Efficient Synchronization of Linux Memory Regions over a Network

A Comparative Study and Implementation

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Introduction

Introduction

In today's technological landscape, numerous methods exist for accessing remote resources, such as via databases or custom APIs. The same applies to resource synchronization, which is typically addressed on a case-by-case basis via methods such as third-party databases, file synchronization services, or bespoke synchronization protocols. Resource migration is also a frequent challenge, solutions for which often rely on APIs better suited for long-term persistence, like storing the resource in a remote database. Existing solutions for resource synchronization are generally custom-built per application, despite the typical internal resource abstraction being a memory region or file.

What if, instead of applying application-specific protocols and abstractions for accessing, synchronizing, and migrating resources, these processes could be universally managed by directly operating on the memory region? While systems for

Technology

User Space and Kernel Space

The kernel represents the core of an operating system. It directly interacts with hardware, manages system resources such as CPU time, memory and others, and enforces security policies. In addition to this, it is also responsible for progress scheduling, memory management, drivers and many more responsibilities depending on the implementation. Kernel space refers to the memory region that this system is stored and executed in[1].

User space on the other hand is the portion of system memory where user applications execute. Applications can't directly access hardware or kernel memory; instead they use APIs to access them[2]. This API is provided in the form of syscalls, which serve as a bridge between user and kernel space. Well-known syscalls are open(), read(), write(), close() and ioctl(). While most syscalls have a specific purpose, ioctl serves as a more generic, universal one based on file descriptors

Linux Kernel

The Linux kernel was released by Linus Torvalds in 1991. Developed primarily in the C language, it has recently seen the addition of Rust as an approved option for further expansion and development, esp. for drivers[4]. The kernel powers millions of devices across the globe, including servers, desktop computers, mobile phones, and embedded devices. As a kernel, it serves as an intermediary between hardware and applications. It is engineered for compatibility with a wide array of architectures, such as ARM, x86, RISC-V, and others. The open-source nature of the Linux kernel makes it especially interesting for academic exploration and usage. It offers transparency, allowing anyone to inspect the source code in depth. Furthermore, it encourages collaboration by enabling anyone to modify and contribute to the source code.

The kernel does not function as a standalone operating system

UNIX Signals and Sockets

UNIX signals are an integral component of UNIX-like systems, including Linux. They function as software interrupts, notifying a process of significant occurrences, such as exceptions. Signals may be generated from various sources, including the kernel, user input, or other processes, making them a versatile tool for inter-process notifications.

Aside from this notification role, signals also serve as an asynchronous communication mechanism between processes or between the kernel and a process. As such, they have an inherent ability to deliver important notifications without requiring the recipient process to be in a specific state of readiness[6]. Each signal has a default action associated with it, the most common of which are terminating the process or simply ignoring the signal.

Principle of Locality

The principle of locality, or locality of reference, refers to the tendency of a processor to recurrently access the same set of memory locations within a brief span of time. This principle forms the basis of a predictable pattern of behavior that is evident across systems, and can be divided into two distinct types: temporal locality and spatial locality.

Temporal locality is based on the frequent use of particular data within a limited time period. Essentially, if a memory location is accessed once, it is probable that this same location will be accessed again in the near future. To make use of this pattern and to improve performance, systems are designed to maintain a copy of this frequently accessed data in a faster memory storage, which in turn, significantly reduces the latency in subsequent references.

Memory Hierarchy

The memory hierarchy in computers is an organized structure based on factors such as size, speed, cost, and proximity to the Central Processing Unit (CPU). It follows the principle of locality, which suggests that data and instructions that are accessed frequently should be stored as close to the CPU as possible[10]. This principle is crucial primarily due to the limitations of "the speed of the cable", where both throughput and latency decrease as distance increases due to factors like signal dampening and the finite speed of light. While latency increases the further away a cache is from the CPU, the capacity of these caches typically also increases, which can be a worthwhile trade-off depending on the application.

At the top of the hierarchy are registers, which are closest to the CPU. They offer very high speed, but provide limited storage space, typically accommodating 32-64 bits of data

Memory Management

Memory management forms an important aspect of any kernel, serving as a critical buffer between applications and physical memory; as such, it can be considered one of the fundamental purposes of a kernel itself. This helps maintain stability and provides security guarantees, such as ensuring that only a specific process can access its allocated memory.

Within the context of Linux, memory management is divided into the two aforementioned major segments of kernel space and user space. The kernel memory module is responsible for managing kernel space. Slab allocation is a technique employed in managing this segment; the technique groups objects of the same size into caches, enhancing memory allocation speed and reducing fragmentation of memory[13]. User space is the memory segment where applications and certain drivers store their memory in Linux. User space memory management

Swap Space

Swap space refers to a designated portion of the secondary storage utilized as virtual memory in a computer system. This plays an important role in systems that run multiple applications simultaneously; since when memory resources are strained, swap space comes into play, moving inactive parts of the RAM to secondary storage. This action frees up space in primary memory for other processes, enabling smoother operation and preventing a potential system crash due to memory exhaustion.

In the case of Linux, the swap space implementation aligns with a demand paging system. This means that memory is allocated only when required. Swap space in Linux can be a swap partition, which is a distinct area within secondary storage, or it can take the form of a swap file, which is a standard file that can be expanded or truncated based on need. The usage of

Page Faults

Page faults are instances in which a process attempts to access a page that is not currently available in primary memory. This situation triggers the operating system to swap the necessary page from secondary storage into primary memory. These are significant events in memory management, as they determine how efficiently an operating system utilizes its resources.

They can be broadly categorized into two types: minor and major. Minor page faults occur when the desired page resides in memory but isn't linked to the process that requires it. On the other hand, a major page fault takes place when the page has to be loaded from secondary storage, a process that typically takes more time and resources.

To minimize the occurrence of page faults, memory management algorithms such as the aforementioned LRU and

mmap

mmap is a UNIX system call, used for mapping files or devices into memory, enabling a variety of tasks like shared memory, file I/O, and fine-grained memory allocation. Due to its powerful nature, it is commonly used in applications like databases.

A particularly useful feature of mmap is its ability to create what is essentially a direct memory mapping between a file and a region of memory[17]. This connection means that read operations performed on the mapped memory region directly correspond to reading the file and vice versa, enhancing efficiency as the amount of expensive context switches (compared to i.e. the read or write system calls) can be reduced.

A significant advantage of mmap is its ability to do zero-copy operations. In practical terms, this means that data can be accessed directly as if it were positioned in memory, eliminating

inotify

inotify is an event-driven notification system of the Linux kernel, designed to monitor the file system for different events, such as modifications and accesses, among others. It's particularly useful because it can be configured to watch only some operations on certain files, i.e. only write operations. This level of control can offer considerable benefits in cases where there is a need to focus system resources on specific events.

The API also comes with some other advantages; for example, it reduces overhead and resource use when compared to polling strategies. Polling is an I/O-heavy approach as it continuously checks the status of the file system, regardless of whether any changes have occurred. In contrast, inotify works in a more event-driven way, where it only takes action when a specific event actually occurs. This is usually more efficient, reducing overhead especially where there are infrequent changes to the

Linux Kernel Caching

Disk caching in Linux is a feature that temporarily stores frequently accessed data in RAM. It is implemented through the page cache subsystem, and operates based on the principle of locality. By retaining data close to the CPU where it can be quickly accessed without expensive disk reads can significantly reduce overall access time. The data within the cache is also managed using the LRU algorithm, which removes the least recently used items from the cache first when space is needed. Linux also caches file system metadata in specialized structures known as the dentry and inode caches. This metadata contains information such as file names, attributes, and locations. The key benefit of this is that it speeds up the resolution of path names and file attributes, such as tracking when files were last changed for polling.

While such caching mechanisms can improve performance, they

RTT, LAN and WAN

Round-trip time (RTT) represents the time data takes to travel from a source to a destination and back. It provides a valuable insight into application latency, and can vary according to many factors such as network type, system load and physical distance. Local area networks (LAN) are geographically small networks characterized by having a low RTT, resulting in a low latency due to the short distance (typically no more than across an office or data center) that data needs to travel. As a result of their small geographical size and isolation, perimeter security is often applied to such networks, meaning that the LAN is viewed as a trusted network that doesn't necessarily require authentication or encryption between internal systems, resulting in a potentially lower overhead.

Wide area networks (WAN) on the other hand typically span a large geographical area, with the internet being an example

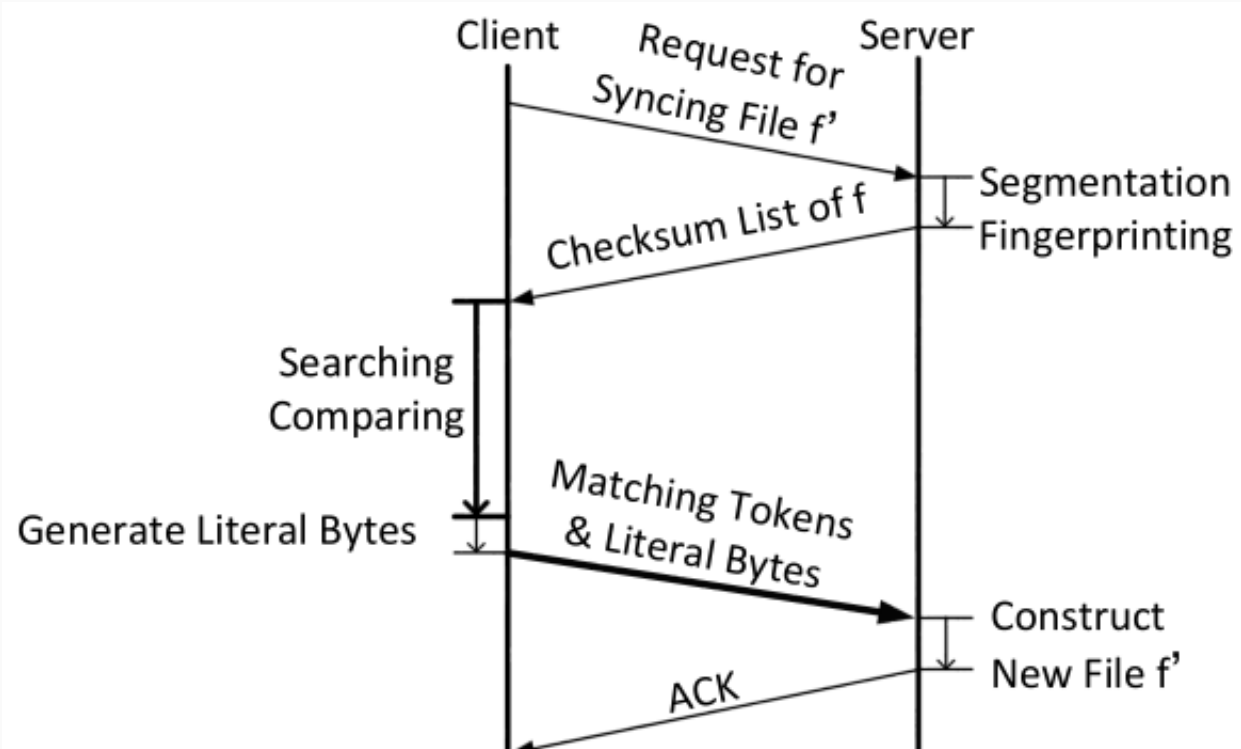
TCP, UDP, TLS and QUIC

TCP (Transmission Control Protocol), UDP (User Datagram Protocol), and QUIC (Quick UDP Internet Connections) are three key communication protocols utilized on the internet today, while TLS serves as a commonly used encryption and authentication mechanism.

TCP forms the backbone of internet communication today due to its connection-oriented nature. It ensures the guaranteed delivery of data packets and their correct order, making it a highly dependable means for data transmission. Significantly, TCP includes error checking, allowing the detection and subsequent retransmission of lost packets. TCP also includes a congestion control mechanism to manage data transmission during high traffic. Due to these features and it's long legacy, TCP is widely used to power the majority of the web where reliable, ordered, and error-checked data transmission is

Delta Synchronization

Delta synchronization is a technique that allows for efficient synchronization of files between hosts, transferring only those parts of the file that have undergone changes instead of the entire file in order to reduce network and I/O overhead. The most recognized tool that uses this method of synchronization is rsync, an open-source data synchronization utility.



