io_uring for High-Performance DBMSs: When and How to Use It

[Experiment, Analysis & Benchmark]

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Abstract

We study how modern database systems can leverage the Linux io_uring interface for efficient, low-overhead I/O. io_uring is an asynchronous system call batching interface that unifies storage and network operations, addressing limitations of existing Linux I/O interfaces. However, naively replacing traditional I/O interfaces with io_uring does not necessarily yield performance benefits. To demonstrate when io_uring delivers the greatest benefits and how to use it effectively in modern database systems, we evaluate it in two use cases: Integrating io_uring into a storage-bound buffer manager and using it for high-throughput data shuffling in networkbound analytical workloads. We further analyze how advanced io_uring features, such as registered buffers and passthrough I/O, affect end-to-end performance. Our study shows when low-level optimizations translate into tangible system-wide gains and how architectural choices influence these benefits. Building on these insights, we derive practical guidelines for designing I/O-intensive systems using io_uring and validate their effectiveness in a case study of PostgreSQL's recent io_uring integration, where applying our guidelines yields a performance improvement of 14%.

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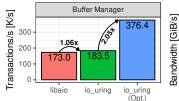
The source code, data, and/or other artifacts have been made available at https://github.com/mjasny/vldb26-iouring.

1 Introduction

Modern hardware and the I/O bottleneck. Modern PCIe 5.0 hardware, including NVMe SSDs such as the Kioxia CM7-R (2.45M IOPS) and NICs such as the ConnectX-7 (400 Gbit/s), sustains millions of IOPS and hundreds of gigabits per second of throughput, yet conventional I/O interfaces struggle to saturate them [23, 24, 34, 38, 40]. In particular, kernel-based I/O interfaces, as still used by

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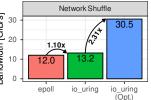


Figure 1: Performance comparison between traditional I/O interfaces and io_uring in a buffer manager and network shuffle. Naive use only yields modest gains, whereas designs that fully exploit io_uring more than double the performance.

production-grade database systems, incur system-call and context-switch overhead, consuming a significant fraction of CPU cycles without saturating these devices [41]. These inefficiencies widen the hardware-software gap and make low-overhead I/O mechanisms central to modern database systems.

Challenges of user-space I/O. User-space I/O frameworks such as DPDK, SPDK, and RDMA bypass the kernel and can deliver high performance on dedicated hardware [27, 35, 41]. However, operating entirely in user space removes OS abstractions such as file systems and TCP networking, making integration difficult for production databases that rely on them. These stacks also require exclusive control of SSDs or NICs [11, 18, 30], which may conflict with deployments where devices must be shared. Consequently, user-space I/O, despite its advantages, has not seen wide adoption and is used mainly in specialized, tightly controlled environments rather than general-purpose systems [11, 22].

io_uring features for efficient I/O. The Linux io_uring interface [4] is a promising candidate for bridging the gap between efficient I/O and the preservation of common kernel abstractions. It combines three key features, distinguishing it from earlier kernel I/O interfaces. First, a unified interface integrates storage, network, and other system calls into one framework. Second, fully asynchronous execution overcomes limitations of existing asynchronous interfaces, allowing applications to perform useful work while I/O operations complete in the background. Third, batched submission and completion process multiple operations with a single system call, amortizing system call overhead and context switches. These features make io_uring attractive for database systems that issue large numbers of storage and network I/O operations.

Low-overhead I/O with io_uring? However, io_uring is not a panacea. Simply replacing traditional I/O interfaces with io_uring does not necessarily yield substantial performance benefits. As

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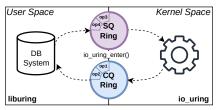


Figure 2: io_uring architecture. The database system in user space communicates with the kernel via two shared ring buffers: the Submission Queue (SQ) for enqueuing I/O requests and the Completion Queue (CQ) for receiving results.

Figure 1 shows, using io_uring off the shelf instead of libaio for storage I/O in a buffer manager, or instead of epol1 for a network shuffle, only modestly improves performance (by 1.06× and 1.10×, respectively). In contrast, when the system is explicitly designed around io_uring's capabilities (e.g., batching) and uses appropriate optimizations (e.g., registered buffers), the end-to-end performance improvements become much more pronounced: 2.05× for the buffer manager and 2.31× for the network shuffle.

These observations motivate our three research questions to guide DBMS system builders in using io_uring:

- (1) When to use io_uring? Under which system conditions especially high I/O-intensive scenarios does io_uring provide the greatest benefit?
- (2) How to integrate io_uring? How should a DBMS architecture incorporate io_uring to exploit its capabilities effectively?
- (3) How to tune io_uring? Which io_uring features most strongly influence DBMS performance?

