# CS268 Final Project: The Predictability and Consistency of Cloud Networks

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***Abstract*—As more companies are transitioning to the cloud and an increasing number of large workloads are experiencing bottlenecks in the network rather than in compute and storage, cloud providers must provide more consistent and performant virtualized networks in order to remain competitive. Over the years, we've seen innovations in data-center network topologies to provide greater bisection bandwidths as well as more powerful and performant switches. We've also seen innovations in routing protocols as well as hardware offloads. However, we've yet to see a comprehensive analysis of cloud networks from a consistency point-of-view. We believe that it's time to take a step back and to answer the question of just how predictable and consistent cloud networks are in reality.**

**In this paper, we present a measurement study to characterize the predictability and consistency of cloud networks across several cloud providers. We measure the packet loss, latency and throughput of pings and file transfers both across virtual machines within a single data-center as well as across the wide area network. Our results show that the network performance characteristics vary greatly across cloud providers and that most networks studied in our experiment aren't very predictable. We also discuss potential reasons for these network instabilities as well as implications of these findings.**

## I. Introduction

In recent years, we've observed two emerging trends in the software industry. On one hand, we see the rise of cloud computing where an increasing number of workloads are being ran in multi-tenant data-centers due to scalability and economies of scale. On the other hand, we observe that distributed systems and computing have become the norm for large-scale applications as Moore's law no longer holds true. Distributed computing mainly works by splitting large workloads across many CPUs and nodes. While this provides the compute and storage requirements of these workloads, network bandwidth often becomes the bottleneck. For example, while MapReduce [1] allows for running huge workloads in parallel across thousands of nodes, it is notoriously bandwidth-hungry with I/O taking up to 79% of the operation [2].

As multi-tenant data-centers and cloud computing continue to rise in popularity, we see that networking (as opposed to storage or compute) increasingly becomes the bottleneck of many workloads. Over the years, we've seen innovations in data-center network topologies to provide greater bisection bandwidths as well as more powerful and performant switches. We've also seen innovations in routing protocols as well as hardware offloads. However, we've yet to see a comprehensive analysis of cloud networks from a consistency point-of-view. We believe that it's time to take a step back and to answer the question of just how predictable and consistent cloud networks are in reality. Over the past few months, we have set up and ran multiple tests across major cloud providers such as Amazon Web Services (AWS), Google Cloud Platform (GCP), Microsoft Azure (Azure) and Digital Ocean (DO) in order to answer this question from an empirical perspective. We believe that the observations we'd gathered through our experiments will provide more insight to better understand cloud network performances.

The rest of the paper is organized as follows. In Section II we introduce and discuss some existing studies on cloud network performance, and argue why they fail to answer the above question. Section III introduces the background on programs used in our experiment such as Ping and Secure Copy Protocol (scp) as well as on the various cloud primitives we use in our experiments. Section IV introduces the set-up for our experiments as well as our virtual machine (VM) configurations. Section V and VI introduces and analyzes the experimental results gathered from our ping and scp tests, both within a single data-center as well as across the wide area network (WAN). We then discuss some potential implications of network consistency issues in Section VII, based on our findings. Finally, we conclude in Section VIII.

## II. Related Work

A few existing academic studies have evaluated the performance of individual cloud provider's networks. However, none of these studies, to the best of our knowledge, fully explore and compare the predictability and consistency of these networks across providers.

In a recent study by a group at Rice University [4], they explored the impact of virtualization on network performance within Amazon's EC2 Data Center. Their study shows that machine virtualization in the cloud can cause significant throughput instability and abnormal delay variations. While their study only focuses on the network performance within Amazon Web Services for pings and short TCP/UDP flows, our experiment focuses on both pings and long TCP flows across multiple different cloud providers.

One of the larger scale study is conducted by ThousandEyes annually [5]. While their large-scale cloud network performance study is quite comprehensive, their experiments target the global connectivity performance of cloud networks and

| Cloud Provider | VM Configurations |
|---|---|
| AWS | T2.small instance with shared-core 1 vCPU, 2 GiB RAM and 25 GiB SSD. |
| Azure | Standard_A1_v2 instance with shared-core 1 vCPU, 2 GiB RAM and 20 GB SSD. |
| DO | Shared-core 1 vCPU droplet with 1 GB RAM and 25 GB SSD. |
| GCP | E2-micro instance with shared-core 2 vCPU, 1 GB RAM and 10 GB SSD. |

Fig. 1: Detailed VM configuration for our experiments.

not so much on the intra-datacenter communication performances. We find that many of their conclusions complement ours. For instance, their results show that AWS demonstrates significantly less network performance stability than GCP and Azure, which is also quite evident in our intra-datacenter tests. Moreover, their final conclusion is that ”Performance variations in certain geographies highlight the reality that public cloud vendors do not yet have consistent performance globally”, which again is a conclusion we share.

Another group of researchers conducted a study on the effects of private wide area networks on cloud performance [6]. Their experiments primarily focus on the effects on private wide area networks on performance for AWS and GCP whereas our study also explores the performance of intra-datacenter network communications across AWS, GCP, Azure and Digital Ocean.

