it's about time

Technical Whitepaper

Migrating a kdb+ HDB to Amazon EC2

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Contents

Migrating a kdb+ HDB to Amazon EC2 3
In-house vs EC2 5
Historical data layouts and performance testing 10
Data locality 12
Getting your data into EC2 13
Security of your data and secure access 15
Getting your data out of EC2 16
Storing your HDB in S3 17
Disaster recovery 22
Licensing kdb+ in the Cloud 23
Encryption 24
Benchmarking methodology 25
Observations from kdb+ testing 32
Network configuration 35
Appendix A - Elastic Block Store (EBS) 36
Appendix B – EFS (NFS) 45
Appendix C – Amazon Storage Gateway (File mode) 47
Appendix D – MapR-FS 49
Appendix E - Goofys 53
Appendix F - S3FS 55
Appendix G - S3QL 56
Appendix H - ObjectiveFS 57
Appendix I – WekaIO Matrix 61
Appendix J – Quobyte 66

Migrating a kdb+ HDB to Amazon EC2

Kx has an ongoing project of evaluating different cloud technologies to see how they interact with kdb+. If you are assessing migrating a kdb+ historical database (HDB) and analytics workloads into the Amazon Elastic Compute Cloud[1] (EC2), here are key considerations:

- performance and functionality attributes expected from using kdb+, and the associated HDB, in EC2
- capabilities of several storage solutions working in the EC2 environment, as of March 2018
- performance attributes of EC2, and benchmark results

You must weigh the pros and cons of each solution. The key issues of each approach are discussed in the Appendices. We highlight specific functional constraints of each solution.

We cover some of the in-house solutions supplied by Amazon Web Services (AWS), as well as a selection of some of the third-party solutions sold and supported for EC2, and a few open-source products. Most of these solutions are freely available for building and testing using Amazon Machine Images (AMI) found within the Amazon Marketplace.

Why Amazon EC2?

Gartner[2], and other sources such as Synergy Research[3], rank cloud-services providers:

1. Amazon Web Services
2. Microsoft Azure
3. Google Cloud Platform

This is partly due to the fact that Amazon was first to market, and partly because of their strong global data-center presence and rich sets of APIs and tools.

Amazon EC2 is one of many services available to AWS users, and is managed via the AWS console. EC2 is typically used to host public estates of Web and mobile-based applications. Many of these are ubiquitous and familiar to the public. EC2 forms a

1. https://aws.amazon.com/ec2/
2. http://fortune.com/2017/06/15/gartner-cloud-rankings/
3. https://www.srgresearch.com/articles/microsoft-google-and-ibm-charge-public-cloud-expense-smaller-providers

significant part of the 'Web 2.0/Semantic Web' applications available for mobile and desktop computing.

Kdb+ is a high-performance technology. It is often assumed the Cloud cannot provide a level of performance, storage and memory access commensurate with dedicated or custom hardware implementations. Porting to EC2 requires careful assessment of the functional performance constraints both in EC2 compute and in the supporting storage layers.

Kdb+ users are sensitive to database performance. Many have significant amounts of market data – sometimes hundreds of petabytes – hosted in data centers. Understanding the issues is critical to a successful migration.

Consider the following scenarios:

- Your internal IT data services team is moving from an in-house data center to a cloud-services offering. This could be in order to move the IT costs of the internal data center from a capital expense line to an operating expense line.

- You need your data analytics processing and/or storage capacity to be scaled up *instantly*, *on-demand*, and without the need to provide extra hardware in your own data center.

- You believe the Cloud may be ideal for burst processing of your compute load. For example, you may need to run 100s of cores for just 30 minutes in a day for a specific risk-calculation workload.

- Your quants and developers might want to work on kdb+, but only for a few hours in the day during the work week, a suitable model for an on-demand or a spot-pricing service.

- You want to drive warm backups of data from in-house to EC2, or across instances/regions in EC2 – spun up for backups, then shut down.

- Development/UAT/Prod life-cycles can be hosted on their own instances and then spun down after each phase finishes. Small memory/core instances can cost less and can be increased or decreased on demand.

Hosting both the compute workload and the historical market data on EC2 can achieve the best of both worlds:

- reduce overall costs for hosting the market data pool

- flex to the desired performance levels

As long as the speed of deployment and ease of use is coupled with similar or *good enough* runtime performance, EC2 can be a serious contender for hosting your market data.

In-house vs EC2

Kdb+ is used to support

- real-time data analytics
- streaming data analytics
- historical data analytics

The historical database in a kdb+ solution is typically kept on a non-volatile persistent storage medium (a.k.a. *disks*). In financial services this data is kept for research (quant analytics or back-testing), algorithmic trading and for regulatory and compliance requirements.

Low latency and the Cloud

In the current state of cloud infrastructure, Kx does not recommend keeping the high-performance, low-latency part of market data – or streaming data collection – applications in the Cloud.

When speed translates to competitive advantage, using AWS (or cloud in general) needs to be considered carefully.

Carefully-architected cloud solutions are acceptable for parts of the application that are removed from from the cutting-edge performance and data-capture requirements often imposed on kdb+. For example, using parallel transfers with a proven simple technology such as `rsync`, that can take advantage of the kdb+ data structures (distinct columns that can safely be transferred in parallel) and the innate compressibility of some of the data types to transfer data to historical storage in a cloud environment at end of day.

Storage and management of historical data can be a non-trivial undertaking for many organizations:

- capital and running costs
- overhead of maintaining security policies
- roles and technologies required
- planning for data growth and disaster recovery

AWS uses tried-and-tested infrastructure, which includes excellent policies and processes for handling such production issues.

Before we get to the analysis of the storage options, it is important to take a quick look at the performance you might expect from compute and memory in your EC2 instances.

CPU cores

We assume you require the same number of cores and memory quantities as you use on your in-house bare-metal servers. The chipset used by the instance of your choice will list the number of cores offered by that instance. The definition used by AWS to describe cores is vCPUs. It is important to note that with very few exceptions, the vCPU represents a hyper-threaded core, not a physical core. This is normally run at a ratio of 2 hyper-threaded cores to one physical core. There is no easy way to eliminate this setting. Some of the very large instances do deploy on two sockets. For example, `r4.16xlarge` uses two sockets.

If your sizing calculations depend on getting one q process to run only on one physical core and not share itself with other q processes, or threads, you need to either

- use CPU binding on q execution
- invalidate the execution on even, or odd, core counts

Or you can run on instances that have more vCPUs than there will be instances running. For the purposes of these benchmarks, we have focused our testing on single socket instances, with a limit of 16 vCPUs, meaning eight physical cores, thus:

```
[centos@nano-client1 ~]$ lscpu
Architecture: x86_64
CPU op-mode(s): 32-bit, 64-bit
Byte Order: Little Endian
CPU(s): 16
On-line CPU(s) list: 0-15
Thread(s) per core: 2
Core(s) per socket: 8
Socket(s): 1
NUMA node(s): 1
Vendor ID: GenuineIntel
CPU family: 6
Model: 79
Model name: Intel(R) Xeon(R) CPU E5-2686 v4 @ 2.30GHz
```

System memory

Memory sizes vary by the instance chosen.

Memory lost to hypervisor

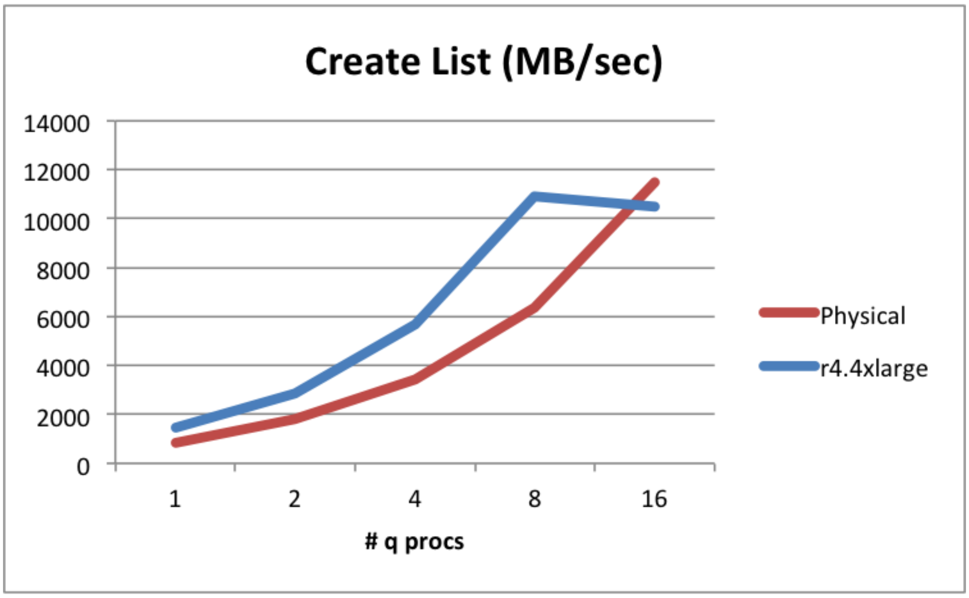
Memory is reduced from the nominal 'power of two' RAM sizing, as some is set aside for the Xen hypervisor. For example, a nominal 128 GB of RAM gets sized to approximately 120 GB.

Take account of this in your memory sizing exercises.

Compute and memory performance

For CPU and memory, the EC2 performance matches that seen on physical systems, when correlated to the memory specifications. So the default HVM mode of an AMI under Xen seems to work efficiently when compared to a native/physical server.

There is one caveat to this, in testing kdb+ list creation speeds we observe a degradation of memory list creation times when the number of q processes running exceeds the number of vCPUs in the virtual machine. This is because the vCPU in EC2 is actually a single hyperthreaded core, and not a physical core. In this example, we see competition on the physical cores. For a 16 vCPU instance we notice this only when running above 8 q processes:



Megabytes and mebibytes

Throughout this paper, MB and GB are used to refer to MiBytes[4] and GiBytes respectively.

4. https://en.wikipedia.org/wiki/Mebibyte

Network and storage performance

As expected, we see more noticeable performance variations with the aspects of the system that are virtualized and shared in EC2, especially those which in principle are shared amongst others on the platform. For kdb+ users, the storage (I/O) and the networking access are virtualized/shared, being separated from the bare metal by the Xen hypervisor. Most of the AMIs deployed into EC2 today are based on the Hardware Virtual Machine layer (HVM). It seems that in recent instantiations of HVM, the performance for I/O aspects of the guest have improved. For the best performance, AWS recommends current-generation instance types and HVM AMIs when you launch your instances. Any storage solution that hosts historical market data must:

- support the Linux-hosted POSIX file system[5] interfaces
- offer suitable performance for streaming and random I/O mapped read rates
- offer acceptable performance for random-region reads of a table (splayed) columns, constituting large record reads from random regions of the file

These aspects, and inspection of metadata performance, are summarized in the tests. The term *metadata* is used to refer to file operations such as listing files in a directory, gathering file size of a file, appending, finding modification dates, and so on.

Using Amazon S3 as a data store

Because kdb+ does not directly support the use of an object store for its stored data, it cannot support direct use of an object-store model such as the Amazon S3. If you wish to use Amazon S3 as a data store, kdb+ historical data must be hosted on a POSIX-based file system layer fronting S3.

Several solutions offer a POSIX interface layered over an underlying S3 storage bucket. These can be included alongside native file-system support that can also be hosted on EC2.

Although EC2 offers both physical systems and virtual systems within the Elastic Cloud, it is most likely customers will opt for a virtualized environment. There is also a choice in EC2 between spot pricing of an EC2, and deployed virtual instances. We focus here on the attribute and results achieved with the deployed virtual instance model. These are represented by instances that are tested in one availability zone and one placement group.

A *placement group* is a logical grouping of instances within a single availability zone. Nodes in a placement group should gain better network latency figures when compared to nodes scattered anywhere within an availability zone. Think of this as placement subnets or racks with a data center, as opposed to the datacenter itself. All of our tests use one placement group, unless otherwise stated.

5. https://en.wikipedia.org/wiki/POSIX

Kdb+ is supported on most mainstream Linux distributions, and by extension we support standard Linux distributions deployed under the AWS model.

Testing within this report was carried out typically on CentOS 7.3 or 7.4 distributions, but all other mainstream Linux distributions are expected to work equally well, with no noticeable performance differences seen in spot testing on RHEL, Ubuntu and SuSe running on EC2.

Does kdb+ work in the same way under EC2?

Yes – mostly.

When porting or hosting the HDB data to EC2, we expect our customers to:

1. Use one of the many POSIX-based file systems solutions available under EC2.
2. Use (partly or fully) the lower-cost object storage via a POSIX or POSIX-like access method.
3. Not store the historical data on Hadoop HDFS file systems.

If kdb+ runs alongside one of the solutions reviewed here, your HDB will function identically to any internally-hosted, bare-metal system. You can use this report as input to determine the performance and the relative costs for an HDB solution on EC2.

Historical data layouts and performance testing

The typical kdb+ database layout for a stock tick-based system is partitioned by date, although integer partitioning is also possible. Partitioning allows for quicker lookup and increases the ability to parallelize queries. Kdb+ splays in-memory table spaces into representative directories and files for long-term retention. Here is an example of an on-disk layout for quote and trade tables, with date partitions:

```
├── 2011.12.27/
│   ├── quote/
│   │   ├── .d
│   │   ├── asize
│   │   ├── ask
│   │   ├── bid
│   │   ├── bsize
│   │   ├── ex
│   │   ├── mode
│   │   ├── sym
│   │   └── time
│   └── trade/
│       ├── .d
│       ├── cond
│       ├── ex
│       ├── price
│       ├── size
│       ├── stop
│       ├── sym
│       └── time
└── 2011.12.29/
    ├── quote/
    │   ├── .d
    │   ├── asize
    │   ├── ask
    │   ├── bid
    │   ├── bsize
    │   ├── ex
    │   ├── mode
    │   ├── sym
    │   └── time
    └── trade/
        ├── .d
        ├── cond
        ├── ex
        ├── price
        ├── size
        ├── stop
        ├── sym
        └── time
```

On-disk layout for quote and trade tables with date partitions

Usually, updates to the HDB are made by writing today's or the last day's in-memory columns of data to a new HDB partition. Q programmers can use a utility built into q for this which creates the files and directories organized as in the table above. Kdb+ requires the support of a POSIX-compliant file system in order to access and process HDB data.

Kdb+ maps the entire HDB into the runtime address space of kdb+. This means the Linux kernel is responsible for fetching HDB data. If, for example, you are expecting a query that scans an entire day's trade price for a specific stock symbol range, the file system will load this data into the host memory as required. So, for porting this to EC2, if you expect it to match the performance you see on your in-house infrastructure you will need to look into the timing differences between this and EC2.

Our testing measured the time to load and unload data from arrays, ignoring the details of structuring columns, partitions and segments – we focused on just the raw throughput measurements.

All of these measurements will directly correlate to the final operational latencies for your full analytics use-case, written in q. In other words, if a solution reported here shows throughput of 100 MB/sec for solution A, and shows 200 MB/sec for solution B, this will reflect the difference in time to complete the data fetch from backing store. Of course, as with any solution, you get what you pay for, but the interesting question is: how much more could you get within the constraints of one solution?

To give an example: assuming a retrieval on solution A takes 50 ms for a query comprised of 10 ms to compute against the data, and 40 ms to fetch the data, with half the throughput rates, it might take 90 ms (10+80) to complete on solution B. Variations may be seen depending on metadata and random read values.

This is especially important for solutions that use networked file systems to access a single namespace that contains your HDB. This may well exhibit a significantly different behavior when run at scale.

Data locality

Data locality is the basic architectural decision.

You will get the best storage performance in EC2 by localizing the data to be as close to the compute workload as is possible.

EC2 is divided into various zones. Compute, storage and support software can all be placed in pre-defined availability zones. Typically these reflect the timezone location of the data center, as well as a further subdivision into a physical instance of the data center within one region or time zone. Kdb+ will achieve the lowest latency and highest bandwidth in the network by using nodes and storage hosted in the same availability zone.

Getting your data into EC2

Let's suppose you already have a lot of data for your historical database (HDB). You will need to know the achievable bandwidth for data loading, and note that you will be charged by the amount of data ingested. The mechanics of loading a large data set from your data center which hosts the HDB into EC2 involves the use of at least one of the two methods described below.

EC2 Virtual Private Cloud

We would expect kdb+ customers to use the EC2 Virtual Private Cloud (VPC) network structure. Within the VPC you can use either an anonymous IP address, using EC2 DHCP address ranges, or a permanently-allocated IP address range. The anonymous DHCP IP address range is free of charge. Typically you would deploy both the front and backend domains (subnets) within the same VPC, provisioned and associated with each new instance in EC2. Typically, an entire VPC allocates an entire class-C subnet. You may provision up to 200 class-C subnets in EC2, as one account. Public IP addresses are reachable from the internet and are either dynamically allocated on start, or use the same pre-defined elastic IP address on each start of the instance.

Private IP addresses refer to the locally defined IP addresses only visible to your cluster (e.g. the front/backend in diagram below). Private IP addresses are retained by that instance until the instance is terminated. Public access may be direct to either of these domains, or you may prefer to set up a classic ' 'demilitarized zone' ' for kdb+ access.

An elastic IP address is usually your public IPv4 address, known to your quants/users/applications, and is reachable from the Internet and registered permanently in DNS, until you terminate the instance or elastic IP. AWS has added support for IPv6 in most of their regions. An elastic IP address can mask the failure of an instance or software by remapping the address to another instance in your estate. That is handy for things such as GUIs and dashboards, though you should be aware of this capability and use it. You are charged for the elastic IP address if you close down the instance associated with it, otherwise one IP address is free when associated. As of January 2018 the cost is, $0.12 per Elastic IP address/day when not associated with a running instance. Additional IP addresses per instance are charged.

Ingesting data can be via the public/elastic IP address. In this case, routing to that connection is via undefined routers. The ingest rate to this instance using this elastic IP address would depend on the availability zone chosen. But in all cases, this would be a shared pubic routed IP model, so transfer rates may be outside your control.

In theory this uses publicly routed connections, so you may wish to consider encryption of the data over the wire, prior to decryption.

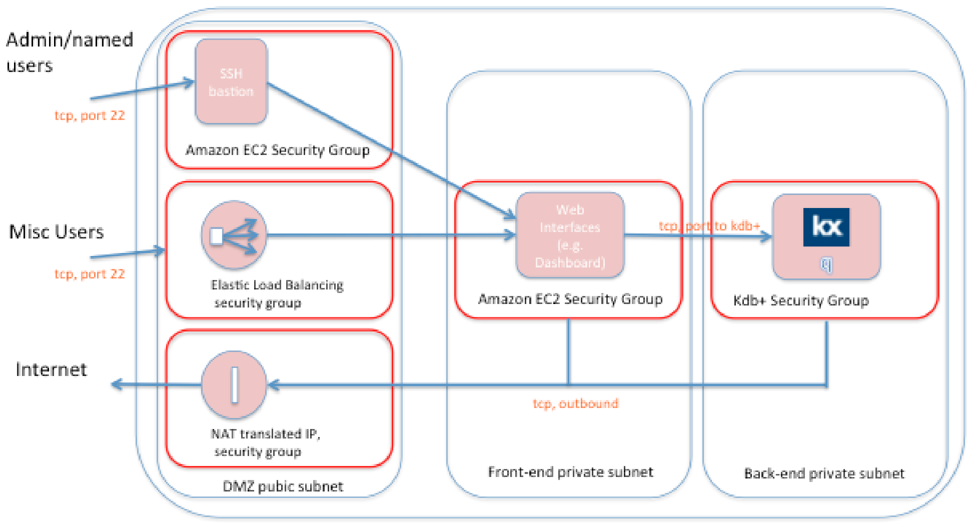
Direct Connect

Direct Connect is a dedicated network connection between an access point to your existing IP network and one of the AWS Direct Connect locations. This is a dedicated physical connection offered as a VLAN, using industry standard 802.1q VLAN protocol. You can use AWS Direct Connect instead of establishing your own VPN connection over the internet to VPC. Specifically, it can connect through to a VPC domain using a private IP space. It also gives a dedicated service level for bandwidth. There is an additional charge for this service.

