WHITE PAPER

Intel® Optane™ Persistent Memory

Maximize Your Database Density and Performance

NetApp Memory Accelerated Data (MAX Data) uses Intel Optane persistent memory to provide a low-latency, high-capacity data tier for SQL and NoSQL databases.

Executive Summary

To stay competitive, modern businesses need to ingest and process massive amounts of data efficiently and within budget. Database administrators (DBAs), in particular, struggle to reach performance and availability levels required to meet service-level agreements (SLAs). The problem stems from traditional data center infrastructure that relies on limited data tiers for processing and storing massive quantities of data. NetApp MAX Data helps solve this challenge by providing an auto-tiering solution that automatically moves frequently accessed hot data into persistent memory and less frequently used warm or cold data into local or remote storage based on NAND or NVM Express (NVMe) solid state drives (SSDs). The solution is designed to take advantage of Intel Optane persistent memory (PMem)—a revolutionary non-volatile memory technology in an affordable form factor that provides consistent, low-latency performance for bare-metal and virtualized single- or multi-tenant database instances.

Testing performed by Intel and NetApp (and verified by Evaluator Group) demonstrated how MAX Data increases performance on bare-metal and virtualized systems and across a wide variety of tested database applications, as shown in Table 1. Test results also showed how organizations can meet or exceed SLAs while supporting a much higher number of database instances, without increasing the underlying hardware footprint.

This paper describes how NetApp MAX Data and Intel Optane PMem provide low-latency performance for relational and NoSQL databases and other demanding applications. In addition, detailed test configurations and results are provided for FIO benchmark testing on bare-metal and virtualized environments and for database latency and transactional performance testing across four popular database applications.

Table 1. Benchmark test results

Test	NetApp MAX Data vs. XFS
Flexible I/O (FIO) Benchmark Testing on FlexPod	
Bare Metal[1]	Up to 6.5x faster Up to 42.4x lower latency
Virtualized[2]	Up to 2.2x faster Up to 19.2x lower latency
Database Testing	
PostgreSQL Database[3]	Up to 1.9x more transactions per minute (TPM) Up to 1.4x lower latency
MySQL Database[4]	Up to 2.4x more transactions per second (TPS) Up to 3x lower latency
MongoDB[5]	Up to 3x more TPS Up to 3x lower latency
Oracle Database	Bare Metal: Up to 1.9x more TPM[6] Virtualized: Up to 3x more TPM[7]

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Meeting Performance and Availability SLAs in a Sea of Data

Enterprise businesses face both opportunities and challenges from the increasing volumes and importance of data. To stay competitive and take advantage of digital transformation, companies rely on deep analysis and real-time sharing of data that can provide critical insights and enable development of modern services for customers. But handling massive datasets efficiently can be daunting for IT and database admins, who constantly strive to increase performance for analytics. In addition, admins worry about keeping all that data protected in the event of a system failure or disaster.

Cloud service providers (CSPs) face the added challenge of ensuring that SLAs for performance, availability, and application data recovery are met for their customers. Those SLA challenges are compounded by the desire of CSPs to maximize virtual machine (VM) density on existing infrastructure, without sacrificing performance.

And finally, both enterprise businesses and CSPs need to meet their performance and data-protection needs within the real-world constraints of limited or shrinking budgets.

Unfortunately, traditional data center infrastructure isn't well suited to solving these challenges. For example, organizations typically have only limited data tiers available for managing their data and workloads. Admins might try to improve performance by deploying flash storage arrays and faster networking, but these options can be prohibitively expensive and still might not provide the necessary levels of performance. Admins also might try moving large quantities of data into DRAM, which offers much lower latencies than NAND SSDs for fast data access. But DRAM is costly and limited in terms of capacity. In addition, DRAM is volatile, which can make high availability and application data recovery problematic and time consuming; in-memory data needs to be backed up regularly and reloaded into memory after an unplanned restart or a scheduled one, such as after performing routine maintenance or installing security patches.

Businesses would clearly benefit from an alternative option that combines the performance benefits of DRAM with the capacity and non-volatility benefits of NAND SSDs.

NetApp and Intel have combined their technical expertise to offer companies a solution that helps overcome the limitations of traditional data center infrastructure.

NetApp MAX Data, Built with Intel Optane Persistent Memory

NNetApp MAX Data enterprise software uses Intel Optane PMem to provide affordable, low-latency performance for relational and NoSQL databases and other applications that require higher read/write performance than can be achieved using traditional data-management solutions. In addition, MAX Data is designed to make full use of the data-protection, availability, security, and management features provided by NetApp ONTAP data-management software and NetApp Memory Accelerated Recovery (MAX Recovery).

This paper describes Intel Optane PMem and how it integrates with MAX Data to accelerate application performance and boost database transactions while simultaneously increasing VM capacity, so you can meet SLAs without expanding hardware.

Throughput performance results are provided for a bare-metal configuration and a VMware vSphere VM configuration built with FlexPod solutions from NetApp and Cisco. Both configurations ran MAX Data with Intel Optane PMem.

In addition, benchmark test results highlight performance benefits for the following SQL and NoSQL databases when running in both bare-metal and virtualized environments on systems configured with MAX Data and Intel Optane PMem:

- PostgreSQL
- MySQL
- MongoDB
- Oracle Database

Intel Optane Persistent Memory

Intel Optane persistent memory is based on a revolutionary non-volatile memory technology from Intel, offered in a DIMM form factor. It offers users a new data tier that closes the large performance gap between DRAM and storage, which helps better manage large datasets by providing:

- Higher capacities than DRAM, at up to 512 GB per DIMM
- Full data persistence, unlike volatile DRAM
- Low-latency performance, approaching that of DRAM (which averages about 70 nanoseconds), and much better than the performance of NAND SSDs, as shown in Figure 1[8]

NetApp MAX Data

Intel Optane PMem is non-volatile when used in App Direct Mode, which is *byte-addressable*. However, applications are traditionally written to use *block-addressable* storage. Many application vendors are already rewriting code to take advantage of the byte-addressable nature of Intel Optane PMem; but in the meantime, MAX Data offers a way to reap the benefits of this remarkable technology without rewriting (or waiting for vendors to rewrite) application code or having to upgrade existing software.

MAX Data provides a fast path for organizations to realize the full potential of Intel Optane PMem today. MAX Data is a seamless, plug-and-play software solution, with no rewriting of apps required. It is a POSIX-compliant file system that automatically tiers data between Intel Optane PMem and slower local or remote storage.

Unlike other data-management solutions, MAX Data does not cache metadata, log files, and index files. The solution stores all hot data in the fast, low-latency persistent memory tier, and it then automatically moves less-frequently-used data to a storage tier, which can be a NetApp AFF system based on NetApp ONTAP or other locally attached or remote storage. Conversely, frequently accessed data is automatically moved back to the hot data tier, as needed. Together, MAX Data software and Intel Optane PMem deliver near-DRAM speed at the scale and cost of flash storage.

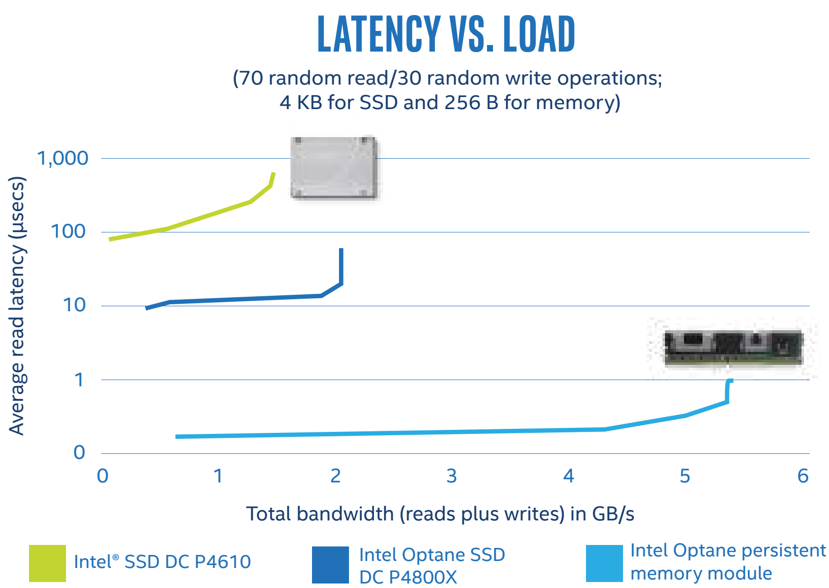

Figure 1. Intel Optane persistent memory offers orders-of-magnitude lower latency than a NAND SSD and up to 3.7 times the read/write bandwidth of a NAND SSD[8]

MAX Data can be deployed directly on a server or within a virtual environment, as shown in Figure 2.

NetApp AFF Offers Data-Protection Services

Administrators can reap the persistent-memory benefits provided by MAX Data with any storage tier, but the simplest way for organizations to take advantage of the full data-protection and management benefits of ONTAP and NetApp MAX Recovery is to deploy MAX Data with ONTAP Select software-defined storage, NetApp FAS hybrid flash arrays, or—for optimum performance—NetApp AFF arrays. These storage solutions extend the memory-like performance and tiering features offered by MAX Data by providing:

- Automated snapshots
- Automated backups
- Application data recovery capabilities
- Full replication to a MAX Recovery server
- A smaller footprint than standard JBOD storage tiers

ONTAP provides enterprise data services to back up and protect data with minimal impact on performance. It also offers last-write safety to ensure consistency of database applications. MAX Recovery enables mirroring of Intel Optane PMem between the MAX Data server and the MAX Recovery server, which can significantly reduce recovery time after a server failure.

Testing NetApp MAX Data and Intel Optane Persistent Memory with Database Workloads

Modern businesses often put a heavy burden on their database applications by asking them to process large amounts of data for time-critical workloads, such as financial trading, healthcare diagnostics, e-commerce, artificial intelligence (AI), and others. MAX Data can accelerate performance for many databases and workloads, including a wide range of relational and NoSQL databases, such as PostgreSQL, MySQL, MongoDB, and Oracle Database.

