made available summarized results of our measurement study [5].

## 2.2 Related Work

There is a large body of work that is relevant to the above scenarios. Here we focus on the measurement studies and proposals that are most relevant to our goal of understanding the characteristics of cloud paths.

**Cloud Measurements.** Several measurement studies have analyzed different networking aspects of cloud-based systems(e.g., [9, 24, 13, 34, 16, 45]). The studies have either focused on the *intra*-data center networks (e.g., [9]) or the performance between the users and the cloud (or content delivery network) (e.g., [16, 17, 15, 40, 45]). The few studies that include inter-data center measurements [34, 47] have mainly focused on inter-data center *bandwidth* whereas we conduct a detailed analysis of path characteristics, such as loss, latency variation, and packet reordering.

**Internet based measurements.** Our work is inspired by, and benefits from, a large body of measurement work on Internet path characteristics. This includes seminal studies by Bolot [14] and Paxson [38], and insights by measurement based systems (e.g., RON [10], iplane [35], etc). Throughout the paper, we refer to the insights provided by these studies, and identify similarities and differences between Internet and cloud path characteristics.

**Inter Data Center Proposals.** Recently, there is growing interest in issues related to inter-data center networking. This includes application of software defined networking (SDN) (e.g., SWAN [28], B4 [28]) in such environments, techniques for specific workload needs (e.g., application deadlines [47, 32]), and performing geo-distributed analytics [43, 44]). While these systems offer valuable insights regarding workloads and topologies, they do not focus on path characteristics of cloud paths.

**Overcoming network outages.** Many techniques have been proposed in the context of recovering against network outages or packet losses. This include use of overlay networks, in the form of careful path selection (e.g., RON [10], Akamai CDN [39]) or one-hop detour routing [25], straggler mitigation techniques for cloud systems [30], and restoration routing in the context of MPLS networks [21, 11]. FEC is a standard technique to recover against packet losses and is typically used by real time applications as well as WAN middleboxes [12]. Our work *leverages* these known techniques – we evaluate their effectiveness in recovering against packet losses and degradation periods observed on the cloud paths.

| Provider | Location | VM Type | Paths |
|---|---|---|---|
| Amazon | Virginia, California (US), Ireland (EU), Singapore (Asia), Sydney (Aus) | t2 micro | 9 |
| Microsoft | Virginia, California (US), Ireland (EU), Singapore (Asia) | f1 micro | 7 |
| Google | Iowa(US), Belgium (EU), Taiwan (Asia) | A0 basic | 6 |

**Table 1: VM Type and locations**

# 3. MEASUREMENT METHODOLOGY

**Overview.** Our measurements span the three major cloud providers (Amazon [2], Google [4], Microsoft [3]). They all have data centers spread all over the world, including multiple data centers within US. Our focus is on wide area paths, so we only consider inter-continental cloud paths (e.g., US-Europe). All three providers have data centers in US, Europe, and Asia – the only exception is Australia, where we only had access to Amazon's data center.

Our measurements are done over sixteen weeks, which are spread over a period of eighteen months from November 2014 to June 2016; in total we measure 22 paths where each path is between a pair of virtual machines (VM). The path locations, the type of VMs, and other relevant cloud specific details are noted in Table 1[2]. The focus of our measurements is on three path properties: loss rate, latency, and available bandwidth.

**Measurement Tools and Probing Methodology.** We use a combination of well-known tools for our experiments (see Table 2 for details).

- We use ping to measure bi-directional loss rate over longer durations, enabling a head-to-head comparison with similar measurements conducted for the Internet. We used both ICMP and TCP ping and found their results to be similar. Our reported results[3] correspond to ICMP ping as it allows a direct comparison with the data we use to analyze Internet path characteristics.
- We use UDP based probes to differentiate between forward and reverse path characteristics, packet reordering, and to also investigate the nature of losses by varying the packet spacing and burst duration of the probes.
- We use traceroute to identify the routes between VMs. Only Amazon allows ICMP responses on its internal network. For Google and Microsoft, we used traceroute between VM and external (public Internet) hosts in order to identify the routes to/from the cloud.
- We use iperf3 [6] to measure the bandwidth between VMs.

**Internet Path Characteristics.** To compare cloud path performance with the Internet, we refer to insights from prior studies (e.g., [38, 14]) on Internet path measurements. In addition, we also use results from the PingER project [7] as well as use PlanetLab nodes for active measurements.

The PingER project measures wide area path properties between multiple hosts located over the Internet. Overall, their measurements involve over 700 sites that are distributed in different continents. Their results span a period of more than a decade, which allows a direct comparison with prior and more recent Internet measurement studies (e.g.,[10, 38, 33, 41] as well as our recent cloud path measurements. Our analysis shows that PingER loss rates are improving over time (in the last decade) and are similar to or better than the results reported in prior studies (for the same time period). For any inter-continent path (e.g., USA-Europe), we consider *all* PingER measurements between their hosts located in the two chosen continents.