Contributions and outline. To answer these questions, we present the first analysis of io_uring across both storage- and network-bound workloads in database systems. We evaluate io_uring using two complementary use cases supplemented with microbenchmarks. First, we integrate io_uring into a transactional storage engine on NVMe SSDs to examine storage-bound workloads (Section 3). Second, we employ io_uring for data shuffling in a distributed analytics engine on 400 Gbit/s networks, representing network-bound workloads (Section 4). From these case studies, we derive general principles for effective io_uring use and validate them by improving PostgreSQL's io_uring backend to achieve more than 10% of additional speedup (Section 5).

2 Background: Understanding io_uring

io_uring was introduced into the Linux kernel in 2019 and has since been actively developed and optimized. Despite this progress, there has been little work on understanding how to adapt it to the requirements of database systems. This section therefore provides the background needed to understand how io_uring can be used in DBMSs and how its design influences performance. We highlight two aspects that distinguish io_uring from existing I/O backends: its application interface and its internal execution model, both of which enable high performance for data-intensive systems.

2.1 Interface of io_uring

Through its three key capabilities (unified I/O, asynchronous execution, and batching), io_uring provides an interface that aligns

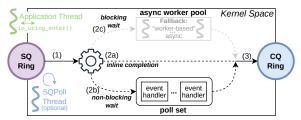


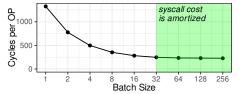
Figure 3: io_uring provides three execution paths: inline completion (2a), asynchronous execution via the poll set (2b), and a fallback to worker threads for blocking operations (2c). An optional SQPoll thread can submit requests without syscalls.

well with the demands of high-speed DBMSs. Below, we describe these capabilities in more detail and their implications for DBMSs. Unification of I/O with io_uring. Traditional DBMSs rely on synchronous system calls such as read() and write(), which provide a simple, uniform abstraction but scale poorly due to their blocking behavior. To enable non-blocking network I/O, Linux introduced epoll, which allows applications to monitor multiple sockets for readiness. For storage, libaio provided a separate API that in practice was mostly restricted to direct block I/O and often lacked true asynchronous execution. This fragmentation of asynchronous I/O interfaces forced developers to combine epol1 and libaio, leading to duplicated code paths and limited concurrency between storage and network operations. io_uring eliminates the need for such hybrid designs by unifying storage and network (as well as other system calls) under a single fully asynchronous API. Its capabilities continue to expand beyond I/O-related system calls (e.g., madvise), moving toward a general-purpose asynchronous execution model for Linux. The unified interface enables DBMSs to overlap network and disk I/O more efficiently within a single path, simplifying system design and reducing context switching.

Asynchronous architecture. At a high level, io_uring serves as a unified asynchronous layer atop existing kernel I/O subsystems, such as the block layer for storage devices and the TCP/IP stack for networking. It is implemented in the Linux kernel (Figure 2, right) and typically accessed through the liburing user-space library [9]. In contrast to epoll's readiness-based polling approach, io_uring employs a completion-based model, notifying applications after operations complete rather than when they become possible. It implements this model using two memory-mapped ring buffers with configurable capacity: the Submission Queue (SQ) and the Completion Queue (CQ). These queues are shared between user space and the kernel, avoiding additional data copies when submitting and completing requests. Applications enqueue I/O requests in the SQ, and their corresponding completions later appear in the CQ. Because completions may arrive out of order, each request carries a user-defined identifier to match submissions and completions. io_uring further supports request linking to enforce operation ordering for multiple elements in the SQ.

Batch processing. While epoll can report multiple readiness events, each I/O operation, such as read(), still requires its own syscall. In contrast, io_uring enables applications to enqueue multiple I/O requests in the SQ before triggering their submission with a single io_uring_enter syscall. Similarly, multiple completions can be retrieved from the CQ in one step. This batching capability

amortizes syscall overhead and reduces context switches, allowing the kernel to process operations in bulk. Even modest batch sizes (e.g., 16 operations) reduce the CPU cycles per operation by roughly 5–6× compared to single-operation submission as shown below:



As we will show in our use case discussions, DBMSs often have opportunities to issue I/O requests in batches, for example, during buffer-pool eviction or group commits [32, 36, 37]. However, excessive batching can also introduce drawbacks; therefore, it must be tuned carefully to yield clear benefits.

2.2 Inner Workings of io_uring

To effectively tailor DBMSs to io_uring, it is important to understand how I/O requests are executed. In the following, we examine the internals of io_uring and discuss other important aspects.