A similar intra-datacenter study was conducted by a group of researchers for Azure [7]. In their work, they provide an intra-cloud network performance characterization of Azure's cloud network and explore how the throughput varies over time and as various configurations change. While we share a very similar goal as the authors of the paper in that we aim to address the gap in existing literature in terms of cloud network performance, our study also provides detailed results from wide area network tests and across multiple cloud providers.

As such, we see that while there are several existing studies in the literature on this topic, most of them either focus on a single cloud provider or on a single subset of tests such as intra-datacenter or wide area network. In this paper, we attempt to provide a more comprehensive study by exploring various cloud providers' networks both across WAN and within a single datacenter.

## III. Background

### A. Ping

The ping command found on almost all operating systems is the main program used in our experiment in order to test short-flow network performance and consistencies. Ping is typically used to test the reachability of hosts over the internet protocol (IP), and measures the round-trip-time for ping messages sent by the sending host and echoed back by the receiving host. Under the hood, the ping program sends an echo message over the Internet Control Message Protocol (ICMP) to the target host and waits for a reply. The program outputs several measurement outputs such as the packet loss and minimum / average / maximum / standard deviations of round-trip-times. It is important to note that ping, which runs over ICMP, is connectionless and does not guarantee packet reliability, hence packet losses are not uncommon.

### B. Secure Copy Protocol

The Secure Copy Protocol (SCP) program implements the SCP protocol and can be found in most operating systems. It is typically used to securely transfer files between a local and remote hosts. SCP runs on top of the Secure Shell (SSH) protocol and depends on it for both authentication and data transfers. In contrast with the ping command and ICMP, SCP depends on SSH which runs over TCP. This means that SCP calls are connection-based, and there will be overhead associated with the three-way-handshake and book-keeping of TCP connections. From previous works, researchers found that on shared-core virtual machine instances in the cloud, the virtualization technology can affect the performance of TCP [3], which will consequently affect the performance of SCP for long-flow connections. We will dive deeper into these results in Section VI.

### C. Virtual Machines

All of our experiments were ran on virtual machine instances in various cloud providers. Here we provide a high level overview of the different virtual machine virtualization stacks offered by different cloud providers and defer analysis on the impact of these different virtualization technologies on network performance to later sections.

*1) Amazon Elastic Cloud Computing (EC2):* Amazon EC2 is the service within Amazon's Web Services which allows users to rent virtualized compute instances across Amazon's datacenters. EC2 uses the Xen virtualization technique under the hood where multiple Xen virtual machines called instances are co-located onto physical servers. In terms of network virtualization, Xen only allows the driver domain, which is a special privileged VM, to directly control the network devices and all other guest VMs have to communicate through the driver to access the physical network device on the host.

*2) Google Compute Engine (GCE):* Google's GCE depends on the KVM hypervisor to manage its VM instances. As oppposed to Xen which is not supported by Linux and requires a patched kernel in order to run it, KVM runs directly within the Linux kernel and turns it into a hypervisor which allows the host to run multiple isolated VM instances.

*3) Microsoft Azure Virtual Machines:* Microsoft's Azure VMs run on their in-house Hyper-V hypervisors. Unlike Xen and KVM, Hyper-V runs on x86-64 systems running Windows on the host machines. Functionally, Hyper-V works similar to

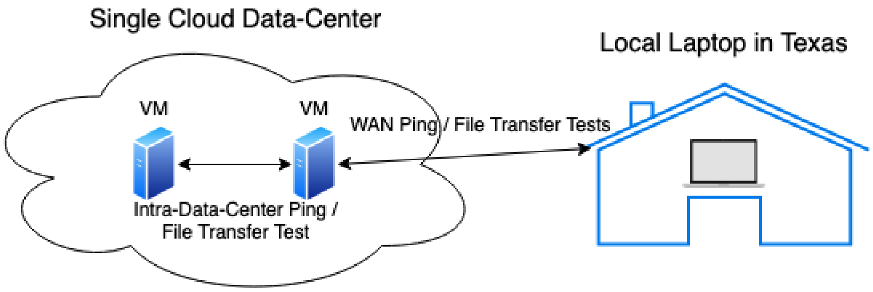


Fig. 2: In our intra-data-center tests, 2 VMs are instantiated within the same cloud data-center and repeated run pings / file transfers. The same set of tests are repeated over the WAN where a local laptop in Texas now pings / initializes a file transfer request from a VM in the cloud providers' data-centers.