We also use the PlanetLab testbed [8] for some of our experiments. It allows us more control over the experiments (unlike PingER) but we do not have historical data to compare PlanetLab results with other prior studies (in order to calibrate whether the PlanetLab results are better or worse than typical Internet paths). However, because PlanetLab uses well-connected hosts for the measurements, we expect its results to be similar or better than the performance reported by prior studies on Internet path characteristics. With our focus on inter-continental cloud paths, we only consider PlanetLab paths that span different continents. Unless otherwise stated we pick all available nodes in a continent for our experiments, which provide up to 1200 paths for some of our larger experiments. For experiments that have higher overhead, we use a smaller number of paths by randomly selecting a subset of active nodes.

[2]More details of paths are available at [5]

[3]For Microsoft, we report results of TCP based ping, as ICMP has only been recently allowed on the Microsoft network

# 4. MEASUREMENT RESULTS

We now present results of our measurement study of cloud paths. We quantify packet loss (§4.1), latency (§4.2), bandwidth (§4.3), and packet reordering (§4.4) properties of cloud paths and compare the results with Internet paths. Finally, we discuss possible reasons why cloud path characteristics are different from typical Internet paths (§4.5).

## 4.1 Loss Characteristics

Loss rate is an important factor that influences application performance – it impacts interactive applications as well as TCP-based applications. For interactive applications, losses lead to poor user experience while for TCP-based applications, given the high bandwidth delay product of typical cloud paths, even a small loss rate can have significant impact on throughput [12]. We conduct a longitudinal analysis of loss rate of cloud paths and do an in-depth analysis of the loss characteristics (e.g., burst size, etc). We also compute loss correlation of cloud paths.

### *4.1.1 Loss Rate - A Longitudinal Analysis*

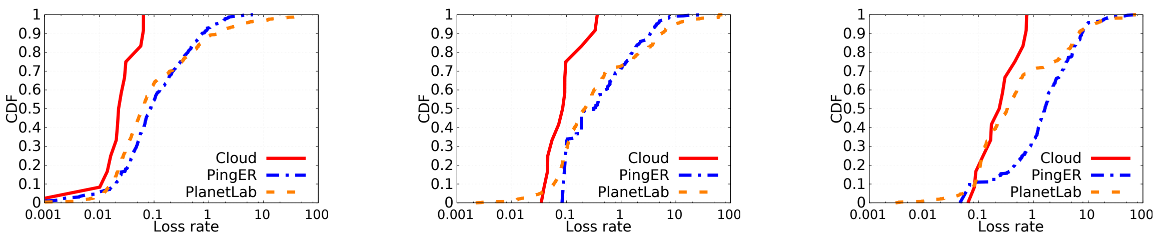
Our first goal is to quantify the loss rate of cloud paths and compare it to typical Internet paths. We look at difference in loss rate across cloud providers as well as across different continents. Our longitudinal analysis also allows us to observe how the loss rates of cloud paths evolve over time.

To measure loss rate, we use the ping probes, as described in table 2). To compute the aggregate loss rate for a path, we consider *all* probes sent on that particular path (across all time periods). It corresponds to roughly 7 million probes for every path. We also compute loss rate on a per day basis, in order to understand the variations at shorter time scale (later in the section, we further zoom into shorter time scales to look at the specific loss patterns).

We compare cloud paths with PlanetLab and PingER paths. We use data from 300 PingER and 1200 PlanetLab paths collected during the same duration as our study. While PlanetLab paths use the exact same probing frequency, PingER paths have lower frequency; however, we have verified that this difference does not impact our analysis (by considering a subset of probes to exactly match the PingER probing frequency).

| Probe Type | Probes/minute | Inter-probe gap | Probes/Path | Probe size | Analysis |
|---|---|---|---|---|---|
| ICMP, TCP ping | 60 | 1s | 7.14M | 64 Bytes | Loss rate (§4.1.1) |
| UDP | 60 | 1s | 2.6M | 44 Bytes | Loss Correlation (§4.1.3), Latency (§4.2) |
| | 15<br>500 | 10ms<br>10ms | 800K<br>9M | 44 Bytes | Reordering (§4.4), Burst nature (§4.1.2) |
| iPerf | 100 (Flows) | 4GB(file size) | 5(runs) | High VM (8 Core, 16G Mem),<br>Moderate VM (4 Core, 8GB Mem),<br>Low VM (0.5 Core, 0.5G Mem) | Bandwidth (§4.3) |

**Table 2: Probing methods and their use throughout the study**




(a) Aggregate Loss Rate

(b) 95th Percentile (Per-Day)

(c) 99th Percentile (Per-Day)

**Figure 2: Loss rates of cloud paths (based on ping probes) and Internet paths (PlanetLab & PingER results). (95th & 99th Percentiles are based on daily path loss rates. Note the log scale for the x-axis for all three graphs. Results show Internet paths have longer tail compared to cloud paths.**

| Path | US-EU (%) | US-Asia (%) | EU-Asia (%) | Agg (%) |
|---|---|---|---|---|
| Amazon | 0.015 | 0.016 | 0.065 | 0.028 |
| Google | 0.063 | 0.071 | 0.021 | 0.052 |
| Microsoft | 0.024 | 0.032 | 0.022 | 0.026 |