Issuing I/O requests. io_uring supports two ways to issue I/O in the kernel (step (1) in Figure 3). In the default mode, the application thread (top left) calls io_uring_enter and transitions into kernel mode, where it processes submissions and completions. The syscall can either block until a specified number of completions are available or return immediately. In contrast, when applications set up io_uring with the SQPoll mode, they avoid user-kernel transitions (syscalls) on the submission path by decoupling submission from execution. A dedicated kernel thread (cf. Figure 3, bottom left) continuously polls the SQ, issues I/O on behalf of the application, and posts results to the CQ. When no new requests are submitted, the SQPoll thread enters a sleep state after a configurable timeout. In a dedicated microbenchmark, we measured that waking this thread introduces a non-trivial latency of roughly 30 microseconds. As our study later demonstrates, choosing the most beneficial execution strategy requires a thorough understanding of the application architecture and workload characteristics.

Execution paths in io_uring. I/O in io_uring can follow three main paths as shown in Figure 3 (steps 2a-c):

(2a) Inline execution. When processing submissions, io_uring first attempts to complete requests inline, for example, when reading from a socket that has data already available. Such operations execute immediately and their completion is posted to the CQ.

(2b) Non-blocking execution. If an operation cannot be completed inline, its handling depends on its type. For pollable operations, such as non-blocking socket reads, io_uring installs an internal event handler (io_async_wake()) that is executed when the socket becomes readable (Figure 3, 2b). By default, io_uring waits indefinitely for the operation unless a timeout via OP_LINK_TIMEOUT is set.

(2c) Blocking execution. Certain operations cannot be executed asynchronously; for instance, blocking filesystem calls, such as fsync, or large storage reads. In such cases, io_uring delegates execution to worker threads (io_worker). This fallback is slower and incurs higher overhead than the native asynchronous paths. Applications can explicitly request this behavior using the IOSQE_ASYNC flag, which forces execution in a worker thread. In a dedicated

microbenchmark, issuing NOPs that were handled by io_worker threads added an average overhead of 7.3 microseconds compared to inline execution. This additional cost results from offloading to a separate thread and synchronization between the worker and submission context. Frequent fallback or a large number of active io_worker threads typically indicates suboptimal I/O patterns and may warrant application-level redesign [5–7].

Avoiding preemptions for completion-handling. When an asynchronous operation finishes, io_uring must run task work in the kernel to place the completion entry into the CQ (step 3 in Figure 3). By default, this task work runs whenever the application transitions from user to kernel space. If the thread is busy (for example, during a join or scan), the kernel may issue an inter-processor interrupt (IPI) to process pending completions. This effectively preempts the application, disrupts cache locality, increases jitter, and reduces batching efficiency. To mitigate these effects, io_uring offers the COOP_TASKRUN flag (CoopTR), which reduces IPIs and allows applications to delay task work. However, completions are still processed on any kernel-user transition, including unrelated syscalls such as malloc(). Because preemptions have side effects, both the default and cooperative modes are ill-suited for modern highperformance DBMSs. The DEFER_TASKRUN flag (DeferTR) only runs task_work on io_uring_enter calls, making it the recommended mode since it gives applications more control and eliminates unwanted preemptions. We therefore use it for the remainder of the paper unless stated otherwise.

Other features for modern hardware. io_uring is designed to fully exploit modern hardware capabilities, supporting a variety of additional features. These span both high-level application optimizations and low-level runtime tuning for efficient asynchronous I/O. Key features include buffer registration and pinning to reduce memory management overhead, multishot operations, polling modes, and advanced request scheduling. In the remainder of this paper, we examine how database engines leverage these mechanisms to implement efficient I/O.

3 Efficient Storage I/O with io_uring

Modern NVMe devices can sustain millions of IOPS, yet conventional I/O stacks rarely reach this potential [23, 27]. To explore if and how io_uring can close this gap, we discuss our three research questions (when to use, how to integrate, and how to tune io_uring) in the context of a buffer-managed storage engine.

We follow a stepwise approach during its design to highlight how io_uring's key capabilities impact system performance. After our use case discussion, we use targeted microbenchmarks to isolate specific io_uring behaviors in the storage context and provide insights for estimating achievable I/O gains.

3.1 Use Case: Buffer-Managed Storage Engine

We use a buffer-managed storage engine as our primary use case because the buffer manager is a critical component in out-of-memory database workloads, sitting directly on the I/O path of every transaction. It continuously orchestrates data movement between memory and high-performance SSDs, making it a crucial component for DBMSs as the main interface to the storage. Before diving into the details, we first outline the buffer manager's core responsibilities

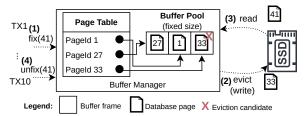


Figure 4: Overview of the buffer-managed storage engine design. Cold pages are evicted and written to disk freeing space that is used to cache frequently accessed pages.

and architecture (see Figure 4). A solid understanding of the application characteristics is essential for exploiting io_uring effectively. **Buffer manager overview.** A buffer manager caches frequently accessed pages and loads or evicts them as needed. When a requested page is not present in the buffer pool, a *page fault* triggers a read I/O to retrieve it from storage. If the buffer pool is full, the buffer manager must select a page for eviction; if it is dirty, it is written back before its buffer frame is reused. Because these operations lie on the critical transaction path, their efficiency is crucial for sustaining high throughput. Although background tasks, such as checkpointing, also interact with the buffer manager and issue additional I/O, we ignore them for simplicity.