File Systems in User Space (FUSE)

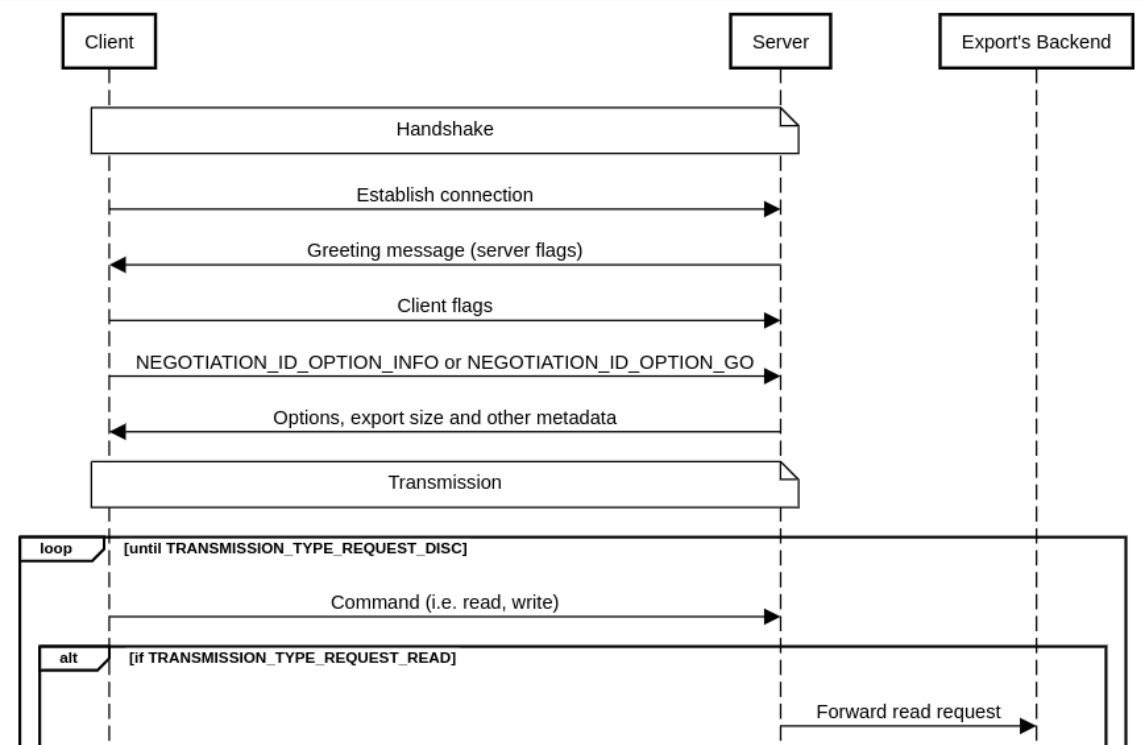
File Systems in User Space (FUSE) is an API that enables the creation of custom file systems in the user space, as opposed to developing them as kernel modules. This reduces the need for the low-level kernel development skills that are usually associated with creating new file systems.

The FUSE APIs are available on various platforms; though mostly deployed on Linux, they can also be found on macOS and FreeBSD. In FUSE, a user space program registers itself with the FUSE kernel module and provides callbacks for the file system operations. A simple read-only FUSE can for example implement the following callbacks:

The getattr callback is responsible for getting the attributes of a file. For a real file system, this would include things like the file's size, its permissions, when it was last accessed or modified,

Network Block Device (NBD)

Network Block Device (NBD) is a protocol for connecting to a remote Linux block device. It typically works by communicating between a user space-provided server and a kernel-provided client. Though usable over WAN, it is primarily designed for LAN or localhost usage. The protocol is divided into two phases: the handshake and the transmission[31]:



Virtual Machine Live Migration

Virtual machine live migration involves moving a virtual machine, its state, and its connected devices from one host to another, with the intention of reducing disrupted service by minimizing downtime during the process. Algorithms that implement this use case can be categorized into two broad types: pre-copy migration and post-copy migration.

Pre-Copy

The primary characteristic of pre-copy migration is its "run-while-copy" nature, meaning that the copying of data from the source to the destination occurs concurrently while the VM continues to operate. This method is also applicable in a generic migration context where other state is being updated.

In the case of a VM, the pre-copy migration procedure starts with transferring the initial state of a VM's memory to the destination host. During this operation, if modifications occur to any chunks of data, they are flagged as dirty. These dirty chunks of data are then transferred to the destination until only a small number remain; this should be an amount small enough to stay within the allowed maximum downtime criteria. After this, the VM is suspended at the source, enabling the synchronization of the remaining chunks of data to the destination without having to continue tracking dirty chunks

Post-Copy

Post-copy migration is an alternative live migration approach. While pre-copy migration operates by copying data before the VM halt, post-copy migration immediately suspends the VM operation on the source and resumes it on the destination, with only a minimal subset of the VM's data.

During this resumed operation, whenever the VM attempts to access a chunk of data not initially transferred during the move, a page fault arises. A page fault, in this context, is the type of interrupt generated when the VM tries to read or write a chunk that is not currently present on the destination. This causes the system to retrieve the missing chunk from the source host, enabling the VM to continue its operations.

The main advantage of post-copy migration is that it eliminates the necessity of re-transmitting chunks of "dirty" or changed

Workload Analysis

Recent studies have explored different strategies to determine the best point in time for virtual machine migration. Even though these mostly focus on virtual machines, the methodologies could be adapted for use with generic migration implementations, too.

One method proposed identifies cyclical workload patterns of VMs and leverages this to delay migration when it is beneficial. This is achieved by analyzing recurring patterns that may unnecessarily postpone VM migration, and then constructing a model of optimal cycles within which VMs can be migrated. In the context of VM migration, such cycles could for example be triggered by a large application's garbage collector, which results in numerous changes to VM memory, which could cause the migration to take longer.

Streams and Pipelines

Streams and pipelines are fundamental constructs that enable efficient, sequential processing of large datasets without the need for loading an entire dataset into memory. They form the backbone of modular and efficient data processing techniques, with each concept having its unique characteristics and use cases.

A stream represents a continuous sequence of data, serving as a connector between different points in a system. Streams can be either a source or a destination for data. Examples include files, network connections, and standard input/output devices and many others. The power of streams comes from their ability to process data as it becomes available; this aspect allows for minimization of memory consumption, making streams particularly useful for scenarios involving long-running processes where data is streamed over extended periods of time[36].

Go

Go is a statically typed, compiled open-source programming language released by Google in 2009. It is typically known for its simplicity, and was developed to address the unsuitability of many traditional languages for modern distributed systems development. Thanks to input from many people affiliated with UNIX, such as Rob Pike and Ken Thompson, as well as good support for concurrency, Go is particularly popular for the development of cloud services and other types of network programming. The headline feature of Go is “Goroutines”, a lightweight feature that allows for concurrent function execution similarly to threads, but is more scalable to support millions of Goroutines per program. Synchronization between different Goroutines is provided by using channels, which are type- and concurrency-safe conduits for data[38].

gRPC and Protocol Buffers

gRPC is an open-source, high-performance remote procedure call (RPC) framework developed by Google in 2015. It is recognized for its cross-platform compatibility, supporting a variety of languages including Go, Rust, JavaScript and more. gRPC is being maintained by the Cloud Native Computing Foundation (CNCF), which ensures vendor neutrality.

One of the notable features of the gRPC is its usage of HTTP/2 as the transport protocol. This allows it to benefit from features of HTTP/2 such as header compression, which minimizes bandwidth usage, and request multiplexing, enabling multiple requests to be sent concurrently over a single connection. In addition to HTTP/2, gRPC utilizes Protocol Buffers (Protobuf), more specifically proto3, as the Interface Definition Language (IDL) and wire format. Protobuf is a compact, high-performance, and language-neutral mechanism

fRPC and Polyglot

fRPC is an open-source RPC framework released by Loophole labs in 2022. It is proto3-compatible, meaning that it can be used as a drop-in replacement for gRPC, promising better performance characteristics. A unique feature is its ability to stop the RPC system to retrieve an underlying connection, which makes it possible to re-use connections for different purposes[40]. Internally, it uses Frisbee as it's messaging framework to implement the request-response semantics[41], and Polyglot, a high-performance serialization framework, as it's Protobuf equivalent. Polyglot achieves a similar goal as Protobuf, which is to encode data structures in a platform-independent way, but does so with less legacy code and a simpler wire format. It is also language-independent, with implementations for Go, Rust and TypeScript[42].

Redis

Redis (Remote Dictionary Server) is an in-memory data structure store, primarily utilized as an ephemeral database, cache, and message broker introduced by Salvatore Sanfilippo in 2009. Compared to other key-value stores and NoSQL databases, Redis supports a multitude of data structures, including lists, sets, hashes, and bitmaps, making it a good choice for caching or storing data that does not fit well into a traditional SQL architecture[43].

One of the primary reasons for Redis's speed is its usage of in-memory data storage rather than on disk, enabling very low-latency reads and writes. While the primary use case of Redis is in in-memory operations, it also supports persistence by flushing data to disk. This feature broadens the use cases for Redis, allowing it to handle applications that require longer-term data storage in addition to a caching mechanism

S3 and Minio

S3 is a scalable object storage service, especially designed for large-scale applications with frequent reads and writes. It is one of the prominent services offered by Amazon Web Services (AWS). S3's design allows for global distribution, which means the data can be stored across multiple geographically diverse servers. This permits fast access times from virtually any location on the globe, which is important for globally distributed services or applications with users spread across different continents.

It offers a variety of storage classes for different needs, i.e. for whether the requirement is for frequent data access, infrequent data retrieval, or long-term archival. This ensures that it can meet a wide array of demands through the same HTTP API. S3 also comes equipped with comprehensive security features, including authentication and authorization mechanisms. Access

Cassandra and ScylllaDB

Apache Cassandra is a wide-column NoSQL database tailored for large-scale, distributed data management tasks. It is known for its scalability, designed to handle large amounts of data spread across numerous servers. Unique to Cassandra is the absence of a single point of failure, which is critical for systems requiring high uptime guarantees. Cassandra's consistency model is adjustable according to needs, ranging from eventual to strong consistency. It does not require master nodes due to its usage of a peer-to-peer protocol and a distributed hash ring design; these design choices eradicate the bottlenecks and failure risks associated with other archictures[47].

Despite these capabilities, Cassandra does come with certain limitations. Under heavy load, it demonstrates high latency, which can negatively affect performance. Besides this, it also demands complex configuration and fine-tuning to perform

Planning

Pull-Based Synchronization With userfaultfd

userfaultfd is a technology that allows for the implementation of a post-copy migration scenario. In this setup, a memory region is created on the destination host. When the migrated application starts to read from this remote region after it was resumed, it triggers a page fault, which can be resolved by fetching the relevant offset from the remote.

Typically, page faults are resolved by the kernel. While this makes sense for use cases where they can be resolved by loading a local resource into memory, here page faults are handled using a user space program instead. Traditionally, this is possible by registering a signal handler for the SIGSEGV signal, and then responding to the fault from the program. This however is a fairly complicated and inefficient process; instead, the userfaultfd system can be used to register a page fault handler directly without having to go through a signal first.

Push-Based Synchronization With mmap and Hashing

As mentioned before, mmap allows mapping a memory region to a file. Similarly to how a region registered with userfaultfd can be used to store the state or application which is being migrated, mmap can be used to do the same. Since the region is linked to a file, when writes happen to the region, they will also be written to the corresponding file. If it is possible to detect these writes and copy the changes to the destination host, this setup can be used to implement a pre-copy migration system.

While writes done to a mmaped region are eventually being written back to the underlying file, this is not the case immediately, since the kernel still uses caching on a mmaped region in order to speed up reads/writes. As a workaround, the msync syscall can be used, which works similarly to the sync syscall by flushing any remaining changes from the cache to the backing file.

Push-Pull Synchronization with FUSE

Using a file system in user space (FUSE) can serve as the basis for implementing either a pre- or a post-copy live migration system. Similarly to the file-based pre-copy approach, mmap can be used to map the migrated resource's memory region to a file. Instead of storing this file on the system's default file system however, a custom file system is implemented, which allows removing the expensive polling system. Since a custom file system allows catching reads (for a post-copy migration scenario, were reads would be responded to by fetching from the remote), writes (for a pre-copy scenario, where writes would be forwarded to the destination) and other operations by the kernel, the use of inotify is no longer required.

While implementing such a custom file system in the kernel is possible, it is a complex task that requires writing a custom kernel module, using a supported language by the kernel

Mounts with NBD

Another mmap-based approach for both pre- and post-copy migration is to mmap a block device instead of a file. This block device can be provided through a variety of APIs, most notably NBD.

By providing a NBD device through the kernel's NBD client, the device can be connected to a remote NBD server, which hosts the resource as a memory region. Any reads/writes from/to the mmaped memory region are resolved by the NBD device, which forwards it to the client, which then resolves them using the remote server; as such, this approach is less so a synchronization (as the memory region is never actually copied to the destination host), but rather a mount of a remote memory region over the NBD protocol.

From an initial overview, the biggest benefit of mmaping such a

Overview

This approach also leverages mmap and NBD to handle reads and writes to the resource's memory region, similarly to the prior approaches, but differs from mounts with NBD in a few significant ways.

Usually, the NBD server and client don't run on the same system, but are instead separated over a network. This network commonly a LAN, and the NBD protocol was designed to access a remote hard drive in this network environment. As a result of the protocol being designed for these low-latency, high-throughput characteristics, there are a few limitations of the NBD protocol when it is being used in a WAN, an environment that can not guarantee the characteristics.

While most wire security issues with the protocol can be worked around by simply using (m)TLS, the big issue of its latency

Chunking

An additional issue that was mentioned before that this approach can approve upon is better chunking support. While it is possible to specify the NBD protocol's chunk size by configuring the NBD client and server, this is limited to only 4 KB in the case of Linux's implementation. If the RTT between the backend and the NBD server however is large, it might be preferable to use a much larger chunk size; this used to not be possible by using NBD directly, but thanks to this layer of indirection it can be implemented.