**Table 3: Loss rate comparison of cloud providers – overall as well as for specific regions (shaded cells highlight lowest loss rate)**

**Cloud path have lower loss rate than typical Internet paths.** Figure 2(a) shows the CDF of all cloud paths (across all providers) and PlanetLab and PingER paths, as a function of the aggregate loss rate. We observe that the best paths in all three settings are comparable, with loss rates less than 0.02%. However, if we look at the median and high percentiles, cloud paths have lower loss rates compared to the public Internet paths, i.e., the Internet paths have a much longer tail compared to cloud paths. Specifically, all of the cloud paths have a loss rate of less than than 0.08% whereas roughly 5% paths of PlanetLab and PingER have a loss rate of more than 2% (these public Internet path loss number numbers lie in the same region as reported by prior studies [24, 18, 10, 38, 14, 41, 33].

To further understand the tail, we look at the daily loss rates for all paths (cloud and Internet) and compute their 95th and 99th percentile loss rate – these correspond to the "bad days" for each path. Figure 2(b) shows the CDF of all paths as a function of their 95th percentile loss rate. We see that even on the "bad days", the cloud loss rate remains below 0.8% whereas for PingER and PlanetLab, at least 30% of paths have loss rates greater than 1%. Figure 2(c) shows the same trend for the 99th percentile daily loss rate. The results show that cloud path performance (in terms of loss rate) is more predictable compared to an average Internet path.

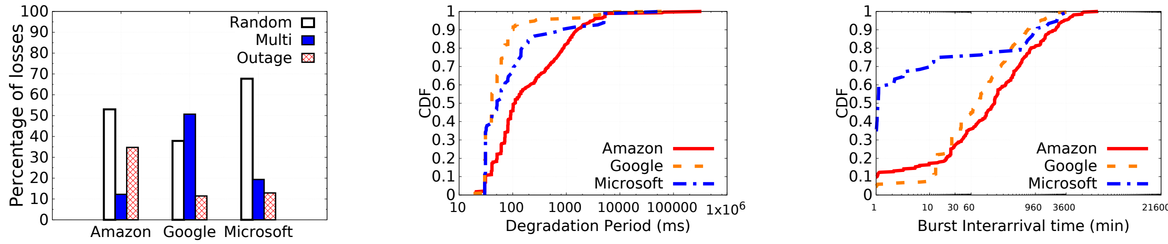
**No clear winner among cloud providers.** We now zoom into individual providers and compare their loss rates, both at an aggregate level as well as for specific regions. Table 3 shows the average loss rate for all cloud providers – both at an aggregate level as for specific regions. Accounting for the variations, we conclude that all cloud providers have similar performance and there is no clear winner. For example, Amazon has lower loss rates on US-EU and US-Asia paths but it performs slightly worse on EU-Asia path as compared to other providers. Note that the similarity observation is based on the overall loss rates – as we show later, the underlying loss characteristics (e.g., burstiness) of these paths differ across providers.

### 4.1.2 *Loss Characterization*

To better understand how losses may impact application performance, we do an in-depth characterization of losses observed on the cloud paths. For this analysis, we use the UDP based probes – we send a burst of UDP packets for 5 seconds, after every one minute and divide each burst in to buckets of 15 packets each; this corresponds to packets sent over a period of 150 milliseconds, which is on the order of a round-trip-time for most of our cloud paths. We are interested in buckets that have at least one packet loss – we call this a *loss episode*.

For each loss episode, we quantify the number of packets lost and categorize the nature of losses as: i) random: if only 1 packet is lost; 2) multi: if between 2 to 14 packets are lost; and 3) outage: if all 15 packets are lost.

**All cloud providers experience random loss episodes.** Fig 3(a) shows the breakup of different types of loss episodes for all three cloud providers. It shows that all cloud providers experience at least 35% random loss episodes (i.e., episodes with just one packet loss). For Amazon and Microsoft, these episodes are more than 50% of the total episodes. While we do not know the reason for such high number of random losses, we believe this could be due to random loss in fiber optic based long distance links [12]. Such loss episodes are amenable to FEC style recovery without incurring too much overhead. For example, for a burst of 15 packets, a single FEC packet, with an overhead of less than 10%, can recover *all* random losses. We quantify the benefits of using FEC for each provider as part of our case study (§5.2).




(a) Loss episodes characteristics (b) Degradation period duration (c) Inter-arrival time

**Figure 3: Loss burst nature of cloud paths. a) Breakup of loss episodes for cloud paths.Three types of losses within a burst of 15 packets are shown : random (1 packet loss); multi (2-14 packet drops), and outage (all 15 packets get lost). b) Duration of degradation periods for the three cloud providers c) Inter-arrival time between degradation periods for the three cloud providers**

**Multi packet losses and outages are also common.** The contribution of the other two types (multi packet and outages) varies from one provider to another. For example, Amazon experiences more outages than multi packet losses whereas it is the opposite for Google. Overall, both these loss types contribute a significant fraction of the outages experienced by each provider because these two types contain most of the packet losses (our experiments in Section 5.1 validate this observation). We call loss episodes that have either multi packet losses or outages (but not random losses) as a *degraded period*. Next, we analyze degraded periods observed on cloud paths in more detail.