Buffer manager architecture. The buffer manager maintains a preallocated pool of buffer frames and a page table mapping logical page identifiers to frames, along with metadata such as reference bits and dirty flags. It exposes two primitives [16]: fix(page_id) (1) checks whether the requested page resides in the buffer pool and loads it from storage (3) if not, evicting (2) another page if necessary, while unfix(page_id) (4) releases the page and marks it dirty if modified. When the pool is full, a replacement policy selects victims. In this paper, we use clock-sweep [20], a common algorithm in DBMS: pages are marked during the first pass and, if still unreferenced on the second pass, dirty pages are written back before the frame is reused. The storage engine includes a B-tree index for tuple access and updates. When the working set fits in memory, these operations complete without I/O; otherwise, page faults and evictions place I/O on the critical path, coupling buffer management with application logic.

3.2 Workload & System Conditions

As mentioned in Section 1, the question when to use io_uring — when io_uring provides measurable performance gains — depends on the given workload and system conditions. In this section, we present a simple back-of-the-envelope model to estimate the expected performance impact of various design choices, based on I/O cost and CPU utilization. These models show how engineers can predict expected gains from io_uring optimizations and validate their system implementation.

Workload conditions. To capture the impact of different workload characteristics, we use two standard DBMS benchmarks: single-statement, I/O-intensive YCSB-like transactions and the more complex, compute-bound TPC-C workload. The experiments use a small 1 GB buffer pool. For YCSB, we load 10 million tuples (8-byte key, 128-byte value), which with index structures and metadata results

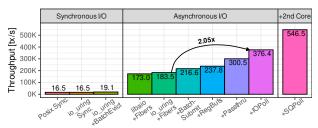


Figure 5: YCSB throughput (100% uniform updates, one update per transaction) under different buffer manager designs and I/O execution modes. io_uring features and design optimizations are enabled incrementally from left to right, increasing transaction throughput from 16.5 k to 546.5 k TPS.

in a roughly 70% page fault probability under uniform updates with 4 KiB pages, producing an I/O-bound workload well suited for storage analysis. For TPC-C, we use 1 and 100 warehouses to study the effects of a mostly in-memory vs. a mostly out-of-memory setting. **System conditions.** We evaluate several buffer manager configurations on our 3.7 GHz AMD server (Kernel 6.15) with an array of eight modern PCIe 5.0 NVMe SSDs (Kioxia CM7-R). The configurations range from fully synchronous to batched and asynchronous variants to study how the workloads interact with system conditions. All configurations utilize a single-threaded setup, in which one core handles transaction processing and I/O requests. This setup isolates I/O behavior from concurrency effects, allowing more precise analysis of performance improvements. Later, in Sections 4 and 5.2, we extend the analysis to multithreaded configurations.

3.3 Using io_uring in the Storage Engine

Traditional buffer managers perform I/O through blocking system calls such as pread() and pwrite(), where each I/O request must complete before the thread can proceed. As a performance baseline, we implement a synchronous buffer manager on top of io_uring by submitting one request at a time and waiting for its completion, ensuring that the DBMS thread has at most one outstanding I/O. Although this baseline uses io_uring's submission and completion queues for consistency with later variants, it does not exploit its asynchronous or batching features.

When io_uring does not help. This setup is the simplest form of I/O execution, where the transaction thread blocks on every page fault or for eviction. Consequently, throughput is directly tied to device latency, and using io_uring does not result in performance gains. For the update-heavy YCSB workload mentioned earlier, our posix-based and io_uring-based implementation reaches a single-threaded throughput of 16.5 k tx/s (Figure 5, *Posix* and *io_uring*). Because in-memory updates are negligible compared to storage latency, both implementations are *I/O-latency bound*.

Modeling the bottleneck. To validate the performance results, we use a simple latency-based model derived from the operation costs in Table 1. Assuming a 70% page fault rate and an average read-plus-write latency of $70+12=82~\mu s$ for our SSD device, the expected throughput is $\frac{1}{0.7\times82\times10^{-6}}\approx17.4~k$ tx/s. The estimate aligns with the measured 16.5~k tx/s, confirming that I/O latency rather than CPU or software overhead limits synchronous performance.

As a consequence, higher throughput can be achieved by reducing effective I/O latency or amortizing the latency of one request through batching.