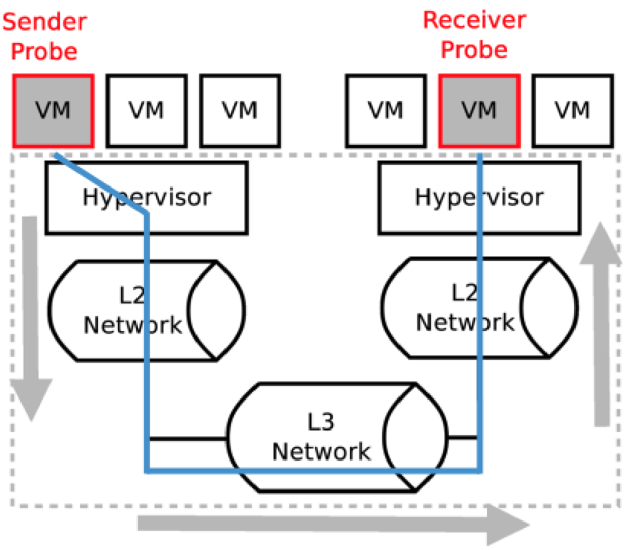


Fig. 3: Intra-Cloud VM Communication Architecture [7]

both Xen and KVM to allow isolated VM instances colocate on the same physical host.

*4) Digital Ocean Droplets:* Similar to GCE, Digital Ocean's Droplets, which is their VM instances, run on a KVM hypervisor.

## IV. Experiment Methodology

### A. Cloud Configurations

Our experiment included four cloud providers: Amazon Web Services (AWS), Digital Ocean (DO), Microsoft Azure (Azure), and Google Cloud Platform (GCP). We wanted to test the networks of larger providers like AWS, but also include smaller providers like DO. We set up 2 virtual machines running Ubuntu in every cloud provider's west coast region data center and attempted to utilize as similar specifications as possible. For most of the providers, we utilized 1 virtual centralized processing unit (vCPU). GCP was tested with 2 vCPUs because that is their smallest instance. In addition, all the providers' instances operated on a shared core with 1-2 GiB RAM and were all located in their West Coast Data Center Region. A detailed description of each cloud provider's virtual machine configuration is shown in Table 1. A reference architecture of the intra-cloud communication flow between 2 VMs in a single data-center is also shown in Fig. 3.

### B. Short-flow Tests

We wanted to determine the performance and consistency of cloud networks for short-flow tasks such as pings. For this set of tests, we setup 2 virtual machines, $vm_a$ and $vm_b$, and scripted a cron-job on $vm_a$ to have it repeatedly ping $vm_b$ for 500 times per hour over a 24 hour period. The logs generated by the pings are then written to log-files on disk, which are then used for analysis later on, as detailed in Section V. We wanted to measure the performance and consistency of the pings both within a single data-center as well as across the wide area network. Thus, we repeated the ping test for each cloud provider in two variants. Firstly, to measure the performance within a single data-center, both $vm_a$ and $vm_b$ are instantiated in the same data-center for each cloud provider and thus the repeated ping test measures the performance of intra-data-center short flow communications. Secondly, in order to measure the performance of each cloud provider's network across the WAN, we initialized $vm_b$ in each of the cloud providers' west-coast region data-centers and ran the cron-job initializing the repeated pings on a local 8-core Macbook Pro with 32GB RAM and 1TB disk located in Texas.

### C. Long-flow Tests

We also wanted to explore the performance and consistency of cloud networks for long-flow tasks such as file transfers. For this set of tests, we again setup 2 virtual machines, $vm_a$ and $vm_b$. On $vm_b$, we generated a 105Mb file and had $vm_a$ ran a cron-job to copy it over (using the scp program) for 10 times per hour over a 24 hour period. The logs are then written to disk and used for analysis later on, which we will explore in Section VI. Similar to the set of ping tests, our long-flow file transfer tests were ran both within a single data-center as