**Degraded periods can last up to minutes.** Fig 3(b) shows the CDF of the duration of degraded periods. For this analysis, we combine degraded periods that span consecutive bursts, so we can look at the total duration of the degraded periods. The graph shows that degraded periods can last up to minutes, but most degraded periods (around 70%) last for less than a second. Amazon experiences degradation periods of longer duration compared to the other providers. Our conjecture is that this is because Amazon experiences more outages (Fig 3(a)) and outages are likely to last longer than bursty losses.

**Inter-arrival time between degraded periods is typically low with a long tail.** We also analyze the inter-arrival time between degraded periods. Fig 3(c) shows that for almost half of the degraded periods, the inter-arrival time is less than 2 hours. This is even lower for Microsoft where 70% of the degraded periods have an inter-arrival time of 10 minutes or less. All paths have a relatively long tail (note the log scale on the x-axis). These results show that inter-arrival time between degraded period is non-uniform, making it difficult to predict *when* a degraded period will occur.

In summary, the results show that degraded periods are long and can contribute significantly to the downtime of the cloud path.

### *4.1.3 Loss Correlation*

Next, we turn our attention to analyzing loss correlation on the cloud paths. This is important for understanding the possible techniques to avoid or recover packet losses. For example, an application may use multiple cloud providers for increased availability, but this may not prove useful, if the cloud providers have shared paths (i.e., experience losses at the same time).

For all our results, we use the UDP uni-directional probes to compute losses on a per-minute granularity. We compute the pearson correlation coefficient to compare losses on any two paths. Our analysis of different types of cloud paths shows that losses on these paths are independent, i.e., they have a low correlation coefficient. Specifically, our results show that:

- Losses on the forward and reverse paths (for the same provider) are independent. For example, correlation between US-EU and EU-US paths for Amazon is 0.015.
- Losses across paths of the same cloud provider (even with the same source/destination) are independent. For example, correlation between US-Asia and US-EU paths for Microsoft is 0.0061.
- Losses on paths of different cloud providers (even across the same regions) are independent. For example, correlation between Amazon and Microsoft for US-EU path is 0.001.

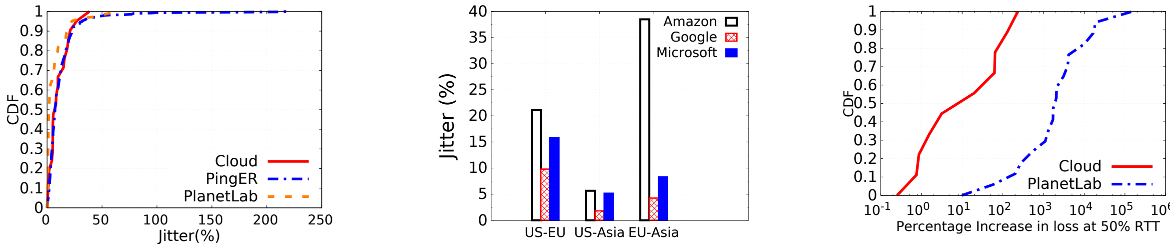
## 4.2 Latency

Data centers host many user facing applications with tight latency requirements (e.g., geo-distributed database). It is therefore important to analyze the latency and its variation on the cloud paths. Typically, it is the variation (i.e., jitter) which turns out to be difficult to control; it also translates into high tail latency for applications. Jitter is also important for interactive applications (e.g., voice) as well as transport protocols like TCP that use round trip times for retransmissions and timeouts.

Because absolute latency depends on the location of the nodes (which differ based on providers), we focus our analysis on the latency variation (jitter) in round-trip-time (RTT) of cloud paths using ping probes and compare them against the jitter observed on PlanetLab and PingER paths. We define jitter as the percentage difference between 95th percentile RTT and the median RTT observed on a particular path. We also analyze the difference in latency between the forward and reverse direction of cloud paths, using uni-directional UDP probes[4].

**Cloud paths have lower jitter (at the tail) compared to Internet paths.** Figure 4(a) shows the CDF of the jitter for all cloud, PingER and PlanetLab paths in our study. We observe that for most paths jitter is similar and within 30% but both PingER and PlanetLab paths suffer from long tail. Specifically, the worst 1% of the public Internet paths have more than 100% jitter. This means that latency on cloud paths is more predictable as compared to public Internet paths. We also compute jitter for uni-directional UDP probes on cloud paths and find that it is less than 15% on all cloud paths. Figure 4(b) shows the jitter for individual providers across different regions. We can see

[4]We synchronized the clocks at the sender and receiver VMs.