Table 1: I/O numbers used for performance modeling.

Single Read	Single Write	Transaction Execution	Single Read	Batch Batch Read Write				
70 μs	12 μs	8264 clk	10200 clk	5400 clk	5700 clk			
I/O La	TENCY		CPU CYCLES					

3.3.1 Using io_uring to Batch Writes

With synchronous I/O, performance is bound by I/O latency, since each page fault triggers a blocking writeback of a dirty page before the next read can proceed. Although io_uring cannot magically reduce device latency, its *batching feature* can enable us to reduce the impact on the critical path.

Amortizing eviction cost. We leverage io_uring to introduce batched write submission for the buffer manager's eviction path. Instead of evicting and writing one page at a time, the buffer manager collects multiple victims and issues their writes together with a single io_uring_enter() call. While execution remains synchronous and reads and writes do not yet overlap, batching lowers submission overhead and exploits device-level parallelism, demonstrating how a minor architectural change can benefit from io_uring's strengths. **Performance implications.** Batching write operations improves performance by about 14%, reaching 19 k tx/s (compare Figure 5, +BatchEvict) because submission overhead for eviction is amortized. Eviction writes are issued in batches, so their latency is incurred once per batch rather than per eviction. This amortizes the cost across N evictions and leaves the 70μ s read latency as the dominant term in the latency model from the previous section. The expected throughput is $\frac{1}{0.7 \times 70 \times 10^{-6}} \approx 20.4 \,\mathrm{k} \,\mathrm{tx/s}$. The measured and predicted results align closely, confirming that batching removes the write latency from the latency-bound path and effectively mitigates latency through amortization rather than elimination.

3.3.2 Using io_uring for Asynchronous I/O

While batched writes amortize write latency, the buffer manager still operates synchronously, blocking on page faults and leaving the CPU idle during I/O. Multiple threads, as studied in Section 3.6, hide this latency but introduce synchronization and scheduling overhead. To hide latency in our single-threaded design, we therefore adopt asynchronous transaction execution to overlap I/O and computation. Overlapping compute & I/O. io_uring's completion-based model integrates naturally with asynchronous runtimes such as coroutines or fibers. We extend the buffer manager with Boost . fibers [2] for cooperative scheduling, where each transaction runs as a fiber that issues asynchronous I/O requests and yields on page faults. During this time, the io_uring-based runtime schedules other ready fibers, keeping the CPU active.

Cooperative transaction execution. Fiber context switches cost only tens of CPU cycles since they save and restore only register state, providing efficient user-level concurrency suited for I/O-intensive workloads. When a suspended fiber's I/O completes, it is marked ready and resumed by the scheduler. Since all concurrency is cooperative, the B-tree implementation requires no locks or atomic operations between fibers. If a fiber resumes after an I/O delay and the data structure has changed, it restarts the B-tree traversal to ensure correctness and preserve isolation without explicit

synchronization. Considering such details is important for accurate performance modeling, as shown later.

CPU, the new bottleneck. With up to 128 fibers, throughput rises by nearly an order of magnitude to 183 k tx/s (Figure 5, +Fibers). Under the same asynchronous execution scheme, *libaio* reaches 173 k tx/s, so we continue the analysis on io_uring, which provides higher throughput and exposes additional optimization opportunities. At this concurrency level, the system becomes CPU- rather than latency-bound: concurrent fiber execution hides I/O latency and the CPU is fully utilized. We therefore switch from a latency-to a cycle-based model that accounts for per-transaction CPU cost.

Using hardware cycle counters (rdtsc), we measure transaction logic (B-tree traversal and update) as $c_{\rm tx}=8,264$ cycles in an inmemory run, and I/O processing (submission and completion) as $c_{\rm io}=c_{\rm read\text{-}single}+c_{\rm write\text{-}batch}=15,900$ cycles (Table 1). For a 3.7 GHz core and a page fault rate of $r_{pf}=70\%$, the expected throughput is $\frac{\text{clock frequency}}{c_{tx}+r_{pf}\times c_{io}}=\frac{3.7\times 10^9}{8264+0.7\times 15900}\approx 190.8\,\text{k}\,\text{tx/s}$, which matches the measured 183 k tx/s. This confirms that CPU overhead, rather than I/O latency, now dominates performance, as intended with asynchronous execution.

3.3.3 Using io_uring to Batch Reads

In the initial asynchronous design, each fiber submits its I/O request right before blocking and is woken up once the I/O completes. This hides I/O latency by overlapping reads and writes but incurs syscall overhead for each I/O. We therefore introduce *batched read submission*, which groups read requests from multiple fibers before entering the kernel via io_uring_enter(). The batched submission amortizes syscall overhead and exploits device-level parallelism, reducing per-I/O cycle cost (Table 1) and improving CPU efficiency beyond latency hiding.