Similarly to the Linux kernel's NBD client, backends themselves might also have constraints that prevent them from working without a specific chunk size, or otherwise require aligned reads. This is for example the case for tape drives, where reads and writes must occur with a fixed block size and on aligned offsets; furthermore, these linear storage devices work the best if

Background Pull and Push

A pre-copy migration system for the managed API is realized in the form of preemptive pulls that run asynchronously in the background. In order to optimize for spatial locality, a pull priority heuristic is introduced; this is used to determine the order in which chunks should be pulled. Many applications and other resources commonly access certain parts of their memory first, so if a resource should be accessible locally as quickly as possible (so that reads go to the local cache filled by the preemptive pulls, instead of having to wait at least one RTT to fetch it from the remote), knowing this access pattern and fetching these sections first can improve latency and throughput significantly.

And example of this can be data that consists of one or multiple headers followed by raw data. If this structure is known, rather than fetching everything linearly in the background, the headers

Overview

Similarly to the managed mount API, the migration API tracks changes to the memory of the resource using NBD. As mentioned before however, the managed mount API is not optimized for the migration use case, but rather for efficiently accessing a remote resource. For live migration, one metric is very important: maximum acceptable downtime. This refers to the time that an application, VM etc. must be suspended or otherwise prevented from writing to or reading from the resource that is being synchronized; the higher this value is, the more noticeable the downtime becomes.

To improve on this the pull-based migration API, the migration process is split into two distinct phases. This is required due the constraint mentioned earlier; the mount API does not allow for safe concurrent access of a remote resource by two readers or writers at the same time. This poses a significant problem for

Migration Protocol and Critical Phases

The migration protocol that allows for this defines two new actors: The seeder and the leecher. A seeder represents a resource that can be migrated from or a host that exposes a resource, while the leecher represents a client that intents to migrate a resource to itself. The protocol starts by running an application with the application's state on the region mmaped to the seeder's block device, similarly to the managed mount API. Once a leecher connects to the seeder, the seeder starts tracking any writes to its mount, effectively keeping a list of dirty chunks. Once tracking has started, the leecher starts pulling chunks from the seeder to its local cache. After it has received a satisfactory level of locally available chunks, it asks the seeder to finalize. This then causes the seeder to suspend the app accessing the memory region on its block device, msync/flushes it, and returns a list of chunks that were changed

Implementation

Registration and Handlers

By listening to page faults, it is possible to know if a process wants to access a specific offset of memory that is not yet available. As mentioned before, this event can be used to then fetch this chunk of memory from the remote, mapping it to the offset on which the page fault occurred, thus effectively only fetching data when it is required. Instead of registering signal handlers, can use the userfaultfd system introduced with Linux 4.3[50] can also be used to handle these faults in user space in a more idiomatic way.

In the Go implementation created for this thesis, userfaultfd−go[51], userfaultfd works by first creating a region of memory, e.g. by using mmap, which is then registered with the userfaultfd API:

```
// Creating the `userfaultfd` API
```

userfaultfd Backends

Thanks to userfaultfd being mostly useful for post-copy migration, the backend can be simplified to a simple pull-only reader interface (ReadAt(p []byte, off int64) (n int, err error)). This means that almost any io.ReaderAt can be used to provide chunks to a userfaultfd-registered memory region, and access to this reader is guaranteed to be aligned to system's page size, which is typically 4 KB. By having this simple backend interface, and thus only requiring read-only access, it is possible to implement the migration backend in many ways. A simple backend can for example return a pattern to the memory region:

```
func (a abcReader) ReadAt(p []byte, off int64) (n i
    n = copy(p, bytes.Repeat([]byte{'A' + byte(off%

    return n, nil
```

Caching Restrictions

As mentioned earlier, this approach uses mmap to map a memory region to a file. By default, however, mmap doesn't write back changes to memory; instead, it simply makes the backing file available as a memory region, keeping changes to the region in memory, no matter whether the file was opened as read-only or read-writable. To work around this, Linux provides the MAP_SHARED flag; this tells the kernel to eventually write back changes to the memory region to the corresponding regions of the backing file.

Linux caches read to the backing file similarly to how it does if read etc. are being used, meaning that only the first page fault would be responded to by reading from disk; this means that any future changes to the backing file would not be represented in the mmaped region, similarly to how userfaultfd handles it. The same applies to writes, meaning that in the same way that

Detecting File Changes

In order to actually watch for changes, at first glance, the obvious choice would be to use inotify, which would allow the registration of write or sync event handlers to catch writes to the memory region by registering them on the backing file. As mentioned earlier however, Linux doesn't emit these events on mmaped files, so an alternative must be used; the best option here is to instead poll for either attribute changes (i.e. the "Last Modified" attribute of the backing file), or by continuously hashing the file to check if it has changed. Hashing continuously with this polling method can have significant downsides, especially in a migration scenario, where it raises the guaranteed minimum latency by having to wait for at least the next polling cycle. Hashing the entire file is also an I/O- and CPU-intensive process, because in order to compute the hash, the entire file needs to be read at some point. Within the

Synchronization Protocol

The delta synchronization protocol for this approach is similar to the one used by rsync, but simplified. It supports synchronizing multiple files at the same time by using the file names as IDs, and also supports a central forwarding hub instead of requiring peer-to-peer connectivity between all hosts, which also reduces network traffic since this central hub could also be used to forward one stream to all other peers instead of having to send it multiple times. The protocol defines three actors: The multiplexer, file advertiser and file receiver.

Multiplexer Hub

The multiplexer hub accepts mTLS connections from peers. When a peer connects, the client certificate is parsed to read the common name, which is then being used as the synchronization ID. The multiplexer spawns a Goroutine to allow for more peers to connection. In the Goroutine, it reads the type of the peer. If the type is src−control, it starts by reading a file name from the connection, and registers the connection as the one providing a file with this name, after which it broadcasts the file as now being available. For the dst−control peer type, it listens to the broadcasted files from the src−control peers, and relays and newly advertised and previously registered file names to the dst−control peers so that it can start receiving them:

```
case "src−control":
    // Decoding the file name
    file := ""
```

File Advertisement and Receiver

The file advertisement system connects to the multiplexer hub and registers itself a src−control peer, after which it sends the advertised file name. It starts a loop that handles dst peer types, which, as mentioned earlier, send an ID. Once such an ID is received, it spawns a new Goroutine, which connects to the hub again and registers itself as a src−data peer, and sends the ID it has received earlier to allow connecting it to the matching dst peer. After this initial handshake is complete, the main synchronization loop is started, which initiates the file transmission to the dst peer through the multiplexer hub. In order to allow for termination, it checks if a flag has been set by a context cancellation which case it returns. If this is not the case, it waits for the specified polling interval, after which it restarts the transmission.

The file receiver also connects to the multiplexer hub, this time

File Transmission

This component does the actual transmission in each iteration of the delta synchronization algorithm. It receives the remote hashes from the multiplexer hub, calculates the matching local hashes and compares them, which it sends the hashes that don't match back to the file receiver via the multiplexer hub:

```
// Receiving remote hashes
remoteHashes := []string{}
utils.DecodeJSONFixedLength(conn, &remoteHashes)
// ...

// Calculating the hashes
localHashes, cutoff, err := GetHashesForBlocks(para

// Comparing the hashes
blocksToSend := []int64{}
```

Hash Calculation

The hash calculation implements the concurrent hashing of both the file transmitter and receiver. It uses a semaphore to limit the amount of concurrent access to the file that is being hashed, and a wait group to detect that the calculation has finished. Worker Goroutines acquire a lock of this semaphore and calculate a CRC32 hash, which is a weak but fast hashing algorithm. For easier transmission, the hashes are hex-encoded and collected:

```
// The lock and semaphore
var wg sync.WaitGroup
wg.Add(int(blocks))

lock := semaphore.NewWeighted(parallel)

// ...
```

File Reception

This is the receiving component of one delta synchronization iteration. It starts by calculating hashes for the existing local copy of the file, which it then sends to the remote before it waits to receive the remote's hashes and potential truncation request:

```
// Local hash calculation
localHashes, _, err := GetHashesForBlocks(parallel,
// Sending the hashes to the remote
// Receiving the remote hashes and the truncation r
blocksToFetch := []int64{}
utils.DecodeJSONFixedLength(conn, &blocksToFetch)
// ...
cutoff := int64(0)
utils.DecodeJSONFixedLength(conn, &cutoff)
```

If the remote detected that the file needs to be cleared (by

FUSE Implementation in Go

Implementing a FUSE in Go can be split into two separate tasks: Creating a backend for a file abstraction API and creating an adapter between this API and a FUSE library.

Developing a backend for a file system abstraction API such as afero.Fs instead of implementing it to work with FUSE bindings directly offers several advantages. This layer of indirection allows splitting the FUSE implementation from the actual inode structure of the system, which makes it unit testable[52]. This is a high priority due to the complexities and edge cases involved with creating a file system. A standard API also offers the ability to implement things such as caching by simply nesting multiple afero.Fs interfaces, and the required interface is rather minimal[53]:

```
type Fs interface {
```

Overview

Due to a lack of existing, lean and maintained NBD libraries for Go, a custom pure Go NBD library was implemented[56]. Most NBD libraries also only provide a server and not the client component, but both are needed for the NBD-/mount-based migration approach to work. By not having to rely on CGo or a pre-existing NBD library like nbdkit, this custom library can also skip a significant amount of the overhead that is typically associated with C interoperability, particularly in the context of concurrency in Go with CGo[57].

Server

The NBD server is implemented completely in user space, and there are no kernel components involved. The backend interface that is expected by the server is very simple and only requires four methods to be implemented; ReadAt, WriteAt, Size and Sync:

```
type Backend interface {
    ReadAt(p []byte, off int64) (n int, err error)
    WriteAt(p []byte, off int64) (n int, err error)
    Size() (int64, error)
    Sync() error
}
```

The key difference between this backend design and the one used for userfaultfd−go is that it also supports writes and other operations that would typically be expected for a

Client

Unlike the server, the client is implemented by using both the kernel's NBD client and a user space component. In order to use the kernel NBD client, it is necessary to first find a free NBD device (/dev/nbd∗); these devices are allocated by the kernel NBD module and can be specified with the nbds_max parameter[59]. In order to find a free device, it can be specified manually, or check sysfs for a NBD device that reports a zero size. After a free NBD device has been found, the client can be started by calling Connect with a net.Conn and options, similarly to the server.

```
func Connect(conn net.Conn, device *os.File, option
```

The options can define additional information such as the client's preferred block size, connection timeouts or requested export name, which, in this scenario, can be used to refer to a

Client Lifecycle

The final DO_IT ioctl never returns until it is disconnected, meaning that an external system must be used to detect whether the device is actually ready. There are two fundamental ways of doing this: By polling sysfs for the size parameter as it was done for finding an unused NBD device, or by using udev.

udev manages devices in Linux, and as a device becomes available, the kernel sends an event using this subsystem. By subscribing to this system with the expected NBD device name to catch when it becomes available, it is possible to have a reliable and idiomatic way of detecting the ready state:

```
// Connecting to `udev`
udevConn.Connect(netlink.UdevEvent)


// Subscribing to events for the device name
```

Optimizing Access to the Block Device

When opening the block device that the client is connected to, the kernel usually provides a caching/buffer mechanism, requiring an expensive sync syscall to flush outstanding changes to the NBD client. By using O_DIRECT it is possible to skip this caching layer and write all changes directly to the NBD client and thus the server, which is particularly useful in a case where both the client and server are on the same host, and the amount of time for syncing should be minimal, as is the case for a migration scenario. Using O_DIRECT however does come with the downside of requiring reads/writes that are aligned to the system's page size, which is possible to implement in the specific application using the device to access a resource, but not in a generic way.

Combining the NBD Client and Server to a Mount

When both the client and server are started on the same host, it is possible to connect them efficiently by creating a connected UNIX socket pair, returning a file descriptor for both the server and the client respectively, after which both components can be started in a new Goroutine. This highlights the benefit of not requiring a specific transport layer or accept semantics for the NBD library, as it is possible to skip the usually required handshakes.

This form of a combined client and server on the local device, with the server's backend providing the actual resource, forms a direct path mount - where the path to the block device can be passed to the application consuming or providing the resource, which can then choose to open, mmap etc. it. In addition to this simple path-based mount, a file mount is provided. This simply opens up the path as a file, so that it can be accessed

Stages

In order to implement a chunking system and related components, a pipeline of readers/writers is a useful abstraction layer; as a result, the mount API is based on a pipeline of multiple ReadWriterAt stages:

```
type ReadWriterAt interface {
    ReadAt(p []byte, off int64) (n int, err error)
    WriteAt(p []byte, off int64) (n int, err error)
}
```

This way, it is possible to forward calls to the NBD backends like Size and Sync directly to the underlying backend, but can chain the ReadAt and WriteAt methods, which carry actual data, into a pipeline of other ReadWriterAts.