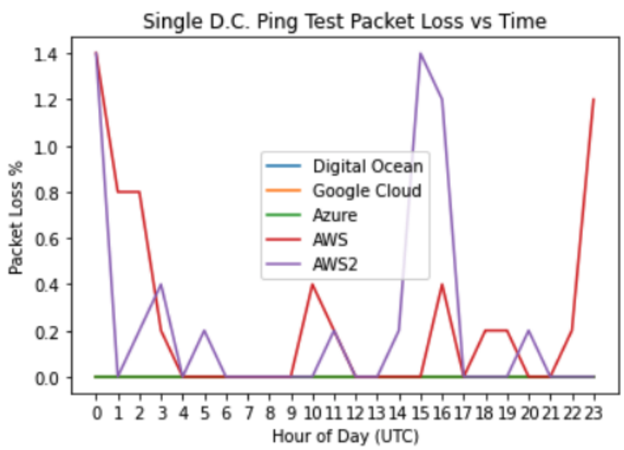


Fig. 4: Intra-Data Center Ping Packet Loss

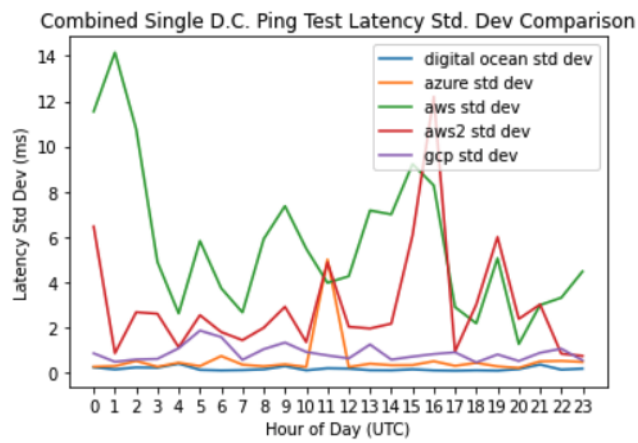


Fig. 5: Intra-Data Center Ping Latency Std. Dev

well as across the WAN for each cloud provider. The setup for the intra-datacenter file transfer test is straightforward where both VMs for each cloud provider are instantiated within the same data-center. For the WAN file transfer tests, $vm_b$ holds the 105Mb file and is copied over to the same Macbook Pro used in the WAN ping tests located in Texas.

It is important to note that the ping and file-transfer tests were ran on separate days in order to minimize resource contention over the two tasks. Also, unlike the intra-data center tests, we only collected data at night for WAN tests as most bandwidth-hungry applications typically occur during the day and we worry that they would interfere with our WAN measurements. A high-level visualization of the test setups in shown in Fig. 2.

## V. Ping Analysis

In this section, we analyze the results from our ping tests. We first analyze our results from the intra-data center ping tests, noting that AWS performs significantly worse than the other cloud providers for this suite of tests. We then analyze our results from the WAN ping tests, showing that all 4 cloud providers perform similarly across the WAN.

### A. *Intra-Data Center Tests*

In our intra-data center ping tests, as shown in Fig. 4, AWS is the only cloud provider with packet losses. Across a 24-hour period where $vm_a$ pings $vm_b$ 500 times each hour, AWS experiences some amounts of ping packet losses over multiple hours, whereas other cloud providers' results show that all 500 pings per hour are echoed back successfully. In order to ensure that our result wasn't an outlier, we repeated the test on AWS, as labelled by "AWS2" on Fig. 4 and again we see non-negligible packet losses for the intra-data center ping tests. When examining the jitter or standard deviation of the ping latencies across the 24-hour period, as in Fig. 5, we also see that AWS' ping latencies vary significantly higher than those of other cloud providers. Furthermore, we analyzed the indices of the pings packet losses on an hourly basis in order to see if the ping packet losses followed certain patterns (e.g. if most packet losses occured within the first few pings). However, our results show that the packet losses occur at random indices at each hour and there doesn't seem to be a recurring pattern. Here, it is evident that AWS' intra-data center short flow performance is significantly less consistent and predictable than other cloud providers. In terms of latency and jitter, the other 3 cloud providers have comparable performances.

The results gathered in our test were also observed in a study by Rice University [4]. The authors also observed that small AWS EC2 instances often experience high delay variations and some amounts of packet loss even when the network isn't congested. In their paper, the authors conjecture that these delay variations are due to the machine virtualization. Specifically, the long queuing delay at the Xen driver domain causes these high latency variations. As these VM instances share the same underlying cores as other VMs located on the same physical host, when the receiver instance is not currently scheduled to run, the ping echo packets will be buffered at the Xen driver domain until the instance is scheduled back on. As such, we suspect that AWS' significant ping latency jitter and packet loss may be due to the underlying Xen virtualization being less performant and predictable than other virtualization layers used by the other clouds, such as KVM and Hyper-V. In future works, we hope to do a concrete study on the effects of various virtualization frameworks on network performance and consistency.

Another set of interesting results is from Digital Ocean's intra-data center ping tests. We came across two interesting findings in the analysis. Firstly, we observed that the first ping (from the 500 pings per hour) of each hour will always experience a significant ping spike as compared to the subsequent pings (Fig. 6). While the average ping took about 0.4ms, the first ping typically spikes up to above 4ms, a 10x latency spike. Secondly, we observed that at the 0th and 30th minute of each hour, DO's network performance reduces drastically for about a minute before returning to normal levels. The original set of ping tests were set to run on the 0th minute of each hour.

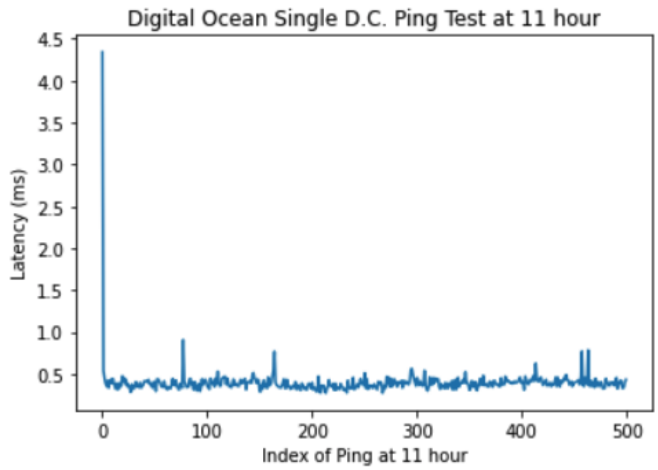


Fig. 6: Digital Ocean Ping Latencies on the 11th hour. Here we see that the first ping has a significantly higher latency than the rest. Though this plot only shows the latencies on the 11th hour, the results mirror in every other other in the 24-hour duration.