Security of your data and secure access

The EC2 application machine image model (AMI) has tight security models in place. You would have to work very hard to remove these.

The following diagram is a typical scenario for authenticating access to kdb+ and restricting networking access. The frontend and backend private subnets are provisioned by default with one Virtual Private Cloud (VPC) managed by EC2. Typically, this allocates an entire class-C subnet. You may provision up to 200 class-C subnets in EC2. The public access may be direct to either of these domains, or you may prefer to setup a classic 'demilitarized zone' :



Typical scenario for authenticating access

Amazon has spent a lot of time developing security features for EC2[7]. Key issues:

- A newly-provisioned node comes from a trusted build image, for example, one found in the AWS Marketplace.
- The Amazon Linux AMI Security Center provides patch and fix lists, and these can be automatically inlaid by the AMI. The Amazon Linux AMI is a supported and maintained Linux image provided by AWS for use on EC2.
- Encryption at rest is offered by many of the storage interfaces covered in this report.

Amazon Security[8]

7. https://aws.amazon.com/security/

8. https://aws.amazon.com/blogs/security/

Getting your data out of EC2

Storing billions and billions of records under kdb+ in EC2 is easily achievable. Pushing the data into EC2 can be easily done and in doing so incurs no data transfer charges from AWS. But AWS will charge you to extract this information from EC2. For example, network charges may apply if you wish to extract data to place into other visualization tools/GUIs, outside the domain of kdb+ toolsets.

Replication

Or you may be replicating data from one region or availability zone, to another. For this, there is a cost involved. At time of writing, the charges are $.09/GB ($92/TB), or $94,200 for 1 PB transferred out to the Internet via EC2 public IP addresses. That is raw throughput measurements, not the raw GBs of kdb+ columnar data itself. This is billed by AWS at a pro-rated monthly rate. The rate declines as the amount of data transferred increases. This rate also applies for all general traffic over a VPN to your own data center. Note that normal Internet connections carry no specific service-level agreements for bandwidth.

Network Direct

If you use the Network Direct option from EC2, you get a dedicated network with guaranteed bandwidth. You then pay for the dedicated link, plus the same outbound data transfer rates. For example, as of January 2018 the standard charge for a dedicated 1 GB/sec link to EC2 would cost $220/month plus $90/month for a transfer fee per TB.

Consider these costs when planning to replicate HDB data between regions, and when exporting your data continually back to your own data center for visualization or other purposes. Consider the migration of these tools to coexist with kdb+ in the AWS estate, and if you do not, consider the time to export the data.

Storing your HDB in S3

S3 might be something you are seriously considering for storage of some, or all, of your HDB data in EC2. Here is how S3 fits into the landscape of all of the storage options in EC2.

Locally-attached drives

You can store your HDB on locally-attached drives, as you might do today on your own physical hardware on your own premises.

EC2 offers the capability of bringing up an instance with internal NVMe or SAS/SATA disk drives, although this is not expected to be used for anything other than caching data, as this storage is referred to as ephemeral data by AWS, and might not persist after system shutdowns. This is due to the on-demand nature of the compute instances: they could be instantiated on any available hardware within the availability zone selected by your instance configuration.

EBS volumes

You can store your HDB on EBS volumes[9]. These appear like persistent block-level storage. Because the EC2 instances are virtualized, the storage is separated at birth from all compute instances.

By doing this, it allows you to start instances on demand, without the need to co-locate the HDB data alongside those nodes. This separation is always via the networking infrastructure built into EC2. In other words, your virtualized compute instance can be attached to a real physical instance of the storage via the EC2 network, and thereafter appears as block storage. This is referred to as *network attached storage* (Elastic Block Storage).

Alternatively, you can place the files on a remote independent file system, which in turn is typically supported by EC2 instances stored on EBS or S3.

Amazon S3 object store

Finally, there is the ubiquitous Amazon S3 object store, available in all regions and zones of EC2. Amazon uses S3 to run its own global network of websites, and many high-visibility web-based services store their key data under S3. With S3 you can create and deploy your HDB data in buckets of S3 objects.

9. http://docs.aws.amazon.com/AWSEC2/latest/UserGuide/RootDeviceStorage.html

- *Storage prices* are lower (as of January 2018): typically 10% of the costs of the Amazon EBS model.
- S3 can be configured to offer *redundancy and replication* of object data, regionally and globally.

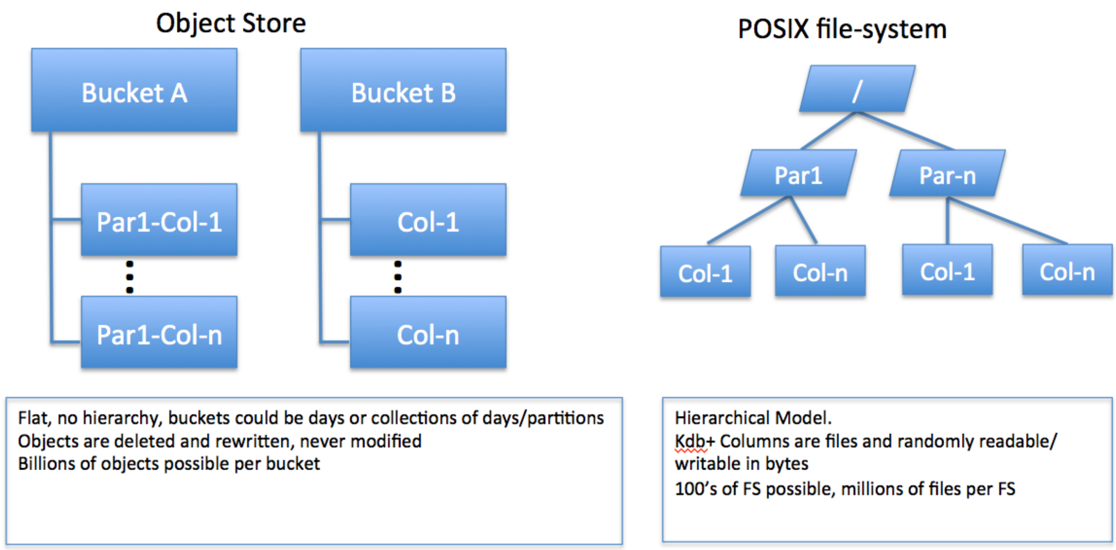
Amazon can be configured to duplicate your uploaded data across multiple geographically diverse repositories, according to the replication service selected at bucket-creation time. S3 promises 99.999999999%[10] durability.

🌐 AWS S3 replication[11]

However, there are severe limitations on using S3 when it comes to kdb+. The main limitation is the API.

API limitations

An S3 object store is organized differently from a POSIX file system.



S3 uses a web-style RESTful interface[13] HTTP-style interface with eventual-consistency[14] semantics of put and change. This will always represent an additional level of abstraction for an application like kdb+ that directly manages its virtual memory. S3 therefore exhibits slower per–process/thread performance than is usual for kdb+. The lack of POSIX interface and the semantics of RESTful interfaces prevents kdb+ and other high-performance databases from using S3 directly.

10. https://aws.amazon.com/s3/faqs/

11. https://docs.aws.amazon.com/AmazonS3/latest/dev/crr.html

13. https://en.m.wikipedia.org/wiki/Representational_state_transfer

14. https://en.wikipedia.org/wiki/Eventual_consistency

However, S3's low cost, and its ability to scale performance horizontally when additional kdb+ instances use the same S3 buckets, make it a candidate for some customers.

Performance limitations

The second limitation is S3's performance, as measured by the time taken to populate vectors in memory.

Kdb+ uses POSIX file-system semantics to manage HDB structure directly on disk. It exploits this feature to gain very high-performance memory management through Linux-based memory mapping functions built into the kernel, from the very inception of Linux.

S3 uses none of this.

On EC2, kdb+ performance stacks up in this order (from slowest to faster):

1. S3
2. EBS
3. Third-party distributed or managed file system
4. Local drives to the instance (typically cache only)

Although the performance of S3 as measured from one node is not fast, S3 retains comparative performance for each new instance added to an HDB workload in each availability zone. Because of this, S3 can scale up its throughput when used across multiple nodes within one availability zone. This is useful if you are positioning large numbers of business functions against common sets of market data, or if you are widely distributing the workload of a single set of business queries. This is not so for EBS as, when deployed, the storage becomes owned by one, and only one, instance at a time.

Replication limitations

A nice feature of S3 is its built-in replication model between regions and/or time zones.

Note you have to choose a replication option; none is chosen by default.

The replication process may well duplicate incorrect behavior from one region to another. In other words, this is not a backup.

However, the data at the replica site can be used for production purposes, if required. Replication is only for cross-region propagation (e.g. US-East to US-West). But, given that the kdb+ user can design this into the solution (i.e. end-of-day copies to replica sites, or multiple pub-sub systems), you may choose to deploy a custom solution within kdb+, across region, rather than relying on S3 or the file system itself.

Summary

- The *POSIX file system interface* allows the Linux kernel to move data from the blocks of the underlying physical hardware, directly into memory mapped space of the user process. This concept has been tuned and honed by over 20 years of Linux kernel refinement. In our case, the recipient user process is kdb+. S3, by comparison, requires the application to bind to an HTTP-based RESTful (get, wait, receive) protocol, which is typically transferred over TCP/IP LAN or WAN connection. Clearly, this is not directly suitable for a high-performance in-memory analytics engine such as kdb+. However, all of the file-system plug-ins and middleware packages reviewed in this paper help mitigate this issue. The appendices list the main comparisons of all of the reviewed solutions.

- Neither Kdb+, nor any other high-performance database, makes use of the *RESTful object-store interface*.

- There is no notion of *vectors, lists, memory mapping* or optimized placement of objects in memory regions.

- S3 employs an *eventual-consistency* model, meaning there is no guaranteed service time for placement of the object, or replication of the object, for access by other processes or threads.

- S3 exhibits relatively low *streaming-read performance*. A RESTful, single S3 reader process is limited to a read throughput[15] of circa 0.07 GB/sec. Some of the solutions reviewed in this paper use strategies to improve these numbers within one instance (e.g. raising that figure to the 100s MB/sec – GB/sec range). There is also throughput scalability gained by reading the same bucket across multiple nodes. There is no theoretical limit on this bandwidth, but this has not been exhaustively tested by Kx.

- Certain *metadata operations*, such as kdb+'s append function, cause significant latency vs that observed on EBS or local attached storage, and your mileage depends on the file system under review.

Performance enhancements, some of which are bundled into *third-party solutions* that layer between S3 and the POSIX file system layer, are based around a combination of: multithreading read requests to the S3 bucket; separation of large sequential regions of a file into individual objects within the bucket and read-ahead and caching strategies.

There are some areas of synergy. Kdb+ HDB data typically stores billions and billions of time-series entries in an immutable read-only mode. Only updated new data that lands in the HDB needs to be written. S3 is a shared nothing[16] model. Therefore, splitting a single segment or partitioned column of data into one file, which in turn is segmented into a few objects of say 1 MB, should be a lightweight operation, as

15. http://blog.zachbjornson.com/2015/12/29/cloud-storage-performance.html

16. https://en.wikipedia.org/wiki/Shared-nothing_architecture

there is no shared/locking required for previously written HDB data. So the HDB can easily tolerate this eventual consistency model. This does not apply to all use-cases for kdb+. For example, S3, with or without a file system layer, cannot be used to store a reliable ticker-plant log.

Where S3 definitely plays to its strengths, is that it can be considered for an *off-line deep archive* of your kdb+ formatted market data.

Kx does not make recommendations with respect to the merits, or otherwise, of storing kdb+ HDB market data in a data retention type 'WORM' model, as required by the regulations SEC 17-a4[17].

17. https://en.wikipedia.org/wiki/SEC_Rule_17a-4

Disaster recovery

In addition to EC2's built-in disaster-recovery features, when you use kdb+ on EC2, your disaster recovery process is eased by kdb+'s simple, elegant design.

Kdb+ databases are stored as a series of files and directories on disk. This makes administering databases extremely easy because database files can be manipulated as operating-system files. Backing up a kdb+ database can be implemented using any standard file-system backup utility. This is a key difference from traditional databases, which have to have their own cumbersome backup utilities and do not allow direct access to the database files and structure.

Kdb+'s use of the native file system is also reflected in the way it uses standard operating-system features for accessing data (memory-mapped files), whereas traditional databases use proprietary techniques in an effort to speed up the reading and writing processes. The typical kdb+ database layout for time-series data is to partition by date.

Licensing kdb+ in the Cloud

Existing kdb+ users have a couple of options for supporting their kdb+ licenses in the Cloud:

Existing license

You can use your existing license entitlement but must transfer or register coverage in the Cloud service. This would consume the specified number of cores from your license pool. An enterprise license can be freely used in EC2 instance(s). This might apply in the situation where the Cloud environment is intended to be a permanent static instance. Typically, this will be associated with a virtual private cloud (VPC) service. For example, AWS lets you provision a logically isolated section of the Cloud where you can launch AWS resources in a virtual network. The virtual network is controlled by your business, including the choice of IP, subnet, DNS, names, security, access, etc.

On-demand licensing

You can sign up for an on-demand license, and use it to enable kdb+ on each of the on-demand EC2 nodes. Kdb+ on-demand usage registers by core and by minutes of execution.

Encryption

Consider the need for access to any keys used to encrypt and store data. Although this is not specific to AWS, do not assume you have automatic rights to private keys employed to encrypt the data.

Where a third-party provider supplies or uses encryption or compression to store the market data on S3, you will need to check the public and private keys are either made available to you, or held by some form of external service.

Benchmarking methodology

For testing raw storage performance, we used a lightweight test script developed by Kx, called `nano`, based on the script `io.q` written by Kx's Chief Customer Officer, Simon Garland. The scripts used for this benchmarking are freely available for use and are published on Github at KxSystems/nano[18]

These sets of scripts are designed to focus on the relative performance of distinct I/O functions typically expected by a HDB. The measurements are taken from the perspective of the primitive IO operations, namely:

test	*what happens*
Streaming reads	One list (e.g. one column) is read sequentially into memory. We read the entire space of the list into RAM, and the list is memory-mapped into the address space of kdb+.
Large Random Reads (one mapped read and map/unmapped)	100 random-region reads of 1 MB of a single column of data are indexed and fetched into memory. Both single mappings into memory, and individual map/fetch/unmap sequences. Mapped reads are triggered by a page fault from the kernel into `mmap`'d user space of kdb+. This is representative of a query that requires to read through 100 large regions of a column of data for one or more dates (partitions).
Small Random Reads (mapped/unmapped sequences)	1600 random-region reads of 64 KB of a single column of data are indexed and fetched into memory. Both single mappings into memory, and individual map/fetch/unmap sequences. Reads are triggered by a page fault from the kernel into `mmap`'d user space of kdb+. We run both fully-mapped tests and tests with map/unmap sequences for each read.
Write	Write rate is of less interest for this testing, but is reported nonetheless.
Metadata: (`hclose hopen`)	Average time for a typical open/seek to end/close loop. Used by TP log as an 'append to' and whenever the database is being checked. Can be used to append data to an existing HDB column.
Metadata: (`();,;2 3)`	Append data to a modest list of 128 KB, will open/stat/seek/write/close. Similar to ticker plant write down.
Metadata: (`();:;2 3)`	Assign bytes to a list of 128 KB, stat/seek/write/link. Similar to initial creation of a column.
Metadata: (`hcount`)	Typical open/stat/close sequence on a modest list of 128 KB. Determine size. e.g. included in `read1`.
Metadata: (`read1`)	An atomic mapped map/read/unmap sequence open/stat/seek/read/close sequence. Test on a modest list of 128 KB.

This test suite ensures we cover several of the operational tasks undertaken during an HDB lifecycle.

For example, one broad comparison between direct-attached storage and a networked/shared file system is that the networked file-system timings might reflect

18. https://github.com/KxSystems/nano

higher operational overheads vs. a Linux kernel block-based direct file system. Note that a shared file system will scale up in-line with the implementation of horizontally distributed compute, which the block file systems will not easily do, if at all. Also note the networked file system may be able to leverage 100s or 1000s of storage targets, meaning it can sustain high levels of throughput even for a single reader thread.

Baseline result – using a physical server

All the appendices refer to tests on AWS.

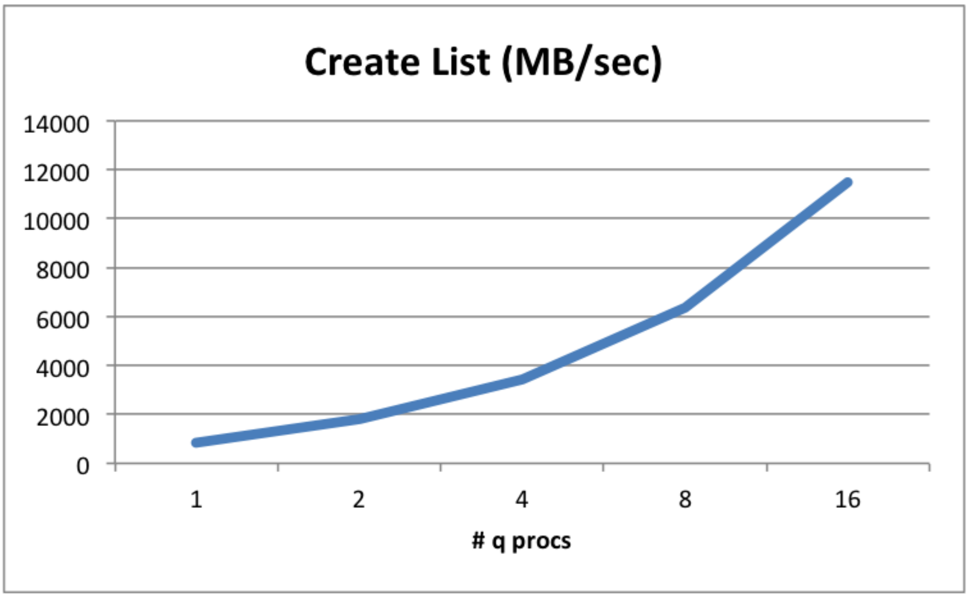
To see how EC2 nodes compare to a physical server, we show the results of running the same set of benchmarks on a server running natively, bare metal, instead of on a virtualized server on the Cloud.

For the physical server, we benchmarked a two-socket Broadwell E5-2620 v4 @ 2.10 GHz; 128 GB DDR4 2133 MHz. This used one Micron PCIe NVMe drive, with CentOS 7.3. For the block device settings, we set the device read-ahead settings to 32 KB and the queue depths to 64. It is important to note this is just a reference point and not a full solution for a typical HDB. This is because the number of target drives at your disposal here will limited by the number of slots in the server.

Highlights:

Creating a memory list

The MB/sec that can be laid out in a simple list allocation/creation in kdb+. Here we create a list of longs of approximately half the size of available RAM in the server.