Chunking

One such ReadWriterAt is the ArbitraryReadWriterAt. This chunking component allows breaking down a larger data stream into smaller chunks at aligned offsets, effectively making every read and write an aligned operation. In ReadAt, it calculates the index of the chunk that the currently read offset falls into as well as the offset within the chunk, after which it reads the entire chunk from the backend into a buffer, copies the requested portion of the buffer into the input slice, and repeats the process until all requested data is read:

```
totalRead := 0
remaining := len(p)

buf := make([]byte, a.chunkSize)
// Repeat until all chunks that need to be fetched
for remaining > 0 {
```

Background Pull

The Puller component asynchronously pulls chunks in the background. It starts by sorting the chunks with the pull heuristic mentioned earlier, after which it starts a fixed number of worker threads in the background, each which ask for a chunk to pull:

```
// Sort the chunks according to the pull priority c
sort.Slice(chunkIndexes, func(a, b int) bool {
    return pullPriority(chunkIndexes[a]) > pullPrio
})

// ...

for {
    // Get the next chunk
    chunk := p.getNextChunk()
```

Background Push

In order to also allow for writes back to the remote source host, the background push component exists. Once it has been opened, it schedules recurring writebacks to the remote by calling Sync; once this is called by either the background worker system or another component, it launches writeback workers in the background. These wait to receive a chunk that needs to be written back; once they receive one, they read it from the local ReadWriterAt and copy it to the remote, after which the chunk is marked as no longer requiring a writeback:

```
// Wait until the worker gets a slot from a semapho
p.workerSem <- struct{}{}

// First fetch from local ReaderAt, then copy to re
b := make([]byte, p.chunkSize)
p.local.ReadAt(b, off)
```

Pipeline

For the direct mount system, the NBD server was connected directly to the remote; managed mounts on the other hand have an internal pipeline of pullers, pushers, a syncer, local and remote backends as well as a chunking system.

Using such a pipeline system of independent stages and other components also makes the system very testable. To do so, instead of providing a remote and local ReadWriterAt at the source and drain of the pipeline respectively, a simple in-memory or on-disk backend can be used in the unit tests. This makes the individual components unit-testable on their own, as well as making it possible to test and benchmark edge cases (such as reads that are smaller than a chunk size) and optimizations (like different pull heuristics) without complicated setup or teardown procedures, and without having to initialize the complete pipeline.

Concurrent Device Initialization

The background push/pull components allow pulling from the remote pipeline stage before the NBD device itself is open. This is possible because the device doesn't need to start accessing the data in a post-copy sense to start the pull, and means that the pull process can be started as the NBD client and server are still initializing. Both components typically start quickly, but the initialization might still take multiple milliseconds. Often, this amounts to roughly one RTT, meaning that making this initialization procedure concurrent can significantly reduce the initial read latency by preemptively pulling data. This is because even if the first chunks are being accessed right after the device has been started, they are already available to be read from the local backend instead of the remote, since they have been pulled during the initialization and thus before the mount has even been made available to application.

Device Lifecycles

Similarly to how the direct mount API used the basic path mount to build the file and slice mounts, the managed mount API provides the same interfaces. In the case of managed mounts however, this is even more important, since the synchronization lifecycle needs to be taken into account. For example, in order to allow the Sync() API to work, the mmaped region must be msynced before the SyncedReadWriterAt's Sync() method is called. In order to support these flows without tightly coupling the individual pipeline stages, a hooks system exists that allows for such actions to be registered from the managed mount, which is also used to implement the correct lifecycle for closing/tearing down a mount:

```
type ManagedMountHooks struct {
    OnBeforeSync func() error
    OnBeforeClose func() error
```

WAN Optimization

While the managed mount system functions as a hybrid pre- and post-copy system, optimizations are implemented that make it more viable in a WAN scenario compared to a typical pre-copy system by using a unidirectional API. Usually, a pre-copy system pushes changes to the destination host. In many WAN scenarios however, NATs prevent a direct connection. Since the source host needs to keep track of which chunks have already been pulled, the system also becomes stateful on the source host and events such as network outages need to be recoverable from.

By using the pull-only, unidirectional API to emulate the pre-copy setup, the destination can simply keep track of which chunks it still needs to pull itself, meaning that if there is a network outage, it can resume pulling or decide to restart the pre-copy process. Unlike the pre-copy system used for the file

Overview

As mentioned in Pull-Based Synchronization with Migrations earlier, the mount API is not optimal for a migration scenario. Splitting the migration into two discrete phases (see figure 6) can help fix the biggest problem, the maximum guaranteed downtime; thanks to the flexible pipeline system of ReadWriterAts, a lot of the code from the mount API can be reused for the migration, even if the API and corresponding wire protocol are different.

Seeder

The seeder defines a new read-only RPC API, which, in addition the known ReadAt, also adds new RPCs such as Sync, which is extended to return dirty chunks, as well as Track(), which triggers the new tracking phase:

```
type SeederRemote struct {
    ReadAt func(context context.Context, length int
    Size   func(context context.Context) (int64, er
    Track  func(context context.Context) error
    Sync   func(context context.Context) ([]int64,
    Close  func(context context.Context) error
}
```

Unlike the remote backend, the seeder also exposes a mount through the familiar path, file or slice APIs, meaning that even as the migration is in progress, the underlying resource can still

Leecher

The leecher then takes this abstract service struct provided by the seeder, which is implemented by an RPC framework. Using this, as soon as the leecher is opened, it calls Track() in the background and starts the NBD device in parallel to achieve a similar reduction in initial read latency as the mount API. The leecher introduces a new pipeline stage, the LockableReadWriterAt. This component simply blocks all read and write operations to/from the NBD device until Finalize has been called by using a sync.Cond. This is required because otherwise, stale data (before Finalize marked the chunks as dirty) could have poisoned the kernel's file cache if the application read data before finalization.

Once the leecher has started the device, it sets up a syncer in the same way as the mount API. A callback can again be used to monitor the pull progress, and once the reported availability

Pluggable Encryption, Authentication and Transport

Compared to existing remote memory and migration solutions, r3map is designed for a new field of application: WAN. Most existing systems that provide these solutions are intended to work in high-throughput, low-latency LAN, where assumptions concerning authentication and authorization as well as scalability can be made that are not valid in a WAN deployment. For example encryption: While in trusted LAN networks, it can be a viable option to assume that there are no bad actors in the local subnet, the same can not be assumed for WAN. While depending on i.e. TLS for the APIs would have been a viable option for r3map if it were to only support WAN deployments, it should still be functional and be able to take advantage of the guarantees if it is deployed in a LAN, which is why it is transport agnostic.

This makes adding guarantees such as encryption as simple as

Concurrent Backends

In high-RTT scenarios, the ability to fetch chunks concurrently is important. Without concurrent backgrounds pulls, latency can add up quickly, since every read to an offset of the memory region would have at least one RTT as it's latency, while concurrent pulls allow for multiple offsets' chunks to be pulled at the same time.

The first requirement for supporting this is that the remote backend has to be able to read from multiple regions without globally locking it. For the file backend for example, this is not the case, as a lock needs to be acquired for the entire file before an offset can be accessed:

```
func (b *FileBackend) ReadAt(p []byte, off int64) (
    b.lock.RLock()
    defer b.lock.RUnlock()
```

Overview

RPC backends provide a dynamic way to access a remote backend. This is useful for lots of use cases, esp. if the backend exposes a custom resource or requires custom authorization or caching. For the mount API specifically however, having access to a remote backend that doesn't require a custom RPC system can be useful, since the backend for a remote mount maps fairly well to the concept of a remote random-access storage device, for which many protocols and systems exist already.

Key-Value Stores with Redis

On such option is Redis, an in-memory key-value (KV) store with network access. To implement a mount backend, chunk offsets can be mapped to keys, and since bytes are a valid key type, the chunk itself can be stored directly in the KV store; if keys don't exist, they are simply treated as empty chunks:

```
func (b *RedisBackend) ReadAt(p []byte, off int64)
    // Retrieve a key corresponding to the chunk fro
    val, err := b.client.Get(b.ctx, strconv.FormatI
    // If a key does not exist, treat it as an emp
    if err == redis.Nil {
        return len(p), nil
    }
    // ...
}
```

Object Stores with S3

While Redis is interesting for high-throughput scenarios, when it comes to making a memory region available on the public internet, it might not be the best choice due to its low-level, custom protocol and (mostly) in-memory nature. This is where S3 can be used; a S3 backend can be a good choice for mounting public information, i.e. media assets, binaries, large file systems and more into memory. While S3 has traditionally been mostly an AWS SaaS offering, projects such as Minio have helped it become the de facto standard for accessing files over HTTP. Similarly to the directory backend, the S3 backend is chunked, with one S3 object representing one chunk; if accessing a chunk returns a 404 error, it is treated as an empty chunk in the same way as the Redis backend, and multi-tenancy can once again be implemented either by using multiple S3 buckets or a prefix:

```
func (b *S3Backend) ReadAt(p []byte, off int64) (n
```

Document Databases with ScylllaDB

Another option to access persistent remote resource is a NoSQL database such as Cassandra, specifically ScyllaDB, which improves on Cassandra's latency, a key metric for mounting remote resources. While this backend is more of a proof of concept rather than a real use case, it does show that even a database can be mapped to a memory region, which does allow for the interesting use case of making the databases' contents available directly in memory without having to use a database-specific client. Here, ReadAt and WriteAt are implemented by issues queries through ScylllaDB's DSL, where each row represents a chunk identified by its offset as the primary, and as with Redis and S3, non-existing rows are treated as empty chunks:

```
func (b *CassandraBackend) ReadAt(p []byte, off int
    // Executing a select query for a specific chun
```

Overview

Another aspect that plays an important role in performance for real-life deployments is the choice of RPC framework and transport protocol. As mentioned before, both the mount and migration APIs are transport-independent, and as a result almost any RPC framework can be used. An RPC framework developed as part of r3map is Dudireka[60]. As such, it was designed specifically with the hybrid pre-and post-copy scenario in mind. To optimize for this, it has support for concurrent RPCs, which allows for efficient background pulls as multiple chunks can be pulled at the same time.

The framework also allows for defining functions on both the client and the server, which makes it possible to initiate pre-copy migrations and transfer chunks from the source host to the destination without having the latter be dialable; while making the destination host available by dialing it is possible in

Usage

Dudirekta is reflection based; both RPC definition and calling an RPC are completely transparent, which makes it optimal for prototyping the mount and migration APIs. To define the RPCs to be exposed, a simple implementation struct can be created for both the client and server. In this example, the server provides a simple counter with an increment RPC, while the client provides a simple Println RPC that can be called from the server. Due to protocol limitations, RPCs must have a context as their first argument, not have variadic arguments, and must return either a single value or an error:

```
// Server
type local struct { counter int64 }

func (s *local) Increment(ctx context.Context, delta
    return atomic.AddInt64(&s.counter, delta), nil
```

Protocol

The protocol used for Dudirekta is simple and based on JSONL, a format for exchanging newline-delimited JSON data[62]; a function call, i.e. to Println looks like this:

```
[true, "1", "Println", ["Hello, world!"]]
```

The first element marks the message as a function call, while the second one is the call ID, the third represents the name of the RPC that is being called followed by an array of arguments. A function return messages looks similar:

```
[false, "1", "", ""]
```

Here, the message is marked as a return value in the first element, the ID is passed with the second element and both the actual return value (third element) and error (fourth element) are nil and represented by an empty string. Because it includes

RPC Providers

If an RPC (such as ReadAt in the case of the mount API) is called, a method with the provided RPC's name is looked up on the provided implementation struct and if it is found, the provided argument's types are validated against those of the implementation by unmarshalling them into their native natives. After the call has been validated by the RPC provider, the actual RPC implementation is executed in a new Goroutine to allow for concurrent RPCs, the return and error value of which is then marshalled into JSON and sent back the caller.