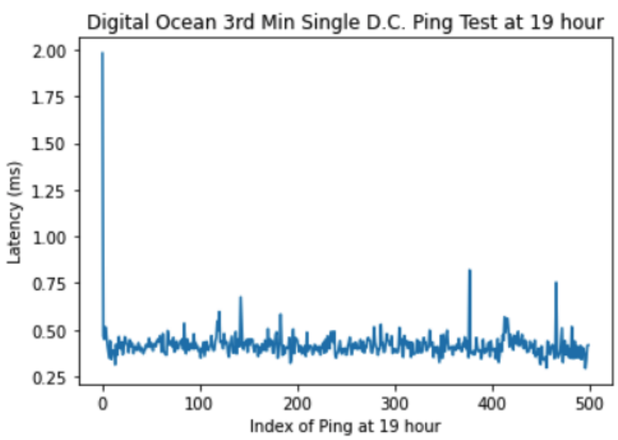


Fig. 7: Digital Ocean Ping Latencies when the test starts at the 3rd minute. Here we see that the first ping still has a significantly higher latency than the rest, though at a much lower magnitude than compared to when starting the test at the 0th or 30th minute of each hour.

When we repeated the tests to run at the 3rd minute (Fig. 7) and 30th minute (Fig. 8) of each hour, our results confirmed our hypothesis that there might be background tasks scheduled by Digital Ocean occurring every 30 minutes, which causes resource / network contention for our VM instances. As seen in the plots, the ping tests ran on the 3rd minute of each hour also experiences latency spikes for the first ping, albeit at a significantly lower magnitude (on average it spikes to about 2ms rather than 4ms). Furthermore, for the ping tests ran on the 30th minute of each hour, the first ping again spikes up to above 4ms, which mirrors the pattern seen in the original set of tests ran on the 0th minute of each hour.

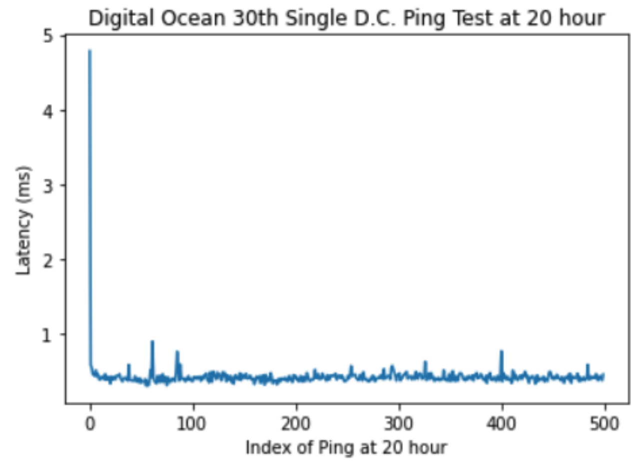


Fig. 8: Digital Ocean Ping Latencies when the test starts at the 30th minute. Here we see that the first ping's latency spike mirrors that of starting the test at the 0th minute.

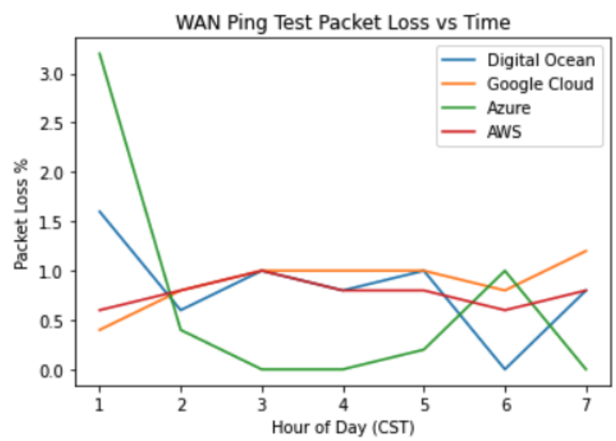


Fig. 9: Wide Area Network Ping Packet Loss

While we tried digging deeper into these interesting patterned spikes on DO, we couldn't find any similar reports. However, these results do show us that cloud networks aren't as predictable and consistent as we would like them to be, which is probably also a main reason why cloud providers seldom make any promise about network performances.

