



DPFS: DPU-Powered File System Virtualization

Peter-Jan Gootzen*

IBM Research
Zurich, Switzerland
peter.jan.gootzen@ibm.com

Jonas Pfefferle

IBM Research
Yorktown Heights, USA
jpf@ibm.com

Radu Stoica

IBM Research
Zurich, Switzerland
rst@zurich.ibm.com

Animesh Trivedi

VU Amsterdam
Amsterdam, Netherlands
a.trivedi@vu.nl

ABSTRACT

As we move towards hyper-converged cloud solutions, the efficiency and overheads of distributed file systems at the cloud tenant side (i.e., client) become of paramount importance. Often, the client-side driver of a cloud file system is complex and CPU intensive, deeply coupled with the backend implementation, and requires optimizing multiple intrusive knobs. In this work, we propose to decouple the file system client from its backend implementation by virtualizing it with an off-the-shelf DPU using the Linux virtio-fs software stack. The decoupling allows us to offload the file system client execution to a DPU, which is managed and optimized by the cloud provider, while freeing the host CPU cycles. DPFS, our proposed framework, is 4.4× more host CPU efficient per I/O, delivers comparable performance to a tenant with zero-configuration and without modification of their host software stack, while allowing workload and hardware specific backend optimizations. The DPFS framework and its artifacts are publically available at <https://github.com/IBM/DPFS>.

CCS CONCEPTS

• **Networks** → Network File System (NFS) protocol; • **Software and its engineering** → File systems management; • **Information systems** → Cloud based storage; • **Hardware** → Networking hardware.

KEYWORDS

DPU, SmartNIC, Offloading, File system, Virtualization, Cloud, Storage, Framework, Datacenter, RDMA, NFS, Virtio-fs, FUSE

1 INTRODUCTION

File systems are a popular choice for cloud data storage with offerings such as traditional distributed file systems (HadoopFS, Ceph, GlusterFS), and *cloud-native file systems* (CNFS) services like Amazon EFS [3], Alibaba Pangu [10] or Azure Files [27]. With the recent push for hyper-converged infrastructure [13], there is a need for an efficient, scalable and high-performance cloud-native file system service.

Building a high-performance, scalable cloud-native file system for applications is a challenging task. First, the raw performance of storage and networking devices are constantly increasing, while the

*Also with VU Amsterdam.



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	ext4	ext4 + NVMe-oF	XFS	Btrfs
I/O operations	5.2	13.7	3	4.6
Total Bytes (in KiB)	44.7	46.8	12	125.3
Amplification	11.2x	11.7x	3x	16x

Table 1: Analysis of storage (block) or network (packets with NVMeoF) operations for a single 4KiB file write.

CPU performance improvements have stalled [29, 44]. As a result, delivering the full speed of I/O devices in a disaggregated storage setting takes a considerable amount of CPU resources [17, 43]. For example, Alibaba reports 12 CPU cores are required to deliver 200 Gbps of block-level traffic [26]. At the file system level, LineFS reports that with Ceph a single fully-utilized CPU only delivers ~10 Gbps bandwidth on a 100 Gbps link [16]. The question of CPU efficiency is also important for bare-metal machines, which have become popular in clouds recently [6, 34, 48]. Second, client-side CNFS logic can be complex and bloated, as it has to implement logic for communication and coordination with metadata and data servers, client-side buffer and connection management, caches, etc. As a result, it is not uncommon for distributed file system clients to consume GBs of DRAM and a significant amount of CPU cycles, thus limiting how many concurrent tenants (VMs, containers) can be packed on a server [2, 21]. Lastly, the close coupling of the file system API and its implementation makes it difficult to deploy new extensions or optimizations. For example, a bare-metal tenant using Ceph can not easily switch to HopsFS [30] or InfiniFS [25] without significant disruptions if it experiences metadata scalability challenges. Furthermore, many of these CNFS come with hundreds of performance knobs and features, which requires explicit deployment and optimizations from the tenant side to extract the best possible performance.