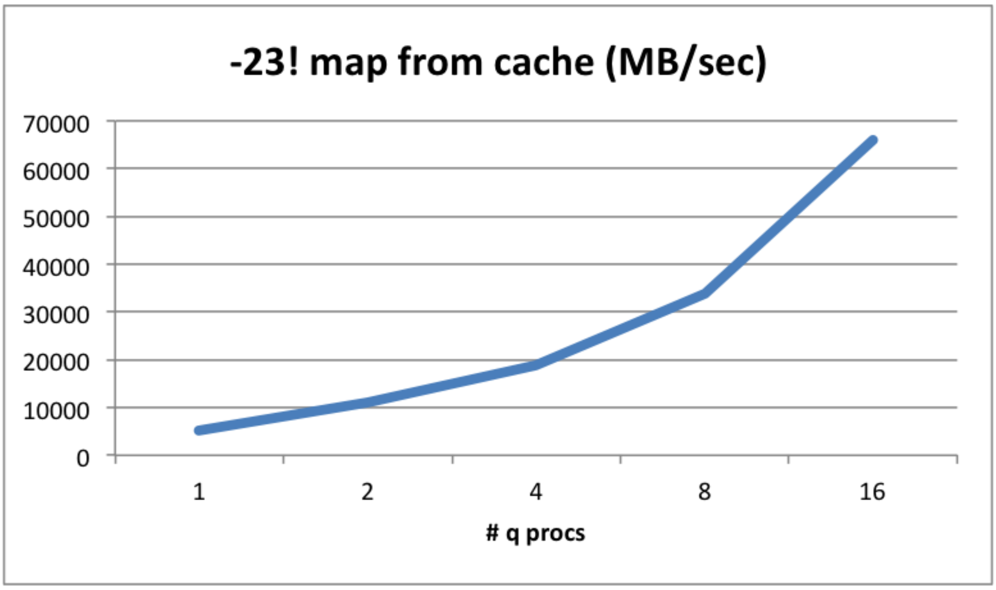


Creating a memory list

Shows the capability of the server when laying out lists in memory; reflects the combination of memory speeds alongside the CPU.

Re-read from cache

The MB/sec that can be re-read when the data is already held by the kernel buffer cache (or file-system cache, if kernel buffer not used). It includes the time to map the pages back into the memory space of kdb+ as we effectively restart the instance here without flushing the buffer cache or file system cache.

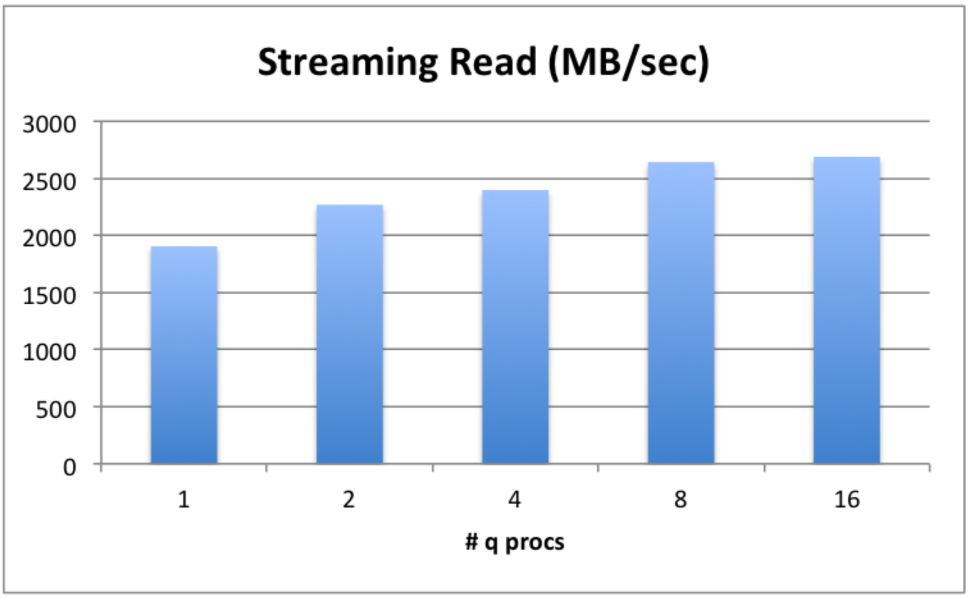


Re-read from cache

Shows if there are any unexpected glitches with the file-system caching subsystem. This may not affect your product kdb+ code per-se, but may be of interest in your research.

Streaming reads

Where complex queries demand wide time periods or symbol ranges. An example of this might be a VWAP trading calculation. These types of queries are most impacted by the throughput rate i.e., the slower the rate, the higher the query wait time.



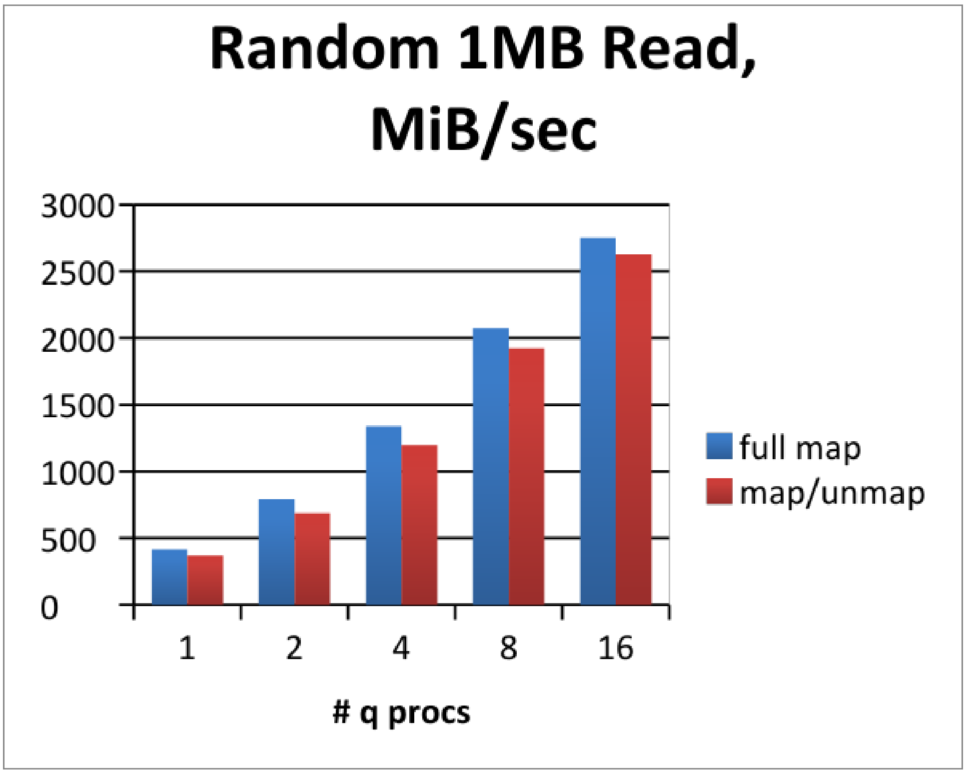
Streaming reads

Shows that a single q process can ingest at 1900 MB/sec with data hosted on a single drive, into kdb+'s memory space, mapped. Theoretical maximum for the device is approximately 2800 MB/sec and we achieve 2689 MB/sec. Note that with 16 reader processes, this throughput continues to scale up to the device limit, meaning kdb+ can drive the device harder, as more processes are added.

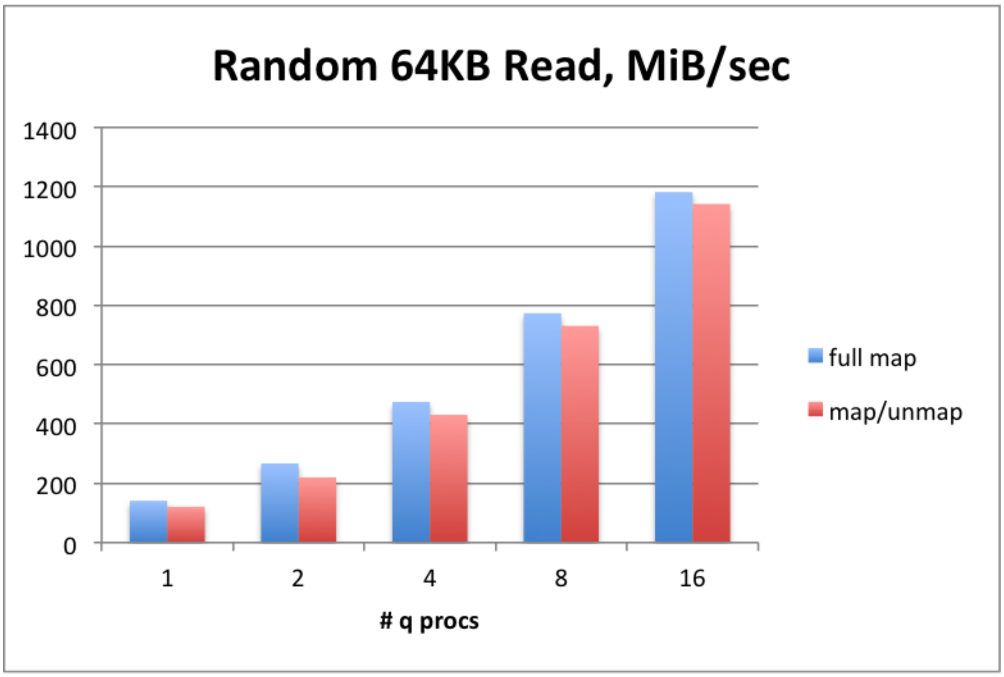
Random reads

We compare the throughputs for random 1 MB-sized reads. This simulates more precise data queries spanning smaller periods of time or symbol ranges.

In all random-read benchmarks, the term *full map* refers to reading pages from the storage target straight into regions of memory that are pre-mapped.



Random 1 MB read



Random 64 KB reads

Simulates queries that are searching around broadly different times or symbol regions. This shows that a typical NVMe device under kdb+ trends very well when we are reading smaller/random regions one or more columns at the same time. This shows that the device actually gets similar throughput when under high parallel load as threads increase, meaning more requests are queuing to the device and the latency per request sustains.

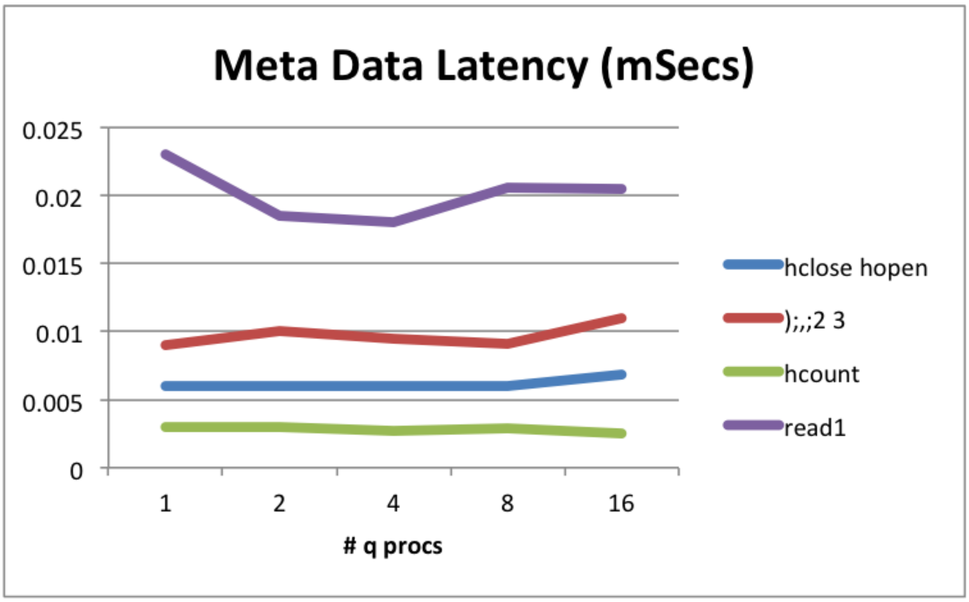
Metadata function response times

We also look at metadata function response times for the file system. In the baseline results below, you can see what a theoretical lowest figure might be.

We deliberately did not run metadata tests using very large data sets/files, so that they better represent just the overhead of the file system, the Linux kernel and target device.

function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.006	`();,;2 3`	0.01
`hcount`	0.003	`read1`	0.022

Physical server, metadata operational latencies - mSecs (headlines)



Metadata latency

This appears to be sustained for multiple q processes, and on the whole is below the multiple µSecs range. Kdb+ sustains good metrics.

AWS instance local SSD/NVMe

We separate this specific test from other storage tests, as these devices are contained within the EC2 instance itself, unlike every other solution reviewed in ‘Appendix A’ . Note that some of the solutions reviewed in the appendixes do actually leverage instances containing these devices.

An instance-local store provides temporary block-level storage for your instance. This storage is located on disks that are physically attached to the host computer.

This is available in a few predefined regions (e.g. US-East-1), and for a selected list of specific instances. In each case, the instance local storage is provisioned for you when created and started. The size and quantity of drives is preordained and fixed in both size and quantity. This differs from EBS, where you can select your own.

For this test we selected the `i3.8xlarge` as the instance under test. `i3` instance definitions will provision local NVMe or SATA SSD drives for local attached storage, without the need for networked EBS.

Locally provisioned SSD and NVMe are supported by kdb+. The results from these two represent the highest performance per device available for read rates from any non-volatile storage in EC2.

However, note that this data is ephemeral. That is, whenever you stop an instance, EC2 is at liberty to reassign that space to another instance and it will scrub the original data. When the instance is restarted, the storage will be available but scrubbed. This is because the instance is physically associated with the drives, and you do not know where the physical instance will be assigned at start time. The only exception to this is if the instance crashes or reboots without an operational stop of the instance, then the same storage will recur on the same instance.

The cost of instance-local SSD is embedded in the fixed price of the instance, so this pricing model needs to be considered. By contrast, the cost of EBS is fixed per GB per month, pro-rated. The data held on instance local SSD is not natively sharable. If this needs to be shared, this will require a shared file-system to be layered on top, i.e. demoting this node to be a file system server node. For the above reasons, these storage types have been used by solutions such as 'WekaIO' , for their local instance of the erasure coded data cache.

function	*instance-local NVMe (4 × 1.9 TB)*	*physical node (1 NVMe)*
streaming read (MB/sec)	7006	2624
random 1-MB read (MB/sec)	6422	2750
random 64-KB read (MB/sec)	1493	1182
metadata (`hclose`, `hopen`)	0.0038 mSec	0.0068 mSec

The variation of absolute streaming rates is reflective of the device itself. These results are equivalent to the results seen on physical servers. What is interesting is that at high parallelism, the targets work quicker with random reads and for metadata service times than the physical server. These instances can be deployed as a high-performance persistent cache for some of the AWS-based file system solutions, such as used in ObjectiveFS and WekaIO Matrix and Quobyte.

Observations from kdb+ testing

CPU and memory speed

For CPU and memory speed/latencies with kdb+, EC2 compute nodes performance for CPU/memory mirrors the capability of logically equivalent bare-metal servers. At time of writing, your main decision here is the selection of system instance. CPUs range from older generation Intel up to Haswell and Broadwell, and from 1 core up to 128 vcores (vCPU). Memory ranges from 1 GB up to 1952 GB RAM.

Storage performance

The best storage performance was, as expected, achieved with locally-attached ephemeral NVMe storage. This matched, or exceeded, EBS as that storage is virtualized and will have higher latency figures. As data kept on this device cannot be easily shared, we anticipate this being considered for a super cache for hot data (recent dates). Data stored here would have to be replicated at some point as this data could be lost if the instance is shut down by the operator.

Wire speeds

Kdb+ reaches wire speeds on most streaming read tests to networked/shared storage, under kdb+, and in several cases we can reach wire speeds for random 1-MB reads using standard mapped reads into standard q abstractions, such as lists.

gp2 vs io1

EBS was tested for both `gp2` and its brethren the `io1` flash variation. Kdb+ achieved wire speed bandwidth for both of these. When used for larger capacities, we saw no significant advantages of `io1` for the HDB store use case, so the additional charges applied there need to be considered.

st1

EBS results for the `st1` devices (low cost traditional disk drives, lower cost per GB) show good (90th-percentile) results for streaming and random 1-MB reads, but, as expected, significantly slower results for random 64-KB and 1-MB reads, and 4× the latencies for metadata ops. Consider these as a good candidate for storing longer term, older HDB data to reduce costs for owned EBS storage.

ObjectiveFS and WekaIO Matrix

ObjectiveFS and WekaIO Matrix are commercial products that offer full operational functionality for the POSIX interface, when compared to open-source S3 gateway products. These can be used to store and read your data from/to S3 buckets.

WekaIO Matrix offers an erasure-encoded clustered file-system, which works by sharing out pieces of the data around each of the members of the Matrix cluster.

ObjectiveFS works between kdb+ and S3 with a per-instance buffer cache plus distributed eventual consistency. It also allows you to cache files locally in RAM cache and/or on ephemeral drives within the instance. Caching to locally provisioned drives is likely to be more attractive vs. caching to another RAM cache.

POSIX file systems

Standalone file systems such as MapR-FS and Quobyte support POSIX fully. Other distributed file systems designed from the offset to support POSIX should fare equally well, as to some degree, the networking infrastructure is consistent when measured within one availability zone or placement group. Although these file system services are encapsulated in the AWS marketplace as AMI's, you are obliged to run this estate alongside your HDB compute estate, as you would own and manage the HDB just the same as if it were in-house. Although the vendors supply AWS marketplace instances, you would own and running your own instances required for the file system.

WekaIO and Quobyte

WekaIO and Quobyte use a distributed file-system based on erasure-coding distribution of data amongst their quorum of nodes in the cluster. This may be appealing to customers wanting to provision the HDB data alongside the compute nodes. If, for example, you anticipate using eight or nine nodes in production these nodes could also be configured to fully own and manage the file system in a reliable way, and would not mandate the creation of distinct file-system services to be created in other AWS instances in the VPC.

What might not be immediately apparent is that for this style of product, they will scavenge at least one core on every participating node in order to run their erasure-coding algorithm most efficiently. This core will load at 100% CPU.

EFS and AWS Gateway

Avoid EFS[21] and AWS Gateway for HDB storage. They both exhibit very high latencies of operation in addition to the network-bandwidth constraints. They appear to impact further on the overall performance degradations seen in generic NFS builds in Linux.

---

21. http://docs.aws.amazon.com/efs/latest/ug/performance.html

This stems from the latency between a customer-owned S3 bucket (AWS Gateway), and an availability zone wide distribution of S3 buckets managed privately by AWS.

Open-source products

Although the open source products that front an S3 store (S3FS, S3QL and Goofys) do offer POSIX, they all fail to offer full POSIX semantics such as symbolic linking, hard linking and file locking. Although these may not be crucial for your use case, it needs consideration.

You might also want to avoid these, as performance of them is at best average, partly because they both employ user-level FUSE code for POSIX support.

Network configuration

The network configuration used in the tests:

The host build was CentOS 7.4, with Kernel 3.10.0-693.el7.x86_64. The ENS module was installed but not configured. The default instance used in these test reports was `r4.4xlarge`.