(a) Jitter comparison with Internet paths (b) Jitter across providers (c) Increase in loss rate due to jitter

**Figure 4: Jitter properties of cloud paths. a) Jitter, calculated using ICMP probes, observed on cloud, PingER and PlanetLab paths. b) Jitter observed in different regions for cloud providers. c) Increase in loss rate due to jitter. We consider all packets which are delayed by more than 0.5RTT as lost packets (i.e., they miss their deadline.**

that except one of the Amazon paths (which we investigate in §4.5, all cloud paths have a jitter for less than 20%.

**Lower jitter translates into more packets meeting their "deadlines".** High jitter means that more packets arrive at the destination after their deadline [47] and thus increase the effective packet loss rate. To quantify the benefits of lower jitter on the cloud paths, we compute the increase in packet loss rate caused by jitter. We compare cloud paths with PlanetLab paths because we have access to per-packet latency for PlanetLab probes (unlike PingER). We set a threshold of 0.5RTT for the jitter – all packets that are delayed by an extra 0.5RTT are included in the packet loss calculation. For PlanetLab, we randomly pick 20 wide area paths for our analysis.

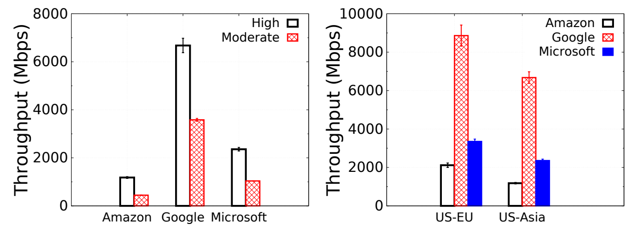
Fig. 4(c) shows the CDF of the percentage increase in loss rate experienced by the different paths. In case of the cloud, the loss rate at most doubles, whereas most PlanetLab paths observe a 10x increase in loss rate. This shows that if we include jitter, the potential improvement in loss rate for cloud paths over Internet paths is even greater.

**Latency of forward and reverse paths are similar.** We observe that average latency in forward and reverse directions for most of the cloud paths is similar and within 7% of each other. The only exception is the EU-Asia path of Amazon where the difference in average latency varies up to 60%. The reverse path latency on this path is 100ms and forward path latency varies between 100-160ms. Our traceroute analysis showed that this was the only path that was using external service providers, and used different paths in the forward and reverse direction (more details in §4.5). Overall, the results show fairly similar latency in both directions.

## 4.3 Bandwidth

We now shift our focus on available bandwidth between VMs across the cloud paths. We note that it is well known that cloud operators do VM level rate limiting, with a prior study also quantifying its impact on inter-DC paths [47]. Our experiments reconfirm some of the earlier findings and also shed new insights on available bandwidth on the cloud paths.

To measure the available bandwidth (throughput), we use iperf3 [6] to send data from one VM to another. Our iperf3 sender uses 100 TCP flows and transfers 4GB amount of data in each run. We pick two different VM types – High and Moderate – with their details mentioned in Table 2. For each path, we make five transfers and use the throughput reported by iperf3 for our results. We note that we have also conducted longer running experiments (over multiple days) on a subset of paths, and the results are quantitatively similar, with no extra variation due to time of day impact.




(a) Bandwidth across machine types (b) Bandwidth across regions

**Figure 5: Average bandwidth variation on cloud paths (error bar shows the deviation). a) Bandwidth varies across VM types for each provider on the US-Asia path. b) Bandwidth varies across regions for each provider (high performance machine).**

**Available Bandwidth is high and varies across providers and VM types.** Figure 5(a) shows the average bandwidth for all cloud providers with different VM types. Our results confirm previous findings that the available bandwidth varies depending on the VM type [47]. However, our results highlight two new aspects. First, the available bandwidth could be higher than 1Gbps (earlier results show a maximum of 1Gbps [47]) with up to 9Gbps achievable in some scenarios (see next result). Second, available bandwidth varies across providers, with Google being the clear winner across both types of VMs.

**Available Bandwidth varies across regions.** Figure 5(b) shows the throughput of different cloud provider paths for different regions. We observe that all providers have lower throughput on their US-Asia paths compared to their US-EU paths. On all these individual paths, Google still provides the highest throughput touching a high of 9Gbps on the US-EU path.

## 4.4 Reordering

Packet reordering is relevant for distributed applications that require consistency. It is also important for transport protocols like TCP, which needs to distinguish between an out-of-order packet and a loss. We analyze the amount of packet reordering on the cloud paths. We use Paxson's [38] definition of packet reordering, which counts late arrivals rather than early arrivals. For example, if packet 4 arrives before packets 1-3, the number of out-of-order packets will be three

| Google DC | PlanetLab Node | AS Path (hop count) | RTT to the 2nd AS |
|---|---|---|---|
| Iowa | University of Leuven,BE | Google (16) - AMX(1) - BELNET (3) | 120ms |
| | Nagoya Institute of Technology -JP | Google (16) - JPIX(1) - SINET (5) | 126ms |
| Belgium | University of Minnesota,MN,USA | Google (11) - Level3 (4) - NMLR (1) | 200ms |
| | Nagoya Institute of Technology, JP | Google (16) - JPIX(1) - SINET (4) | 225ms |
| Taiwan | University of Leuven, BE | Google (19) - AMX(1) - BELNET (3) | 265ms |
| | University of Minnesota, MN, USA | Google (15) - Level3(4) - NMLR (1) | 300ms |

**Table 4: Google traceroute to PlanetLab nodes. The last column shows the RTT between the source and the next AS (after Google) – the high values indicate that Google uses its own infrastructure on the wide area before forwarding the traffic to an external AS.**

rather than one. In general, counting late arrivals result in higher amount of reordering than counting early packets [38].