To address the aforementioned challenges, we propose to *virtualize the access to a file system by offloading the file system client to a DPU* to offer a tenant-transparent, light-weight, high-performance file system service. Such a design has multiple advantages: First, *virtualization decouples the file system API from its backend implementation, which enables us to optimize the backends to support multiple workload needs such as multiple APIs [22], scalable metadata lookups with KV stores, decoupling of data from metadata management [19]. A limited form of such decoupling is currently offered by cloud providers in the form of an NFS gateway to the CNFS client [3, 12, 27]. We argue this approach gives away control of the file system client from the cloud provider, and demonstrate that the Linux kernel NFS client has high overheads (§3.4). Second, by offloading (and leveraging the hardware acceleration of the DPU) the file system implementation, we free host CPU resources for the tenant. One can argue that offloading capabilities can also be leveraged by the host either at the block, or application level. A block-level offloading allows a fully offloadable I/O stack [20, 28],*

however, it suffers from significant I/O amplifications. We quantify this amplification [24] in Table 1, where we report the number of block-level or network-level operations (packets for NVMe-oF storage disaggregation) generated in response to a single 4 KiB file write operation. Depending on the file system, the amplification can be as high as 3-16 \times , thus requiring proportional gains from hardware offloading. Furthermore, in comparison to local block I/O, NVMe-oF also amplifies the average number of I/O operations needed (5.2 vs. 13.7). On the other hand, with file system-level virtualization, this will be a single offloadable file operation from the host to the DPU and then from the DPU to the file system backend. An application-level solution requires rewriting the application to benefit from offloading capabilities of the DPU, which are non-trivial and non-standardized (except for RDMA and NVMe-oF style offloading). Lastly, a DPU-powered design does not require any fine-tuning or configuration from the tenant side. All CNFS-related configuration and optimizations can be consolidated on the DPU, under the cloud provider's purview, freeing the host CPU for tenants. The physical separation of the DPU (which runs the cloud provider logic) from the tenant (on the host) also discourages any resource-sharing based side-channel attacks [6], thereby improving tenant isolation and security.

In this paper, we present DPFS, a DPU-Powered File System virtualization framework for cloud environments. DPFS leverages the virtio-fs protocol to communicate between the host and the DPU. The DPU and host communicate via PCIe memory-mapped virtio [38] queues using the FUSE file I/O command set. As virtio-fs is standardized [46] and included in the Linux kernel [37] (no installation required), this design enables DPFS to avoid the need for running a custom CNFS client on the host. The *de-coupling* of the front-end (a standard file system API) from its backend implementation (i.e., the CNFS) with a bump-in-the-wire architecture on the DPU [9] allows the cloud provider to do a variety of network and storage optimizations (scheduling, caching, quotas, QoS), without having the tenant perform any code installation or change any configuration. To prove DPFS's flexibility, we have implemented three file system backends: (i) **DPFS-null**, a no-op DPU client useful for development and benchmarking; (ii) **DPFS-NFS**, a NFS backend that runs on the DPU and translates the virtio-fs requests into equivalent NFS commands and communicates with a remote NFS server using libnfs with Nvidia XLIO (partial TCP offloading) [33]; (iii) **DPFS-KV**, a RAMCloud-based backend that implements low-latency I/O operations on small files, a suitable fit for KV stores [35].

Our primary contributions in this work include:

- We make a case for transparent file system access virtualization for cloud-native file systems using DPUs.
- We present the design and implementation of DPFS, an open-source file system virtualization framework with support for the Nvidia BlueField-2 DPU [32] (<https://github.com/IBM/DPFS>).
- Evaluation of DPFS that demonstrates that it (i) is lightweight; (ii) delivers equal and better performance than a host NFS client; and (iii) is customizable and modular with multiple file system backend implementations.