MAX Data and Intel Optane PMem improve performance by placing working datasets directly in the memory tier, close to the CPU. That results in reduced latency, allowing databases to support more transactions using fewer computing resources and to complete user queries much faster than traditional systems that rely on higher-latency NAND SSDs.

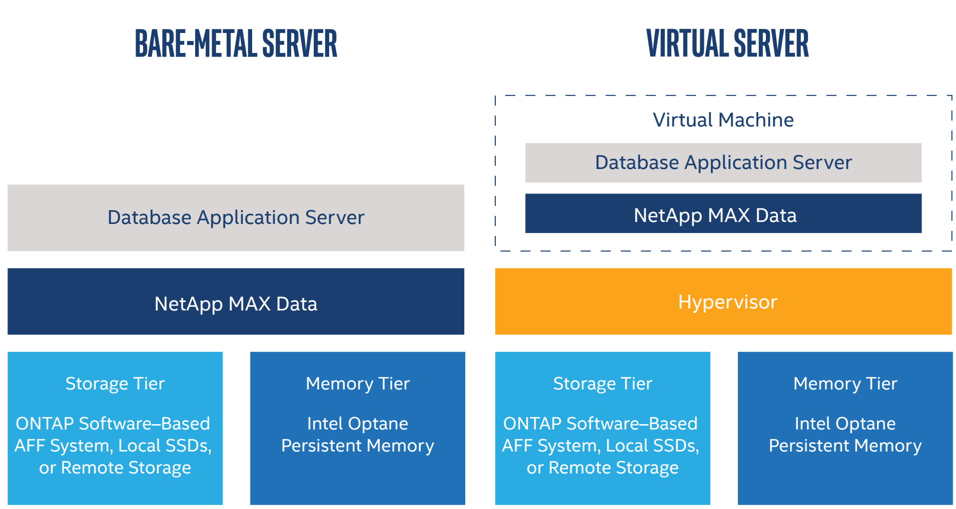

Figure 2. NetApp MAX Data transparently manages the location of application data across memory and storage tiers in bare-metal (left) or virtual-server (right) deployments

The following sections describe benchmark test results for several different configurations and databases. In each test, a configuration without NetApp MAX Data was compared to a configuration built with NetApp MAX Data and Intel Optane PMem, in order to measure performance differences.

Protect Your Data with NetApp MAX Recovery

NetApp MAX Data enables data resilience with minimal impact on performance, and it provides last-write safety, which helps ensure the consistency of database applications. The NetApp MAX Recovery feature enables you to mirror and protect Intel Optane persistent memory in a server and to use snapshot copies for fast data recovery. As data ages, you can tier it to a NetApp AFF system paired with NetApp ONTAP and make full use of all the data-management capabilities in ONTAP, including high availability, cloning, deduplication, snapshot copies, backup, application data recovery, and encryption.

Test Configurations and Results

The following configurations and benchmark tests were used:

- Bare-metal and VM input/output (I/O) tests on FlexPod with the FIO benchmark tool
- PostgreSQL on FlexPod with the DBT-2 test suite
- MySQL with the sysbench benchmark suite
- MongoDB with the Yahoo! Cloud Service Benchmark (YCSB) program suite
- Oracle Database on bare-metal and virtualized environments with HammerDB benchmarking software

Results Summary

In every configuration tested, MAX Data significantly reduced latency, compared to reference systems configured without MAX Data (see Table 1, in the executive summary).

These test results show that MAX Data gives performance-hungry databases a boost in the data center. The solution creates a new tier for fast, efficient management of data by using Intel Optane PMem to significantly reduce latency in bare-metal or virtualized environments. The higher performance levels make it easier for businesses to meet their SLAs. And the virtualization test results show that IT admins can even increase their VM density without sacrificing performance.

In addition, the solution offers admins an affordable alternative to costly upgrades of DRAM, networking, and flash storage, which means that administrators can improve performance, get more from their existing infrastructure, better meet SLAs, and stay within their limited budgets. And when paired with ONTAP on a NetApp AFF system for storage, MAX Data also provides automated snapshots, backups, and data-recovery features for resilience with high availability in the data center.

The following sections contain detailed descriptions and results for each test configuration.

Bare-Metal and VMware VM Testing on FlexPod

Testing was conducted by NetApp and then validated by Evaluator Group.

To determine whether MAX Data provides higher throughput than the standard XFS file system, a FlexPod unit was configured with the following components:

- Cisco Unified Computing System (Cisco UCS)
- Cisco Nexus switches
- Cisco MDS switches
- NetApp AFF system
- Red Hat Enterprise Linux (RHEL)

Throughput was tested on both bare-metal and VM configurations.

Bare-Metal Testing[1]

The solution was validated for performance by using the FIO tester tool to read and write data. The two configurations are shown in Figure 3, with full details in Appendix A: Configuration for FlexPod Tests.

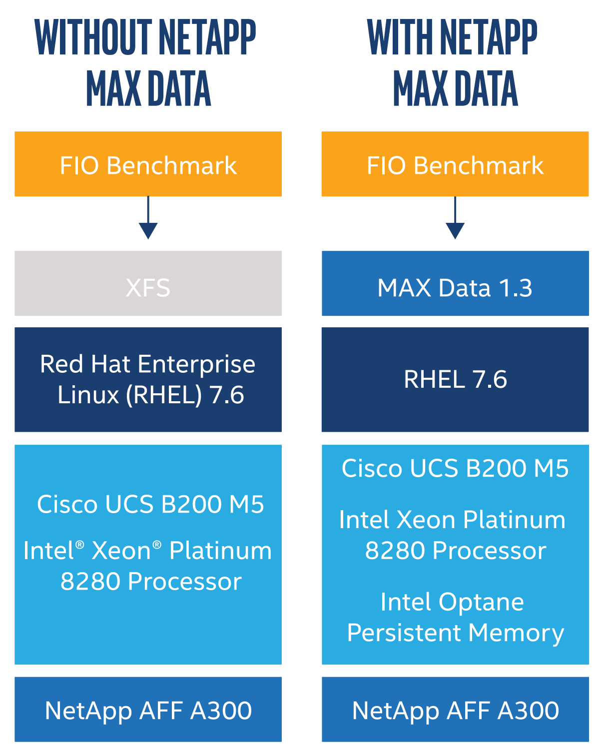

Figure 3. Configuration used to compare performance with and without NetApp MAX Data in a bare-metal environment

Bare-Metal Test Results

The test was run using a Cisco UCS B200 M5 server with two 2nd Generation Intel Xeon Scalable processors and four 256 GB Intel Optane PMem modules with Cisco UCS Virtual Interface Card (VIC) 1340 adapters running Red Hat Enterprise Linux 7.6 with NetApp MAX Data 1.3 and FIO.

Multiple tests were run with the FIO tool iterating on the number of threads (4, 16, 32, 128, and 192 threads for the baseline; 1, 4, 8, 16, and 20 threads for MAX Data reads and writes). A 4-KB block size was used with 100 percent random write and random read operations. I/O operations per second (IOPS) and latency were measured with and without MAX Data.

The baseline tests without MAX Data reached a maximum throughput of 115,000 IOPS at a high latency of at least 1,111 microseconds. With MAX Data, the system reached a maximum write throughput of 578,000 IOPS at a latency of only 34.04 microseconds, and a maximum read throughput of 747,000 IOPS at only 26.19 microseconds. As Figure 4 shows, throughput increases while latency stays consistently low in the configuration using MAX Data with Intel Optane PMem.

VMware Testing[2]

In this scenario, the FIO test was deployed on Red Hat Enterprise Linux within a VMware VM. Again, the performance tool was used to read and write data and increase the number of threads to concurrency. Configurations are shown in Figure 5, with full details in Appendix A: Test Configurations for FlexPod Tests.

VMware Guest Test Results

The configuration for this test used one Cisco UCS B200 M5 server with two 2nd Generation Intel Xeon Scalable processors and four 256 GB Intel Optane PMem modules with Cisco UCS VIC 1340 adapters running VMware ESXi 6.7 Update 2, with a guest VM running Red Hat Enterprise Linux 7.6 with NetApp MAX Data 1.3 and FIO. An NVDIMM of 990 GB was added to the VM and a namespace was automatically created by VMware vSphere.