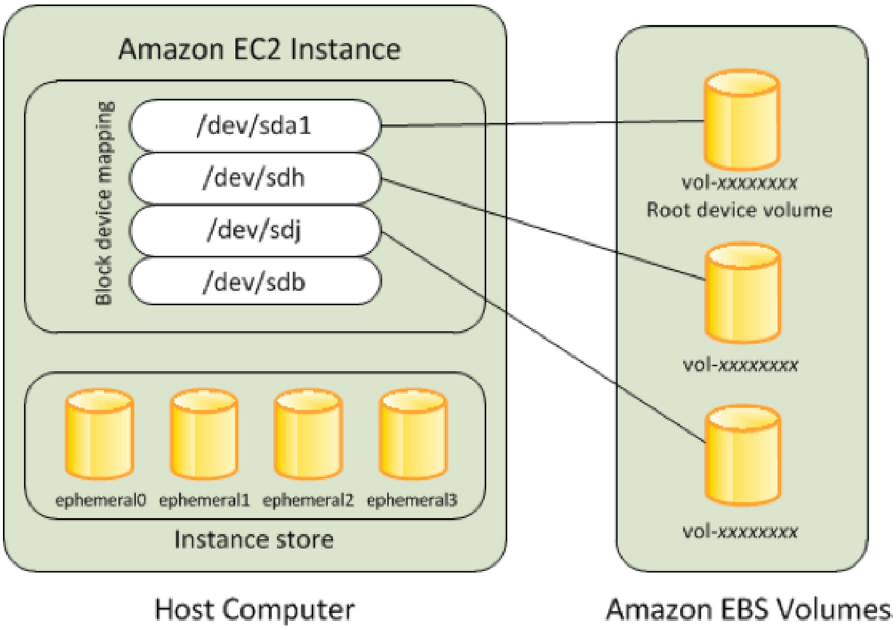
Total network bandwidth on this model is ‘up-to’ 10 Gbps.

For storage, this is documented by AWS as provisioning up to 3,500 Mbps, equivalent to 437 MB/sec of EBS bandwidth, per node, bi-directional. We met these discrete values as seen in most of our individual kdb+ tests.

Appendix A - Elastic Block Store (EBS)

> ⓘ **EBS can be used to store HDB data, and is fully compliant with kdb+.**
>
> It supports all of the POSIX semantics required.

Three variants of the Elastic Block Service[22] (EBS) are all qualified by kdb+: `gp2` and `io1` are both NAND Flash, but offer different price/performance points, and `st1` is comprised of traditional drives. Unlike ephemeral SSD storage, EBS-based storage can be dynamically provisioned to any other EC2 instance via operator control. So this is a candidate for on-demand HDB storage. Assign the storage to an instance in build scripts and then spin them up. (Ref: Amazon EBS)



Amazon EC2 instance

A disadvantage of EBS is that even if the data is read-only (immutable) a specific volume cannot be simultaneously mounted and shared between two or more EC2 instances. Furthermore, the elastic volume would have to be migrated from one instance ownership to another, either manually, or with launch scripts. EBS Snapshots can be used for regenerating an elastic volume to be copied across to other freshly created EBS volumes, which are subsequently shared around under EBS with a new instance being deployed on-demand.

22. http://docs.aws.amazon.com/AWSEC2/latest/UserGuide/RootDeviceStorage.html

Therefore, users of EBS or direct attach containing significant volumes of historical data, may need to replicate the data to avoid constraining it to just one node. You could also shard the data manually, perhaps thence accessing nodes attached via a kdb+ UI gateway.

EBS is carried over the local network within one availability zone. Between availability zones there would be IP L3 routing protocols involved in moving the data between zones, and so the latencies would be increased.

EBS may look like a disk, act like a disk, and walk like a disk, but it doesn't behave like a disk in the traditional sense.

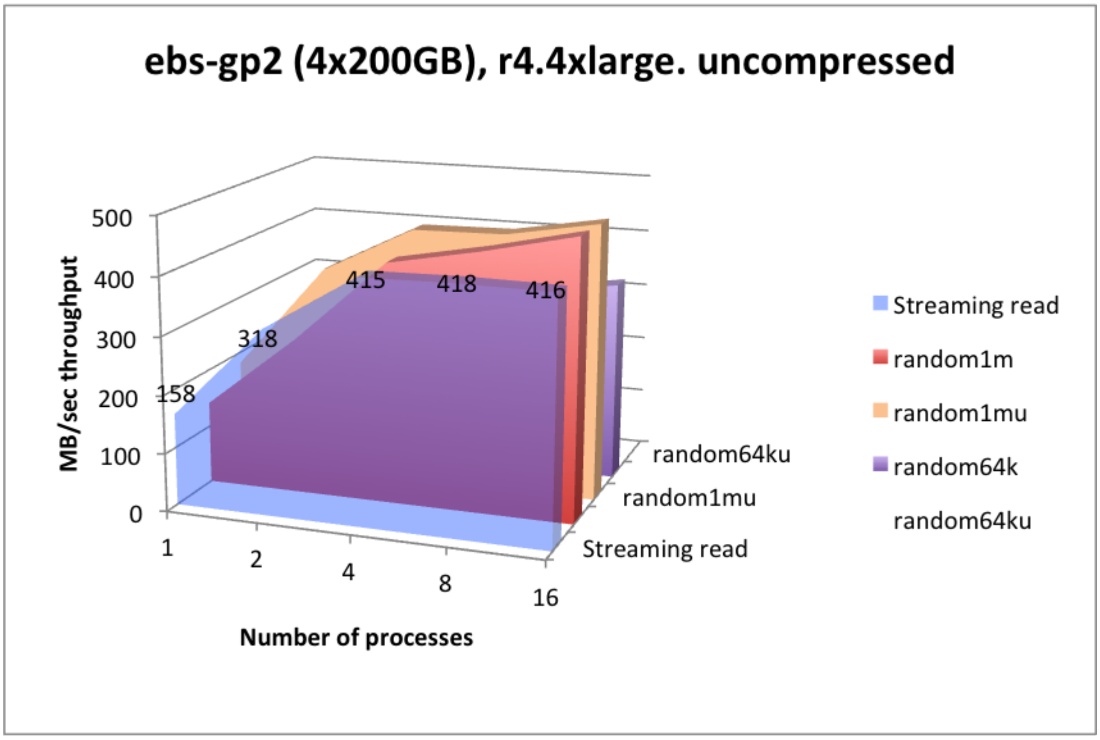
There are constraints on calculating the throughput gained from EBS:

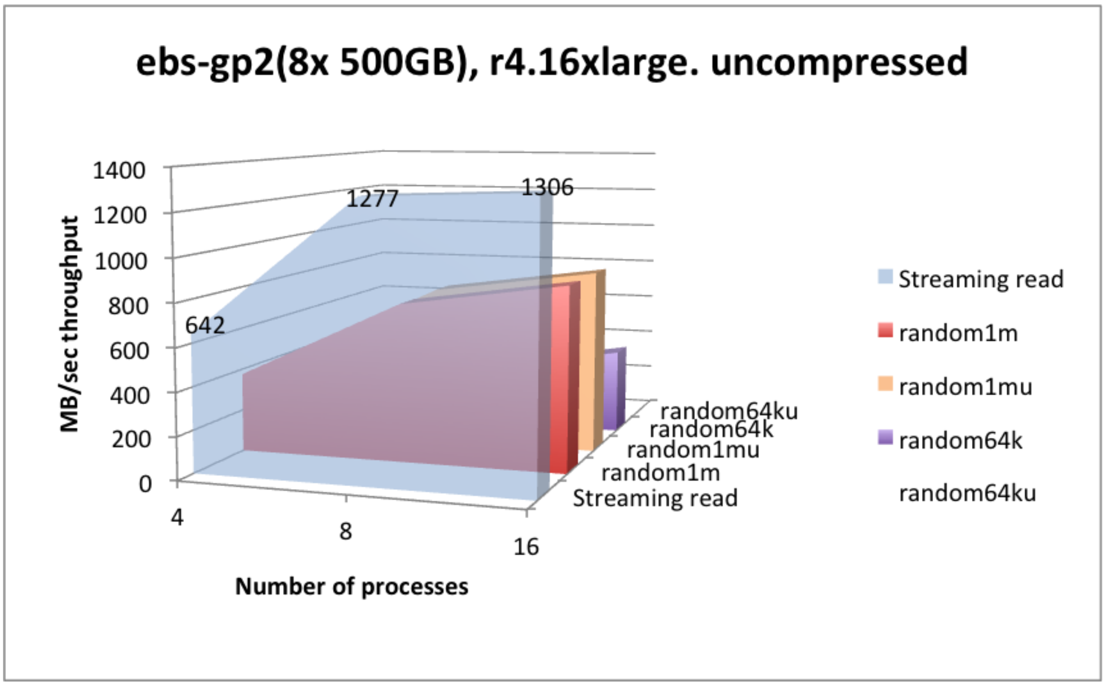
- There is a max throughput to/from each physical EBS volume. This is set to 500 MB/sec for io1 and 160 MB/sec for `gp2`. A `gp2` volume can range in size from 1 GB to 16 TB. You can use multiple volumes per instance (and we would expect to see that in place with a HDB).
- There is a further limit to the volume throughput applied, based on its size at creation time. For example, a GP2 volume provides a baseline rate of IOPs geared up from the size of the volume and calculated on the basis of 3 IOPs/per GB. For 200 GB of volume, we get 600 IOPS and @ 1 MB that exceeds the above number in (1), so the lower value would remain the cap. The burst peak IOPS figure is more meaningful for random, small reads of kdb+ data.
- For `gp2` volumes there is a burst level cap, but this increases as the volume gets larger. This burst level peaks at 1 TB, and is 3000 IOPS. that would be 384 MB/sec at 128 KB records, which, again is in excess of the cap of 160 MB/sec.
- There is a maximum network bandwidth per instance. In the case of the unit under test here we used `r4.4xlarge`, which constrains the throughput to the instance at 3500 Mbps, or a wire speed of 430 MB/sec, capped. This would be elevated with larger instances, up to a maximum value of 25 Gbps for a large instance, such as for `r4.16xlarge`.
- It is important note that EBS scaled linearly across an entire estate (e.g. parallel peach queries). There should be no constraints if you are accessing your data, splayed across different physical across distinct instances. e.g. 10 nodes of `r4.4xlarge` is capable of reading 4300 MB/sec.

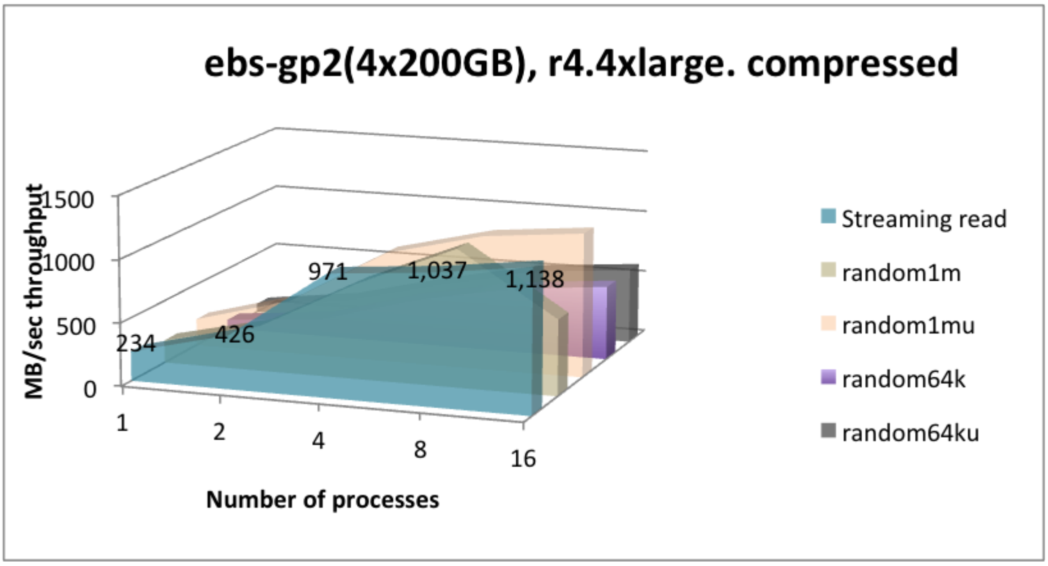
Kdb+ achieves or meets all of these advertised figures. So the EBS network bandwidth algorithms become the dominating factor in any final calculations for your environment.

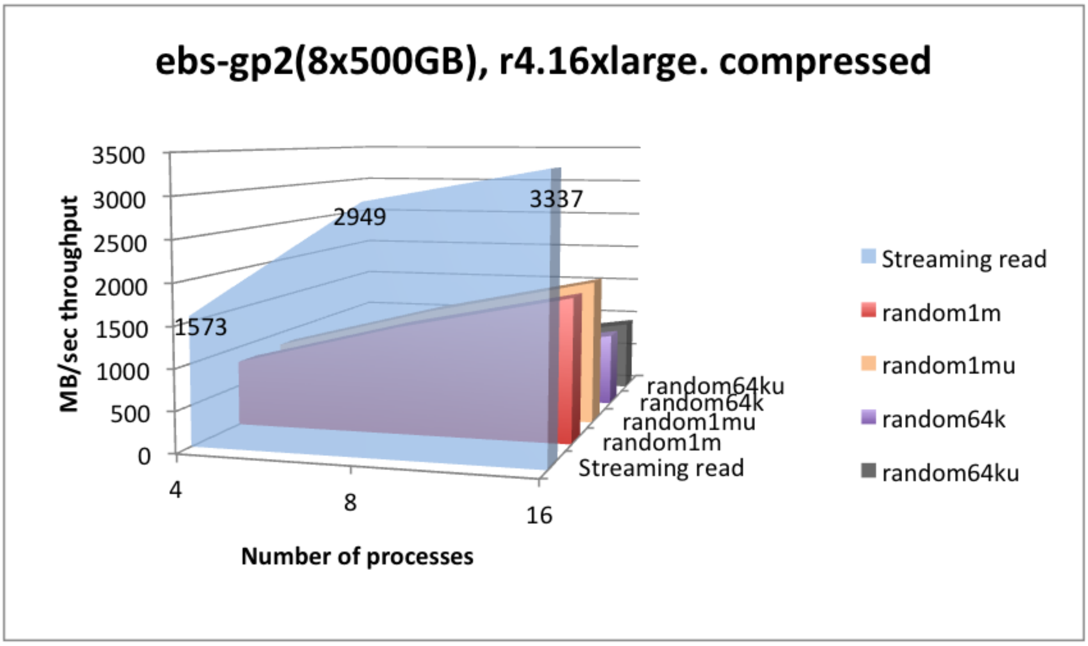
For consistency in all of these evaluations, we tested with a common baseline using an `r4.4xlarge` instance with four 200-GB volumes, each with one xfs file system per volume, therefore using four mount points (four partitions). To show the scale to higher throughputs we used an `r4.16xlarge` instance with more volumes: eight 500-GB targets, (host max bandwidth there of 20 Gbps, compared with max EBS bandwidth of 1280 MB/sec) and we ran the comparison on `gp2` and `io1` versions of EBS storage. For the testing of `st1` storage, we used four 6-TB volumes, as each of these could burst between 240-500 MB/sec. We then compared the delta between two instance sizes.

EBS-GP2





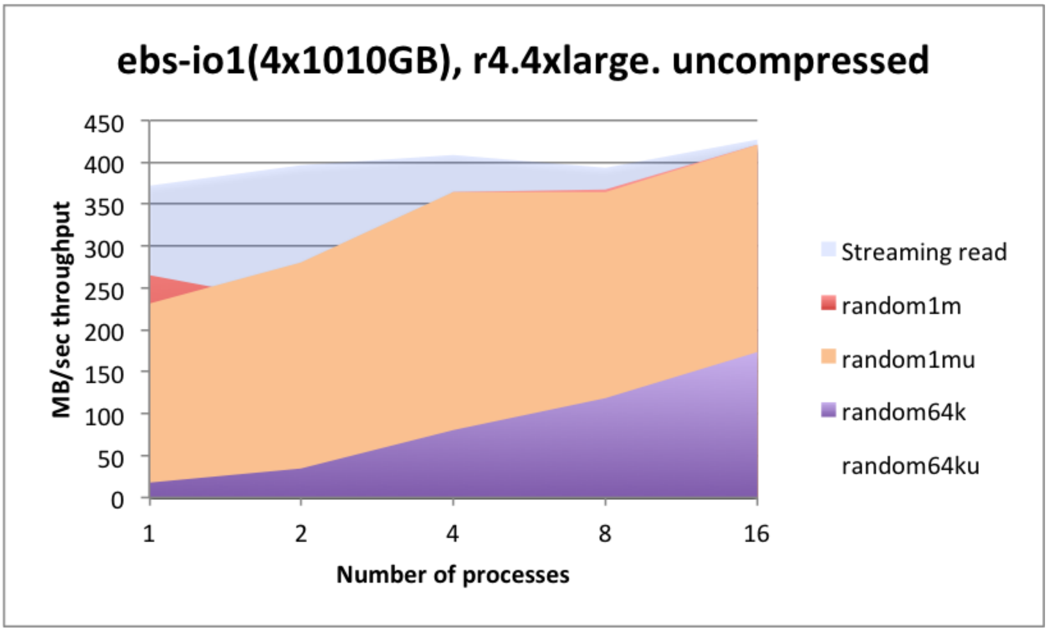


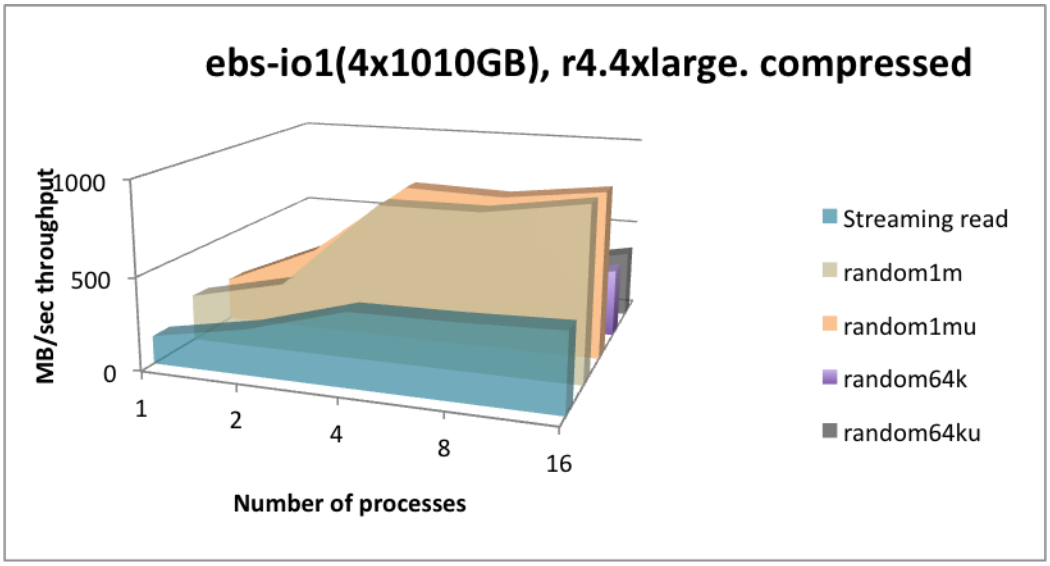


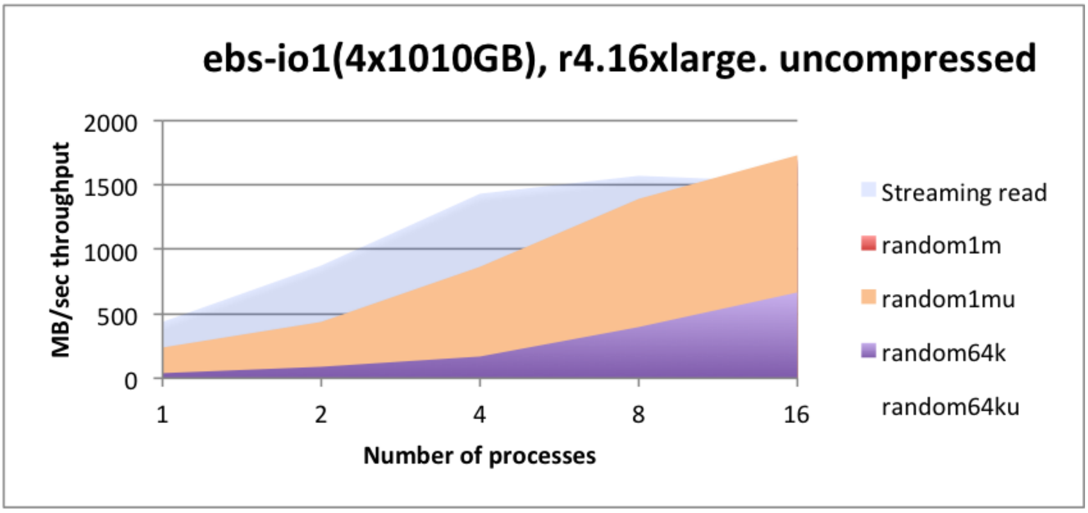
function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.004	`();,;2 3`	0.006
`hcount`	0.002	`read1`	0.018