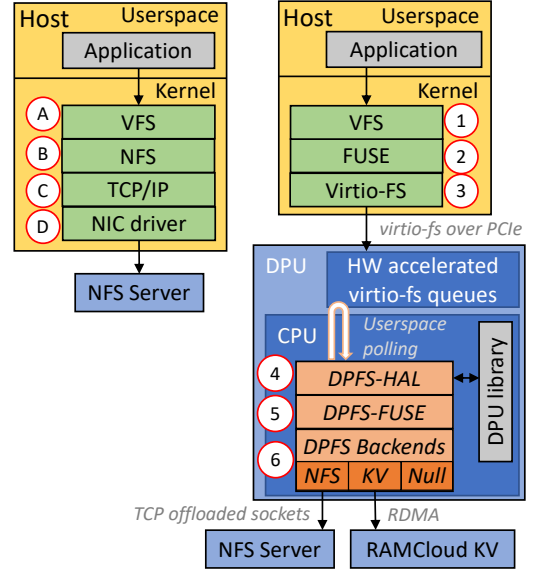


Figure 1: The architecture of DPFS compared to a host NFS client. Green boxes are the standard in-kernel code, and orange boxes are our contributions.

2 DPFS DESIGN AND IMPLEMENTATION

To accelerate the development of DPU-powered file systems, we implemented the DPFS framework. The framework is composed of three layers, each serving a different purpose, as shown in orange in Figure 1. The first layer, (DPFS-HAL) provides a Hardware Abstraction Layer (HAL) for the vendor-specific DPU functionality and the host-DPU optimizations. Its role is to reduce the DPU-specific knowledge required to develop a file system backend, to simplify code maintenance, and to allow a faster transitioning to a new type or new model of a DPU. The second layer implements a FUSE-like API (i.e., *libfuse* [1]) on top of the raw virtio-fs protocol buffers (DPFS-FUSE §2.2). The third layer contains the file system backend implementation (i.e., the DPU logic that allows connecting to the remote file system). Here we provide three implementations. The first client is DPFS-null, which implements a no-op backend that immediately replies to any request. This back-end is used for optimizing and benchmarking of the host-DPU communication, i.e., the DPFS-HAL and DPFS-FUSE layers. The second client is DPFS-NFS (§2.3), an optimized userspace NFS client that allows connecting to existing cloud NFS-based file system services. Using this client, a cloud provider would not have to perform any changes to existing file system back-ends to employ DPU virtualization. The third client is a key-value client (DPFS-KV §2.4) that connects to a RAMCloud [35] back-end and leverages RDMA to access files stored in the KV store. Past research has demonstrated that KV stores can be a better fit for file system implementations [18].

2.1 The DPFS I/O Path

In the host NFS client configuration (see Figure 1, left side), the application submits a file-related syscall (e.g., a *read()* call), that context switches to the kernel. The request traverses the VFS (A) and NFS (B) layers, then the TCP/IP stack (C), and is finally sent

to the NIC driver ①. The NIC communicates with the file system backend. Upon receiving a response, the reversed path is initiated by an interrupt.

On the other hand, the DPFS I/O path (see Figure 1, right side) is much more lightweight on the host, without requiring application or kernel modifications. The request first passes through the VFS layer ① and is then forwarded to the lightweight FUSE layer ② that transforms the VFS operation into a FUSE request message. The FUSE request is then passed to the `virtio-fs` layer ③. It encapsulates and transports the message over PCIe, through virtual functions to the appropriate host tenant and `virtio` queue on the DPU. On the DPU, a DPFS-HAL thread retrieves the message from the queue ④, then passes it to DPFS-FUSE ⑤. DPFS-FUSE extracts the original FUSE request and forwards it to the file system backend ⑥.

The complexity of the code path can be roughly quantified through lines of code in the Linux kernel (v6.2). Steps ①–③ contain 181k lines of source code (assuming IPv4), while steps ②–③ contain 13k lines of source code. On the DPU, the clients operate in userspace, thus no context switching is required. Furthermore, file system backends on the DPU can use hardware acceleration such as RDMA and TCP offload. Overall, the code path and the CPU overhead per operation on the host are significantly reduced, as we show in §3.4.

We emphasize that `virtio-fs` uses FUSE in such a manner that its traditionally large overheads are not incurred. The `virtio-fs` protocol uses FUSE for its standardized encoding of Linux Virtual File System (VFS) operations into the FUSE-ABI. Traditional FUSE encodes VFS operations and sends them back to userspace to be handled by a userspace file system implementation, incurring two extra context switches and significant overhead [47]. Whereas `virtio-fs` encodes the VFS operations using FUSE and sends them to the `virtio-fs` PCIe device (i.e. the DPU) directly from kernel space, thus incurring no extra context switches.