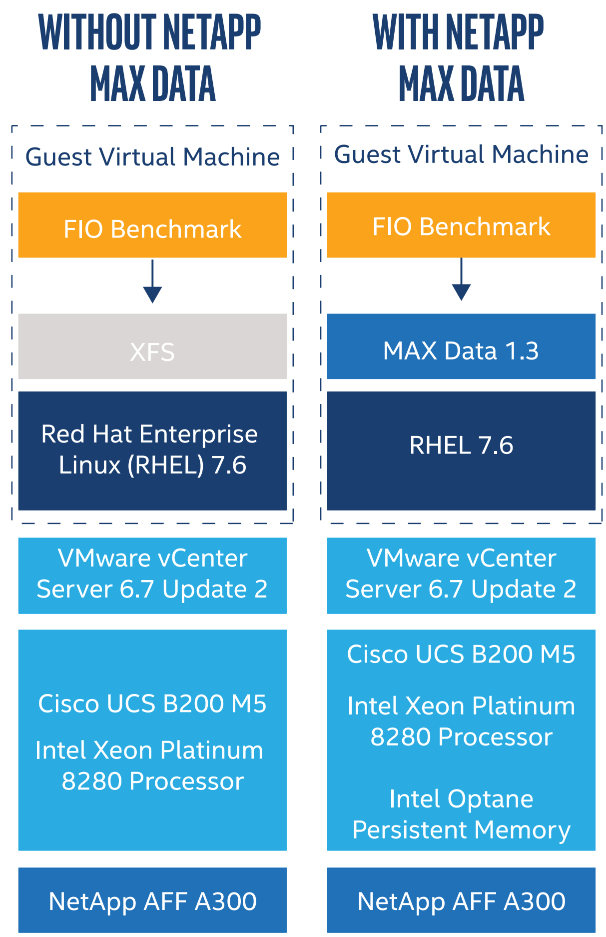

Figure 5. Configuration used to compare performance with and without NetApp MAX Data in a virtualized environment

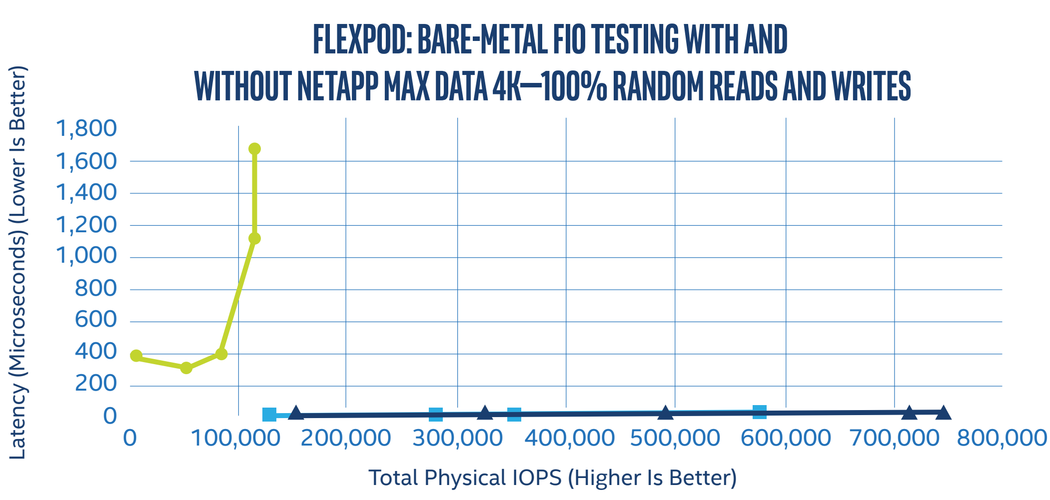

Figure 4. Performance benefits of adding NetApp MAX Data to NetApp AFF A300 in a bare-metal configuration

Multiple tests were run with the FIO tool iterating on the number of threads (1, 4, 8, and 16) using a 4-KB block size with 100 percent random writes operations. IOPS and latency were measured with 20 vCPUs and again with 56 vCPUs. These were compared to the bare-metal base performance without MAX Data.

As a reminder, the bare-metal baseline tests without MAX data reached a maximum throughput of 115,000 IOPS at a high latency of 1,111 microseconds. With MAX Data in a virtualized scenario running 20 vCPUs, the system reached a maximum write throughput of 271,000 IOPS at a latency of only 57.64 microseconds. Even when the system was pushed to accommodate 56 vCPUs, it reached a maximum throughput of 255,000 IOPS at only 61.57 microseconds. As Figure 6 shows, MAX Data with Intel Optane PMem also delivers exceptional throughput with low latency in a virtualized environment.

Key Takeaways

The FlexPod tests showed low-latency throughput for reads and writes in both bare-metal and virtualized environments when using MAX Data and Intel Optane PMem. For businesses, faster performance translates to faster decision making and response times for critical data. In addition, organizations can use the low-latency performance of MAX Data to process more transactions with fewer virtual CPUs. Because MAX Data enables admins to increase VM density while still delivering high performance, businesses can use their infrastructure more efficiently, while still meeting or exceeding SLAs.

PostgreSQL Database Testing

Testing was conducted by NetApp and then validated by Evaluator Group.[3]

As the following test results show, a PostgreSQL database system using MAX Data software running on FlexPod with Intel Optane PMem serves more TPM, at a better response time, compared to a system without MAX Data.

PostgreSQL was installed on a RHEL VM running on VMware vSphere 6.7 Update 2. The tests were run using XFS and then using MAX Data, as shown in Figure 7.

Full details are provided in Appendix B: Configuration for FlexPod PostgreSQL Database Tests.

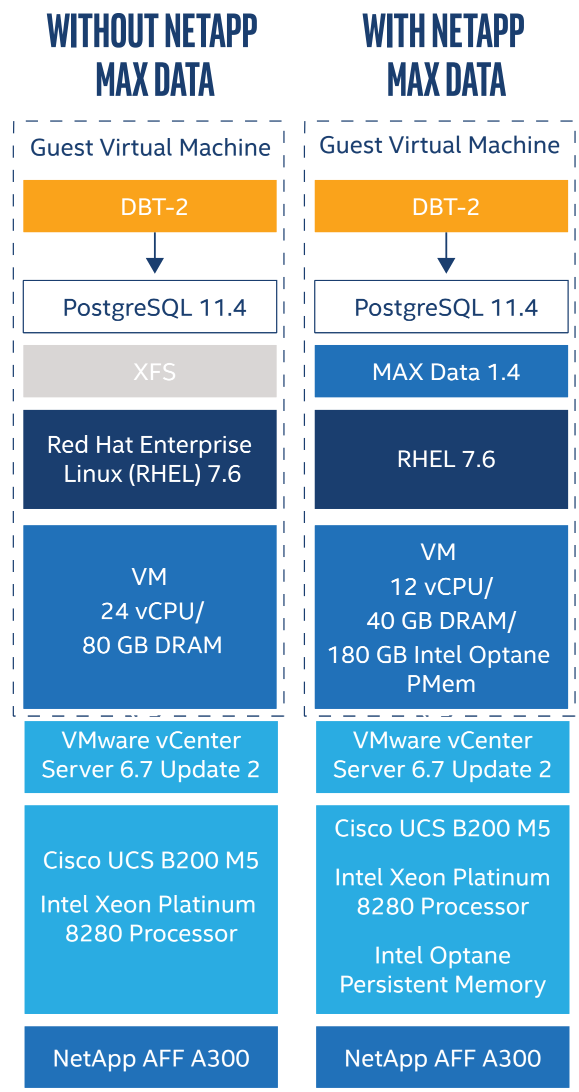

Figure 7. Configuration used to compare PostgreSQL performance with and without MAX Data

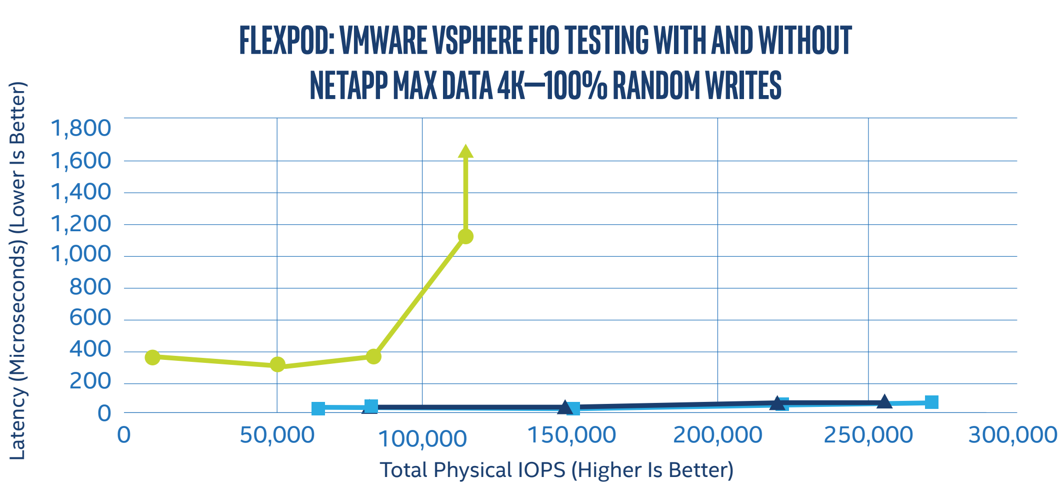

Figure 6. Performance benefits of adding NetApp MAX Data to NetApp AFF A300 running on a VMware VM with Red Hat Enterprise Linux

The DBT-2 benchmark was used to generate a TPC-C-like load. The DBT-2 benchmark is an online transaction processing (OLTP) transactional performance test that simulates a wholesale parts supplier where several workers access a database, update customer information, and check on parts inventories. The MAX Data system was configured with only half the CPU and memory used in the XFS system.

PostgreSQL Performance Test Results

As Figure 8 shows, the MAX Data configuration demonstrated a significant improvement in performance over the XFS system, with 1.9 times more transactions, while reducing the virtual infrastructure from 24 virtual CPUs (vCPUs) to only 12 vCPUs. The MAX Data system also demonstrated response times 1.4 times faster than on the XFS system—again, even as virtual infrastructure was reduced from 24 to 12 vCPUs.

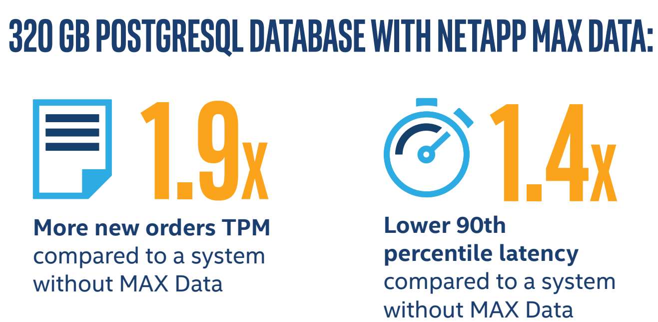

Figure 8. The NetApp MAX Data system increased TPM by 1.9 times and reduced latency 1.4 times, while running on a system configured with only half the vCPUs and DRAM of the comparison system

Key Takeaways

The lower-latency performance offered by MAX Data enabled significantly more transactions to be processed using fewer resources. That could lead directly to total cost of ownership (TCO) savings for businesses because they could purchase servers with fewer cores, while also reducing database core licensing fees, for a lower cost per transaction.