### *B. Wide Area Network Tests*

Interestingly, when repeating the same set of ping tests over WAN, we see that AWS does not experience worse consistency compared to the others. As seen in Fig. 9 and Fig. 10, all four providers experience similar percentages of packet loss as well as similar levels of jitter. Though our WAN ping tests between a host in Texas and a VM in AWS' west-coast data-center do not show that AWS has significantly less stability than GCP or Azure, we suspect that across further geographical distances such instabilities may become more obvious. In fact, an annual report generated by ThousandEyes showed that within some geographical regions like in Asia, AWS performs significantly

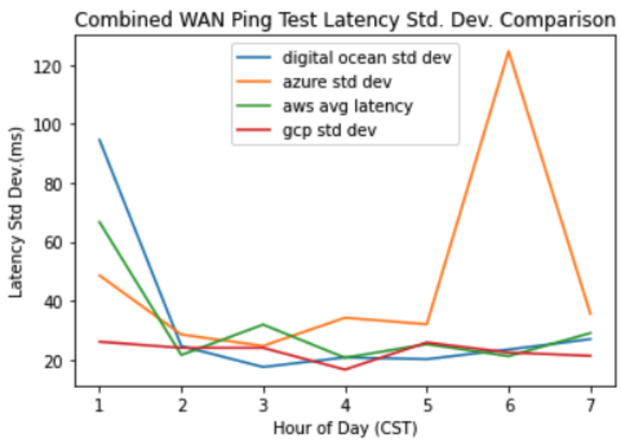


Fig. 10: Wide Area Network Ping Latency Std. Dev

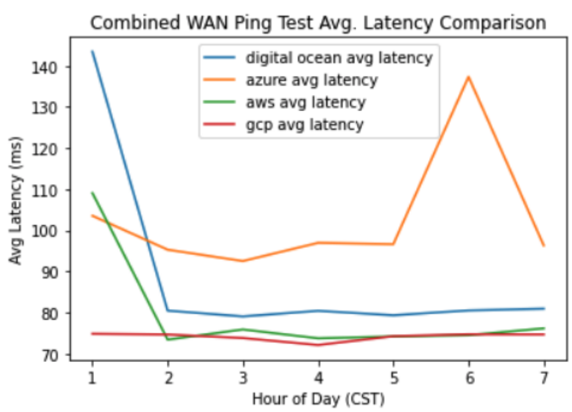


Fig. 11: Wide Area Network Ping Latency

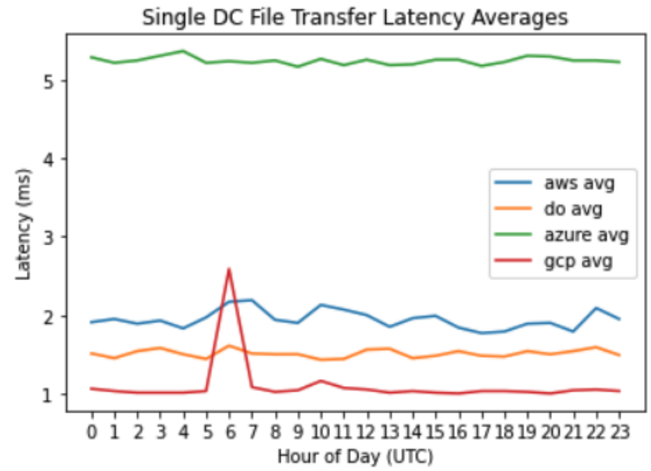


Fig. 12: Intra-Data Center File Transfer Latency Results

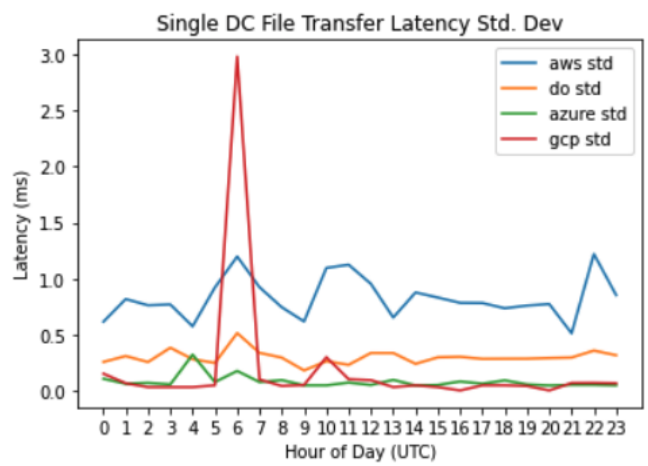


Fig. 13: Intra-Data Center FTP Latency Std Dev Results

worse than its competitors such as GCP and Azure, with up to 56% less performance stability [5]. Also from their report, we learned that AWS relies strongly on the public internet backbone to handle their network traffic. AWS' network design thus routes traffic from end users through the public internet, only to enter the AWS backbone closest to the target region. This is in stark contrast to Azure and GCP which absorbs end-user's traffic into their internal WAN backbone closest to the user irrespective of geographical location, and hence relying less on the public internet infrastructure. With these findings, we conclude that AWS performs worse than its competitors in terms of network stability and consistency, which is rather shocking given that AWS is the largest cloud provider in the market and owns about 32% market share, as compared to Microsoft's 19% and Google's 7% [8].