2.2 DPFS-HAL & DPFS-FUSE Implementation

One of the two main challenges when implementing a file system on top of the `virtio-fs` functionality of the DPU is to transparently handle the DPU's software stack. This includes configuring the software stack, the `virtio-fs` queues, implementing efficient polling and scheduling. For our DPU (the Nvidia BlueField-2), the firmware exposes the `virtio-fs` device in userspace as a RDMA device through *InfiniBand verbs*. Nvidia provides a library (Nvidia SNAP) to setup and configure `virtio` devices and to expose the `virtio-fs` functionality. However, DPFS-HAL (Hardware Abstraction Layer) hides such complexities by exposing only the `virtio-fs` relevant configuration parameters of the DPU's software stack. DPFS-HAL's C-API allows the `virtio-fs` implementation to register a `handle_request` callback, poll on the `virtio` queues (in a thread managed by DPFS-HAL or manually) and complete `virtio-fs` requests in an asynchronous fashion.

Developing a file system backend using the `virtio-fs` protocol that DPFS-HAL exposes is cumbersome, as the file system developer must consume the raw FUSE-ABI that the Linux kernel exposes over the `virtio-fs` protocol. The FUSE-ABI has limited documentation as it is meant to be consumed through the popular *libfuse* library [1], which acts as the reference implementation and API for

CPU	2x Intel Xeon E5-2630 v3, 2.4GHz, 8 cores/socket, C-states disabled during latency experiments
DRAM	128 GiB, DDR4 1,866 MT/s
DPU and network	Nvidia BlueField-2 with 2.75 GHz x 8 ARMv8 A72 64-bit cores, 16 GiB DRAM (max bandwidth: 18 GiB/s), connected via PCI 3.0, 100 Gbps link to a remote server, running BlueField DPU OS 3.9.3 with a prototype firmware to enable <code>virtio-fs</code> support
Host and remote server SW	Ubuntu 22.04 with kernel 6.2, fio 3.28, NFS (v4.2, NFS server params "async, no_subtree_check", NFS client params: "async")

Table 2: Benchmarking hardware and software setup.

the ABI. DPFS-FUSE exposes a C-API that is similar to that of the *libfuse* API. By exposing a well-known and commonly used API, we report increased `virtio-fs` file system development speed. A file system developer could use userspace FUSE as a first step during development and transition to a DPU environment when available. Our DPFS-FUSE API builds on top of *libfuse* with added support for asynchronous operations and optimized function calls to decrease the number of data copies and allocations.

2.3 DPFS-NFS: Hardware-accelerated NFS Backend

The DPFS-NFS backend implementation leverages the accelerated socket API of Nvidia XLIO [33] and the *libnfs* library [39]. Nvidia XLIO is a shared library that overloads the socket C-API to leverage the network offloading capabilities in the BlueField-2 hardware with reduced data copies (not fully zero-copy). This implementation showcases the possibility to leverage hardware acceleration through the DPU without any changes to the host file system client and the remote file system provider. Our experiments show the performance benefits of implementing an userspace hardware-accelerated NFS client. The standard Linux kernel NFS client (running on the DPU), when using *io_uring*, incurs 100.5 μ sec read and 101.9 μ sec write latencies for 4 KiB accesses. The software-only *libnfs* attains 76.0 μ sec and 74.2 μ sec respectively. Adding Nvidia XLIO to *libnfs* further reduces latency to 52.9 μ sec and 52.2 μ sec, respectively.

On the DPFS-HAL queue poller thread, the DPFS-NFS file system implementation translates the FUSE request into NFS v4.1 [31] and sends the NFS request to the remote storage backend using *libnfs* and Nvidia XLIO. A second thread polls on the Nvidia XLIO socket using *libnfs*, translates NFS v4.1 responses back into FUSE, and messages the DPFS-HAL poller thread to complete the `virtio-fs` request.