MySQL Database Testing

Benchmark tests conducted by Intel demonstrate how MAX Data, with Intel Optane PMem, boosts MySQL database transactions while reducing latency.[4]

Testing was performed using sysbench benchmark tests running a TPC-C-like OLTP workload with varied database sizes. A testing architecture diagram is shown in Figure 9, and full hardware and software details are shown in Appendix C: Configuration for MySQL Tests.

MySQL Database Test Results

Figure 10 shows TPS for MAX Data compared to the XFS system across the four VMs used in the test systems. Varying database sizes were run with sysbench TPC-C-like workloads. Each database size on the graph represents database size per VM.

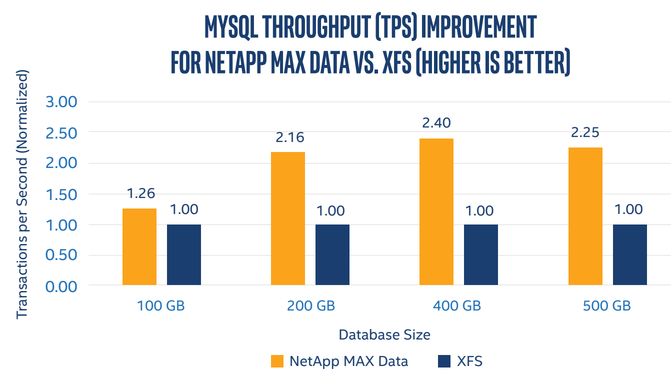

Figure 10. MySQL throughput improvements for NetApp MAX Data compared to XFS, based on sysbench benchmark tests running TPC-C-like workloads with a MySQL database

Testing demonstrated up to a 2.4 times improvement for systems configured with MAX Data, compared to the test systems using XFS without MAX Data.

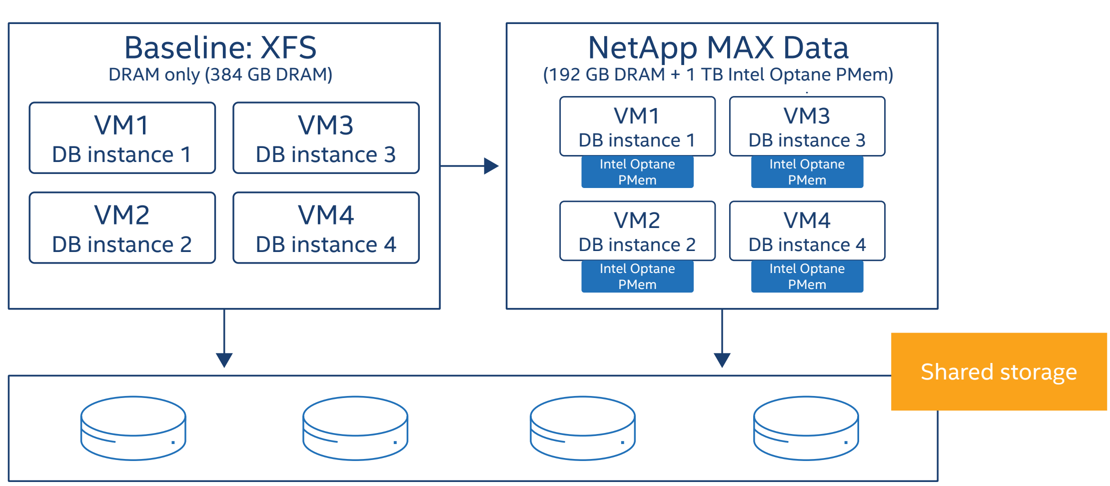

Figure 9. Configuration used to compare MySQL multi-tenant performance with and without NetApp MAX Data

Latency was also measured and compared between test systems with and without MAX Data. Figure 11 shows the median P95 latency values of the VMs, where each database size on the graph represents database size per VM. Again, the results shown are relative to the XFS configuration.

Testing showed that a system running a 500 GB database configured with MAX Data exhibited only one-third the latency of the XFS configuration.

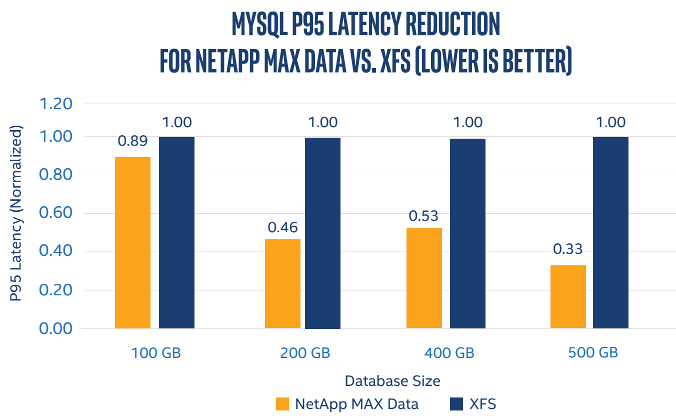

Figure 11. P95 latency improvements for NetApp MAX Data compared to XFS, based on sysbench benchmark tests running TPC-C-like workloads with a MySQL database

Key Takeaways

When configured with MAX Data, MySQL test systems demonstrated:

- Up to 2.4 times TPS improvement
- Ability to maintain or exceed response-time SLAs
- Up to 67 percent drop in P95 latency

By increasing throughput and reducing the amount of DRAM required to run MySQL transactions, users can lower total infrastructure costs while meeting or exceeding SLAs.

MongoDB Testing

Benchmark tests conducted by Intel demonstrate how MAX Data, with Intel Optane PMem, boosts MongoDB throughput while reducing latency.[5] In addition, the tested MAX Data configuration supports more database VM instances at a lower estimated cost, because it requires less hardware and software.

Testing was performed using the YCSB program suite, an open source suite for comparing relative performance of NoSQL database-management systems (DBMSs). The YCSB suite is designed for testing transaction-processing workloads. Figure 12 compares the two tested configurations.

Full hardware and software details for the test systems are shown in Appendix D: Configuration for MongoDB Tests.

MongoDB Test Results

As shown in Figure 13, the total throughput for the MAX Data system was up to three times higher than for the XFS system. Because of the higher total throughput, the MAX Data system was able to run 12 VMs, compared to only 4 VMs for the XFS system, while maintaining similar throughput per VM.

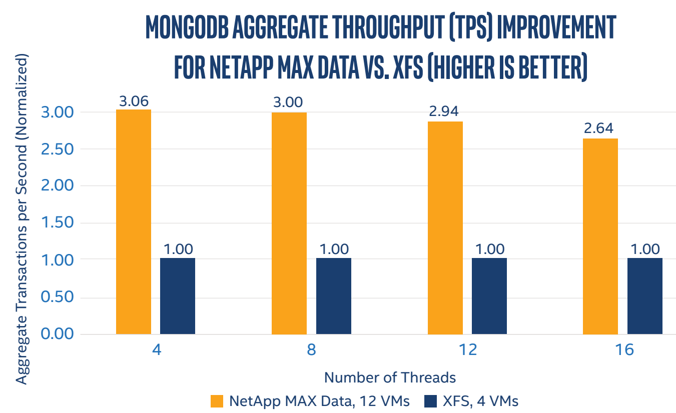

Figure 13. MongoDB benchmark results for 50/50 read/write workloads, comparing throughput for systems with and without NetApp MAX Data; the NetApp MAX Data systems showed up to three times higher throughput, compared to the baseline system

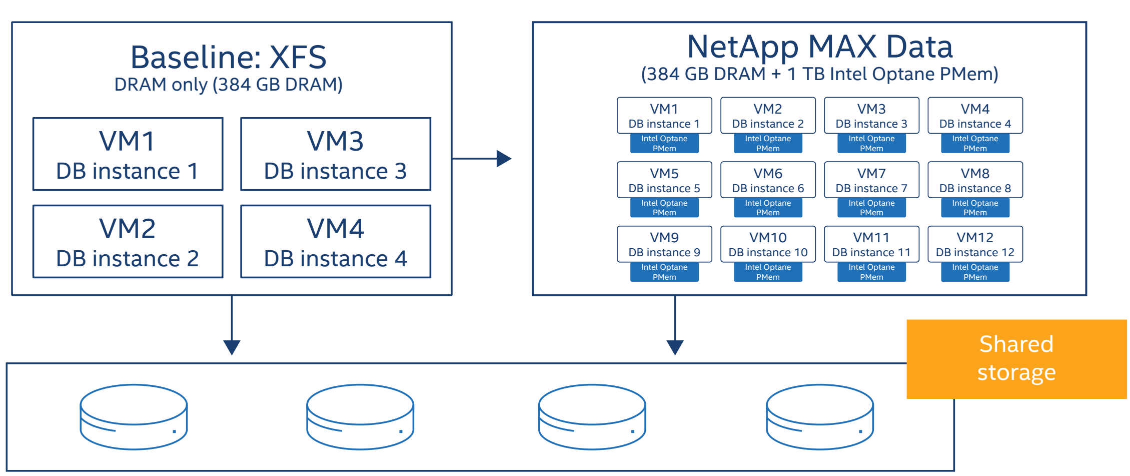

Figure 12. Configuration used to compare MongoDB multi-tenant performance with and without MAX Data

Test results for average P99 latencies at 50/50 read/write workloads are shown in Figure 14. The MAX Data configuration supported 12 VMs with much lower latencies, compared to the XFS system supporting only 4 VMs.