We use UDP probes to measure reordering in both directions of the cloud path and observe negligible reordering for all providers. Also, our analysis of reordering on PlanetLab paths show roughly the same level of reordering as observed on the cloud paths.

**Packet reordering is low.** Overall, we observe that the amount of packet reordering is low: we observe negligible reordering on Microsoft and Amazon paths, and a small amount of reordering on Google paths. The amount of reordering on Google paths range from 0.01% to 0.02%. The use of multi-path, as suggested in B4 [31], may explain the reordering on Google paths. However, we do not know whether Google is using B4 (or a similar system) for their public cloud.

We note that the reordering observed on the Internet has also been decreasing, with older studies citing a single digit (1%-3%) [38] reordering while the more recent ones citing lower reordering [29]. Our analysis of reordering on PlanetLab paths show roughly the same level of reordering as observed on the cloud paths.

## 4.5 Why are Cloud Paths better?

Results in the previous sections show that cloud paths are better than typical Internet paths, in terms of loss rate and jitter. An obvious question is: what is the reason why cloud paths are better?

Our hypothesis is that a wide area backbone which is under full control of the cloud provider is likely to be better managed – both in terms of resource provisioning as well as traffic engineering. While we do not have inside visibility into the cloud paths, we conduct an autonomous system (AS) level path analysis to get a high level topological view of the cloud backbone. We use traceroute for our analysis. For our analysis, we conduct multiple traceroute probes to also observe any changes over time. Note that only Amazon allows ICMP on its internal network whereas Microsoft and Google partially or fully block ICMP. For Amazon paths, we use traceroutes between two VMs, whereas for Microsoft and Google, we conduct traceroutes to/from PlanetLab nodes (in other continents) to the cloud VMs.

Our AS-level path analysis for Amazon shows that on all paths (except one) only the Amazon ASes were observed, i.e., no other service provider was involved (at the network layer). The only exception is the path between EU (Ireland) and Asia (Singapore). We investigate this path in more detail as it is also the only case where we observed a significant difference in forward and reverse path latency.

Figure 6(a) shows the path from Ireland to Singapore. The hops at the edges belong to Amazon (each vertex contains the number of hops), but other service providers are used in the middle, including Level 3, Telina.net, and NTT. However, on the reverse side (Singapore to Ireland) a different set of service providers are used (see Figure 6(b)) – while NTT is still being used, there are two difference: it is getting the traffic from TATA (rather than directly getting it from Amazon)


(a) Forward Path (b) Reverse Path

**Figure 6: Amazon Ireland to Singapore path**

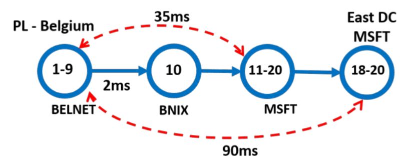



**Figure 7: Microsoft traceroute from US to Europe, hop numbers shown inside the node.**

and it is directly sending the traffic to Amazon (instead of through some other ISPs). This difference in routing also explains the latency difference in forward and reverse directions that we observed earlier.

For Google, we conduct traceroutes from a Google data center to multiple PlanetLab nodes in a different continent. This allows us to infer whether Google uses its own paths to reach the other continent (which are likely to be used for inter-DC communication as well). Table 4 shows the results for multiple source DCs and different vantage points. In all cases, we observe that Google uses its own network to reach the other continent after which it forwards the traffic to an external service provider (in order to reach PlanetLab nodes). This is indicated by the last column which shows that most of the RTT is spent within the Google network. These results suggest that Google has a dedicated wide area backbone for its cloud paths and is likely using it for its inter data center communication as well.

Finally, we observe the same routing behavior for Microsoft as well, i.e., Microsoft uses its own wide area backbone for traffic to/from its VMs to different continents. Fig. 7 shows one specific case for illustration, focusing on traceroutes from PlanetLab nodes to a Microsoft VM in a different continent. As we can see, the traffic moves to the Microsoft network close to the source and uses its own backbone to reach the destination, suggesting that, just like Google, Microsoft also uses its own wide area backbone for communication between data centers.

**Discussion.** The above analysis, as well as anecdotal evidence, supports the case that cloud operators have dedicated wide area infrastructure to support communication between their data centers. We believe that the traffic volume, application requirements, and future growth expectations, all push the cloud operators towards building a well-provisioned infrastructure. Additional gains come from having full control over the infrastructure, such as traffic engineering and improved fault recovery. For example, Microsoft and Google show

how they use software-defined networking to better manage their wide area networks [31, 28]. We believe that the above factors possibly explain why cloud paths are better than the typical Internet paths.