2.4 DPFS-KV: RAMCloud KV store Backend

The file system transparency of DPFS allows one to consume a specialized file system without the need to make changes to the host. We demonstrate this by implementing a DPFS backend for RAMCloud, a distributed, in-memory KV store that provides low-latency access by leveraging RDMA [35]. DPFS-KV maps file system operations from DPFS-FUSE to KV operations by exposing a set of key-value pairs through the file system's root directory, where each file represents a key-value pair. Two tables are stored in RAMCloud, the first to store data (file contents) and the second to store metadata (attributes, name, etc.). To index into the metadata table, the file

name is hashed and used as the key. In the metadata table, a unique inode identifier is stored, which acts as the file's key for the data table. To support listing the contents of the flat file system directory (i.e. `readdir()`), the file name itself is stored in the metadata table.

3 EVALUATION

In this section, we evaluate the performance and efficiency of DPFS through the DPFS-null, DPFS-NFS and DPFS-KV backends. Table 2 shows our experimental setup. All workloads are generated using *fio* with the *io_uring* I/O engine [7]. To generate a consistent load on the system, we use two *fio* threads.

3.1 Virtualization Overheads

We first measure the throughput of the DPFS-null backend for random read and write workloads (10 seconds warm up, followed by a 60 seconds run). The results of this experiment demonstrate the upper bound on the performance DPFS can deliver.

Figure 2a shows throughput of the null-DPU backend (y-axis, in GiB/s) vs. the I/O (queue) depth. We report throughput for 4 KiB, 16 KiB, and 64 KiB block sizes for both read and write operations. Throughput scales for both read and write operations as we increase the I/O depth. It plateaus when using a 64 KiB block size at queue depth between 16-32 at 5.87 GiB/s for read and 4.32 GiB/s for write operations. For a 4 KiB block size, a common I/O size in the kernel, the peak read throughput is 1,278 MiB/s and write throughput is 938 MiB/s, equivalent to 327K and 240K random 4 KiB IOPS respectively. At an I/O depth of 1, we measure a read throughput of 193 MiB/s and a write throughput of 168 MiB/s, which translates to a 38.6 μ s and 43.3 μ s latency baseline DPFS overhead respectively.

3.2 DPFS-NFS Performance

Having established the virtualization overheads (via the peak performance), we now evaluate the complete I/O path to a remote NFS server from the host versus from the DPU (steps ①–⑥ vs. ①–④ in Figure 1) when using 4 KiB block sizes (10 seconds warm up, followed by a 60 seconds run). We select 4 KiB as it is one of the most common block sizes, and is the I/O request size that also matches the granularity of the system memory pages. 4 KiB I/O sizes further stresses the software overheads (memory allocation, scheduling costs), hence, highlighting any inefficiencies.

Figure 2b shows the throughput (y-axis in MiB/s) vs. the I/O depth (x-axis). A host NFS client (path ①–②) delivers better (11%-21%) read and write throughput up to an I/O depth of 3. However, above an I/O depth of 4, DPFS benefits from having a partially offloaded networking stack, and delivers better throughput (12%-32%) than the host NFS. However, all configurations do not scale beyond I/O depth of 16 (see limitations §3.5).

We further analyze the latency of 4 KiB I/O operations in Figure 2c. As discussed above, at an I/O depth of 1, the host NFS is faster than DPFS-NFS. For DPFS-NFS, we break down the overhead into two parts, the DPU induced latency (shown at the bottom bars, 38.6-43.3 μ sec) and the software latency (the upper part, 52.9-52.2 μ sec). We expect the former latency to improve with the newer generation of DPUs. Furthermore, we use *libnfs* with Nvidia XLIO that emulates socket semantics. We expect, a native *libnfs* implementation using RDMA would be able to also lower the userspace NFS overheads. The userspace NFS latency (the latency of NFS from

	NFS	DPFS-KV
Read	71.2 μ s (σ : 10 μ s)	62.6 μ s (σ : 19.4 μ s)
Write	79 μ s (σ : 12.7 μ s)	70.79 μ s (σ : 21.2 μ s)

Table 3: Host NFS vs. DPFS-KV 4 KiB file I/O latencies.