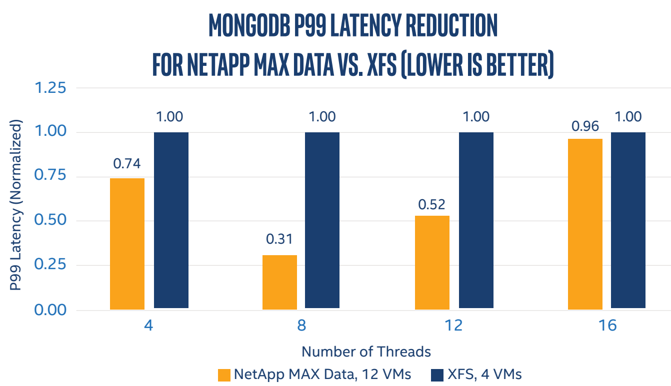

Figure 14. Benchmark results for 50/50 read/write workloads, comparing P99 latencies for systems with and without NetApp MAX Data

Key Takeaways

The MongoDB systems configured with MAX Data were able to support:

- Up to three times higher throughput than systems configured with XFS
- More VMs per node, at a lower estimated cost per VM
- Significantly lower P99 latency, compared to the XFS systems

In addition, results demonstrate that organizations can use MAX Data with Intel Optane PMem to support large databases and still meet customer SLAs, while reducing required infrastructure and overall costs.

Oracle Database Testing

Testing was conducted by Intel.

Benchmark tests demonstrate that MAX Data, with Intel Optane PMem, boosts throughput for Oracle Database in both bare-metal and virtualized environments.

Testing was performed using HammerDB benchmarking software: a free, open source benchmarking and load testing tool that supports both transactional and analytic scenarios.

Bare-Metal Oracle Database Testing[6]

Figure 15 compares the two bare-metal test configurations.

Full configuration test details are provided in Appendix E: Configurations for Oracle Database Tests.

Bare-Metal Oracle Database Test Results

Test results showed a significant increase in TPM, even as the number of virtual users increased to a maximum of 200, as shown in Figure 16.

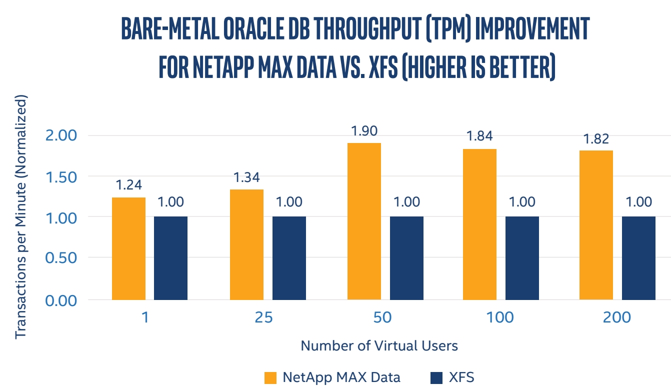

Figure 16. The bare-metal Oracle Database configuration with NetApp MAX Data performed up to 1.9 times better than the XFS system

Virtualized Oracle Database Testing[7]

Figure 17 compares the two virtual environments tested, with and without MAX Data.

Full hardware and software details are provided in Appendix E: Configurations for Oracle Database Tests.

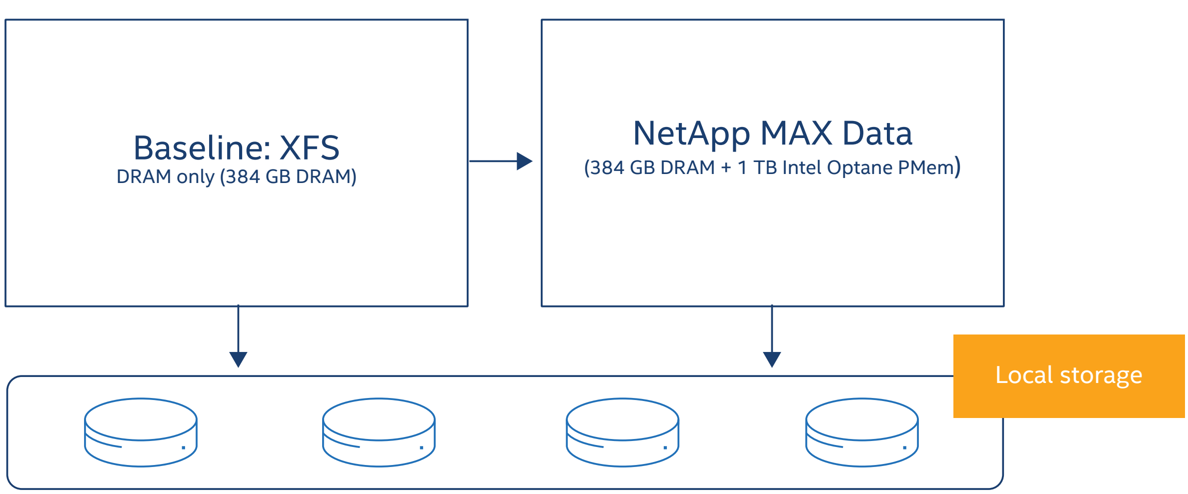

Figure 15. Configuration used to compare Oracle Database bare-metal performance with and without NetApp MAX Data

Virtualized Oracle Database Test Results

Test results showed a significant increase in TPM, even as the number of virtual users increased to a maximum of 200, as shown in Figure 18.

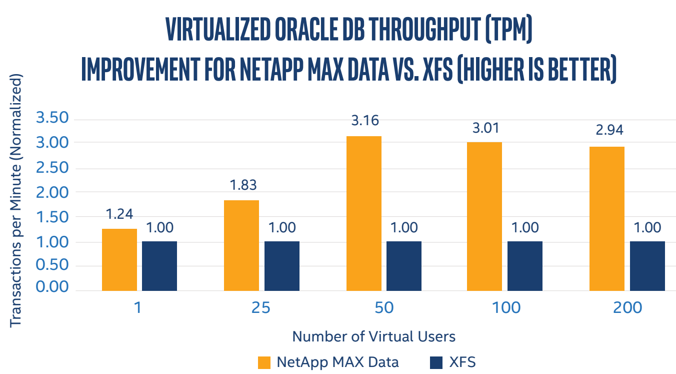

Figure 18. The virtualized Oracle Database configuration with NetApp MAX Data performed up to three times better than the XFS system

Key Takeaways

- HammerDB testing with Oracle Database on the bare-metal system showed that MAX Data with Intel Optane PMem demonstrated up to 1.9 times better performance, compared to the XFS system.
- The virtualized environment running Oracle Database and configured with MAX Data showed up to three times better performance, compared to the XFS system.

Test results demonstrate that MAX Data would be an ideal solution for Oracle Database administrators who are looking for better throughput performance or the ability to run more databases in a multi-tenant database-as-a-service (DBaaS) environment. Intel Optane PMem enables MAX Data to provide consistent, low query latencies for large databases (greater than 1 TB).

Run More Database Instances Faster and with a Lower TCO

MAX Data provides applications with plug-and-play access to Intel Optane technology. In addition, it integrates seamlessly with ONTAP software for full data-management capabilities, such as cloning and snapshots, and MAX Recovery, for high availability and faster application data recovery.

By deploying MAX Data, organizations can make full use of the high capacity, low latency, non-volatile benefits of Intel Optane PMem without needing to wait for software vendors to rewrite applications. As demonstrated by the test results in this paper, database configurations running MAX Data can support more database instances with lower latencies and higher throughputs, with a lower TCO, compared to comparable systems configured without MAX Data and Intel Optane PMem.

Next Steps

- Take advantage of NetApp's 90-day customer evaluation program, or contact your local NetApp sales representative: netapp.com/us/products/data-management-software/max-data.aspx
- Learn more about Intel Optane PMem: intel.com/content/www/us/en/products/memory-storage/optane-dc-persistent-memory.html

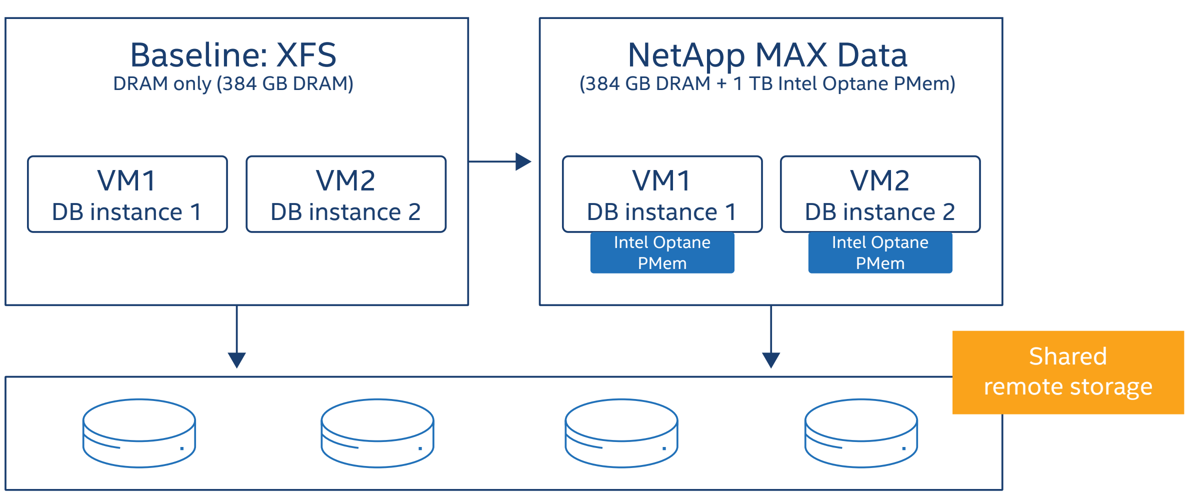

Figure 17. Configuration used to compare Oracle Database virtualized configuration performance with and without NetApp MAX Data

Appendix A: Configuration for FlexPod Tests

FlexPod Bare-Metal Tests

Layer	XFS System	NetApp MAX Data System
Server	Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340	Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340
CPU	2nd Generation Intel Xeon Platinum 8280 processor	2nd Generation Intel Xeon Platinum 8280 processor
Memory	384 GB DRAM (12 x 32 GB)	384 GB DRAM (12 x 32 GB)
Persistent memory	Not applicable (N/A)	4 x 256 GB Intel Optane persistent memory
Network	Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode, release 7.0(3)17(6)	Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode, release 7.0(3)17(6)
Storage network	Cisco MDS 9132T 32 gigabits per second (Gbps) 32-port Fibre Channel switch, release 8.3(2)	Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch, release 8.3(2)
Storage	NetApp AFF A300 ONTAP 9.5P4	NetApp AFF A300 ONTAP 9.5P4
Operating system	Red Hat Enterprise Linux 7.6, kernel 3.10.0-957	Red Hat Enterprise Linux 7.6, kernel 3.10.0-957
Benchmarking software	FIO benchmark tool	FIO benchmark tool
File system	XFS	MAX Data 1.3

FIO Benchmark Configuration Details for Bare-Metal Configuration

Multiple tests were run with the FIO tool iterating on the number of threads (4, 16, 32, 128, and 192 threads for the baseline; 1, 4, 8, 16, and 20 threads for MAX Data reads and writes). A 4-KB block size was used with 100 percent random write and random read operations. IOPS and latency were measured with and without MAX Data.