Adaptive batching. Read batching improves throughput by lowering per-I/O cost but may introduce queuing delays if the runtime waits too long to collect requests, while very small batches negate the amortization benefit. Our runtime therefore uses *adaptive batching*, adjusting the batch size based on the ratio of outstanding I/Os to waiting fibers. When many I/Os are in flight, additional submissions are deferred to increase amortization; when few are pending, batches are flushed earlier to keep the CPU busy. This feedback mechanism maintains high device utilization while avoiding stalls from an empty ready queue.

Impact of adaptive batching. Performance increases by about 18%, from 183 k to 216 k tx/s (Figure 5, +BatchSubmit). Adding I/O cost for batched reads to the cycle model, $c_{\rm io} = c_{\rm read-batch} + c_{\rm write-batch} = 11,100$ cycles (Table 1), yields $\frac{3.7\times10^9}{8264+0.7\times11100} \approx 230$ k tx/s as expected throughput. The estimate aligns with the measured 216 k tx/s, confirming that adaptive read batching reduces CPU overhead in the submission path and improves single-core efficiency.

3.4 Tuning io_uring for the Storage Engine

Utilizing io_uring's key capabilities enabled us to implement an asynchronous architecture whose performance is determined by CPU cycles spent on I/O processing. This forms the basis for applying io_uring's low-level features to reduce I/O overheads. However, the effectiveness of io_uring's features also depends strongly on workload characteristics, as discussed next.

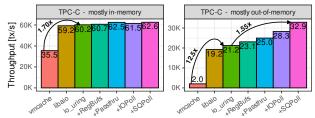


Figure 6: TPC-C with 1 warehouse (left) and 100 warehouses (right) with the default transaction mix. io_uring outperforms libaio, vmcache uses blocking I/O that performs worst if out-of-memory with 100 warehouses (storage-intensive).

3.4.1 Performance Evaluation with YCSB

We cut per-I/O CPU cost by reducing three overheads: data movement (using registered buffers), storage stack (NVMe passthrough), and submission/completion handling (SQPoll & IOPoll).

Registered buffers reduce copies. io_uring allows user-space buffers to be *registered* once during initialization, avoiding perrequest page pinning and kernel-user copies. The kernel then performs DMA directly into user memory, eliminating these overheads. For our YCSB workload, this zero-copy optimization improves throughput by about 11%, reaching 238 k tx/s (Figure 5, +RegBufs). NVMe passthrough skips abstractions. To access NVMe devices directly, io_uring provides the OP_URING_CMD opcode, which issues native NVMe commands via the kernel to device queues. By bypassing the generic storage stack, passthrough reduces softwarelayer overhead and per-I/O CPU cost. This yields an additional 20% gain, increasing throughput to 300 k tx/s (Figure 5, +Passthru).

IOPoll avoids interrupts. With IOPOLL, completion events are polled directly from the NVMe device queue, either by the application or by the kernel SQPOLL thread (cf. Section 2), replacing interrupt-based signaling. This removes interrupt setup and handling overhead but disables non-polled I/O, such as sockets, within the same ring. When using filesystems, IOPOLL requires explicit support and is typically available only for direct block-device access via O_DIRECT. As shown in Figure 5 (*+IOPoll*, right), completion polling provides an additional 21% throughput gain, reaching 376 k tx/s - single-threaded. As we will show later, it also reduces latency for I/O-intensive workloads (cf. Figure 9).

SQPoll eliminates syscalls. In SQPOLL mode, a dedicated kernel thread continuously polls the submission queue, allowing applications to enqueue I/O requests without calling io_uring_enter() for each submission. This dedicates one CPU core to polling but eliminates most syscall and submission overheads. The kernel thread handles I/O completions and places them into the completion queue for later consumption by the application. For our buffer manager (Figure 5, +SQPoll), throughput increases by about 32% to 546k tx/s, corresponding to the cost previously spent in syscall and kernel-side processing.

3.4.2 Performance Evaluation with TPC-C

Unlike YCSB, which issues short, independent transactions dominated by random I/O, TPC-C models an OLTP system with interacting transactions and a larger share of in-memory computation. This workload thus evaluates how io_uring optimizations perform in a less I/O-bound, more CPU-intensive setting. As a baseline, we use

vmcache [32], a state-of-the-art buffer manager. We reuse the asynchronous, batched-read configuration from the YCSB experiments for a fair comparison.