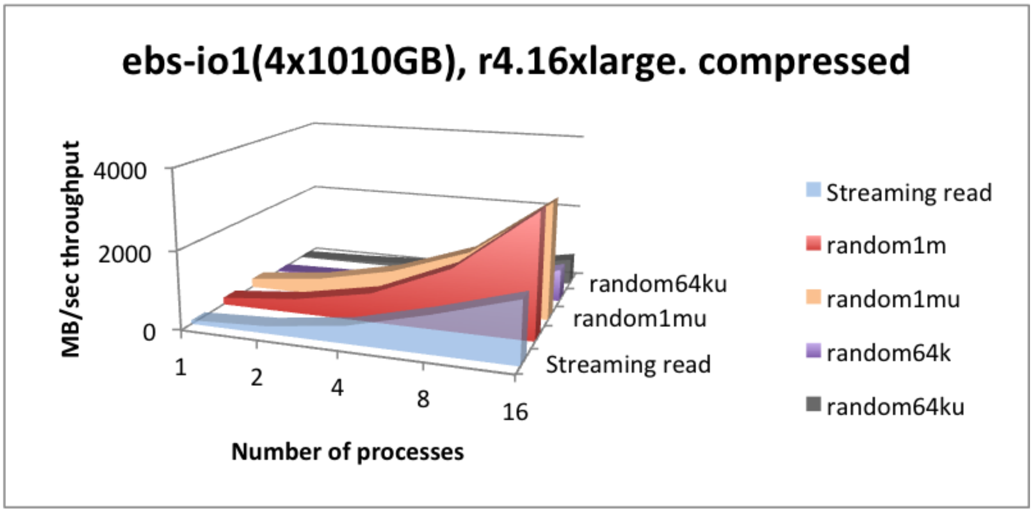
EBS GP2 metadata operational latencies - mSecs (headlines)

EBS-IO1


ebs-io1(4x1010GB), r4.4xlarge. uncompressed
MB/sec throughput
450
400
350
300
250
200
150
100
50
0
1
2
4
8
16
Number of processes
Streaming read
random1m
random1mu
random64k
random64ku


ebs-io1(4x1010GB), r4.4xlarge. compressed
MB/sec throughput
1000
500
0
1
2
4
8
16
Number of processes
Streaming read
random1m
random1mu
random64k
random64ku

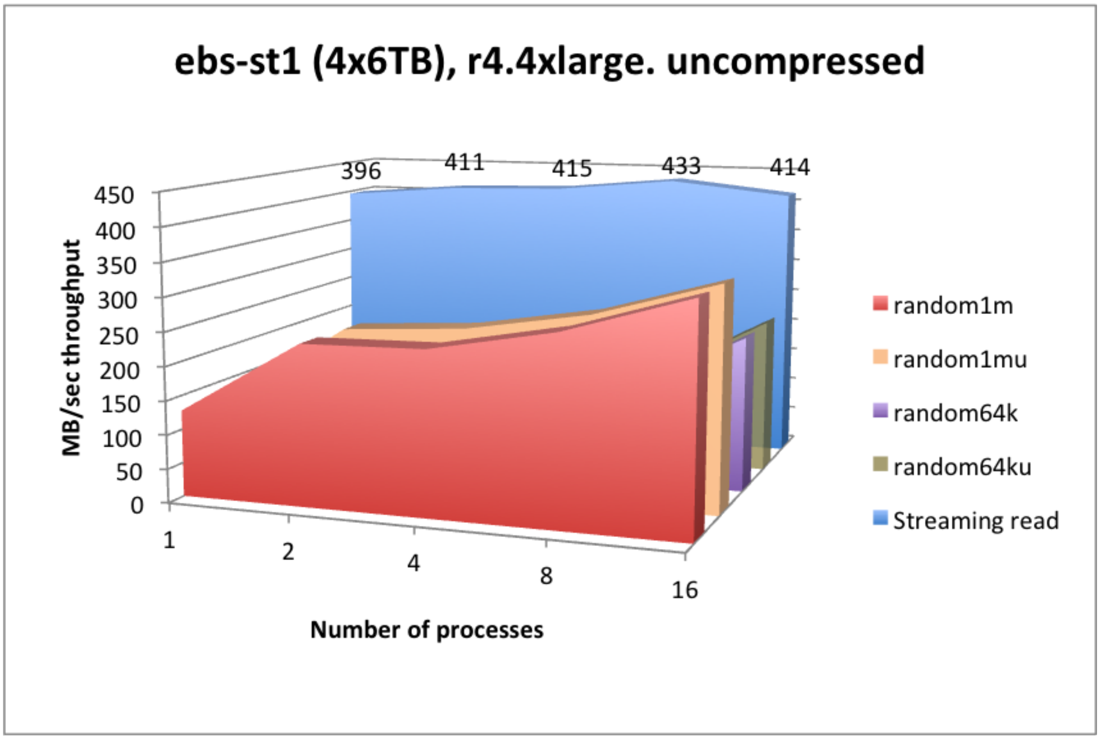

ebs-io1(4x1010GB), r4.16xlarge. uncompressed
MB/sec throughput
2000
1500
1000
500
0
1
2
4
8
16
Number of processes
Streaming read
random1m
random1mu
random64k
random64ku

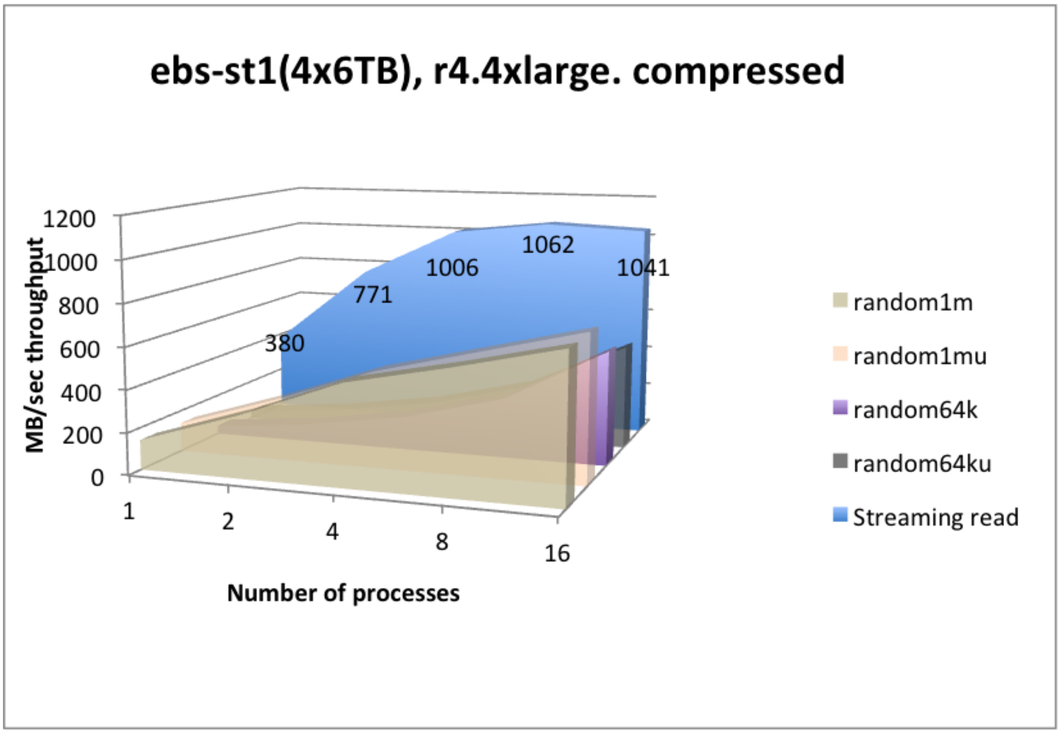


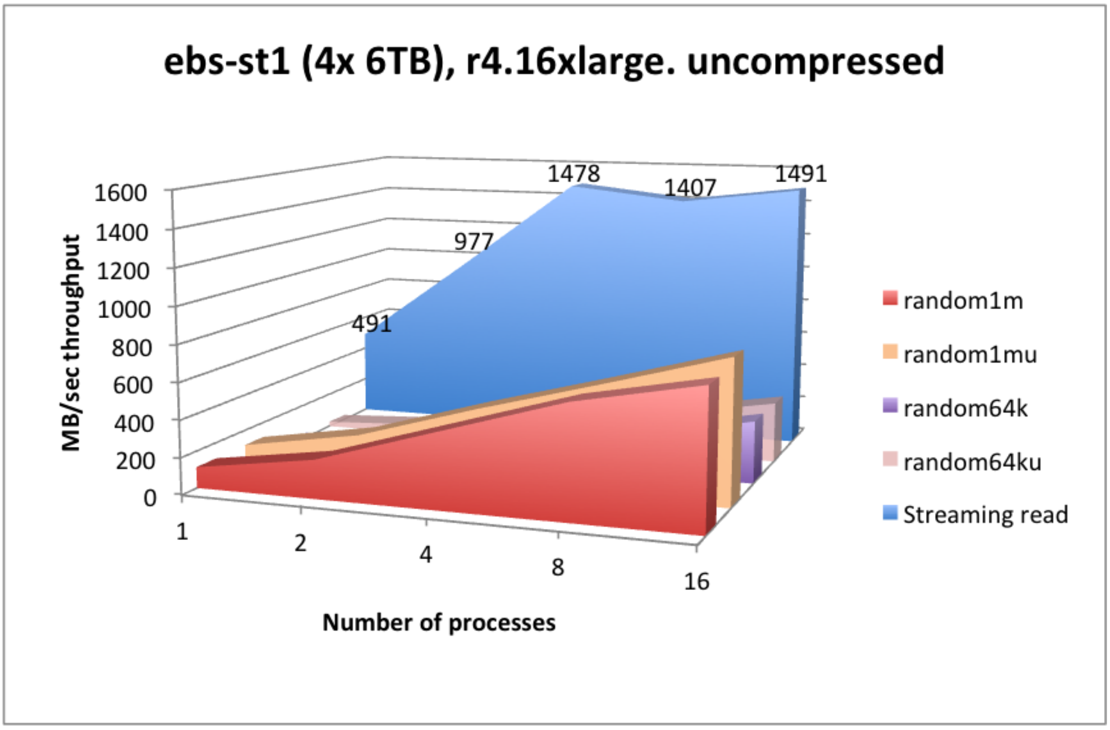
function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.003	`();,;2 3`	0.006
`hcount`	0.002	`read1`	0.017

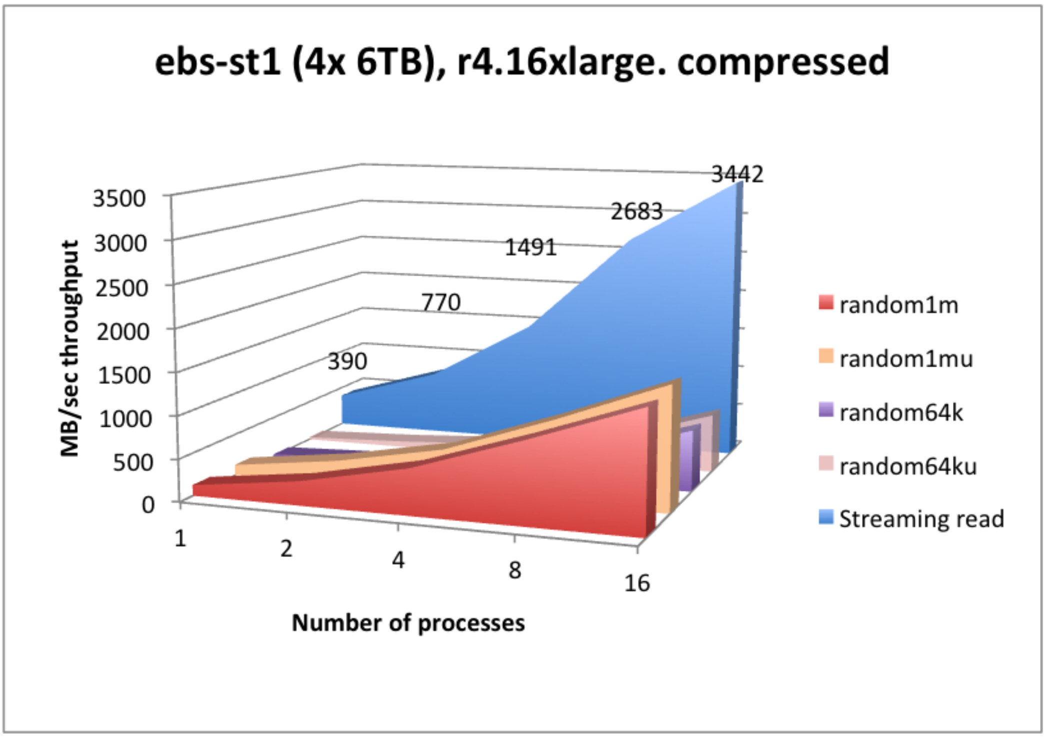
EBS-IO1 metadata operational latencies - mSecs (headlines)

EBS-ST1




ebs-st1(4x6TB), r4.4xlarge. compressed
MB/sec throughput
1200
1000
800
600
400
200
0
380
771
1006
1062
1041
1
2
4
8
16
Number of processes
random1m
random1mu
random64k
random64ku
Streaming read


ebs-st1 (4x 6TB), r4.16xlarge. uncompressed
MB/sec throughput
1600
1400
1200
1000
800
600
400
200
0
491
977
1478
1407
1491
1
2
4
8
16
Number of processes
random1m
random1mu
random64k
random64ku
Streaming read



function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.003	`();,;2 3`	0.04
`hcount`	0.002	`read1`	0.02

EBS-ST1 metadata operational latencies - mSecs (headlines)

Summary

Kdb+ matches the expected throughput of EBS for all classifications, with no major deviations across all classes of read patterns required. EBS-IO1 achieves slightly higher throughput metrics over GP2, but achieves this at a guaranteed IOPS rate. Its operational latency is very slightly lower for meta data and random reads. When considering EBS for kdb+, take the following into consideration:

- Due to private-only presentations of EBS volumes, you may wish to consider EBS for solutions that shard/segment their HDB data between physical nodes in a cluster/gateway architecture. Or you may choose to use EBS for locally cached historical data, with other file-systems backing EBS with full or partial copies of the entire HDB.
- Fixed bandwidth per node: in our testing cases, the instance throughput limit of circa 430 MB/sec for `r4.4xlarge` is easily achieved with these tests. Contrast that with the increased throughput gained with the larger `r4.16xlarge` instance. Use this precept in your calculations.

- There is a fixed throughput per GP2 volume, maxing at 160 MB/ sec. But multiple volumes will increment that value up until the peak achievable in the instance definition. Kdb+ achieves that instance peak throughput.
- Server-side kdb+ in-line compression works very well for streaming and random 1-MB read throughputs, whereby the CPU essentially keeps up with the lower level of compressed data ingest from EBS, and for random reads with many processes, due to read-ahead and decompression running in-parallel being able to magnify the input bandwidth, pretty much in line with the compression rate.
- `st1` works well at streaming reads, but will suffer from high latencies for any form of random searching. Due to the lower capacity cost of `st1`, you may wish to consider this for data that is considered for streaming reads only, e.g. older data.

Appendix B – EFS (NFS)

EFS is an NFS service owned and run by AWS that offers NFS service for nodes in the same availability zone, and can run across zones, or can be exposed externally. The location of where the storage is kept is owned by Amazon and is not made transparent to the user. The only access to the data is via using the service by name (NFS service), and there is no block or object access to said data.

	Amazon EFS	*Amazon EBS Provisioned IOPS*
Availability and durability	Data is stored independently across multiple AZs.	Data is stored redundantly in a single AZ.
Access	Up to thousands of Amazon EC2 instances, from multiple AZs, can connect concurrently to a file system.	A single Amazon EC2 instance can connect to a file system.
Use cases	Big data and analytics, media processing workflows, content management, web serving, and home directories.	Boot volumes, transactional and NoSQL databases, data warehousing, and ETL.

One way to think about EFS is that it is a service deployed in some regions (not all) of the AWS estate. It does indeed leverage S3 as a persistent storage, but the EFS users have no visibility of a single instance of the server, as the service itself is ephemeral and is deployed throughout all availability zones.

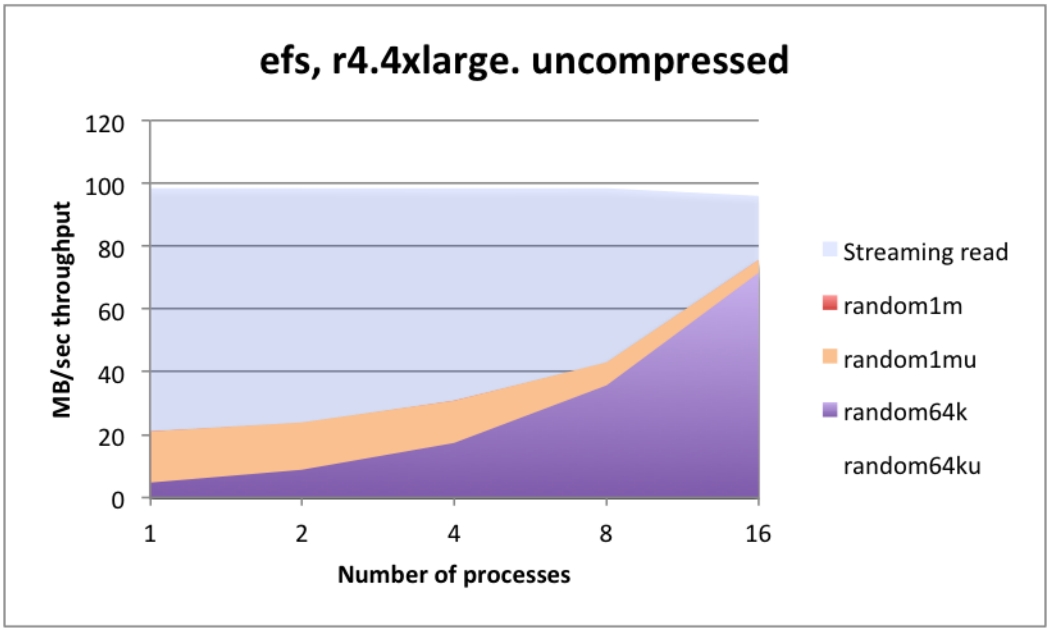
This is different from running your own NFS service, whereby you would define and own the instance by name, and then connect it to an S3 bucket that you also own and define.