When examining the raw latency of the hourly pings across WAN, as seen in Fig. 11, we see that Azure has significantly higher average ping latencies (about 25% higher) when compared to the other clouds, albeit similar levels of jitter (except probably an outlier at 6am CST, which may be due to a network perturbation in the home network in Texas) and packet loss. Despite this increased latency only across WAN, we can't really conclude much about Azure as there are multiple factors such as the default network configurations given by Azure (manually tunable) and the physical distance between Azure's west-coast data-center and the receiver location in Texas which can affect latency itself. However, since its latency jitter is quite stable both within a single data-center and across the WAN, its performance can be said to be relatively predictable and consistent.

## VI. File Transfer Analysis

In this section, we delineate and analyze our results from File Transfer tests from each of the four providers. We have two types of File Transfer Tests: Intra-Data Center Tests, executed between two virtual machines in one data center, and Wide Area Network Tests, executed between a personal computer and a virtual machine.

### A. *Intra-Data Center Tests*

As shown in figure 12, Azure has significantly higher latency than all the other providers for intra-data center long

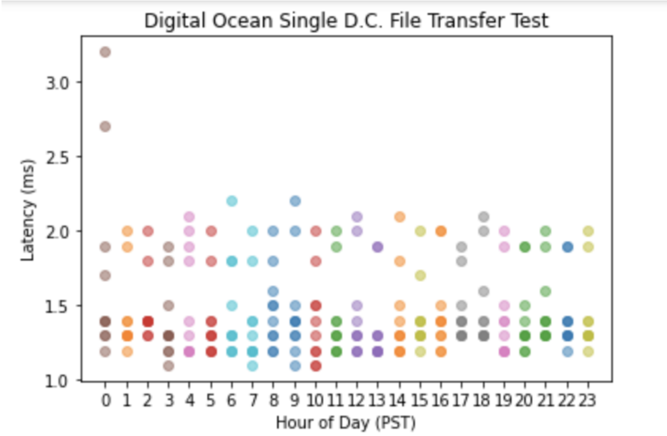


Fig. 14: Digital Ocean Scatter Plot over 24 hours

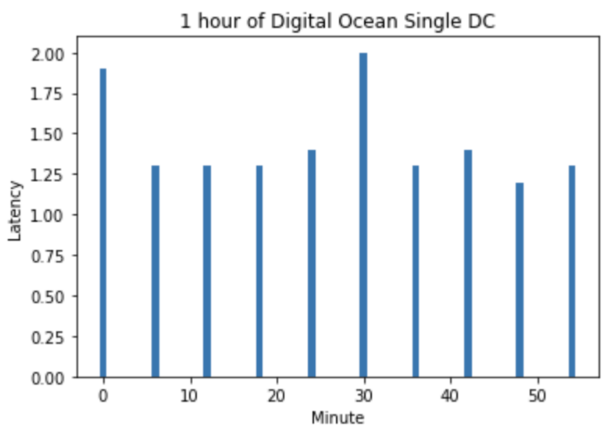


Fig. 15: Latency for File Transfers over a 1 hour period. There is a clear spike at 0 and 30 minutes. This is reflected in the other hours of Digital Ocean original File Transfer tests.

flows. However, Azure is also the most consistent. Google Cloud Platform appears to have the lowest latency and low variability (Std Dev.), aside from a seemingly random spike at 6AM UTC. According to the standard deviation plot, Amazon Web Services clearly has the highest variability. The pattern of inconsistency Amazon Web Services presented in the ping tests continues.

Interestingly, we recognized unique patterns with Digital Ocean's File Transfer test results. While plotting each provider during exploration, we noticed that the Digital Ocean scatter plot had a clear bimodal distribution shown in figure 14. Most of the time, the latency is around 1.25ms to 1.5ms, but a few times an hour, the latency would spike up to around 2ms. We then analyzed when these spikes in latency would occur. In the first round of File Transfer tests, there is a spike at the 0th minute and the 30th minute in nearly every hour we recorded. We hypothesized that background operations are likely running at the Digital Ocean data center at the 0th minute and 30th minute of every hour making the latency spike. So, we retested

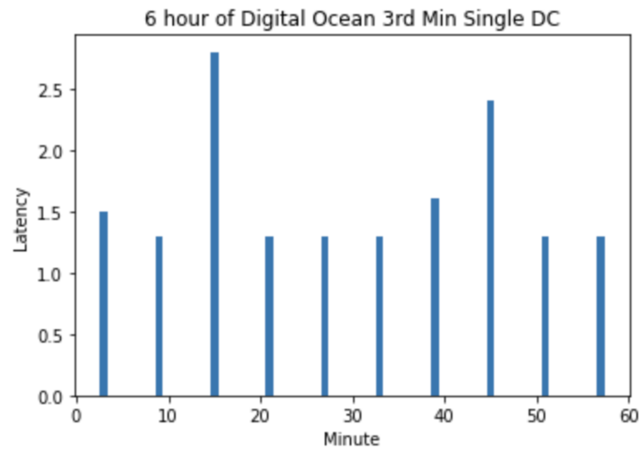


Fig. 16: With file transfers starting at the 3rd minute of every hour, this is a plot of latency for File Transfers over a 1 hour period. This is the 6th hour of our 24 hour test. There is a clear spike at the 15th and 30th minute. This is reflected in the other hours of Digital Ocean File Transfer tests that begun at the 3rd minute.