Workload-dependent benefits. Figure 6 shows the results for TPC-C in a mostly in-memory and a mostly out-of-memory configuration. The io_uring-based buffer manager consistently outperforms vmcache, achieving up to 12.5× higher throughput in the naive configuration. The primary reason is architectural: vmcache relies on blocking reads. Enabling advanced io_uring features further improves throughput, although the relative gains depend on the workload configuration. The memory-intensive TPC-C workload is largely compute-bound and many reads can be answered from memory which limits the effect of I/O-path optimizations. In this case, +IOPoll performs slightly worse than the interrupt-driven baseline because polling wastes CPU cycles when I/O operations are sporadic. +SQPoll provides no benefit for the same reason. In the out-of-memory setting, I/O activity rises significantly due to the increased cost of page loads and evictions, making optimizations more impactful.

3.5 Take-aways and Summary

When to use io_uring. Our buffer manager study shows that io_uring yields meaningful gains for I/O-intensive workloads with many page faults, such as YCSB and TPC-C configurations where a substantial fraction of reads miss the buffer pool and involve SSD page loads and evictions. In compute-heavy (i.e., mostly in-memory) settings, the I/O path contributes little to overall cost, and io_uring optimizations have correspondingly smaller impact.

How to integrate it. A key insight of our study is that io_uring must be integrated as part of an end-to-end architectural design rather than as a drop-in replacement. Using io_uring key features (batching, asynchronous execution) enabled us to shift the bottleneck from device latency to CPU cycles and make the cost of I/O processing explicit, as verified by our model-based analysis.

How to tune it. Once the architecture exposes enough asynchronous I/O, low-level io_uring features can reduce per-operation CPU overhead. However, our study revealed that the tuning benefits depend strongly on the workload: substantial improvements arise when I/O dominates execution time, while CPU-bound or cacheresident workloads gain little.

3.6 Detailed Analysis of io_uring

The results in the previous section showed that realizing performance gains depends on both the system architecture and workload characteristics. In this section, we conduct targeted microbenchmarks to isolate and quantify the effects of individual mechanisms for system builders in depth and also study effects of multi-threading. Batching effects on SSD latency. In the buffer manager design, we used io_uring's batching to hide I/O latency for writes and amortize syscall overhead for reads. However, batching can also increase latency variance, which is problematic for workloads requiring predictable response times. To quantify this effect, we vary batch sizes for write requests to a single SSD via io_uring, fixing throughput at 1.5 MIOPS to stay below the device limit and isolate batching behavior. As shown in Table 2, small batches (e.g., size 8) keep latencies mostly below 25 μs , at the cost of slightly higher syscall frequency.

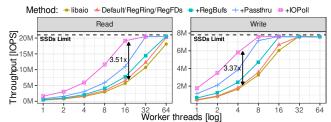


Figure 7: Scale-out performance for random 4 KiB reads & writes between libaio and io_uring with incremental optimizations. io_uring consistently outperforms libaio. Further io_uring optimizations increase throughput by 3.4-3.5×.

Larger batches reduce submission overhead but cause higher variance; with batch size 128, latency spikes up to 200 μs occur as bursts from multiple workers can temporarily overload the SSD queue with many outstanding I/Os. Thus, even below I/O saturation, batch size strongly influences latency distribution. For latency-sensitive DBMSs, overly aggressive batching is counterproductive.

Table 2: Impact of batch size on SSD write latency (8 workers).

Batch size:	1	8	32	64	128	256
Latency ⊘ [μs]	11.51	24.22	60.62	116.40	200.85	317.51
Latency σ [μ s]	±0.95	±1.71	±3.91	± 12.17	±7.47	±33.88

Multi-threaded Performance. The buffer manager in the previous section used a single-threaded setup. We now increase the number of threads to analyze how io_uring behaves under parallelism. We use one ring-per-thread for io_uring and also include libaio for comparison. As shown in Figure 7, io_uring consistently outperforms libaio for both random reads and writes and exhibits near-linear scalability with the number of threads. At higher core counts, the operating system's storage stack becomes the dominant bottleneck. The benefit of io_uring optimizations increases with scale: registered buffers (+RegBufs) reduce CPU overhead, while NVMe passthrough (+Passthru) and IOPoll in particular deliver substantial throughput improvements of 3.4–3.5× saturating the SSD array with 18 and 6 cores, respectively.

Increasing block sizes. Larger block sizes for I/O can further amortize CPU costs when the workload allows coarser-grained access. We therefore evaluate how block size affects SSD performance by measuring CPU cycles per byte for reads and writes while varying the I/O block size in a single-threaded setup. Figure 8 shows that larger blocks substantially reduce CPU cost per byte, as syscall and I/O stack overheads are amortized. With sufficiently large requests, a single core saturates the PCIe 5 SSD array, reaching up to 90 GiB/s for reads and 50 GiB/s for writes, close to hardware limits. This point is reached for writes at 128 KiB and reads at 256 KiB with +Passthru and +IOPoll enabled.