In addition to the RPCs created by analyzing the implementation struct through reflection, to be able to support closures, a virtual CallClosure RPC is also exposed. This RPC is provided by a separate closure management component, which handles storing references to remote closure implementations; it also garbage collects those references after

RPC Calls

As mentioned earlier, on the caller's side, a placeholder struct representing the callee's available RPCs is provided to the registry. Once the registry is linked to a connection, the placeholder struct's methods are iterated over and the signatures are validated for compatibility with Dudirekta's limitations. They are then implemented using reflection; these implementations simply marshal and unmarshal the function calls into Dudirekta's JSONL protocol upon being called, effectively functioning as transparent proxies to the remote implementations; it is at this point that unique call IDs are generated in order to be able to support concurrent RPCs:

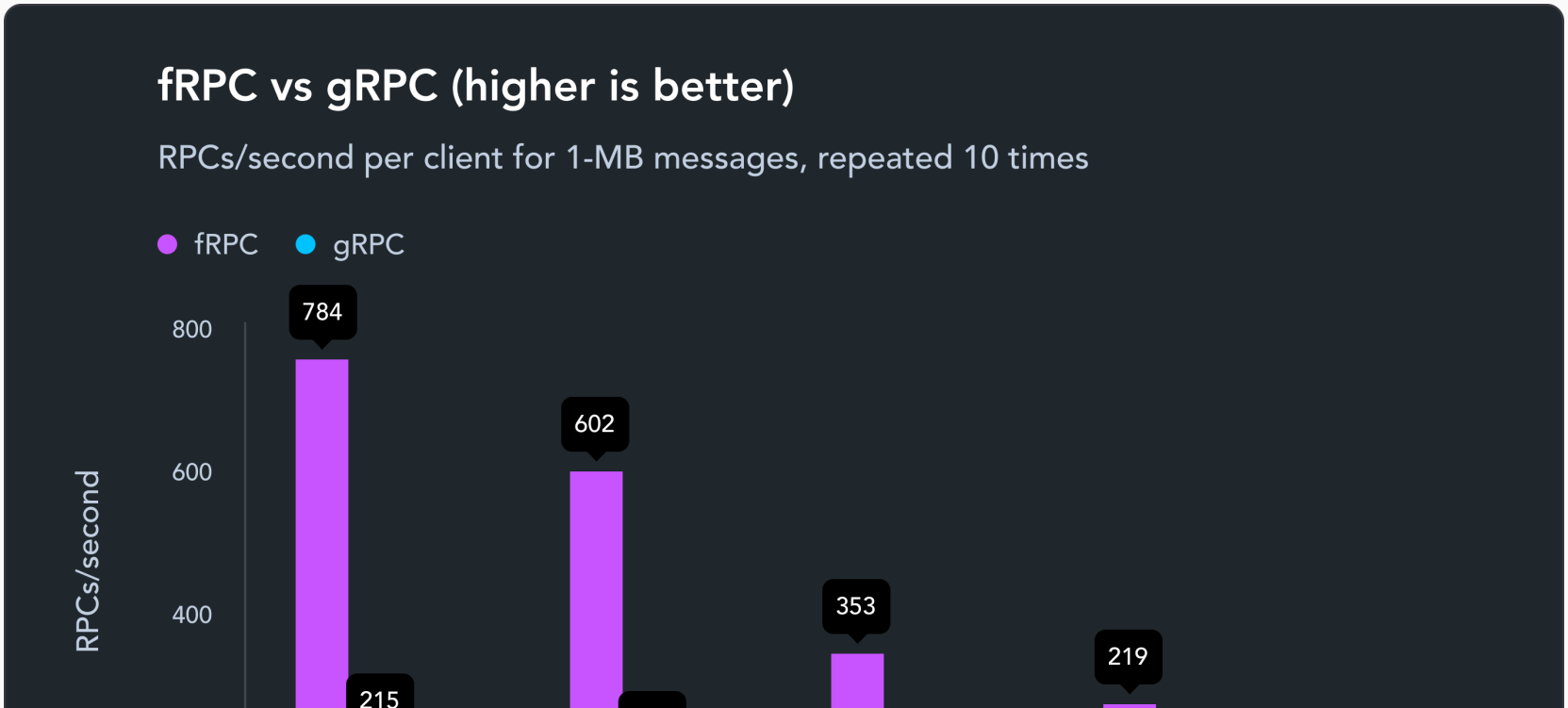
```
// Creating the implementation method
reflect.MakeFunc(functionType, func(args []reflect.
        // Generating a unique call ID
        callID := uuid.NewString()
```

Connection Pooling with gRPC

While the Dudirekta RPC implementation serves as a good reference implementation of how RPC backends work, it has issues with scalability (see figure 23). This is mostly the case because of it's JSONL-based wire format, which, while simple and easy to analyze, is quite slow to serialize. The bidirectional RPCs do also come at a cost, since they prevent an effective use of connection pooling; since a client dialing the server multiple times would mean that server could not reference multiple client connections as one composite client, it would not be able to differentiate two client connections from two separate clients. While implementing a future pooling mechanism based on a client ID is possible in the future, bidirectional RPCs can also be completely avoided entirely by implementing the pull- instead of push-based pre-copy solution described earlier where the destination host keeps track of the pull progress, effectively

Optimizing Throughput with fRPC

While gRPC tends to perform better than Dudirekta due to its support for connection pooling and more efficient binary serialization, it can be improved upon. This is particularly true for protocol buffers, which, while being faster than JSON, have issues with encoding large chunks of data, and can become a real bottleneck with large chunk sizes:



Results

Testing Environment

All benchmarks were conducted on a test machine with the following specifications:

Property	Value
Device Model	Dell XPS 9320
OS	Fedora release 38 (Thirty Eight) x86_64
Kernel	6.3.11-200.fc38.x86_64
CPU	12th Gen Intel i7-1280P (20) @ 4.700GHz
Memory	31687MiB LPDDR5, 6400 MT/s

To make the results reproducible, the benchmark scripts with additional configuration details and notebooks to plot the related visualizations can be found in the accompanying repository[64], and multiple runs have been conducted for each benchmark to ensure consistency.

Latency

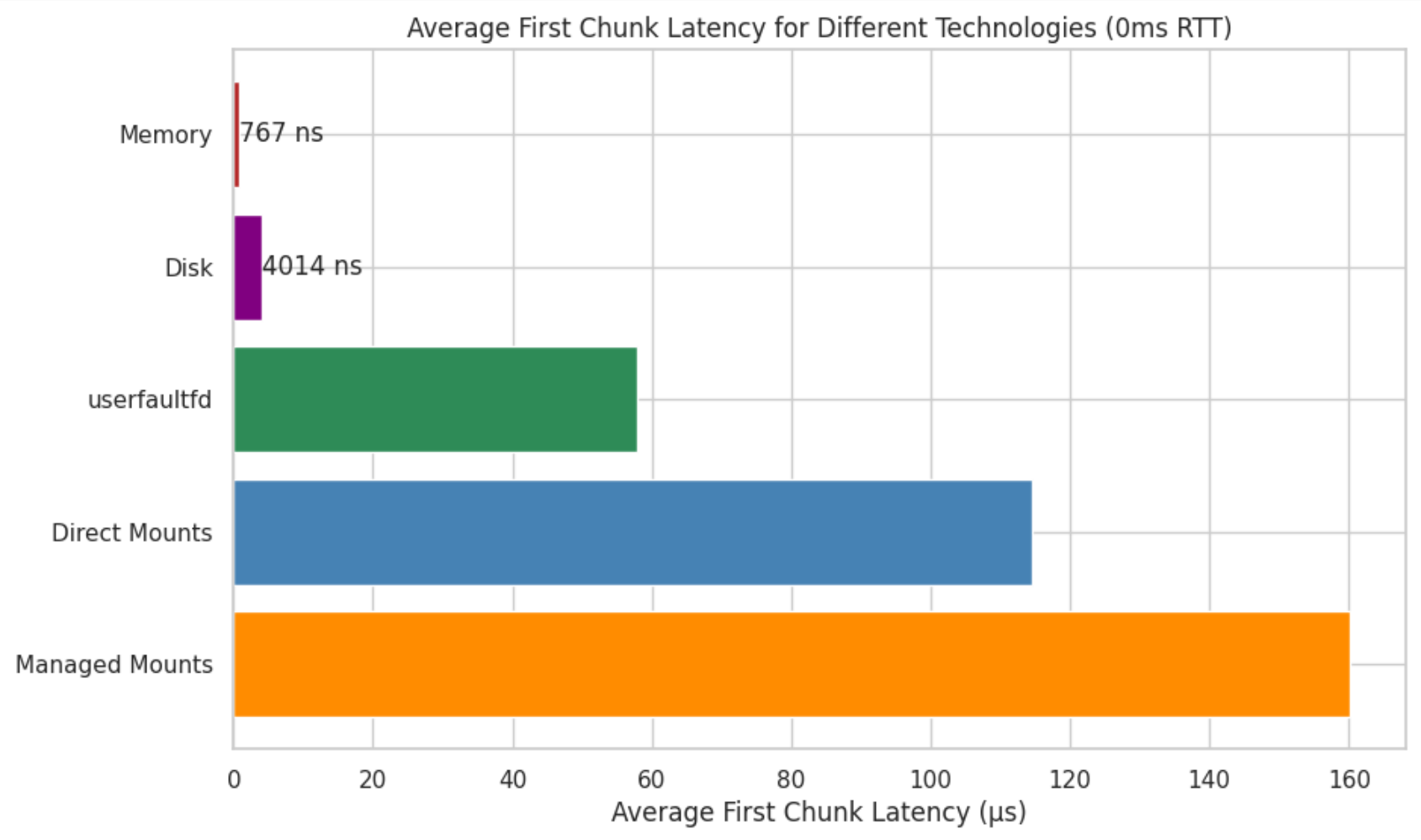


Figure 8: Average first chunk latency for different direct memory access, disk, userfaultfd, direct mounts and managed mounts (0ms RTT)

Read Throughput

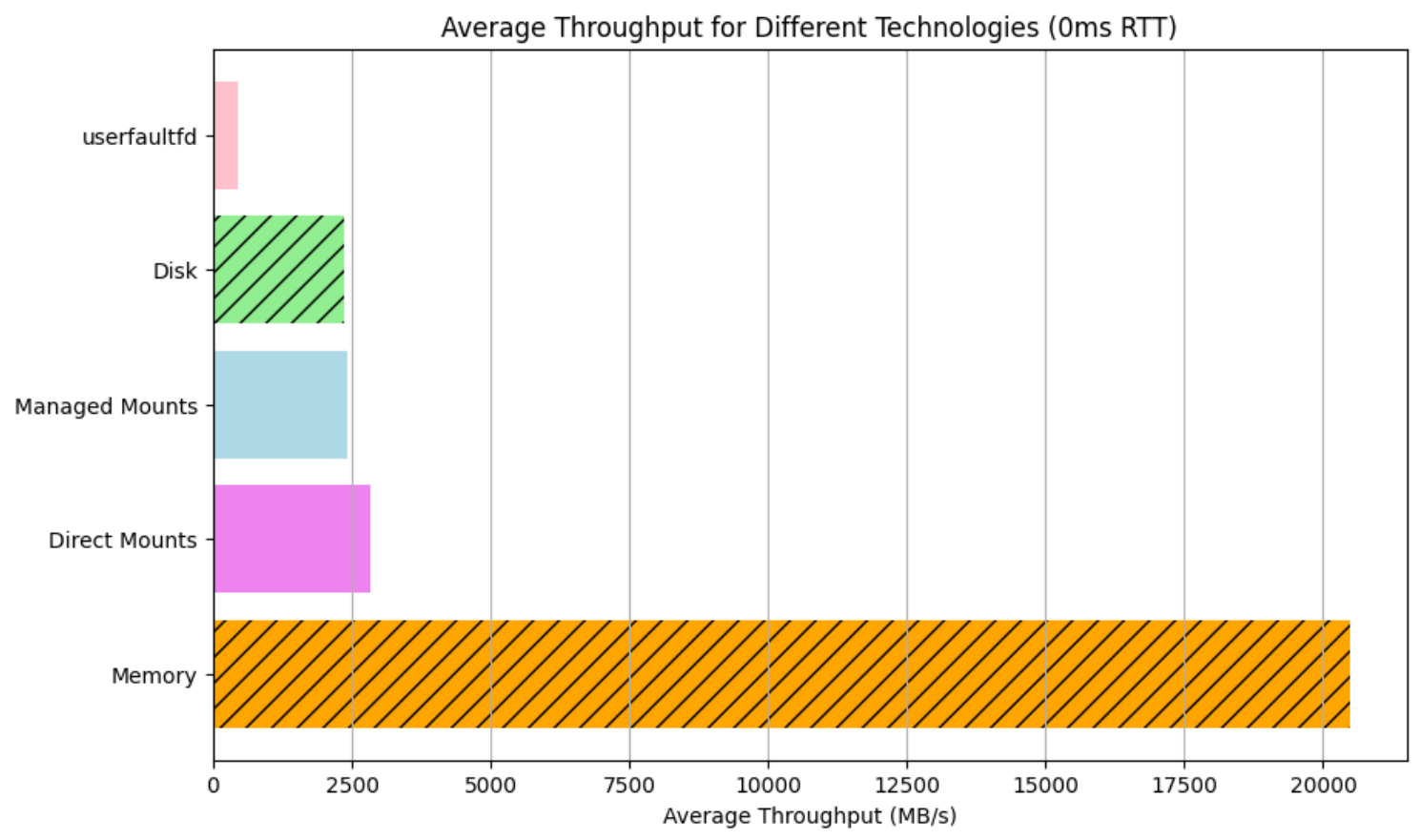


Figure 12: Average throughput for memory, disk, userfaultfd, direct mounts and managed mounts (0ms RTT)

When looking at throughput compared to latency, the trends for memory, disk, userfaultfd and the two mount types are