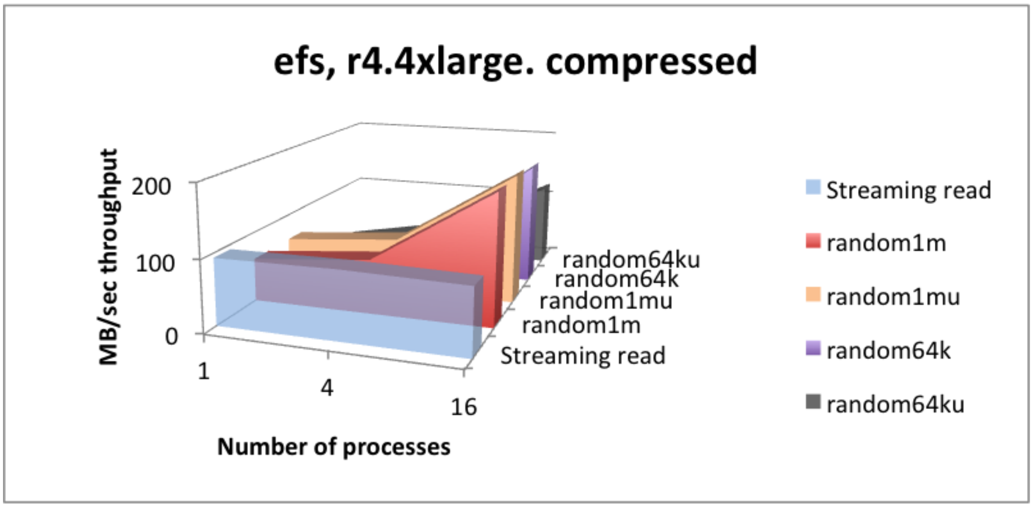
A constraint of EFS for kdb+ is that performance is limited by a predefined burst limit, which is based on the file-system size:

file-system size	*aggregate read/write throughput*
100 GiB	• burst to 100 MiB/s for up to 72 min a day • drive up to 5 MiB/s continuously
1 TiB	• burst to 100 MiB/s for 12 hours a day • drive 50 MiB/s continuously
10 TiB	• burst to 1 GiB/s for 12 hours a day • drive 500 MiB/s continuously
larger	• burst to 100 MiB/s per TiB of storage for 12 hours a day • drive 50 MiB/s per TiB of storage continuously

So, the EFS solution offers a single name space for your HDB structure, and this can be shared around multiple instances including the ability for one or more nodes to be able to write to the space, which is useful for daily updates. We tested kdb+ performance with a 1-TB file system. Testing was done within the burst limit time periods.

The EFS burst performance is limited to 72 minutes per day for a 100-GB file system. Subsequent throughput is limited to 5 MB/sec.





function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	3.658	`();,;2 3`	11.64
`hcount`	3.059	`read1`	6.85

Metadata operational latencies - mSecs (headlines)

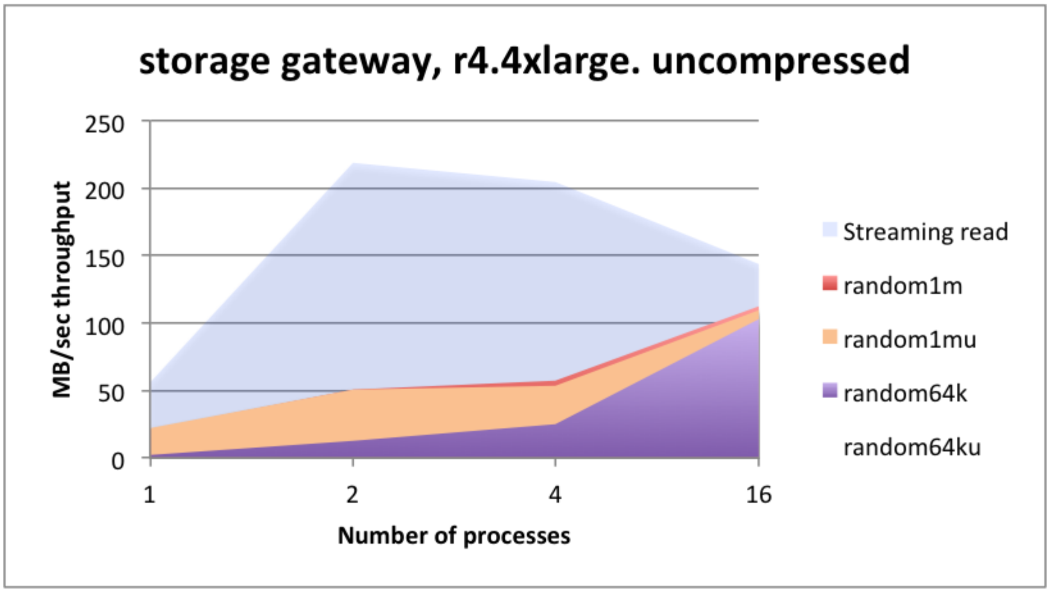
Summary

Note the low rate of streaming read performance, combined with very high metadata latencies (1000× that of EBS). The increase in transfer rate for many-threaded compressed data indicates that there is a capped bandwidth number having some influence on the results as well as the operational latency. Consider constraining any use of EFS to temporary store and not for runtime data access.

Appendix C – Amazon Storage Gateway (File mode)

Amazon Storage Gateway is a pre-prepared AMI/instance that can be provisioned on-demand. It allows you to present an NFS layer to the application with S3 as a backing store. The difference between this and EFS is that the S3 bucket is owned and named by you. But fundamentally the drawback with this approach will be the operational latencies. These appear much more significant than the latencies gained for the EFS solution, and may reflect the communication between the file gateway instance and a single declared instance of S3. It is likely that the S3 buckets used by EFS are run in a more distributed fashion.

One advantage of AWS Gateway is that it is managed by AWS, it can be deployed directly from the AWS console, and incurs no additional fees beyond the normal storage costs which is in line with S3.



function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	3.892	`();,;2 3`	77.94
`hcount`	0.911	`read1`	7.42

Metadata operational latencies - mSecs (headlines)

Summary

The throughput appears to run at about 50% of the line rates available, even when run at scale. The AWS gateway exhibits significantly high operational latency. This manifests as very long wait times when performing an interactive `ls -l` command from the root of the file system, while the file system is under load, sometimes taking several minutes to respond to the directory walk.

Appendix D – MapR-FS

MapR is qualified with kdb+

It offers the full POSIX semantics, including through the NFS interface.

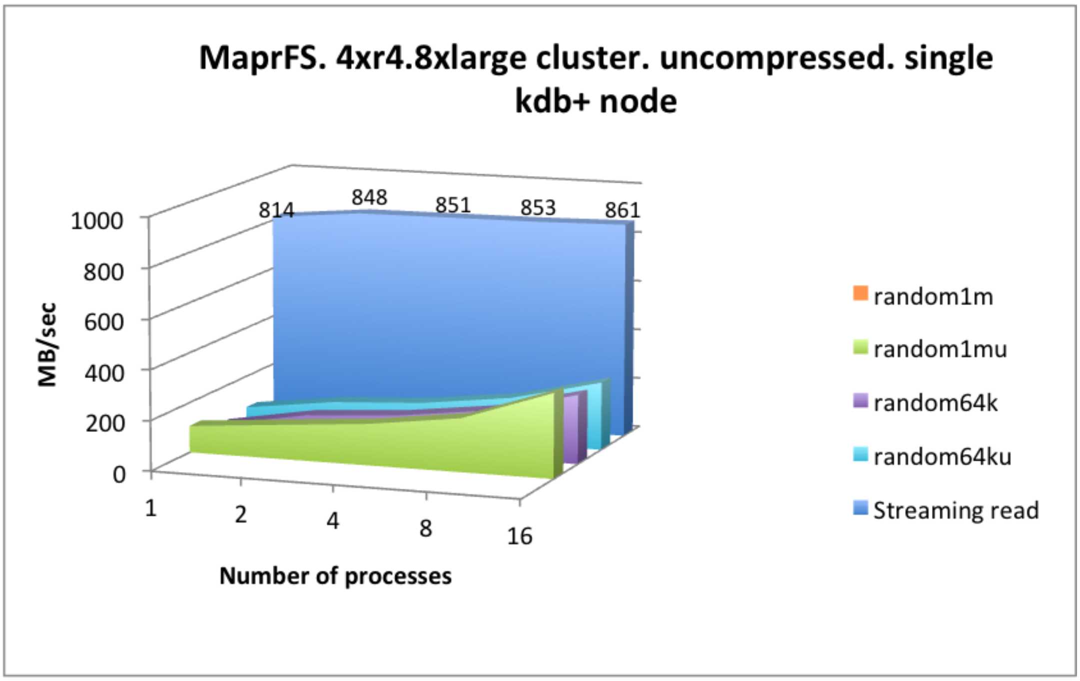
MapR is a commercial implementation of the Apache Hadoop open-source stack. Solutions such as MapR-FS were originally driven by the need to support Hadoop clusters alongside high-performance file-system capabilities. In this regard, MapR improved on the original HDFS implementation found in Hadoop distributions. MapR-FS is a core component of their stack. MapR AMIs are freely available on the Amazon marketplace.

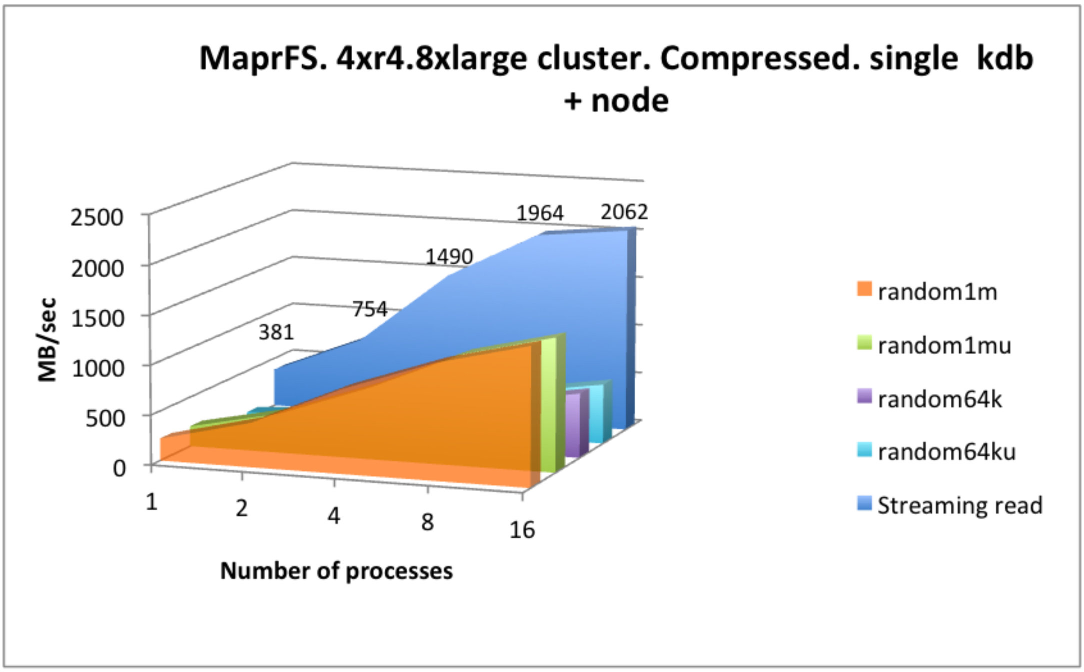
We installed version 6.0a1 of MapR, using the cloud formation templates published in EC2. We used the BYOL licensing model, using an evaluation enterprise license. We tested just the enterprise version of the NFS service for this test, as we were not able to test the POSIX fuse client at the time we went to press.

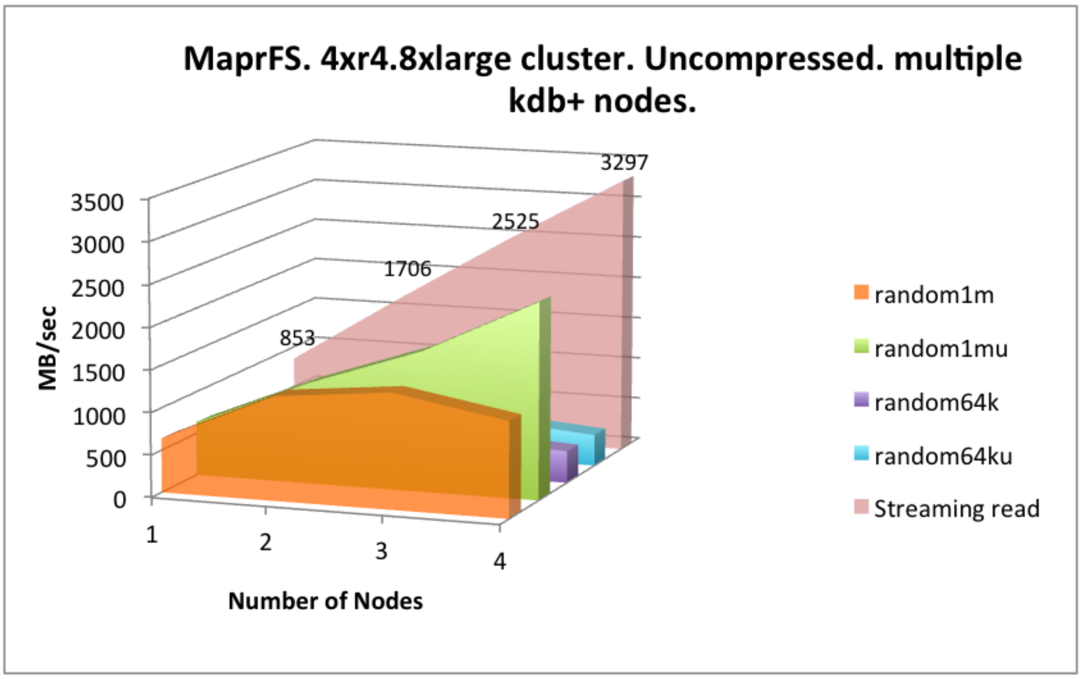
The reasons for considering something like MapR include:

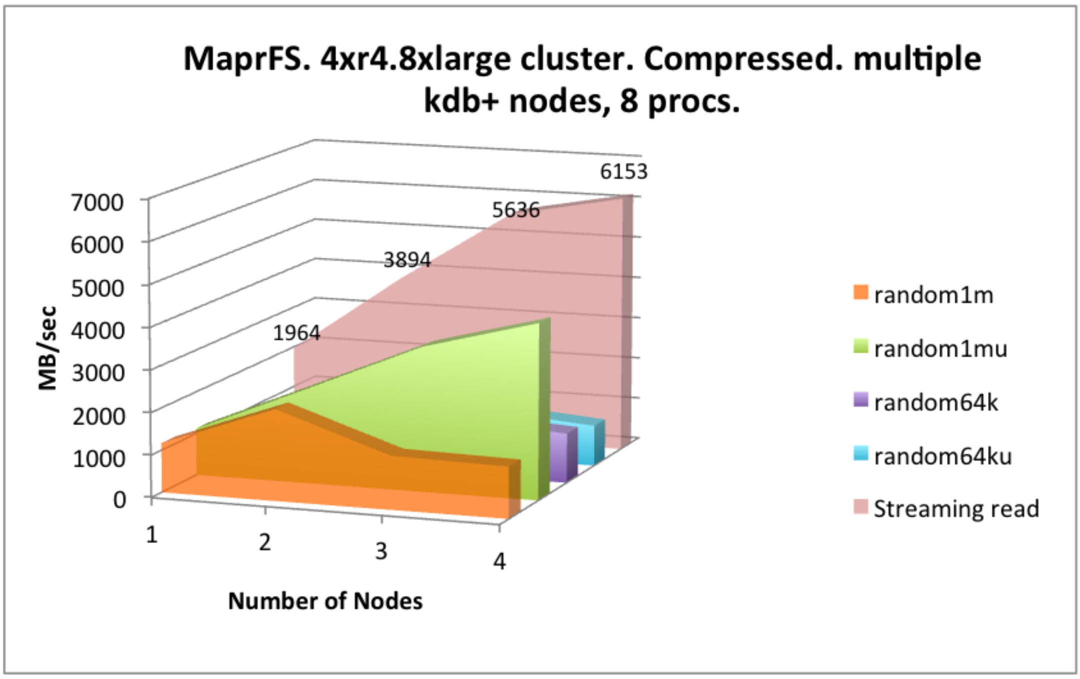
1. Already being familiar with and using MapR in your enterprise, so this may already be a candidate or use case when considering AWS.
2. You would like to read and write HDB structured data into the same file-system service as is used to store unstructured data written/read using the HDFS RESTful APIs. This may offer the ability to consolidate or run Hadoop and kdb+ analytics independently of each other in your organization while sharing the same file-system infrastructure.

Locking semantics on files passed muster during testing, although thorough testing of region or file locking on shared files across multiple hosts was not fully tested for the purposes of this report.


MaprFS. 4xr4.8xlarge cluster. uncompressed. single kdb+ node
MB/sec
1000
800
600
400
200
0
814
848
851
853
861
1
2
4
8
16
Number of processes
random1m
random1mu
random64k
random64ku
Streaming read


MaprFS. 4xr4.8xlarge cluster. Compressed. single kdb + node
MB/sec
2500
2000
1500
1000
500
0
381
754
1490
1964
2062
1
2
4
8
16
Number of processes
random1m
random1mu
random64k
random64ku
Streaming read





function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.447	`();,;2 3`	6.77
`hcount`	0.484	`read1`	0.768

Metadata operational latencies - mSecs (headlines)

Summary

The operational latency of this solution is significantly lower than seen with EFS and Storage Gateway, which is good for an underlying NFS protocol, but is beaten by WekaIO Matrix.

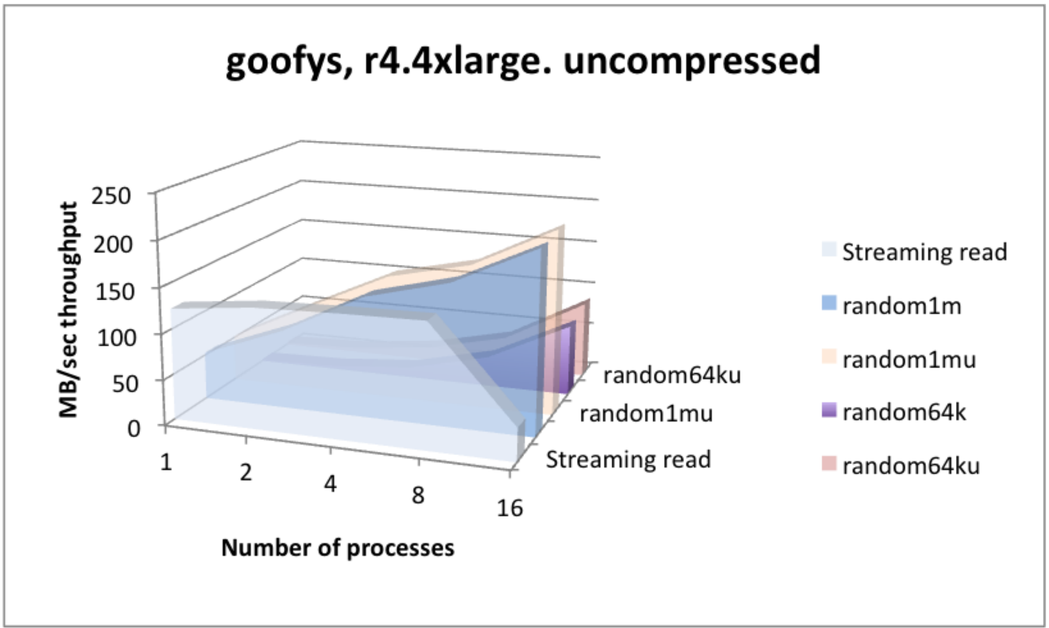
By way of contrast however, this solution scales very well horizontally and vertically when looking at the accumulated throughput numbers. It also appears to do very well with random reads, however there we are likely to be hitting server-side caches in a significant way, so mileage will vary.