The FIO command strings used were similar to the following example:

```
fio --bs=4K --rw=randwrite --direct=1 -numjobs=20 --size=10g --ioengine=psync --
norandommap --time_based --runtime=120 --directory=/mnt/mount --group_reporting --
name=fio_test --output-format=normal -output=outfile.txt
```

FlexPod VMware Tests

Layer	XFS System	NetApp MAX Data System
Server	Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340	Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340
CPU	2nd Generation Intel Xeon Platinum 8280 processor	2nd Generation Intel Xeon Platinum 8280 processor
Memory	384 GB DRAM (12 x 32 GB)	384 GB DRAM (12 x 32 GB)
Persistent memory	N/A	4 x 256 GB Intel Optane persistent memory
Network	Cisco Nexus 93180YC-EX switch in NX-OS standalone mode, release 7.0(3)17(6)	Cisco Nexus 93180YC-EX switch in NX-OS standalone mode, release 7.0(3)17(6)
Storage network	Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch, release 8.3(2)	Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch, release 8.3(2)
Storage	NetApp AFF A300 ONTAP 9.5P4	NetApp AFF A300 ONTAP 9.5P4
Benchmarking software	FIO benchmark tool	FIO benchmark tool
Virtualization	VMware vSphere 6.7 Update 2	VMware vSphere 6.7 Update 2
Guest operating system	Red Hat Enterprise Linux 7.6, kernel 3.10.0-957	Red Hat Enterprise Linux 7.6, kernel 3.10.0-957
File system	XFS	MAX Data 1.3

FIO Benchmark Configuration Details for VMware Configuration

Multiple tests were run with the FIO tool iterating on the number of threads (1, 4, 8, and 16) using a 4-KB block size with 100 percent random writes operations. IOPS and latency were measured with 20 vCPUs and again with 56 vCPUs.

The FIO command strings used were similar to the following example:

```
fio --bs=4K --rw=randwrite --direct=1 -numjobs=20 --size=10g --ioengine=psync --
norandommap --time_based --runtime=120 --directory=/mnt/mount --group_reporting --
name=fio_test --output-format=normal -output=outfile.txt
```

Appendix B: Configuration for FlexPod PostgreSQL Database Tests

Layer	XFS System	NetApp MAX Data System
Server	Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340	Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340
CPU	2nd Generation Intel Xeon Platinum 8280 processor	2nd Generation Intel Xeon Platinum 8280 processor
Memory	384 GB DRAM (12 x 32 GB)	384 GB DRAM (12 x 32 GB)
Persistent memory	N/A	4 x 256 GB Intel Optane persistent memory
Network	Cisco Nexus 93180YC-EX switch in NX-OS standalone mode, release 7.0(3)17(6))	Cisco Nexus 93180YC-EX switch in NX-OS standalone mode, release 7.0(3)17(6)
Storage network	Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch, release 8.3(2)	Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch, release 8.3(2)
Storage	NetApp AFF A300 ONTAP 9.5P4	NetApp AFF A300 ONTAP 9.5P4
Database software	PostgreSQL 11.4	PostgreSQL 11.4
Benchmarking software	DBT-2	DBT-2
Virtualization	VMware vSphere 6.7 Update 2	VMware vSphere 6.7 Update 2
vCPUs	24 vCPUs	12 vCPUs
Virtual memory	80 GB DRAM	40 GB DRAM
Virtual persistent memory (vPMEM)	N/A	180 GB Intel Optane persistent memory
Guest OS	Red Hat Enterprise Linux 7.6, kernel 3.10.0-957	Red Hat Enterprise Linux 7.6, kernel 3.10.0-957
File system	XFS	MAX Data 1.4

Benchmark Configuration Details for PostgreSQL Test

Command lines for running the benchmarks were similar to the following examples:

postgresql.conf file

```
Shared buffers=20gb
max_connections=300
max_wal_size=15gb
max_files_per_process=10000
wal_sync_method= open_sync
checkpoint_completion_target=0.9
```

DBT2 client

```
Load phase: dbt2-pgsql-build-db -r -w {numofwarehouses} (scale=3200 for a 320GB DB
+ 15GB WAL)
Run phase: dbt2-run-workload -a pgsql -D dbt2 -H {host_ip} -l 5432 -d 3600 -w
{warehouses} -o /home/postgres/results -c 32 -t 1 -s 5
```

Appendix C: Configuration for MySQL Tests

Layer	XFS System	NetApp MAX Data System
CPU	2nd Generation Intel Xeon Platinum 8280L processor	2nd Generation Intel Xeon Platinum 8280L processor
CPU per node	28 cores per socket, 2 sockets, 2 threads per core	28 cores per socket, 2 sockets, 2 threads per core
Memory	384 GB DDR4 error correcting code (ECC) DRAM (12 x 32 GB, 2,667 MHz)	192 GB DDR4 dual-rank ECC DRAM (12 x 16 GB, 2,667 MHz) 1 TB Intel Optane persistent memory (8 x 128 GB)
Network	Mellanox ConnectX-4 Lx 25 Gb Ethernet (GbE), 1 port, connected to the target	Mellanox ConnectX-4 Lx 25 GbE, 1 port, connected to the target
Storage	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 1 x 8 TB Intel SSD DC P4510 NVMe, remotely connected from the NVMe over Fabrics (NVMe-oF) TCP target, partitioned into four individual 1.6 TB partitions	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 1 x 8 TB Intel SSD DC P4510 NVMe, remotely connected from the NVMe-oF TCP target, partitioned into four individual 1.6 TB partitions
Operating system	Fedora 29	Fedora 29
Database software	MySQL 8.0.16 with InnoDB storage engine	MySQL 8.0.16 with InnoDB storage engine
Benchmarking software	Sysbench benchmark 1.0.17, 14 threads, 600 seconds runtime TPC-C-like workload with varying database sizes (100 GB–500 GB)	Sysbench benchmark 1.0.17, 14 threads, 600 seconds runtime TPC-C-like workload with varying database sizes (100 GB–500 GB)
Virtualization	QEMU/KVM 4.0.94 (v4.1.0-rc4)	QEMU/KVM 4.0.94 (v4.1.0-rc4)
Guest VMs	4 VMs, 85 GB DRAM, 14 vCPUs each CentOS 7.6 1.6 TB storage for database InnoDB buffer pool size = 64 GB	4 VMs, 42 GB DRAM, 14 vCPUs each CentOS 7.6 225 GB fsdax mode Intel Optane persistent memory 1.6 TB storage for DB InnoDB buffer pool size = 30 GB
File system	XFS used for storing database	NetApp Memory Accelerated File System (MAX FS) 1.5

Benchmark Configuration Details for MySQL Test

Sysbench run with a TPC-C-like workload with varying database sizes.

Appendix D: Configuration for MongoDB Tests

Layer	XFS System	NetApp MAX Data System
CPU	2nd Generation Intel Xeon Gold 6252 processor	2nd Generation Intel Xeon Gold 6252 processor
CPU per node	24 cores per socket, 2 sockets, 2 threads per core	24 cores per socket, 2 sockets, 2 threads per core
Memory	384 GB DDR4 ECC DRAM (12 x 32 GB, 2,667 MHz)	384 GB DDR4 dual-rank ECC DRAM (12 x 32 GB, 2,667 MHz) 1 TB Intel Optane persistent memory (8 x 128 GB)
Network	Mellanox ConnectX-4 Lx 25 GbE, 2 ports, connected to the target	Mellanox ConnectX-4 Lx 25 GbE, 2 ports, connected to the target
Storage	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 1 x RAID 0 device remotely connected from the NVMe-oF TCP target, partitioned into 12 individual 630 GB partitions	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 1 x RAID 0 device remotely connected from the NVMe-oF TCP target, partitioned into 12 individual 630 GB partitions
Operating system	Fedora 29	Fedora 29
Software	MongoDB 4.2 WiredTiger	MongoDB 4.2 WiredTiger
Benchmarking software	YCSB 0.15.0 workload run from a separate host	YCSB 0.15.0 workload run from a separate host

Virtualization	QEMU/KVM 4.0.94 (v4.1.0-rc4)	QEMU/KVM 4.0.94 (v4.1.0-rc4)
Guest VMs	4 VMs, 85 GB vDRAM, 24 vCPUs each CentOS 7.6 630 GB storage for DB Cache size = 64 GB	12 VMs, 28 GB vDRAM, 8 vCPUs each CentOS 7.6 70 GB fsdax mode Memory mapped to Intel Optane persistent memory 630 GB storage for DB Cache size = 16 GB
File system	XFS used for storing the database	NetApp MAX FS 1.5

Benchmark Configuration Details for MongoDB Test

YCSB benchmarks were used to generate diverse types of load, including:

- A balanced 50 percent read, 50 percent update workload
- A read-intensive (95 percent) workload
- A read-only (100 percent) workload
- A balanced 50 percent read, 50 percent read-modify-write workload

Appendix E: Configurations for Oracle Database Tests

Bare-Metal Oracle Database Tests

Layer	XFS System	NetApp MAX Data System
CPU	2nd Generation Intel Xeon Gold 6252 processor	2nd Generation Intel Xeon Gold 6252 processor
CPU per node	24 cores per socket, 2 sockets, 2 threads per core	24 cores per socket, 2 sockets, 2 threads per core
Memory	384 GB DDR4 ECC DRAM (12 x 32 GB, 2,667 MHz)	384 GB DDR4 dual rank ECC DRAM (12 x 32 GB, 2,667 MHz) 1 TB Intel Optane persistent memory (8 x 128 GB)
Storage	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 2 x 8 TB Intel SSD DC P4510 PCIe, RAID 0 (data) + 1 x 8 TB Intel SSD DC P4510 redo	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 2 x 8 TB Intel SSD DC P4510 PCIe, RAID 0 (data) + 1 x 8 TB Intel SSD DC P4510 redo
Operating system	Red Hat Enterprise Linux 7.6	Red Hat Enterprise Linux 7.6
Database software	Oracle Database 19c Enterprise Edition, Release 19.0.0.0.0—Production Version 19.3.0.0.0 Database size: 1 TB	Oracle Database 19c Enterprise Edition, Release 19.0.0.0.0—Production Version 19.3.0.0.0 Database size: 1 TB
Benchmarking software	HammerDB 3.2	HammerDB 3.2
File system	XFS used for storing database	NetApp MAX Data 1.5

Benchmark Configuration Details for Bare-Metal Oracle Database Test

HammerDB used to generate transactional database workloads, with virtual users varying from 1 to 200.

Virtualized Oracle Database Tests

Layer	XFS System	NetApp MAX Data System
CPU	2nd Generation Intel Xeon Gold 6252 processor	2nd Generation Intel Xeon Gold 6252 processor
CPU per node	24 cores per socket, 2 sockets, 2 threads per core	24 cores per socket, 2 sockets, 2 threads per core
Memory	384 GB DDR4 ECC DRAM (12 x 32 GB, 2,667 MHz)	384 GB DDR4 dual rank ECC DRAM (12 x 32 GB, 2,667 MHz) 1 TB Intel Optane persistent memory (8 x 128 GB)
Network	Dual-port Mellanox ConnectX-4Lx 25 GbE (bonded)	Dual-port Mellanox ConnectX-4Lx 25 GbE (bonded)
Storage	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 2 x 8 TB Intel SSD DC P4510 PCIe, RAID 0 (data) + 1 x 8 TB Intel SSD DC P4510 redo	Operating system: 1 x 1.6 TB Intel SSD DC S3610 Database: 2 x 8 TB Intel SSD DC P4510, RAID 0 (data) + 1 x 8 TB Intel SSD DC P4510 redo
Operating system	Fedora 29	Fedora 29
Database software	Oracle Database 19c Enterprise Edition, Release 19.0.0.0.0—Production Version 19.3.0.0.0 Database size: 2 x 1 TB	Oracle Database 19c Enterprise Edition, Release 19.0.0.0.0—Production Version 19.3.0.0.0 Database size: 2 x 1 TB
Virtualization	QEMU/KVM 4.0.94 (v4.1.0-rc4)	QEMU/KVM 4.0.94 (v4.1.0-rc4)
Guest VMs	2 VMs, 160 GB vDRAM, 48 vCPUs each CentOS 7.6 4 TB storage for DB Database cache size: 100 GB	2 VMs, 160 GB vDRAM, 48 vCPUs each 1 TB Intel Optane persistent memory CentOS 7.6 4 TB storage for DB Database cache size: 100 GB
Benchmarking software	HammerDB 3.2	HammerDB 3.2
File system	XFS used for storing database	NetApp MAX Data 1.5

Benchmark Configuration Details for Virtualized Oracle Database Test

HammerDB used to generate transactional database workloads, with virtual users varying from 1 to 200.

[1] Bare-metal I/O tests on FlexPod with the FIO benchmark tool: Based on testing by NetApp and Evaluator Group on October 2 to October 4, 2019. **XFS Configuration:** Cisco UCS 6332-16UP Fabric Interconnect and Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340 (release 4.0[4b]), Intel Xeon Platinum 8280 processor, 12 x 32 GB DRAM, network: Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode (release 7.0[3]I7[6]), storage network: Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch (release 8.3[2]), NetApp AFF A300, NetApp ONTAP 9.5P4, running RHEL 7.6 (kernel 3.10.0-957), Cisco UCS VIC fNIC driver release 2.0.0.42-77.0, and Cisco UCS NIC VIC eNIC driver release 3.2.210.18-738.12. **NetApp MAX Data Configuration:** Cisco UCS 6332-16UP Fabric Interconnect and Cisco UCS B200 M5 Blade Server with Cisco UCS VIC 1340 (release 4.0[4b]), Intel Xeon Platinum 8280 processor, 12 x 32 GB DRAM, 4 x 256 GB Intel Optane PMem, network: Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode (release 7.0[3]I7[6]), storage network: Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch (release 8.3[2]), NetApp AFF A300, NetApp ONTAP 9.5P4, running RHEL 7.6 (kernel 3.10.0-957), NetApp MAX Data 1.3, Cisco UCS VIC fNIC driver release 2.0.0.42-77.0, and Cisco UCS NIC VIC eNIC driver release 3.2.210.18-738.12.

[2] VM I/O tests on FlexPod with the FIO benchmark tool: Based on testing by NetApp and Evaluator Group on October 2 to October 4, 2019. **XFS Configuration:** Cisco UCS 6332-16UP Fabric Interconnect and Cisco UCS B200 M5 Blade Server (BIOS: B200M5.4.0.4c.0.0506190651) with Cisco UCS VIC 1340 (release 4.0[4b]), Intel Xeon Platinum 8280 processor, 12 x 32 GB DRAM, network: Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode (release 7.0[3]I7[6]), storage network: Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch (release 8.3[2]), NetApp AFF A300, NetApp ONTAP 9.5P4, VMware vSphere ESXi 6.7 Update 2, running RHEL 7.6 (kernel 3.10.0-957), XFS, Cisco UCS VIC fNIC driver release 4.0.0.35, and Cisco UCS VIC eNIC driver release 1.0.29.0. **NetApp MAX Data Configuration:** Cisco UCS 6332-16UP Fabric Interconnect and Cisco UCS B200 M5 Blade Server (BIOS: B200M5.4.0.4c.0.0506190651) with Cisco UCS VIC 1340 (release 4.0[4b]), Intel Xeon Platinum 8280 processor, 12 x 32 GB DRAM, 4 x 256 GB Intel Optane PMem, network: Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode (release 7.0[3]I7[6]), storage network: Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch (release 8.3[2]), NetApp AFF A300, NetApp ONTAP 9.5P4, VMware vSphere ESXi 6.7 Update 2, running RHEL 7.6 (kernel 3.10.0-957), NetApp MAX Data 1.3, Cisco UCS VIC fNIC driver release 4.0.0.35, and Cisco UCS VIC eNIC driver release 1.0.29.0

[3] PostgreSQL with the DBT-2 test suite: Based on testing by NetApp and Evaluator Group on October 14, 2019. **XFS Configuration:** Cisco UCS 6332-16UP Fabric Interconnect and Cisco UCS B200 M5 Blade Server (BIOS: B200M5.4.0.4c.0.0506190651) with Cisco UCS VIC 1340 (release 4.0[4b]), Intel Xeon Platinum 8280 processor, 12 x 32 GB DRAM, network: Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode (release 7.0[3]I7[6]), storage network: Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch (release 8.3[2]), NetApp AFF A300, NetApp ONTAP 9.5P4, VMware vSphere ESXi 6.7 Update 2, running RHEL 7.6 (kernel 3.10.0-957), 24 vCPUs configured with 80 GB DDR4 virtual memory, PostgreSQL 11.4, XFS, Cisco UCS VIC fNIC driver release 4.0.0.35, Cisco UCS VIC eNIC driver release 1.0.29.0. **NetApp MAX Data Configuration:** Cisco UCS 6332-16UP Fabric Interconnect and Cisco UCS B200 M5 Blade Server (BIOS: B200M5.4.0.4c.0.0506190651) with Cisco UCS VIC 1340 (release 4.0[4b]), Intel Xeon Platinum 8280 processor, 12 x 32 GB DRAM, 4 x 256 GB Intel Optane PMem, network: Cisco Nexus 93180YC-EX Switch in NX-OS standalone mode (release 7.0[3]I7[6]), storage network: Cisco MDS 9132T 32 Gbps 32-port Fibre Channel switch (release 8.3[2]), NetApp AFF A300, NetApp ONTAP 9.5P4, VMware vSphere ESXi 6.7 Update 2, running RHEL 7.6 (kernel 3.10.0-957), 12 vCPUs configured with 40 GB virtual memory and 180 GB Intel Optane PMem, PostgreSQL 11.4, NetApp MAX Data 1.4, Cisco UCS VIC fNIC driver release 4.0.0.35, Cisco UCS VIC eNIC driver release 1.0.29.0.