Write Throughput

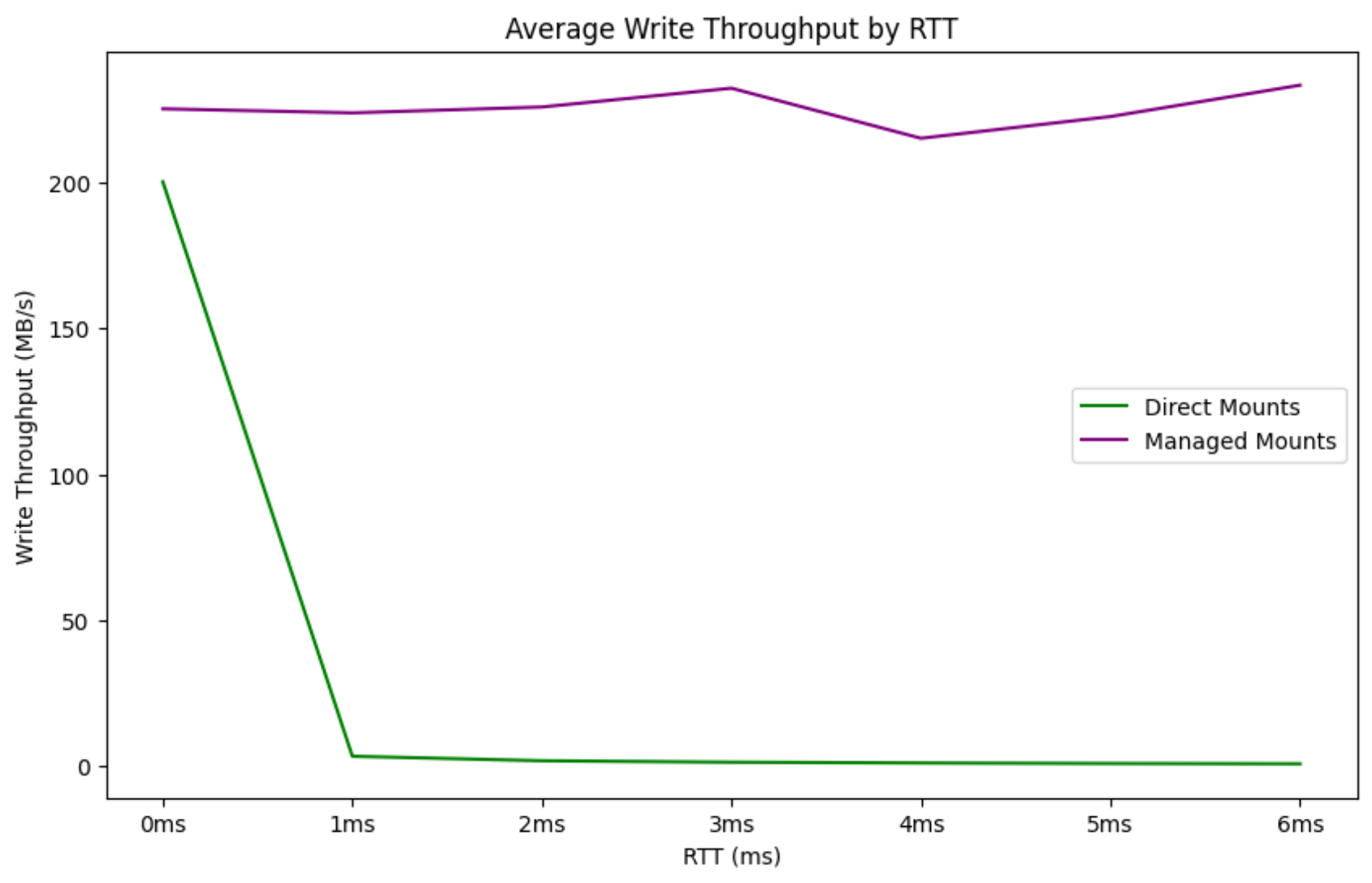


Figure 17: Average write throughput for direct and managed mounts by RTT

Initialization

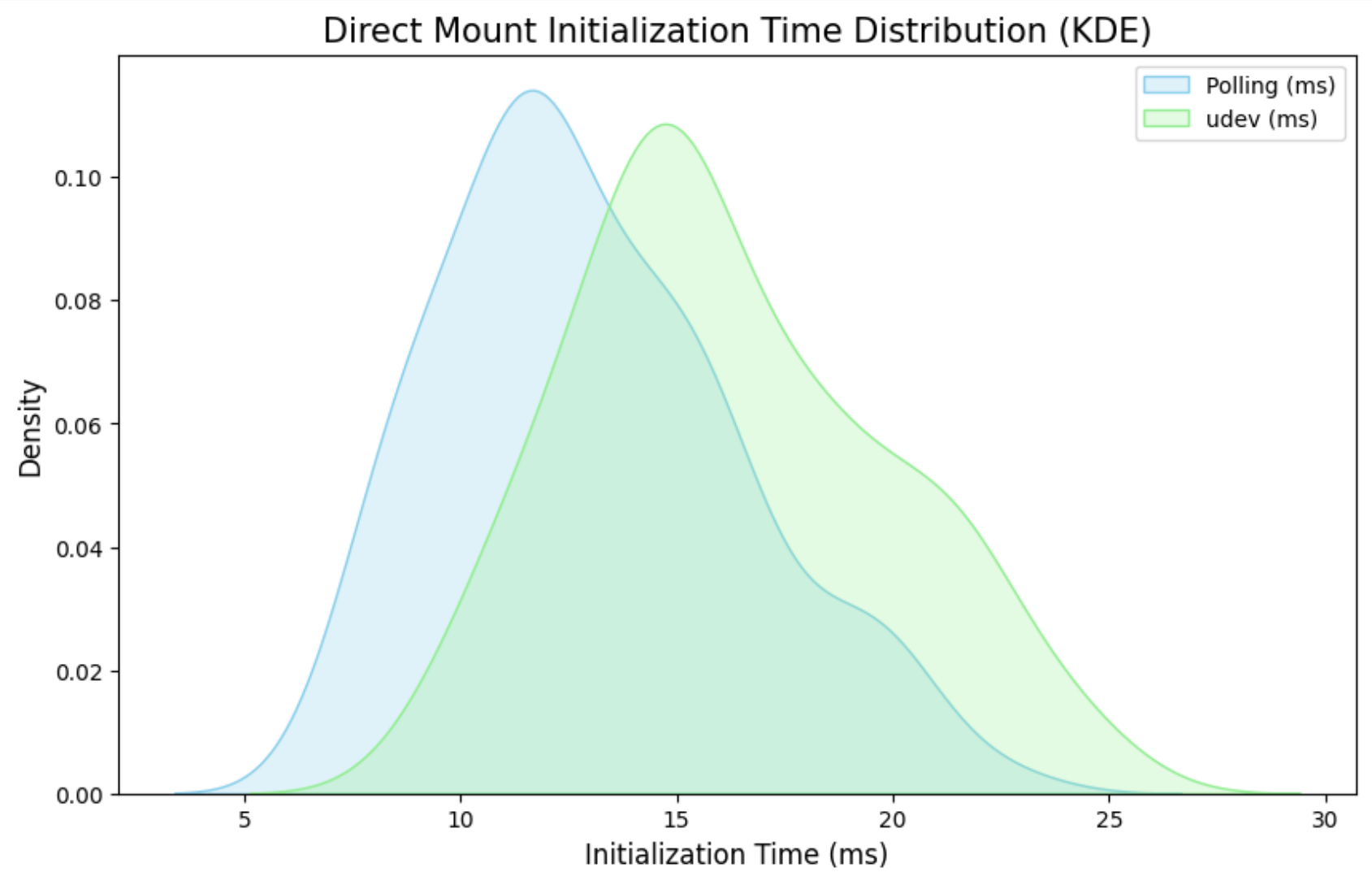


Figure 18: Kernel density estimation for the distribution of direct

Chunking

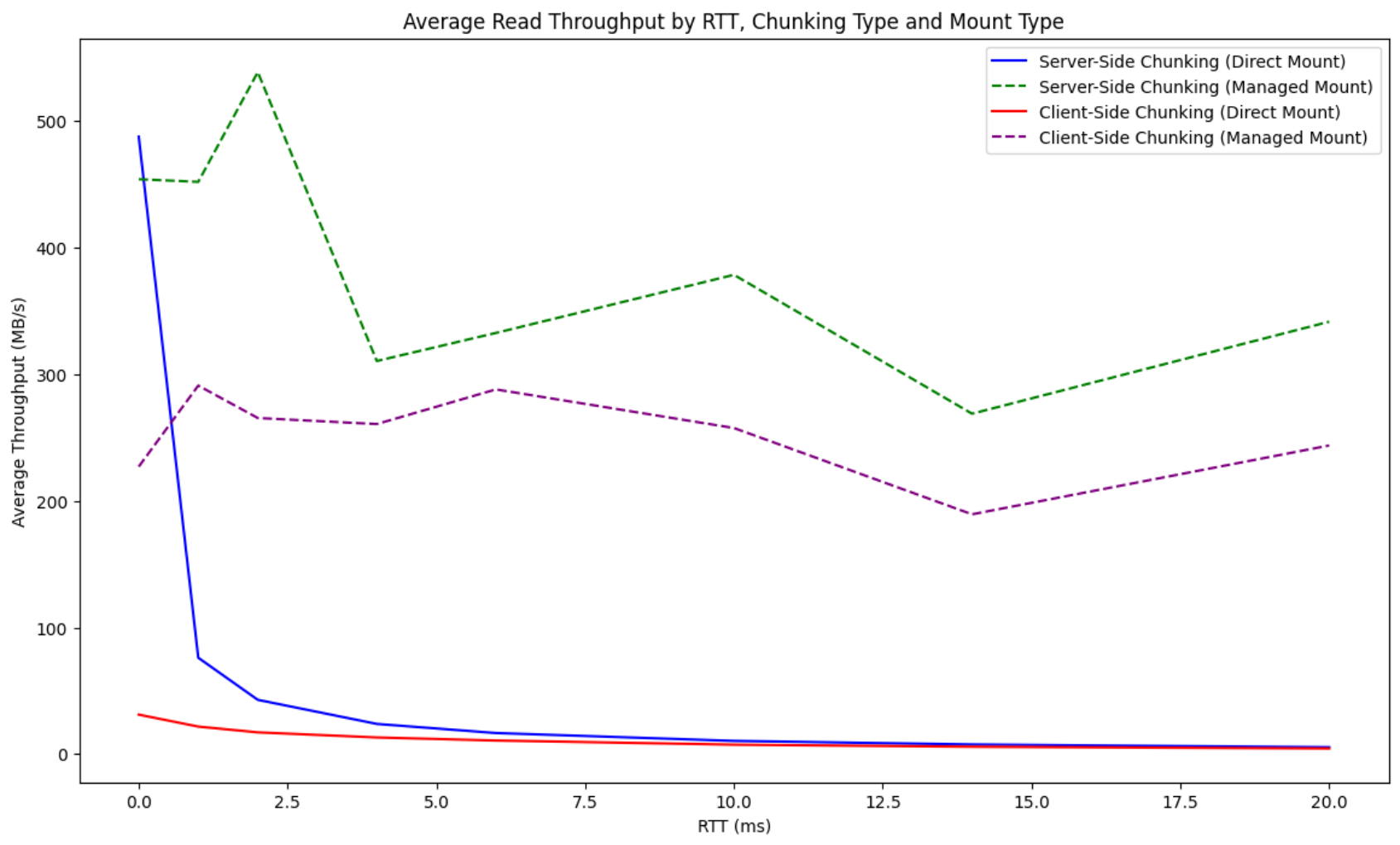


Figure 20: Average read throughput for server-side and client-side chunking, direct mounts and managed mounts by RTT