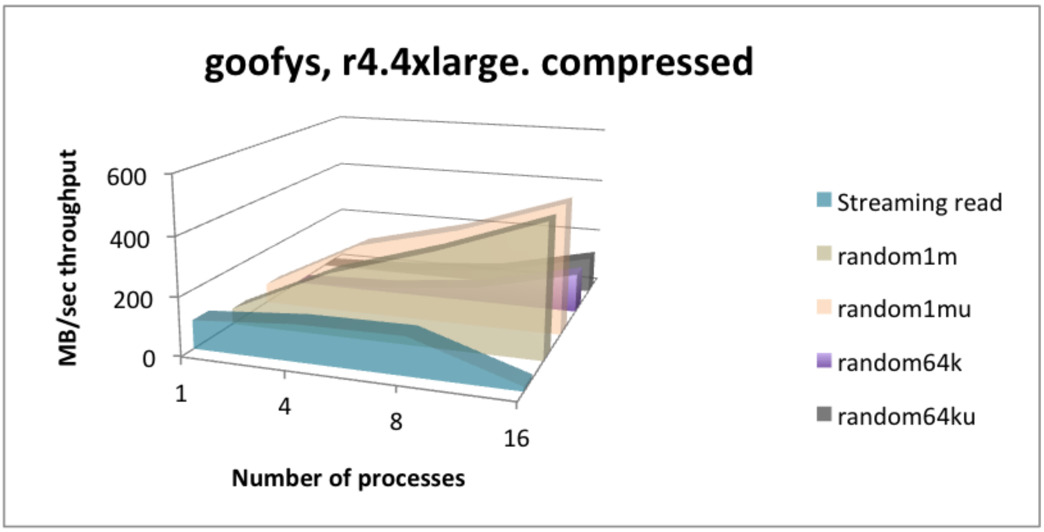
We plan to look at the POSIX MapR client in the future.

Appendix E - Goofys

Goofys is an open-source Linux client distribution. It uses an AWS S3 storage backend, behind a running and a normal Linux AWS EC2 instance. It presents a POSIX file system layer to kdb+ using the FUSE layer. It is distributed in binary form for RHEL/CentOS and others, or can be built from source.

Limitations of the POSIX support are that hard links, symlinks and appends are not supported.





function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.468	`();,;2 3`	DNF
`hcount`	0.405	`read1`	0.487

Metadata operational latencies - mSecs (headlines)

Summary

Operational latency is high. The natural streaming throughput seems to hover around 130 MB/sec, or approximately a quarter of the EBS rate. The solution thrashes at 16 processes of streaming reads. Metadata latency figures are in the order of 100-200× higher that of EBS.

The compressed tests show that the bottleneck is per-thread read speeds, as the data when decompressed rates improve a lot over the uncompressed model.

Appendix F - S3FS

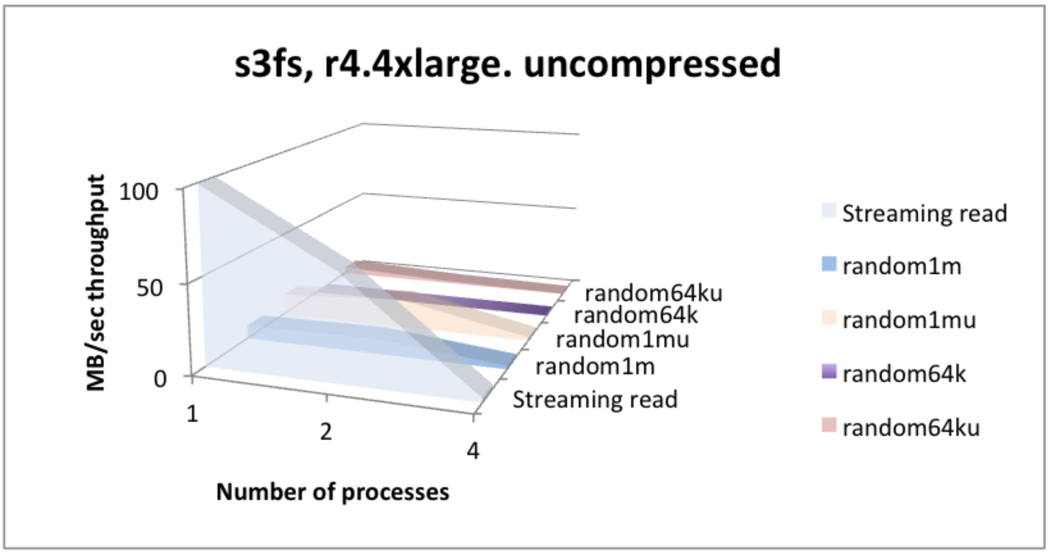
S3FS is an open-source Linux client software layer that arbitrates between the AWS S3 storage layer and each AWS EC2 instance. It presents a POSIX file system layer to kdb+.

S3FS uses the Linux user-land FUSE layer. By default, it uses the POSIX handle mapped as an S3 object in a one-to-one map. It does not use the kernel cache buffer, nor does it use its own caching model by default.

Due to S3's eventual consistency limitations file creation with S3FS can occasionally fail.

Metadata operations with this FS are slow. The append function, although supported is not usable in a production setting due to the massive latency involved.

With multiple kdb+ processes reading, the S3FS service effectively stalled.



s3fs

function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	7.57	`();,;2 3`	91.1
`hcount`	10.18	`read1`	12.64

Metadata operational latencies - mSecs (headlines)

Appendix G - S3QL

The code is perhaps the least-referenced open-source S3 gateway package, and from a vanilla RHEL 7.3 build we had to add a significant number of packages to get to the utility compiled and installed. S3QL is written in Python. Significant additions are required to build S3QL namely: llfuse, Python3, Cython, Python-pip, EPEL and SQlite.

S3QL uses the Python bindings (llfuse) to the Linux user-mode kernel FUSE layer. By default, it uses the POSIX handle mapped as an S3 object in a one-to-one map. S3QL supports only one node sharing one subset (directory) tree of one S3 bucket. There is no sharing in this model.

Several code exception/faults were seen in Python subroutines of the `mkfs.s3ql` utility during initial test so, due to time pressures, we will revisit this later.

Although the process exceptions are probably due to a build error, and plainly the product does work, this does highlight that the build process was unusually complex, due to the nature of so many dependencies on other open-source components. This may play as a factor in the decision process for selecting solutions.

Appendix H - ObjectiveFS

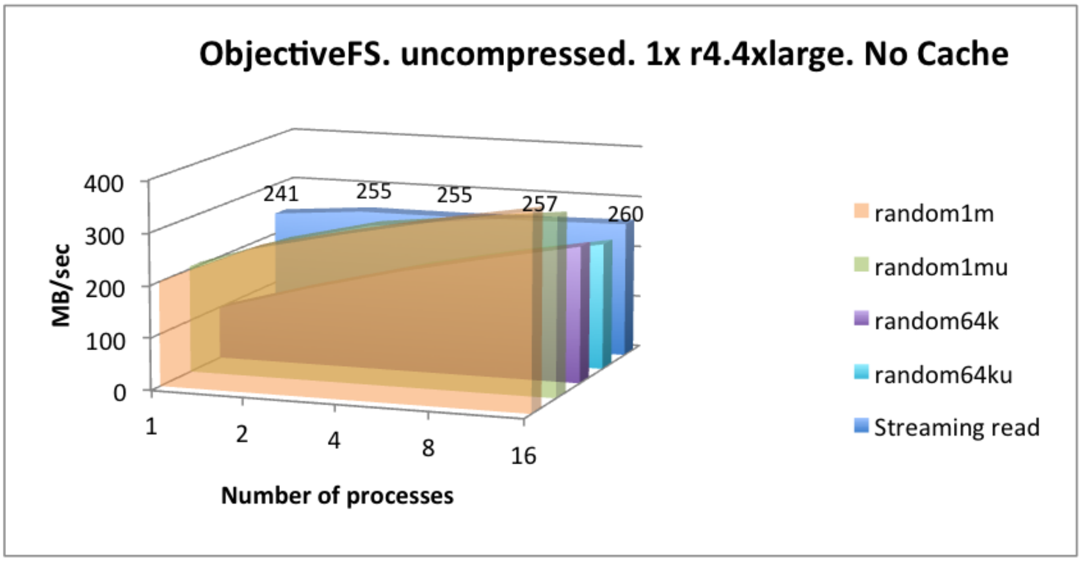
ⓘ **ObjectiveFS is qualified with kdb+.**

ObjectiveFS is a commercial Linux client/kernel package. It arbitrates between S3 storage (each S3 bucket is presented as a FS) and each AWS EC2 instance running ObjectiveFS.

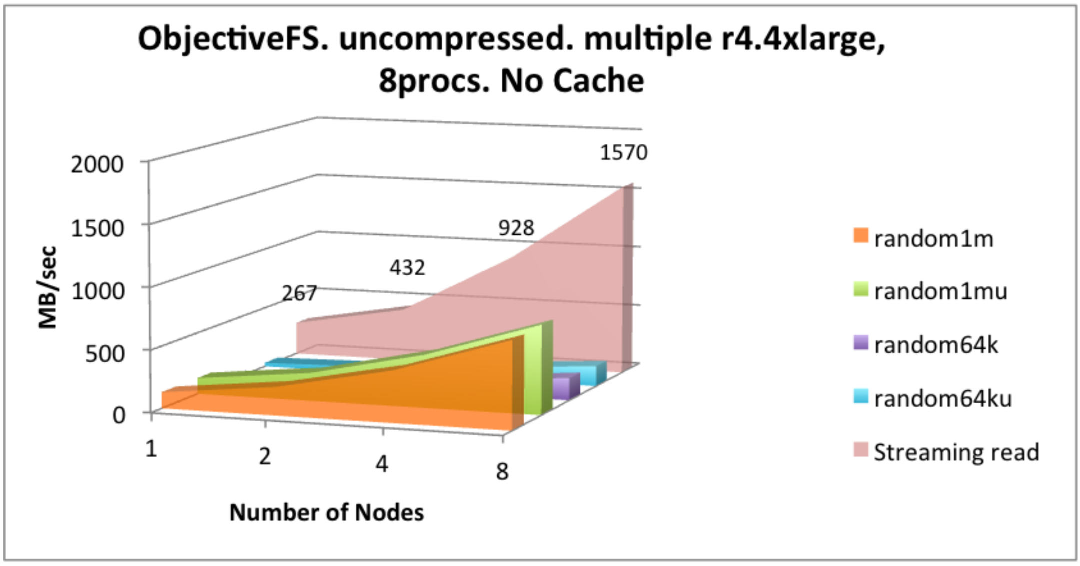
It presents a POSIX file system layer to kdb+. This is distinct from the EFS NFS service from AWS, which is defined independently from the S3 service. With this approach, you pay storage fees only for the S3 element, alongside a usage fee for ObjectiveFS.

ObjectiveFS contains a pluggable driver, which allows for multithreaded readers to be implemented in kernel mode. This gives an increase in the concurrency of the reading of S3 data. ObjectiveFS would be installed on each kdb+ node accessing the S3 bucket containing the HDB data.

ObjectiveFS V5.3.1 is qualified with kdb+. ObjectiveFS achieves significantly better performance than EFS. It also has significantly better metadata operation latency than all of the EFS and open source S3 gateway products. ObjectiveFS also scales aggregate bandwidth as more kdb+ nodes use the same S3 bucket. It scales up close to linearly for reads, as the number of reader nodes increase, since Amazon automatically partitions a bucket across service nodes, as needed to support higher request rates.

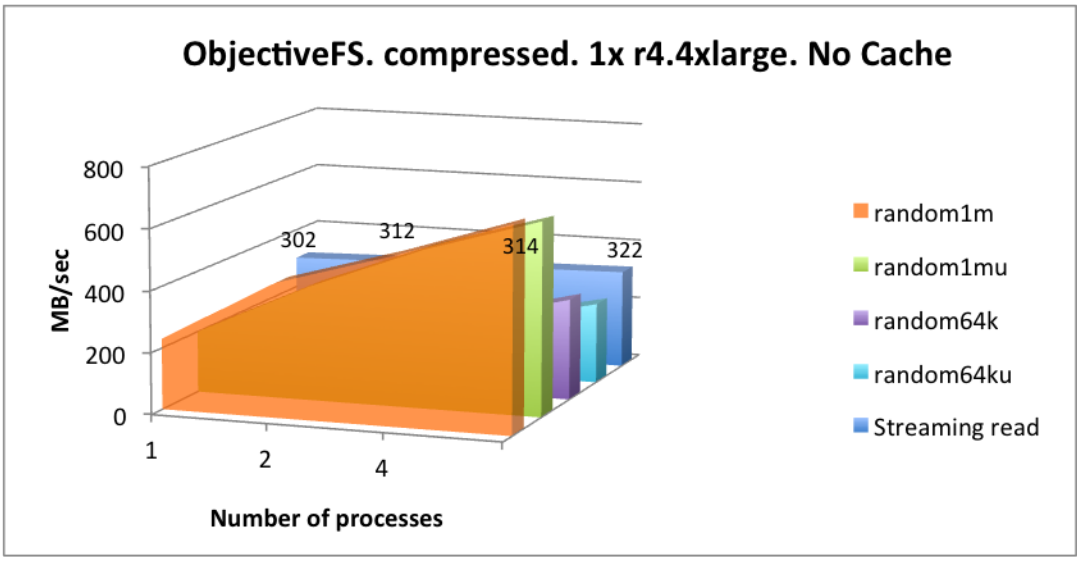


ObjectiveFS



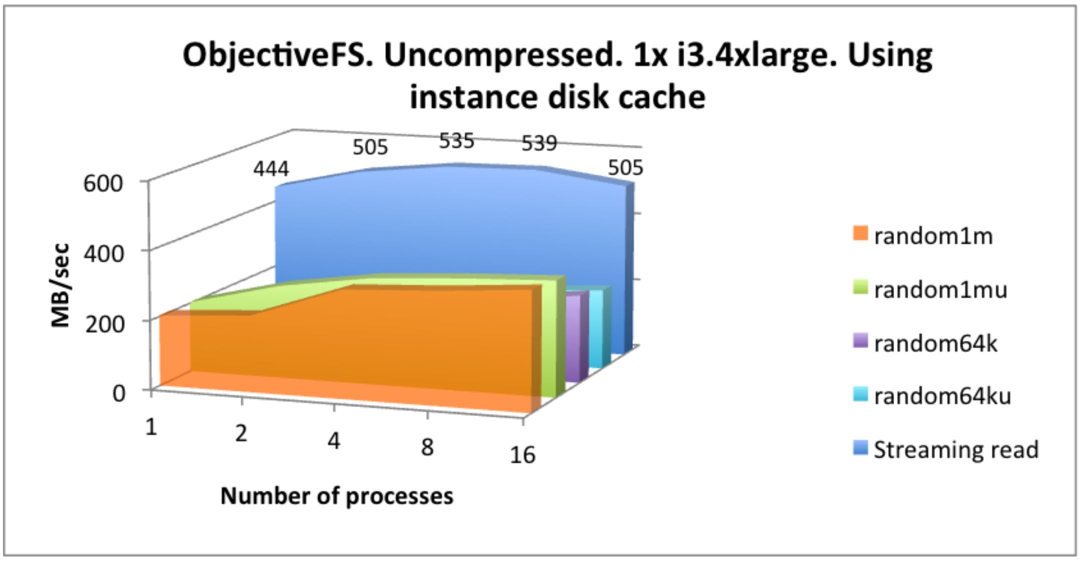
ObjectiveFS

This shows that the read rates from the S3 buckets scale well when the number of nodes increases. This is more noticeable than the read rate seen when measuring the throughput on one node with varying numbers of kdb+ processes. Here it remains around the 260 MB/sec mark irrespective of the number of kdb+ processes reading.

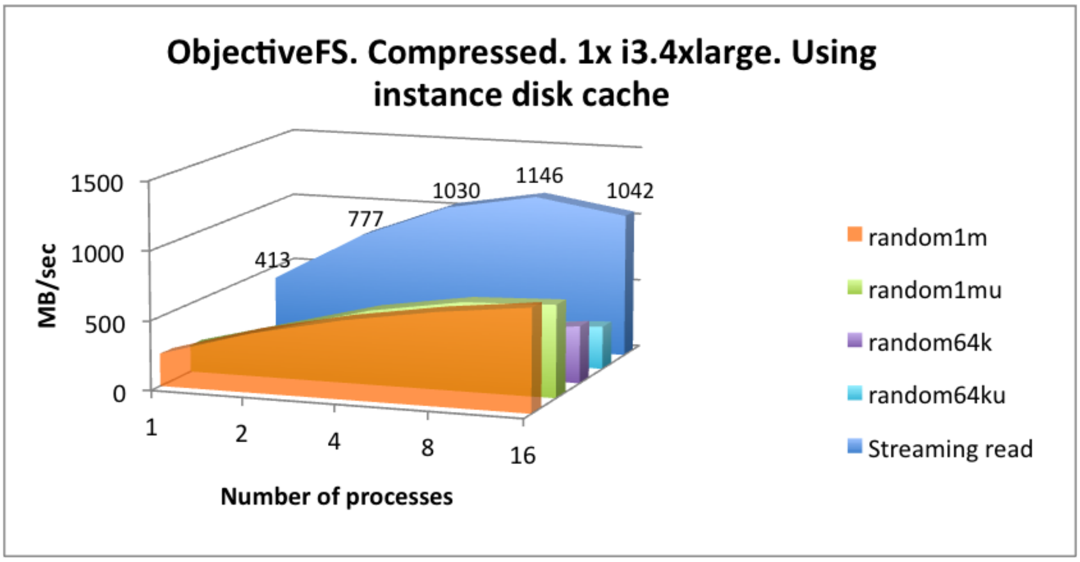


ObjectiveFS

If you select the use of instance local SSD storage as a cache, this can accelerate reads of recent data. The instance local cache is written around for writes, as these go direct to the S3 bucket. But any re-reads of this data would be cached on local disk, local to that node. In other words, the same data on multiple client nodes of ObjectiveFS would each be copies of the same data. The cache may be filled and would be expired in a form of LRU expiry based on the access time of a file. For a single node, the read rate from disk cache is:



ObjectiveFS



ObjectiveFS

function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.162	`();,;2 3`	0.175
`hcount`	0.088	`read1`	0.177

ObjectiveFS metadata operational latencies - mSecs (headlines)

Note that ObjectiveFS encrypts and compresses the S3 objects using its own private keys plus your project's public key. This will require a valid license and functioning software for the length of time you use this solution in a production setting.

Summary

This is a simple and elegant solution for the retention of old data on a slower, lower cost S3 archive, which can be replicated by AWS, geographically or within availability zones. It magnifies the generically very low S3 read rates by moving a 'parallelizing' logic layer into a kernel driver, and away from the FUSE layer. It then multithreads the read tasks.