# 5. CASE STUDY

In this case study, we consider the following question: *how much more reliable can we make the cloud paths, if we apply known loss mitigation and avoidance techniques, like FEC and one-hop detour routing [25]*. We ask this question with an eye towards the future, where emerging applications in health-care (e.g., remote surgery) or emergency relief, may require a highly resilient Internet, which must offer reliability similar to what today's telephony network provides. Our preliminary evaluation shows the promise of the cloud infrastructure (with extra smarts) in providing such a resilient service.

## 5.1 Detour Routing

Detour routing [25, 10] uses a detour point to send packets between a source and destination. It improves reliability in scenarios where the problem is in the "middle" of the end-to-end path. A problem at the edges (source or destination) impacts the detour path as well. Prior studies show that a randomly chosen detour point can recover from almost 56% of failures observed in an Internet environment [25].

To evaluate the benefits of detour routing for cloud paths, we conduct an experiment over a two weeks period. We enhance our UDP probe mechanism to send a duplicate probe through a detour path. A packet is successfully marked as received if it reaches the destination through either the direct path or the detour path. A packet loss indicates that the packet was lost on both the direct and detour paths. Our analysis considers all loss episodes as well as isolates those scenarios where the losses happened in a burst (defined as more than 4 consecutive packet losses).

For cloud paths, we use a PlanetLab node (located in Europe) as the detour point. We use VMs in Microsoft and Google DCs located in US, Asia and EU, and Amazon DCs located in US, Asia, EU and Oceania. We also evaluate how well detour routing works for PlanetLab paths. We use 15 PlanetLab nodes in three regions (5 nodes each in Asia, Europe and US East Coast) – we run an all-to-all experiment between nodes in different regions (with US nodes only acting as destinations; Europe nodes only acting as sources; and Asia nodes acting as both sources and destinations). Again we use a PlanetLab node in Europe as the detour point in all cases.

**Detour Routing is highly effective for Cloud Paths.** Fig 8(a) shows the comparison of loss recovery using detour routing for cloud paths and Internet paths. We can see that detour routing works better for cloud paths – we can recover the lost packet, with the help of the detour path, in around 87% of the cases. However for public Internet paths we can see only 46% recovery. If we consider bursty losses, the recovery effectiveness decreases, as the bursty losses are more likely to impact both the original and duplicate packets (as they are sent back-to-back) compared to an isolated single, packet loss.

**Effectiveness of detour routing varies across providers.** Fig 8(b) shows the loss rate recovery across cloud providers. We can see that in case of Microsoft, we can recover more than 95% of the packets using the detour path. Google's performance is the worst in this context, as it recover 74% of packets, although it is still better compared to the recovery effectiveness of the public Internet paths. To further understand these differences, we zoom into all the bursty loss episodes and divide the recovery into three cases: when we can recover *all* packets in a bursty loss episode, recover *some* of the packets, or recover *nothing*. Fig 8(c) shows that Microsoft and Amazon rarely see a scenario where all packets in a burst cannot be recovered. However, the corresponding number is higher for Google (it loses all the packets in a burst 20% of times), which explains why Google has lower recovery rates compared to the other providers.

**Discussion.** The above results show that detour routing is highly effective for cloud paths, with some cloud providers able to effectively "hide" most of their losses with the help of the detour. For example, for Microsoft, we can reach five 9's of reliability (1 - loss-rate) with the help of detour routing. These results suggest that cloud providers have well-provisioned edges, and most of their packet loss happens in the middle, which can be avoided through the use of a detour point.

Note that our focus here was on the potential of using detour routing, so we used the detour path *simultaneously* with the direct path. Of course, it is up to the application to decide how it wants to benefit from detour routing. Applications that can afford to pay extra may use the paths simultaneously while other applications may use the detour path in a reactive fashion, i.e., only *after* encountering a degraded period. We believe that intelligently using the detour path, while minimizing the cost of using the cloud path, is an interesting direction for future work.

## 5.2 FEC

We consider packet level FEC, which adds certain number of redundant packets to every burst. We do a *what-if* analysis on the UDP probes to analyze the potential benefits of applying various levels of FEC. For a burst of 15 packets, we consider 4 different FEC levels: one, two, four, and eight FEC packets for every burst.

Fig 9a shows the impact of applying various levels of FEC on loss episodes along with the case when FEC is not used. We can observe that a single FEC packet provides considerable gains in availability (1 - loss-rate) because it is able to recover *all* random loss events. Thus, even with a low FEC overhead of less than 10%, we see considerable gains that raise the availability to close to 99.99% in some cases.

For high levels of FEC, we do not observe any significant change for Amazon and Microsoft because most of their losses are either random or constitute outages. Fig 9b zooms into all the paths for Amazon and show similar observations.