[4] MySQL with the sysbench benchmark suite: Based on testing by Intel on August 27, 2019. **XFS configuration:** one node, two sockets, Intel® Server Board S2600WF, Intel Xeon Platinum 8280L processor (28 cores/socket, 2 sockets, 2 threads per core), 12 x 32 GB (384 GB total) 2,667 MHz DDR4 ECC DRAM, network: Mellanox ConnectX-4 Lx (25 GbE, 1 port, connected to the target), storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 1 x 8 TB Intel SSD DC P4510 NVMe, remotely connected from the NVMe over Fabrics (NVMe-oF) TCP target, partitioned into four individual 1.6 TB partitions; operating system: Fedora 29, Linux kernel 5.2.8, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), microcode: 05000017, running MySQL 8.0.16 with InnoDB storage engine, sysbench benchmark 1.0.17 (14 threads, 600 seconds runtime), and TPC-C-like workload ran with varying database sizes (100 GB–500 GB) on XFS file system; Intel® Hyper-Threading Technology (Intel® HT Technology) on, Intel® Turbo Boost Technology on; virtualization: QEMU/KVM 4.0.94 (v4.1.0-rc4); 4 guest VMs with 85 GB DRAM, 14 vCPUs each, CentOS 7.6, 1.6 TB storage for database. InnoDB buffer pool size = 64 GB. **NetApp MAX Data configuration:** one node, two sockets, Intel Server Board S2600WFT, Intel Xeon Platinum 8280L processor (28 cores/socket, 2 sockets, 2 threads per core), 12 x 16 GB (192 GB total) 2,667 MHz DDR4 dual-rank ECC DRAM, 8 x 128 GB (1 TB total) Intel Optane PMem in a 2-2-1 configuration, Mellanox ConnectX-4 Lx (25 GbE, 1 port, connected to the target), storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 1 x 8 TB Intel SSD DC P4510 NVMe, remotely connected from the NVMe-oF TCP target, partitioned into four individual 1.6 TB partitions; operating system: Fedora 29, Linux kernel 5.2.8, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), Intel Optane PMem firmware: 01.02.00.5410, microcode: 05000017, running MySQL 8.0.16 with InnoDB storage engine, sysbench benchmark 1.0.17 (14 threads, 600 seconds runtime), and TPC-C-like workload ran with varying database sizes (100 GB–500 GB); Intel HT Technology off, Intel Turbo Boost Technology off; virtualization: QEMU/KVM 4.0.94 (v4.1.0-rc4) on NetApp MAX FS 1.5 file system; four guest VMs with 42 GB DRAM, 14 vCPUs each, CentOS 7.6, 225 GB fsdax mode, memory map Intel Optane PMem, 1.6 TB storage for database. InnoDB buffer pool size = 30 GB.

[5] MongoDB with the YCSB program suite: Based on testing by Intel on August 27, 2019. **XFS configuration:** one node, two sockets, Intel Server Board S2600WFT, Intel Xeon Gold 6252 processor (24 cores/socket, 2 sockets, 2 threads per core), 12 x 32 GB (384 GB total) 2,667 MHz DDR4 ECC DRAM, network: Mellanox ConnectX-4 Lx (25 GbE, 2 ports, connected to the target), storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: RAID 0 device remotely connected from the NVMe-oF TCP target, partitioned into 12 individual 630 GB partitions; operating system: Fedora 29, Linux kernel 5.2.8, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), microcode: 05000017, running MongoDB 4.2 WiredTiger, YCSB 0.15.0 workload run from separate host on XFS file system; Intel HT Technology on, Intel Turbo Boost Technology on; virtualization: QEMU/KVM 4.0.94 (v4.1.0-rc4); 4 guest VMs with 85 GB vDRAM, 24 vCPUs each, CentOS 7.6, 630 GB storage for database. Cache size = 64 GB. **NetApp MAX Data configuration:** one node, two sockets, Intel Server Board S2600WFT, Intel Xeon Gold 6252 processor (24 cores/socket, 2 sockets, 2 threads per core), 12 x 32 GB (384 GB total) 2,667 MHz DDR4 dual-rank ECC DRAM, 8 x 128 GB (1 TB total) Intel Optane PMem in a 2-2-1 configuration, Mellanox ConnectX-4 Lx (25 GbE, 2 ports, connected to the target), storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 1 x RAID 0 device remotely connected from the NVMe-oF TCP target, partitioned into 12 individual 630 GB partitions; operating system: Fedora 29, Linux kernel 5.2.8, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), Intel Optane PMem firmware: 01.02.00.5410, microcode: 05000017, running MongoDB 4.2 WiredTiger, YCSB 0.15.0 workload run from separate host; Intel HT Technology off, Intel Turbo Boost Technology off; virtualization: QEMU/KVM 4.0.94 (v4.1.0-rc4) on NetApp MAX FS 1.5 file system; 12 guest VMs with 28 GB vDRAM, 8 vCPUs each, CentOS 7.6, 70G fsdax mode, memory map Intel Optane PMem, 630 GB storage for database. Cache size = 16 GB.

[6] Oracle Database on bare metal with HammerDB benchmarking software: Based on testing by Intel on November 1, 2019. **XFS configuration:** Intel Server Board S2600WF, Intel Xeon Gold 6252 processor (24 cores/socket, 2 sockets, 2 threads per core), 12 x 32 (384 GB total) 2,667 MHz DDR4 ECC DRAM, storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 2 x 8 TB Intel SSD DC P4510 PCIe, RAID 0 (data) + 1 x 8 TB Intel SSD DC P4510 (redo); operating system: RHEL 7.6, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), microcode: 05000017, running Oracle Database 19c Enterprise Edition release 19.0.0.0.0—production version 19.3.0.0.0, HammerDB 3.2, database size = 1 TB on XFS file system. **NetApp MAX Data configuration:** Intel Server Board S2600WF, Intel Xeon Gold 6252 processor (24 cores/socket, 2 sockets, 2 threads per core), 12 x 32 (384 GB total) 2,667 MHz DDR4 dual-rank ECC DRAM, 8 x 128 GB (1 TB total) Intel Optane PMem in a 2-2-1 configuration, storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 2 x 8 TB Intel SSD DC P4510 PCIe (data) + 1 x 8 TB Intel SSD DC P4510 (redo); operating system: RHEL 7.6, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), Intel Optane PMem firmware: 01.02.00.5410, microcode: 05000017, running Oracle Database 19c Enterprise Edition release 19.0.0.0.0—production version 19.3.0.0.0, HammerDB 3.2, database size = 1 TB on NetApp MAX FS 1.5 file system.

[7] Oracle Database on virtualized environment with HammerDB benchmarking software: Based on testing by Intel on November 4, 2019. **XFS configuration:** Intel Server Board S2600WF, Intel Xeon Gold 6252 processor (24 cores/socket, 2 sockets, 2 threads per core), 12 x 32 (384 GB total) 2,667 MHz DDR4 ECC DRAM, network: dual-port Mellanox ConnectX-4 Lx (25 GbE, bonded), storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 2 x 8 TB Intel SSD DC P4510 PCIe, RAID 0 (data) + 1 x 8 TB Intel SSD DC P4510 (redo); operating system: Fedora 29, BIOS: WW26 (SE5C 620.86B.02.01.0008.031920191559), microcode: 05000017, running Oracle Database 19c Enterprise Edition release 19.0.0.0.0—production version 19.3.0.0.0, HammerDB 3.2, database size = 2 x 1 TB on XFS file system; virtualization: QEMU/KVM 4.0.94 (v4.1.0-rc4); 2 guest VMs with 160 GB vDRAM, 48 vCPUs each, CentOS 7.6, 4 TB storage for database. Database cache size = 100 GB. **NetApp MAX Data configuration:** Intel Server Board S2600WF, Intel Xeon Gold 6252 processor (24 cores/socket, 2 sockets, 2 threads per core), 12 x 32 (384 GB total) 2,667 MHz DDR4 dual-rank ECC DRAM, 8 x 128 GB (1 TB total) Intel Optane PMem in a 2-2-1 configuration, network: dual-port Mellanox ConnectX-4 Lx (25 GbE, bonded), storage: operating system: 1 x 1.6 TB Intel SSD DC S3610, database: 2 x 8 TB Intel SSD DC P4510 PCIe (data) + 1 x 8 TB Intel SSD DC P4510 (redo); operating system: Fedora 29, BIOS: WW26 (SE5C620.86B.02.01.0008.031920191559), Intel Optane PMem firmware: 01.02.00.5410, microcode: 05000017, running Oracle Database 19c Enterprise Edition release 19.0.0.0.0—production version 19.3.0.0.0, HammerDB 3.2, database size = 2 x 1 TB on NetApp MAX FS 1.5 file system; virtualization: QEMU/KVM 4.0.94 (v4.1.0-rc4); 2 guest VMs with 160 GB vDRAM, 48 vCPUs each, 1 TB Intel Optane PMem, CentOS 7.6, 4 TB storage for database. Database cache size = 100 GB.

[8] Measurements using FIO 3.1 with 70% read/30% write random accesses for SSDs: 4 KB accesses over the entire SSD with read latency measured per 4 KB access for Intel Optane PMem, 256 B random accesses over the entire module, with read latency measured per 64 B access. SSD performance results are based on Intel testing as of November 15, 2018. Configurations: Intel 2U Server System, CentOS 7.5, kernel 4.17.6-1. el7.x86_64, 2 x Intel Xeon Gold 6154 processor at 3.0 GHz (18 cores), 256 GB DDR4 DRAM at 2,666 MHz with 375 GB Intel Optane SSD DC P4800X and 3.2 TB Intel SSD DC P4610. Intel microcode: 0x2000043; system BIOS: 00.01.0013; Intel® Management Engine (Intel® ME) firmware: 04.00.04.294; baseboard management controller (BMC) firmware: 1.43.91f76955; FRUSDR: 1.43. Intel Optane PMem performance results are based on Intel testing on February 20, 2019. Configuration: 1 x Intel Xeon Scalable processor (28 cores), 256 GB Intel Optane PMem module, 32 GB DDR4 DRAM at 2,666 MHz, Intel Optane PMem firmware: 5,336, BIOS: 573.D10, WW08 BKC, running Linux OS 4.20.4-200. fc29. DRAM performance results are based on Intel testing on February 20, 2019. Configuration: 2 x Intel Xeon Scalable processor (28 cores), 6 x 32 GB DDR4 DRAM at 2,933 MHz, BIOS: 532.D14, running RHEL 7.2.

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