	NFS	DPFS-NFS	+/-
Instructions/op	88,453	32,907	-62.80%
IPC	0.57	0.94	+64.21%
Branch miss rate	2.02	1.06	-47.42%
L1 dCache miss rate	8.82	3.82	-56.65%
dTLB miss rate	0.14	0.15	+7.14%
Savings in CPU cycles/op		4.4 \times	

Table 4: The microarchitectural profile of the host CPU.

the DPU, the top parts) is 26.7%-33% lower than the host NFS latency due to the hardware offloaded network stack used by DPFS-NFS.

3.3 DPFS-KV Performance

Lastly, we demonstrate that by specializing the file storage backend with RAMCloud, DPFS can deliver performance optimizations to workload-specific deployments. Table 3 shows our results of accessing complete 4 KiB files which are stored in NFS and RAMCloud (5 seconds warm up, followed by a 10 second run). These files are accessed in their entirety (i.e. a single I/O operation). In comparison to host NFS, DPFS-KV offers 7-12% latency gains over read and write operations.

3.4 Host microarchitectural analysis

To explain the efficiency gains with DPFS, we conduct a low-level microarchitectural analysis. We measure the instructions/operations (quantifies the software overheads in the I/O path), IPC (quantifies the code path efficiency), branch missprediction rates (quantifies how predictable the code path is), L1 dCache miss rate (quantifies data fetch rates), and lastly, dTLB miss rates (quantifies memory management related overheads). All events are measured using *perf* with the `-kernel-only` flag on the *host CPU*, hence, comparing the cost of in-kernel host NFS with DPFS-NFS. We first measure an idle machine for 10 minutes (5 runs, averaged), and then with a random 4 KiB read/write (50/50 distribution) using an I/O depth of 128 workload for 10 minutes (5 runs, averaged). By subtracting the two, we quantify the cost of the host file system client implementations of host NFS and DPFS (i.e. *virtio-fs*, DPFS-NFS on the DPU).

Table 4 shows that (1) DPFS-NFS is light-weight compared to the host NFS, requiring 62.80% less instructions to complete a random 4 KiB operation; (2) it has better IPC, partially due to the smaller code path, but also due to the polling nature of the DPFS-NFS request dispatching and processing; (3) DPFS-NFS has lower branch and L1 dCache miss rate, implying a simplified execution profile. It has marginally higher dTLB miss rates, which we attribute to the inefficient page usage of *virtio-fs* (see §3.5). Overall, by combining the instructions per I/O and IPC, we find that *the DPFS host I/O path (steps 1-6) is 4.4 \times more efficient than host NFS (steps A-D)*.

3.5 Limitations and Future Work

The current work is limited by a few restrictions, which we expect to be improved as the usage of *virtio-fs* becomes prevalent. Firstly,