It requires the addition of the ObjectiveFS package on each node running kdb+ and then the linking of that system to the target S3 bucket. This is a very simple process to install, and very easy to set up.

For solutions requiring higher throughput and lower latencies, you can consider the use of their local caching on instances with internal SSD drives, allowing you to reload and cache, at runtime, the most recent and most latency sensitive data. This cache can be pre-loaded according to a site-specific recipe, and could cover, for example, the most recent market data written back to cache, even through originally written to S3.

Like some of the other solutions tested, ObjectiveFS does not use the kernel block cache. Instead it uses its own memory cache mechanism. The amount used by it is defined as a percent of RAM or as a fixed size. This allocation is made dynamically.

Therefore attention should be paid to the cases where a kdb+ writer (e.g. RDB or a TP write-down) is growing its private heap space dynamically, as this could extend beyond available space at runtime. Reducing the size of the memory cache for ObjectiveFS and use of disk cache would mitigate this.

Appendix I – WekaIO Matrix

> ⓘ **WekaIO Matrix is qualified with kdb+.**

WekaIO Matrix is a commercial product from WekaIO. Version 3.1.2 was used for testing. Matrix uses a VFS driver, enabling Weka to support POSIX semantics with lockless queues for I/O. The WekaIO POSIX system has the same runtime semantics as a local Linux file system.

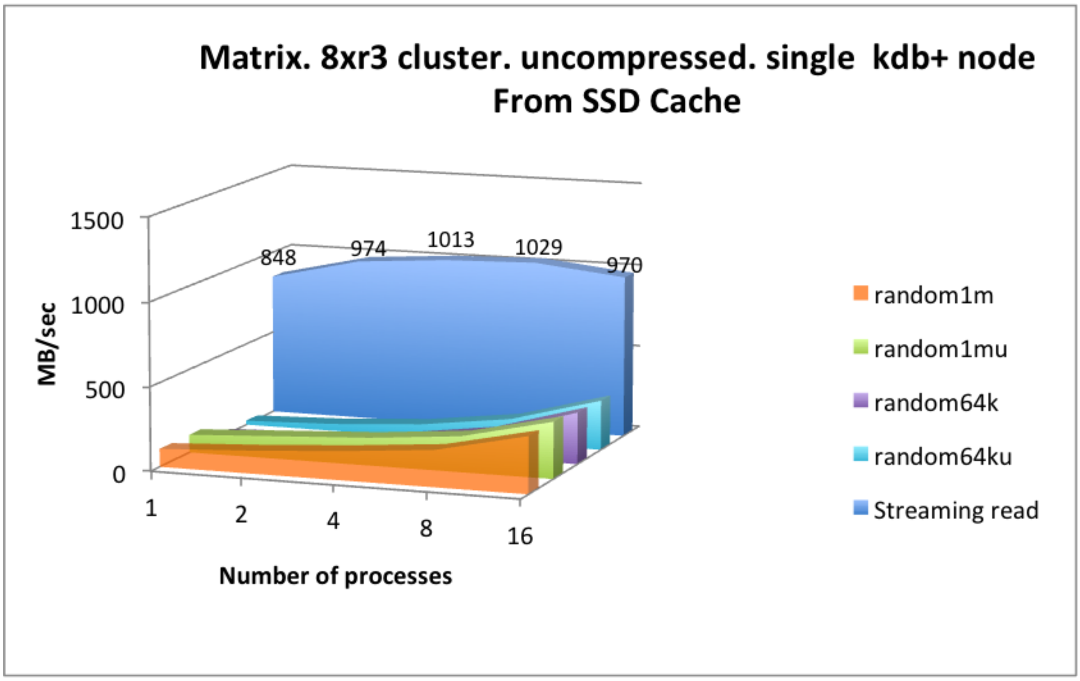
Matrix provides distributed data protection based on a proprietary form of erasure coding. Files are broken up into chunks and spread across nodes (or EC2 instances) of the designated Matrix cluster (minimum cluster size is six nodes = four data + two parity). The data for each chunk of the file is mapped into an erasure-coded stripe/chunk that is stored on the node's direct-attached SSD. EC2 instances must have local SATA or NVMe based SSDs for storage.

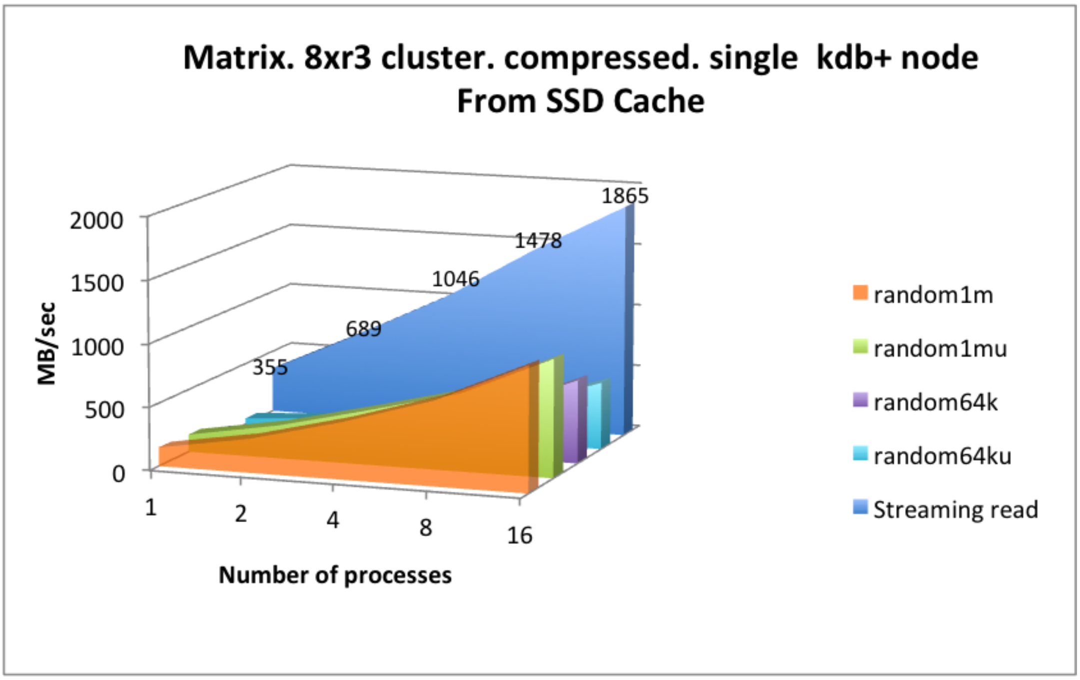
With Matrix, we would anticipate kdb+ to be run in one of two ways. Firstly, it can run on the server nodes of the Matrix cluster, sharing the same namespace and same compute components. This eliminates the need to create an independent file-system infrastructure under EC2. Secondly, the kdb+ clients can run on clients of the Matrix cluster, the client/server protocol elements being included as part of the Matrix solution, being installed on both server and client nodes.

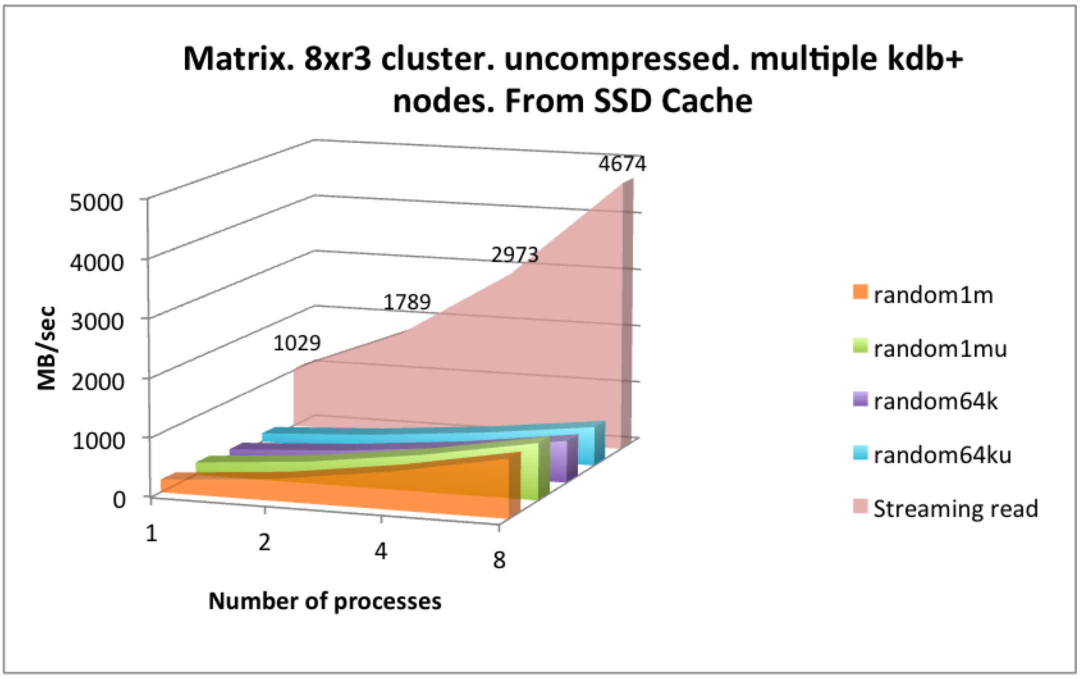
One nice feature is that WekaIO tiers its namespace with S3, and includes operator selectable tiering rules, and can be based on age of file and time in cache, and so on.

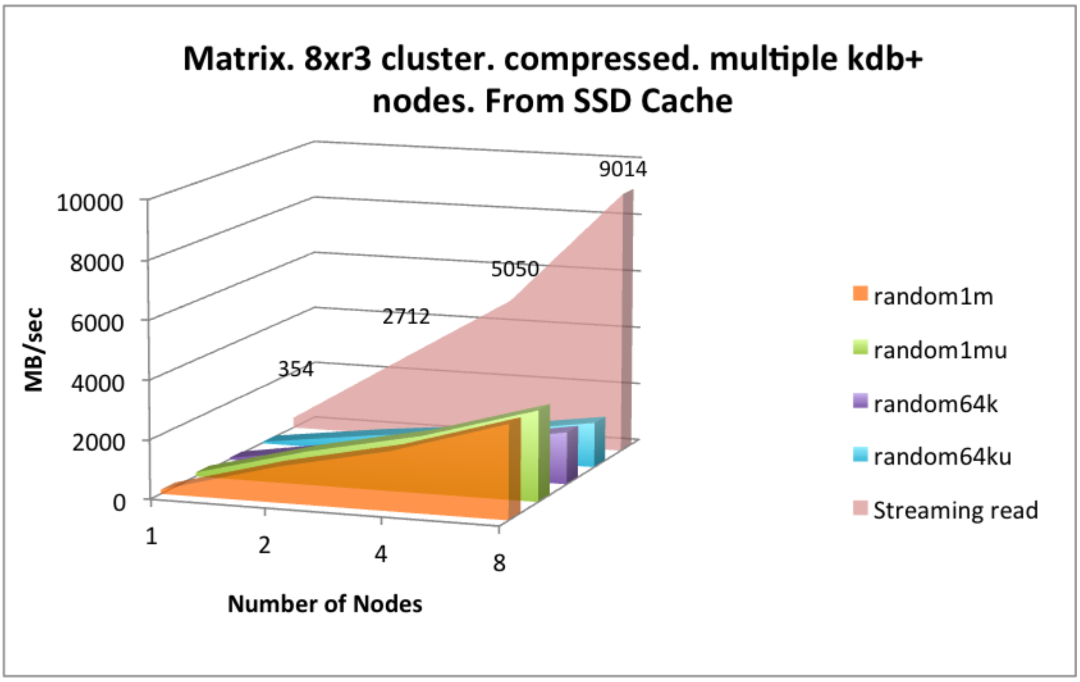
The performance is at its best when running from the cluster's erasure-coded SSD tier, exhibiting good metadata operational latency.

This product, like others using the same design model, does require server and client nodes to dedicate one or more cores (vCPU) to the file-system function. These dedicated cores run at 100% of capability on that core. This needs to be catered for in your core sizing calculations for kdb+, if you are running directly on the cluster.

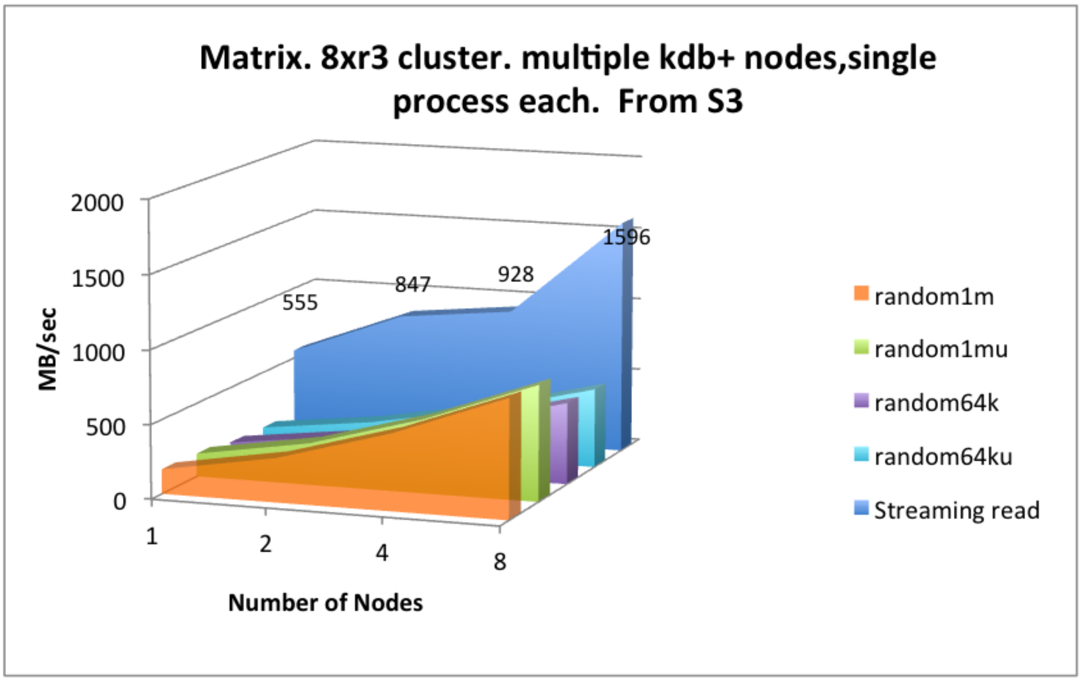

Matrix. 8xr3 cluster. uncompressed. single kdb+ node
From SSD Cache
1500
1000
500
0
MB/sec
848
974
1013
1029
970
1
2
4
8
16
Number of processes
random1m
random1mu
random64k
random64ku
Streaming read

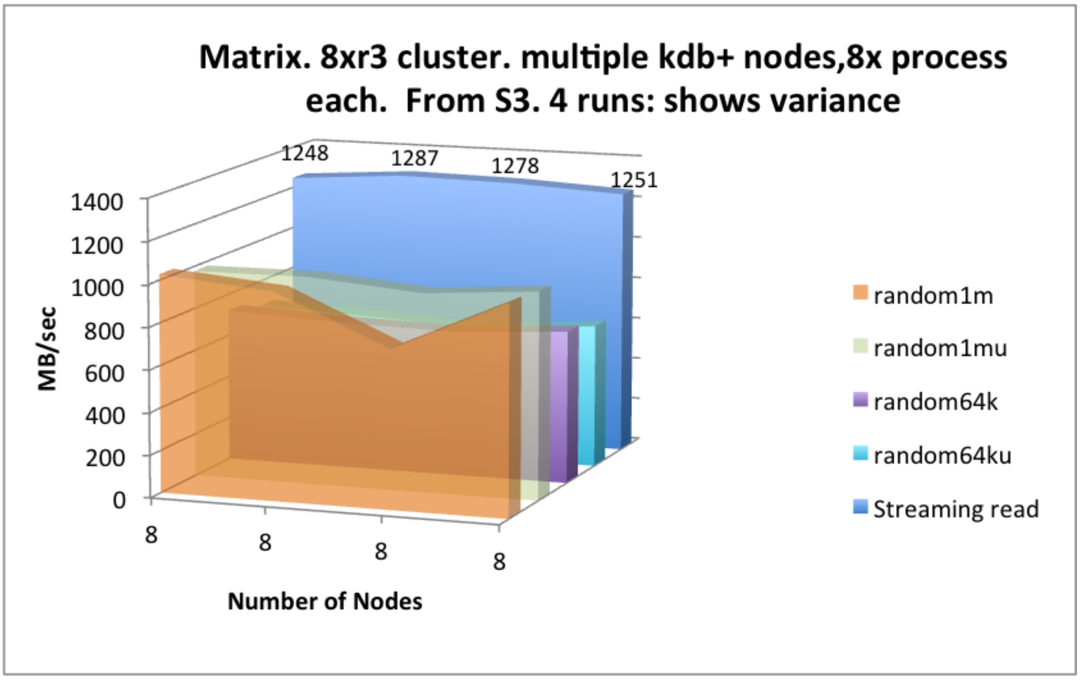

Matrix. 8xr3 cluster. compressed. single kdb+ node
From SSD Cache
2000
1500
1000
500
0
MB/sec
355
689
1046
1478
1865
1
2
4
8
16
Number of processes
random1m
random1mu
random64k
random64ku
Streaming read





When forcing the cluster to read from the data expired to S3, we see these results:





function	*latency (mSec)*	*function*	*latency (mSec)*
`hclose hopen`	0.555	`();,;2 3`	3.5
`hcount`	0.049	`read1`	0.078

WekaIO Matrix metadata operational latencies - mSecs (headlines)

Summary

Streaming reads running in concert across multiple nodes of the cluster achieve 4.6 GB/sec transfer rates, as measured across eight nodes running kdb+, and on one file system. What is interesting here is to observe there is no decline in scaling rate between one and eight nodes. This tested cluster had twelve nodes, running within that a 4+2 data protection across these nodes, each of instance type `r3.8xlarge` (based on the older Intel Ivy Bridge chipset), chosen for its modest SSD disks and not for its latest CPU/mem speeds.

Streaming throughput on one client node is 1029 MB/sec representing wire speed when considered as a client node. This indicates that the data is injected to the host running kdb+ from all of the Matrix nodes whilst still constructing sequential data from the remaining active nodes in the cluster, across the same network.

Metadata operational latency: whilst noticeably worse than EBS, is one or two orders of magnitude better than EFS and Storage Gateway and all of the open source products.

For the S3 tier, a single kdb+ thread on one node will stream reads at 555 MB/sec. This rises to 1596 MB/sec across eight nodes, continuing to scale, but not linearly. For eight processes and eight nodes throughput maximizes at a reasonable 1251 MB/sec. In a real-world setting, you are likely to see a blended figure improve with hits coming from the SSDs. The other elements that distinguish this solution from others are ‘block-like’ low operational latencies for some meta-data functions, and good aggregate throughputs for the small random reads with kdb+.

For setup and installation, a configuration tool guides users through the cluster configuration, and it is pre-configured to build out a cluster of standard r3- or i3-series EC2 instances. The tool has options for both standard and expert users. The tool also provides users with performance and cost information based on the options that have been chosen.

Appendix J – Quobyte

> **Quobyte is functionally qualified with kdb+.**

Quobyte offers a shared namespace solution based on either locally-provisioned or EBS-style storage. It leverages an erasure-coding model around nodes of a Quobyte cluster.

test	*result*
throughput	Multiple thread read saturated the ingest bandwidth of each `r4.4xlarge` instance running kdb+.
fileops attributes	*Test results to follow, please check back at code.kx.com for full results.*