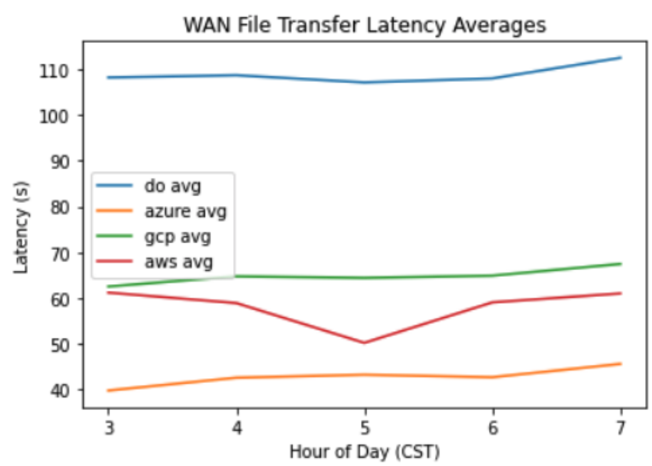


Fig. 17: Wide Area Network File Transfer Latency Results

Digital Ocean and started on the 3rd minute instead of at the top of the hour. We wanted to ensure the spikes were still occurring at the 0th minute and 30th minute of every hour. Surprisingly, the spikes in latency move to the 15th and 45th minute of every hour. This went against our hypothesis in thinking spikes would occur and the 0th minute and 30th minute of the hour regardless of when the test began.

### *B. Wide Area Network Tests*

In the Wide Area Network Tests where the data centers' VMs communicated with a personal computer in Texas, we only included data between 3AM to 7AM in order to minimize the network perturbations due to other network usages within the same household.

Azure performs the best for wide area network long flows by having the lowest latency. This is interesting considering

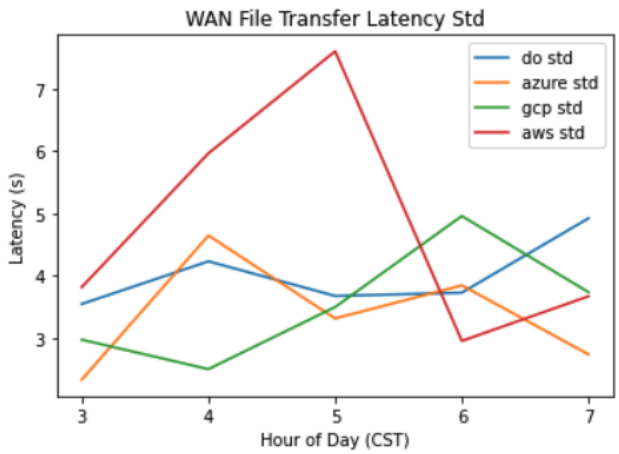


Fig. 18: Wide Area Network File Transfer Latency Std Dev

Azure performed the worst with nearly 3x more latency than other providers in the intra-data center tests. Digital Ocean performed the worst with long flows. Considering it is a smaller provider, Digital Ocean may not have the networking infrastructure and backbone scale that the others do. However, Digital Ocean had to lowest variability (Std Dev) and was fairly consistent with long flows on a Wide Area Network. As with most of the tests we have conducted thus far, Amazon Web Service proved to be inconsistent with a high Std Dev once again.

## VII. Implications

There are many implications of poor network predictability and stability. In recent years we've seen that an increasing amount of application back-ends are shifting towards a micro-service oriented architecture. Coupled with the rise of batch-style machine learning applications and analytics workloads, having poor intra-data center network performance implies a huge bottleneck for computation, as well as poor end-user experience. In fact, it is reported that about 75% of cloud traffic is due to intra-data center communications [7] (instead of Nouth-South traffic), and hence it is important to have stable intra-cloud network performance. Moreover, for tenants, having predictable and consistent cloud network performance also means having more predictable billing and fees. With the current network performance as shown in our study, it can be hard for customers to accurate determine the costs of their workload a priori since even the simplest of workloads such as repeated pings can vary significantly over time. As such, we hope that our work will serve to guide more future works in the direction of improving cloud network stability and predictability.

## VIII. Conclusion

As an increasing amount of workloads are being ran in public clouds, it becomes even more important to better understand the performance characteristics of cloud networks. In our study, we examined short and long flow network performances both within a single data-center and across the wide area network. Our results show that AWS, despite being the largest cloud provider in the market, has considerably less network stability and predictability than its competitors. On a broader scope, we also realize that cloud providers' networks just aren't as predictable as we would like them to be, which can severely compromise consumer experience. We hope that our project can serve as a stepping stone for future work to better understand the predictability and consistency of cloud networks. The complete set of our raw data and analytic scripts can be found at https://github.com/YudiTan/cloud_provider_network_consistency_benchmark.

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