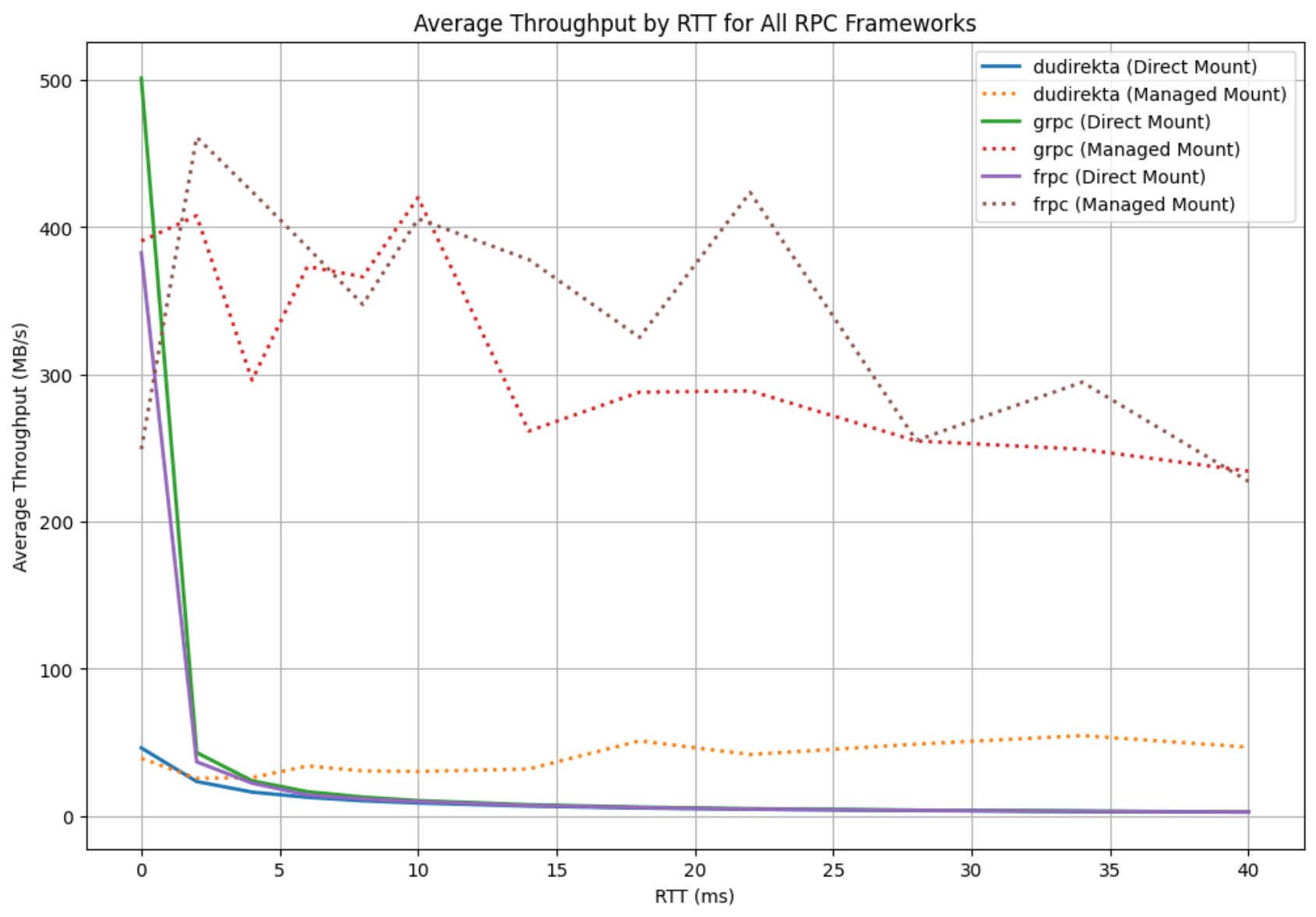
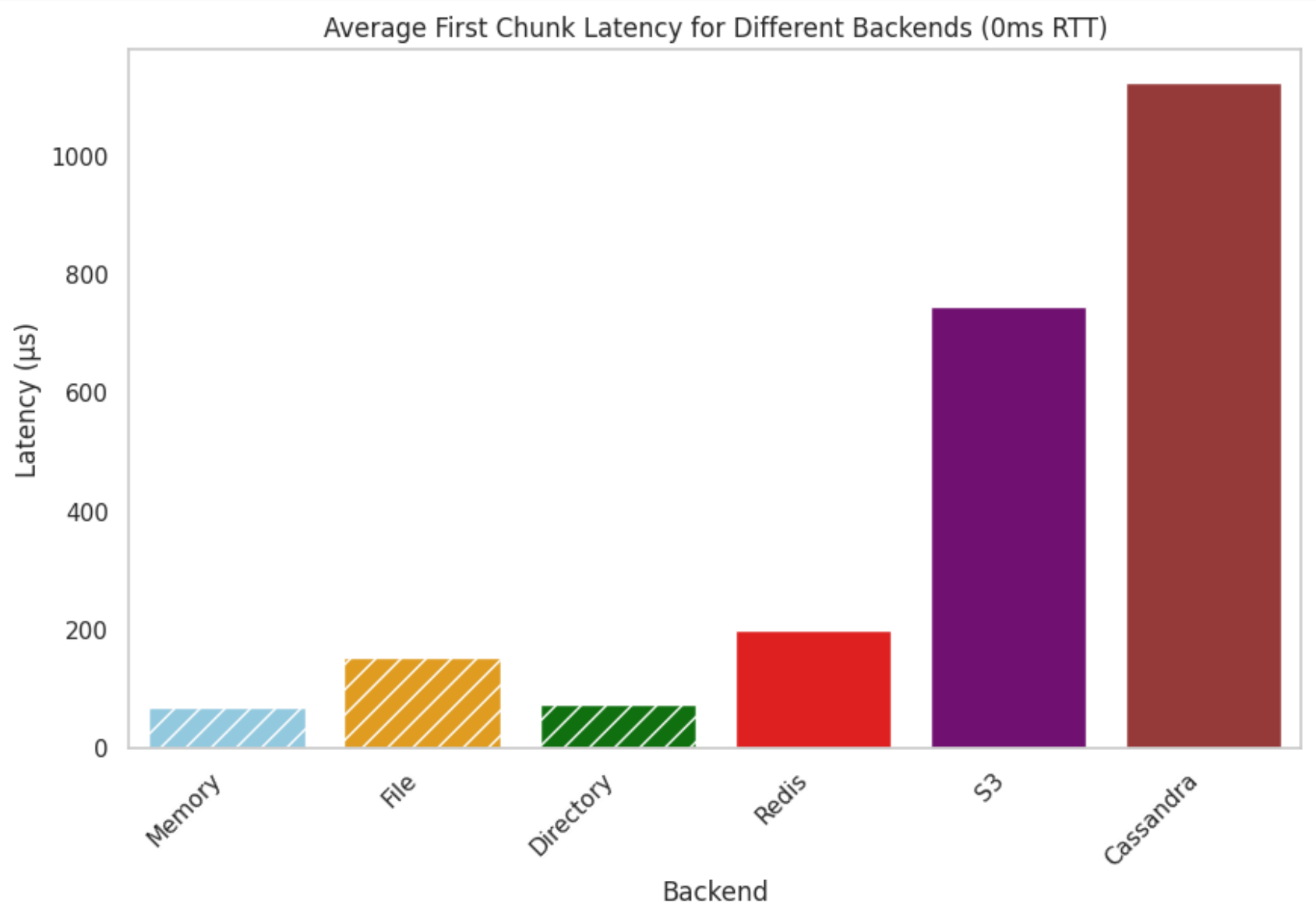


Figure 23: Average throughput by RTT for Dudirekta, gRPC and

Latency


Average First Chunk Latency for Different Backends (0ms RTT)
Latency (µs)
0
200
400
600
800
1000
Memory
File
Directory
Redis
S3
Cassandra
Backend

Throughput

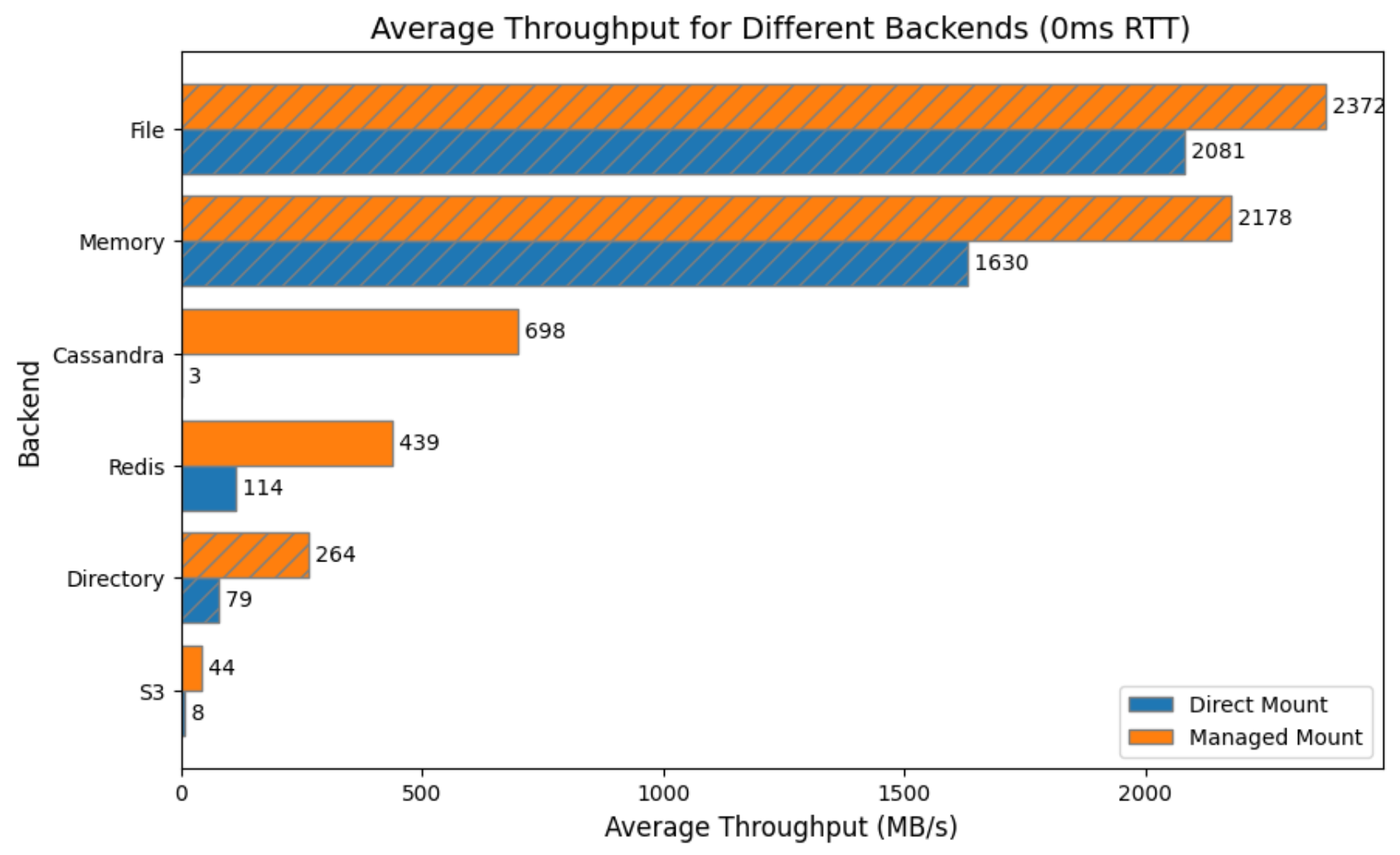


Figure 28: Average throughput for memory, file, directory, Redis, S3 and ScylllaDB backends for direct and managed mounts (0ms RTT)

Discussion

Userfaults

userfaultfd is a simple way to map almost any object into memory. It is a comparatively simple approach, but also has significant architecture-related problems that limit its use. One problem is that it is only able to catch page faults, which means that it can only handle a data request the first time a chunk of memory gets accessed, since all future requests to a memory region handled by userfaultfd will simply return directly from RAM. This prevents the usage of this approach for accessing remote resources that update over time, and also makes it hard to use it for applications with concurrent writers or shared resources, since there would be no way of updating a section with a conflict.

Due to these limitations, userfaultfd is essentially limited to read-only mounts of remote resources, not synchronization. While it could be a viable solution for post-copy migration, it

File-Based Synchronization

Similarly to userfaultfd, the approach based on mmaping a memory region to a file and then synchronizing this file also has limitations. While userfaultfd is only able to catch the first reads to a file, this system is only able to catch wries, making it unsuitable for post-copy migration scenarios. It makes this system write-only, and very inefficient when it comes to adding hosts to the network at a later point, since all data needs to be continuously synchronized to all other hosts that state could potentially be migrated too.

To work around this issue, a central forwarding hub can be used, which reduces the amount of data streams required from the host currently hosting the data, but also adds other drawbacks such as operational complexity and additional latency. Still, thanks to this support for the central forwarding hub, file-based synchronization might be a good choice for

FUSE

File systems in user space provide a solution that allows for both pre- and post-copy migration, but doesn't come without downsides. As it operates in user space, it depends on context switching, which does add additional overhead compared to a file system implementation in kernel space. While some advanced file system features like inotify and others aren't available for a FUSE, the biggest problem is the development overhead of implementing a FUSE, which requires the implementation of a completely custom file system. The optimal solution for memory synchronization is not to provide an entire file system to track reads and writes on, but instead to track a single file; for this use case, NBD serves as an existing API providing this simpler approach, making FUSE not the optimal technology to implement memory synchronization with.

Direct Mounts

Direct mounts have a high spread when it comes to first chunk latency at 0 ms RTT(see figure 9), but are more predictable when it comes to their throughput (see figure 14). Similarly to the drawbacks of userfaultfd , it's first chunk latency grows linearly as the RTT increases (see figure 10), due to the lack of preemptive pulls. Despite this, it has the highest throughput at 0 ms RTT, even higher than managed mounts (see figure 12) due to it having less expensive internal I/O operations as a result of the lack of this pull system. While compared to userfaultfd , its read throughput doesn't drop as rapidly as RTT increases (see figure 15), its write speed is heavily influenced by RTT (see figure 17) since writes need to be written to the remote as they happen, as there is no background push system either. These characteristics make direct mounts a good access method to choose if the internal overhead of using managed

Managed Mounts

Managed mounts have an internal overhead to due to the duplicate I/O operations required for background pull and push, resulting in a worse throughput for low RTT scenarios compared to direct mounts (esp. for 0 ms RTT; see figure 12), as well as higher first chunk latencies (see figure 8). As soon as the RTT reaches levels more typical for a WAN environment however, this overhead becomes negligible compared to the benefits gained over the other access methods thanks to the background push and pull systems (see figure 10 and 15).