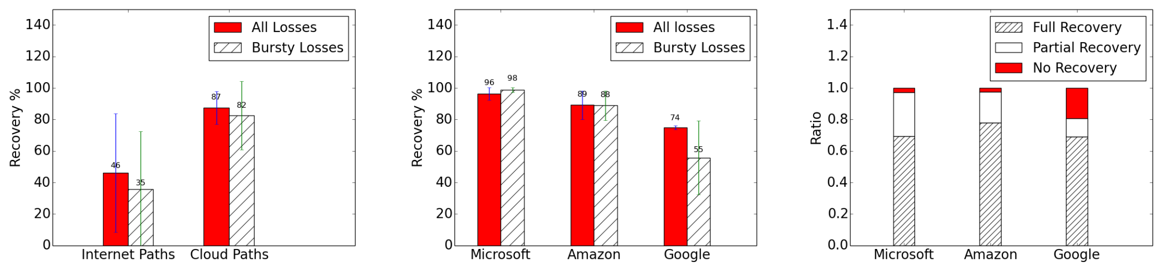
One interesting aspect of the above results is the performance of Google cloud paths. Recall that Google had considerable bursty losses; this explains why it observes most gains as we increase the level of FEC. In fact, it is able to achieve five 9's of reliability with an FEC level of eight (which corresponds to roughly 50% overhead).

The above analysis only considers the potential benefits of FEC. There are practical challenges with realizing FEC – we believe that tuning FEC based on application requirements and cloud path conditions is another interesting avenue for future work.

# 6. DISCUSSION

We believe that our findings have important implications on the use and design of cloud-based applications and systems. We discuss two such examples.

**Performance vs. Cost Tradeoff.** Cloud applications typically have multiple options – in terms of cloud providers as well as data center locations within a provider. Several recent systems (e.g., SPANStore [45]) try to optimize how applications make use of the cloud, keeping in view the application service level objectives as well

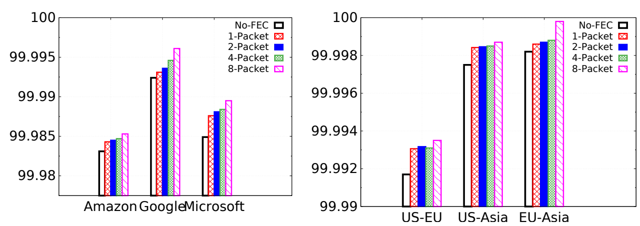



(a) Cloud vs. Internet paths.

(b) Across cloud providers

(c) Bursty losses and their recovery.

**Figure 8: Overview of benefits of using Detour Routing. a) shows that cloud paths benefit more from detour routing compared to Internet paths. b) shows that the recovery effectiveness varies across cloud providers while c) focuses on bursty losses (more than 4 consecutive packet losses) and how each provider is able to recover them.**




(a) Aggregated results for all providers

(b) Amazon results

**Figure 9: Availability of cloud paths after applying different levels of FEC. (Note different scales of y-axis)**

as the cost. Information about cloud path characteristics can further enhance the effectiveness of such systems by enabling them to choose suitable data centers for replication. For example, the primary data center may choose a far-away data center with good path conditions over a closer data center which is experiencing a degraded period. Similarly, we can account for cost differentials while using different data centers. For example, the egress bandwidth charges at non-US data centers is typically higher, so applications may decide to use a far-away data centers (to reduce its cost) as long as it meets the performance (and other) requirements of the application.

Our insights also add an interesting dimension for those applications that have an option to use either the cloud or the Internet paths (e.g., user-user application and user-cloud applications – Figure 1). Given that cloud paths are more reliable, applications would always like to use them; however, cloud paths are much more expensive to use. Thus, applications would want to use them in a *judicious* manner. For example, an application can use cloud paths when Internet paths are down, or use them in an intelligent fashion to send more important data (e.g., an I-frame in video streaming) while using Internet paths for less important data. On such example is ReWAN [27], which uses the cloud overlay to *only* send coded packets across the cloud path to a data center close to the receiver. These coded packets are used only in case of a loss on the direct Internet path. This technique saves on the cloud WAN bandwidth costs while still leveraging the highly reliable cloud paths.

**Cloud Transport.** Our findings have important implications for WAN communication mechanisms (e.g., transport and traffic engineering mechanisms [47, 31], WAN middleboxes and accelerators [12], etc). Given the high bandwidth delay product on these paths, protocols like TCP can experience high drop in throughout even with small loss rates [12]. Many of our findings can be leveraged to improve reliability and performance of these protocols. For example, predictable latency and little or no reordering can motivate a faster recovery mechanism (e.g., using fewer than three duplicate acks) compared to existing Internet based mechanisms used in TCP. Similarly, as we show in the case study, real time applications can leverage standard techniques, like FEC and detour routing, to significantly improve their availability.

# 7. CONCLUSIONS

A wide range of applications use the inter-data center paths of cloud providers. Our study of the inter-continental cloud paths of Amazon, Microsoft, and Google sheds important insights regarding the characteristics of these cloud paths in comparison with traditional wide area Internet paths. We also demonstrate a powerful result i.e., we can achieve almost five 9's of network reliability for wide area communication by using existing techniques (e.g., detour routing) to mask losses on these cloud paths. We believe our insights will prove useful for practitioners and researchers of cloud systems.

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