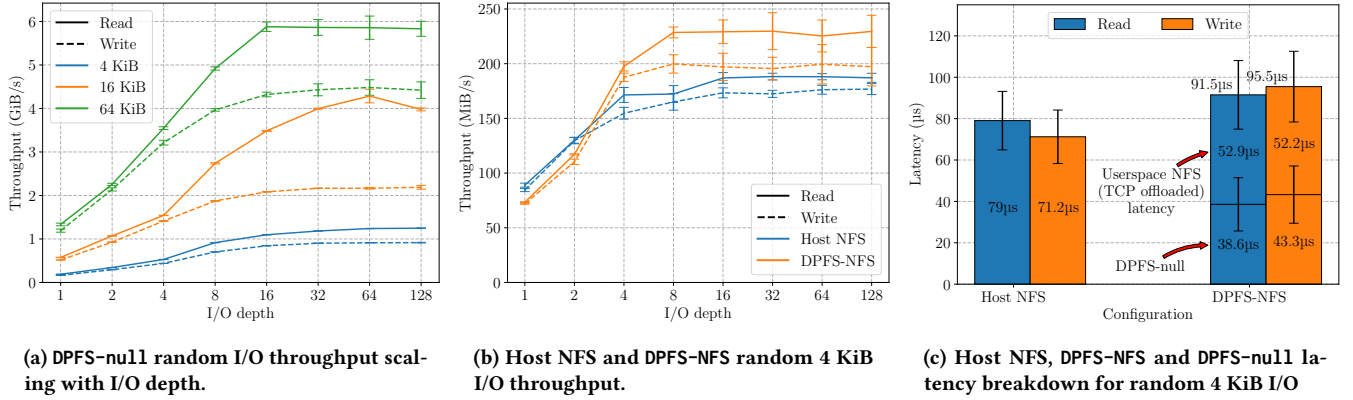


Figure 2: DPFS performance analysis

the current implementation of `virtio-fs` in the kernel does not support multi-queue [37], hence, DPFS currently only supports a single `virtio` queue per tenant. Because of an implementation limitation in DPFS we can only leverage a single DPU thread to process the single `virtio` queue, limiting the throughput achieved in Figure 2a and Figure 2b. A single queue only limits the available throughput per tenant, not the number of tenants supported. We are currently working on adding support for multi-tenancy through SR-IOV [8] on the Nvidia BlueField-2 to DPFS.

Secondly, the FUSE headers use an excessive amount of pages (3 pages for a read I/O, 4 pages for a write I/O) to store their headers [37]. Due to a memory bottleneck of Nvidia XLIO (tight integration with hardware, huge pages, memory pinning) when using large amounts of memory, DPFS-NFS can only configure the `virtio` queue size with a maximum of 64 pages in the DPU. With at least four pages overhead in a `virtio-fs` operation, DPFS-NFS is therefore restricted to a queue depth of only 16 (64/4).

Thirdly, since `virtio-fs` file system operations flow through the DPU's SoC complex, the comparably weak hardware found in the Nvidia BlueField-2 (ARM A72 cores, single-channel DDR3) [32] poses a significant bottleneck. This bottleneck can be seen in the throughput difference of DPFS-null (Figure 2a) and DPFS-NFS (Figure 2b). Where DPFS-NFS is only able to achieve ~20% of the 4 KiB throughput of DPFS-null because of TCP processing and the several extra data copies it incurs.

We expect that the next iterations of the hardware/software stack will help alleviate these limitations, and that tightly integrating the file system implementation with the hardware to prevent memory copies will speed up large block size workloads.

4 RELATED WORK

All cloud providers offer high-performance, scalable file-system services designed for large scale, multi-tenancy, and high availability. However, today, the typical way of accessing cloud file-system services is either through an NFS client (standard in-kernel) [3, 12, 27] or by running a cloud-provider's file system client code on the tenant machine [10, 11, 36]. Such an approach provides poor isolation between cloud tenants and providers, while consuming significant tenant resources (CPU, RAM). With improving DPU capabilities [4, 5], many projects in both academia and industry explored leveraging them for virtualizing and accelerating various cloud

services. Examples include for networking functions [9, 41, 42, 49], for block storage [14, 15, 26, 28], for key-value and object storage [23, 40, 45]. Our work follows in this direction by focusing on offloading and abstracting file-system services, an area overlooked until recently.

The closest works to our paper are (1) LineFS [16], which provides a persistent memory distributed file system that leverages the DPU for offloading noisy background tasks, and (2) FISC [21], which is a cloud-native file system that offloads the complete file system to an FPGA-based DPU and remote servers through a custom `Virtio-Fisc` device interface. DPFS differs from these works in two manners. Firstly, DPFS and FISC utilize DPU-offloading for virtualization, by decoupling the file system client from the file system implementation, the burden on the host CPU is decreased and the control the Cloud provider has over the file system stack is increased. Whereas LineFS utilizes DPU-offloading for performance improvements. Secondly, DPFS differs from FISC in that it offloads the file system implementation to an off-the-shelf CPU-based DPU (e.g. Nvidia BlueField-2) with the existing `virtio-fs` host software-stack and provides an open API for implementing different file system backends.

5 CONCLUSIONS

To address the challenges of providing a light-weight client for distributed file systems, we propose to virtualize and decouple the file system API from its implementation using DPUs. We leverage the Linux `virtio-fs` software stack to pass file operations to a DPU, where various optimized network/storage backends can be implemented by a cloud provider. In our evaluation we demonstrate that DPFS, our framework, is light-weight (40 μsec base latency, 4.4× lower host CPU overhead), has competitive performance, and requires zero configuration or modifications on the host.

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