Adjusting the background workers to the specific environment can substantially increase a managed mounts' performance (see figure 11 and 16), since data can be fetched in parallel. The pull priority function can allow for even more optimized pulls, and preemptive pulls can significantly reduce initial chunk latency since data can be pulled asynchronously before the device is

Chunking

In general, server-side chunking should almost always be the preferred technology due to the much better throughput compared to client-side chunking (see figure 20). For direct mounts, due to their linear/synchronous access pattern, the throughput is low for both server- and client-side chunking as RTT increases, but even with linear access server-side chunking still outperforms the alternative (see figure 21). For managed mounts, client-side chunking can still halve the throughput of a mount compared to server-side chunking (see figure 22). If the data chunks are smaller than the NBD block size, it reduces the number of chunks that can be fetched if the number of workers remains the same. This isn't the case with server-side chunking because it doesn't need an extra worker on the client side for each additional chunk that needs to be fetched. This allows the background pull system to fetch more, thus increasing

RPC Frameworks

Out of the frameworks tested, Dudirekta consistently has lower throughput than the alternatives (see figure 23). It performs better for managed mounts than direct mounts thanks to its support for concurrent RPCs and is less sensitive to RTT compared to gRPC and fRPC for managed mounts, but even for the latter, its throughput is much lower compared to both alternatives (see figure 25) due to its lack of connecting pooling. Despite these drawbacks however, Dudirekta remains an interesting option for prototyping due to the decreased friction in developer overhead, bidirectional RPC support and transport layer independence.

gRPC offers considerably faster throughput compared to Dudirekta for both managed and direct mounts (see figure 23). It has support for connection pooling, giving it a significant performance benefit over Dudirekta for managed mounts (see

Backends

Redis is the network-capable backend with the lowest amount of initial chunk latency at a 0 ms RTT (see figure 26). When used for direct mounts, it has a lower throughput compared to managed mounts (see figure 28), showing good support for concurrent chunk access; it also has the highest throughput for direct mounts by a significant margin (see figure 29) due to its optimized wire protocol and fast key lookups. It also has good throughput in managed mounts due to these optimizations (see figure 31), making it a good choice for ephemeral data like caches, where quick access times are necessary, or the direct mount API provides benefits, i.e. in LAN deployments.

ScylllaDB has the highest throughput for 0 ms RTT deployments for managed mounts, showing a very good concurrent access performance (see figure 31). It does however fall short when it comes to usage in direct mounts, where the

Limitations

While the mount APIs are functional for most use cases, there are performance and usability issues due it being implemented in Go. Go is a garbage collected language, and if the garbage collector is active, it has to stop certain Goroutines. If the mmap API is used to access a managed mount or a direct mount, it is possible that the garbage collector tries to manage an object with a reference to the exposed slice, or tries to release memory as data is being copied from the NBD device. If the garbage collector then tries to access the slice, it can stop the Goroutine providing the slice in the form of the NBD server, causing the deadlock. One workaround for this is to lock the mmaped region into memory, but this will also cause all chunks to be fetched from the remote into memory, which leads to a high Open() latency; as a result, the recommended workaround for this is to simply start the NBD server in a separate process,

Using Mounts for Remote Swap with ram—dl

ram—dl[66] is an experimental tech demo built to demonstrate how the mount API can be used. It uses the fRPC mount backend to expand local system memory, enabling a variety of use cases such as mounting a remote systems RAM locally or easily inspecting a remote systems' memory contents.

It is based on the direct mount API and uses mkswap, swapon and swapoff to enable the Kernel to page out to the mount's block device:

```
// Create a swap partition on the block device
exec.Command("mkswap", devPath).CombinedOutput()

// Enable paging and swapping to the block device
exec.Command("swapon", devPath).CombinedOutput()
```

Overview

tapisk[67] is a tool that exposes a tape drive as a block device. While seemingly unrelated to memory synchronization, it does serve as an interesting use case due to the similarities to STFS (mentioned earlier in the FUSE section), which exposed a tape drive as a file system, and serves as an interesting example for how even seemingly incompatible backends can be used to store and synchronize memory.

Using a tape drive as such a backend is challenging, since they are designed for linear access and don't support random reads, while block devices need support for reading and writing to arbitrary locations. Tapes also have very high read/write latencies due to slow seek speeds, taking up to more than a minute to seek to a specific record depending on the offset of the tape that is being accessed. Due to the modularity of r3map's managed mount API however, it is possible to work

Implementation

To achieve this, the background writes and reads provided by the managed mount API can be used. Using these, a faster storage backend (i.e. the disk) can be used as a caching layer, although the concurrent push/pull system can't be used due to tapes only supporting synchronous read/write operations. By using the managed mount, writes are de-duplicated and both read and write operations can become asynchronous, since both happen on the fast local backend first, and the background synchronization system them handles either periodic writebacks to the tape for write operations or reading a chunk from the tape if it is missing from the cache.

Since chunking works differently for tapes than for block devices, and tapes are append-only devices where overwriting a section prior to the end would result in all following data being overwritten, too, an index must be used to simulate the offsets

tapisk is a unique application of r3map's technology, and shows how flexible it is. By using this index, the effectively becomes tape a standard ReadWriterAt stage (and go—nbd backend) with support for aligned-reads in the same way as the file or directory backends, and thanks to r3map's pipeline design, the regular chunking system could be reused, unlike in STFS where it had to be built from scratch. By re-using the universal RPC backend introduced earlier, which can give remote access to any go—nbd backend over an RPC library like Dudirekta, gRPC or fRPC, it is also possible to access a remote tape this way, i.e. to map a remote tape library robot's drive to a system over the network.

Being able to map a tape into memory without having to read the entire contents first can have a variety of use cases. Tapes

Existing Solutions

r3map can also be used to create mountable remote file systems with unique advantages over existing solutions. Currently, there are two main approaches to implementing cloud storage clients. Dropbox and Nextcloud are examples of systems that listen to file changes on a folder and synchronizes files as changes are detected, similarly to the file-based memory region synchronization approach discussed earlier. The big drawback of this approach is that everything that should be available needs to be stored locally; if a lot of data is stored in the cloud drive, it is common to only choose to synchronize a certain set of data to the local host, as there is no way to dynamically download files as they are being accessed. Read and write operations on such systems are however very efficient, since the system's file system is used and any changes are written to/from this file system asynchronously by the synchronization

Hybrid Approach

Using r3map makes it possible to get the benefits of both approaches by not having to download any files in advance and also being able to write back changes asynchronously, as well as being able to use almost any existing file system with its complete feature set. Files can also be downloaded preemptively to allow for offline access, just like with the approach that listens to file changes in a directory.

This is possible by once again using the managed mount API. The block device is formatted using a valid file system, i.e. EXT4, and then mounted on the host. By configuring the background pull systems workers and pull priority function, it is possible to also download files for offline access, and files have not yet been downloaded to the local system can be pulled from the remote backend as their chunks are being accessed. If a chunk is available locally, reads are also much faster than they

Streaming Access to Remote Databases

Another use case that r3map can be used for is accessing a remote database locally. While using a database backend (such as the ScylllaDB backend introduced earlier) is one option of storing the chunk, this use case is particularly interesting for file-based databases like SQLite that don't define a wire protocol. Using r3map, instead of having to download an entire SQLite database before being able to use it, it can instead be mounted with the mount API, which then fetches the necessary offsets from a remote backend storing the database as they are being accessed. For most queries, not all data in a database is required, especially if indexes are used; this makes it possible to potentially reduce the amount of transferred data by streaming in only what is required.

Since reads are cached using the local backend with the managed mount API, only the first read should potentially have

Making Arbitrary File Formats Streamable

In addition to making databases streamable, r3map can also be used to access files in formats that usually don't support being accessed before they are fully available locally. One such format is MP4; usually, if a user downloads a MP4 file, they can't start playback before the file is available locally completely. This is because MP4 typically stores metadata at the end of the file.

The reason for this being stored at the end is usually that the parameters required for this metadata requires encoding the video first. This results in a scenario where, assuming that the file is downloaded from the first to the last offset, the client needs to wait for the file to be completely accessible locally before playing it. While MP4 and other formats supports ways to encode such metadata in the beginning or once every few chunks in order to make them streamable, this is not the case for many already existing files and comes with other

Streaming App and Game Assets

Another streaming use case relates to the in-place streaming of assets. Usually, a game needs to be fully downloaded before it is playable; for many modern high-budget titles, this can be hundreds of gigabytes of data, resulting in very long download times even on fast internet connections. Usually however, not all assets need to be downloaded before the game can be played; only some of them are, i.e. the launcher, UI libraries or the first level's assets. While theoretically it would be possible to design a game engine in such a way that assets are only fetched from a remote as they are being required, this would require extensive changes to most engine's architecture, and also be hard to port back to existing titles; furthermore, current transparent solutions that can fetch in assets (i.e. mounting a remote NBD drive or FUSE) are unlikely to be viable solutions considering their high sensitivity to network latency and the high network

Modelling State

Synchronization of app state is a fairly complex problem, and even for simple scenarios, a custom protocol is typically built for apps. While it is possible to use real-time databases like Firebase to synchronize some application states, Firebase and similar solutions to it are usually limited in which data structures they can store and require specific APIs to synchronize them. Usually, even for a simple migration of state between two hosts, synchronization requires state to be manually marshalled, sent over a network, received on a destination host, and unmarshalled. This requires a complex synchronization protocol, and decisions such as when to synchronize state and when to start pulling from the remote need to be made manually, which often results in a database on a third host being used even for simple migrations from one host to another instead of implementing a peer-to-peer process.

Mounting State

By allocating all structures on r3map's provided mmaped byte slice, many interesting use cases become possible. For example, a TODO app could use it as its backend. Once loaded, the app mounts the TODO list as a byte slice from a remote server using the managed mount API; since authentication is pluggable and i.e. a database backend like ScylllaDB with a prefix for this user provides a way to do both authentication and authorization, such an approach can scale fairly well. Using the preemptive background pull system, when the user connects, they can not only start streaming in the byte slice from the remote server as the app is accessing it, but also pull the majority of the required data first by using the pull heuristic function. If the TODO list is modified by changing it in the mmaped memory region, the changes are asynchronously written back to the underlying block device, and thus to the local backend, where

Migrating State

In addition to using managed mounts to access remotely stored application state, migration of arbitrary app state also becomes a possibility. If a user has a TODO app running on a host like their smartphone, but wants to continue writing a task description on their desktop system, they can migrate the app's state directly and without a third party/remote database by using r3map. For this use case, the migration API can be used. In order to optimize the migration, the pre-copy phase can be started automatically, i.e. if the phone and desktop are physically close to each other or in the same network; in such a LAN migration case, the process is able to benefit from low latencies and high throughput. It is also possible to integrate the migration API deeply with system events, i.e. by registering a service that migrates applications off a system before a shutdown procedure completes.

It is important to note that there are a few limitations with synchronizing and migrating an application's internal stateful data structures this way; locking is not handled by r3map and would need to be done using a higher-level protocol; moreover, this assumes that the in-memory representation of the data structure is consistent across all hosts, something which is not necessarily the case with programming languages such as Go with multiple processor architectures being involved. While projects such as Apache Arrow[70] allow for application state to represented in a language and CPU architecture independent way, this comes with some of the same restrictions on which state can be synchronized as with other solutions such as Firebase.

In order to keep the possibility of migrating arbitrary state, but also allow for cross-architecture compatibility, VMs can be used

Summary

Summary

As is evident from the discussion, there are multiple ways and configurations for implementing a solution for universally accessing, synchronizing and migrating memory regions, with the individual configurations having different strengths and weaknesses as shown by the benchmarks, making them each suitable for different use cases.

When it comes to access methods, userfaultfd is an interesting API that is idiomatic to both Linux in as a first-party solution and Go due to its fairly low implementation overhead. This approach however falls short when it comes to throughput, especially when used in WAN, where other options can provide better performance. The delta synchronization method for mmaped files provides a simple way of memory synchronization for specific scenarios, but does have a very significant I/O and compute overhead due to its polling and hashing requirements

Conclusion

Conclusion

The proposed solution consisting of the direct mount, managed mount and migration APIs as implemented in the form of the r3map library present an efficient method of accessing, synchronizing and migrating remote memory regions over a network, with example use cases and benchmarks showing that r3map is able to provide both throughput and latency characteristics that make it possible to use as part of applications today.

ram—dl demonstrates how minimal r3map's implementation overhead is by implementing a system to share and mount a remote system's memory in under 300 source lines of code, while tapisk shows that the APIs can be used to efficiently map almost any resource, including a linear-access tape drive, to the concepts provided. Aside from these examples, the proposed solution also makes many entirely new use cases that were

Bibliography

Bibliography

[1]
W. Mauerer, *Professional linux kernel architecture*. Indianapolis, IN: Wiley Publishing, Inc., 2008, pp. 2–4, 7–8, 474–487, 1026–1027.

[2]
A. S. Tanenbaum and A. S. Woodhull, "Operating systems: Design and implementation," 3rd ed., Upper Saddle River, NJ 07458: Pearson Education, Inc. Pearson Prentice Hall, 2006, pp. 27–29.

[3]
D. DeVault, "A hare code generator for finding ioctl numbers." 2022. Accessed: Jul. 28, 2023. [Online]. Available: https://drewdevault.com/2022/05/14/generating-ioctls.html

[4]