Large blocks can backfire. However, exceeding certain thresholds triggers asynchronous worker threads, signaling fallback to slower I/O paths as discussed in Section 2.2. First, if the block size exceeds max_hw_sectors_kb (which can be 128 KiB if the IOMMU were enabled), workers are spawned even at low I/O depth, as a single request surpasses the maximum DMA size. Second, with O_DIRECT, workers appear once the number of batched requests exceeds nr_requests (1023 on bare metal, 127 in our cloud VM),

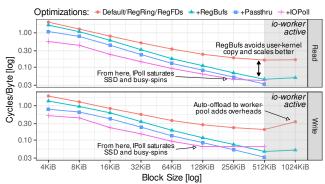


Figure 8: Single thread SSD performance with increasing block sizes. Performance degrades with I/O workers, NVMepassthrough is only supported until 512KiB.

and on some consumer SSDs even without O_DIRECT. Third, when block sizes exceed 512 KiB (max_segments) asynchronous workers are again used internally for I/O. While large blocks improve efficiency and fully utilize PCIe 5 bandwidth, surpassing these software or hardware limits causes worker fallback, reintroducing latency and CPU overhead in io_uring.

The durable write problem. Durable writes are essential for database systems, particularly for write-ahead logging and checkpointing, yet remain costly. The standard approach, fsync, is blocking in io_uring and thus executed by fallback worker threads. Moreover, fsync cannot be issued by rings configured for IOPoll and must be used from a separate ring or as a traditional syscall. These constraints motivate alternatives such as opening files with O_SYNC, which delegates durability to the kernel, or using NVMe flushes via passthrough commands. Figure 9 compares these methods on consumer and enterprise SSDs. Enterprise SSDs with DRAM caches and Power Loss Protection (PLP) achieve microsecond-level latencies, whereas consumer SSDs remain dominated by intrinsic millisecondscale fsync cost, masking worker-thread latencies. Not pinning the fsync I/O worker to the local chiplet (+Chiplet) increases latency by about 5%. O_SYNC-based writes perform poorly, more than twice as slow as explicit writes followed by fsync. NVMe passthrough with explicit flush commands offers a truly asynchronous durability path but requires raw device access. Linking a write and fsync in io_uring offers no improvement over issuing them sequentially in the application. For enterprise SSDs, durability is managed by the device itself, eliminating the need for fsync. Passthrough writes with IOPoll reduce latency by about one microsecond, showing the benefit of bypassing the storage stack in latency-sensitive workloads. While passthrough with flush is the most efficient asynchronous option, its lack of filesystem support restricts it to flash-optimized database systems. Implementing durable writes in io_uring therefore requires careful configuration to avoid performance pitfalls.

4 Efficient Network I/O with io_uring

After analyzing storage, we now focus on the networking aspects of io_uring. High-speed interconnects with link rates in the range of 400 Gbit/s are now a commodity in modern data centers and cloud deployments [1, 40]. We investigate how distributed DBMSs

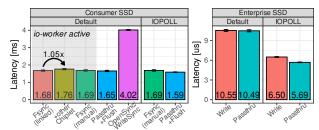


Figure 9: Durable writes with io_uring. Left: Writes and fsync are issued via io_uring or manually linked in the application. Right: Enterprise SSDs do not require fsync after writes.

can saturate these high-throughput rates with io_uring by addressing our three research questions. We again conclude with a set of microbenchmarks that provide an isolated analysis of important io_uring features.

4.1 Use Case: Distributed Data Shuffle

Shuffle operations are a key building block in any distributed DBMS. We now study a bi-directional, all-to-all data shuffle representative of distributed analytical query execution, as used in parallel joins. **Distributed shuffle overview**. In a distributed shuffle, each node scans local data tables and repartitions tuples to other nodes based on a partitioning function. For a distributed hash join of two tables, tuples of the smaller table are shuffled by their join key, and local tuples are inserted into a node's local probe table. Meanwhile, remote tuples are sent over the network and then inserted into the remote probe table. For the larger table, tuples are also shuffled based on their join key and then probed into these hash tables.

Shuffle engine architecture. We implement a distributed hash join using morsel-based processing [33]. Each worker thread repeatedly fetches morsels from a shared iterator, partitions tuples by their hash, and issues send and receive operations for shuffling. In addition to network shuffling, we also execute the hash table build phase of the join, allowing us to study scenarios where computation and I/O compete for CPU cycles. Hash table inserts update pointers rather than copying payloads to reduce memory bandwidth.

4.2 Workload & System Conditions

The previous discussion reveals similarities between the buffer manager in the previous section and the distributed shuffle, as both involve computation (B-tree traversal/probe table build) and I/O operations that compete for precious CPU cycles. However, there are important differences in workload and system conditions, motivating a different stepwise approach.

Workload conditions. To study when io_uring yields measurable benefits, we vary the tuple size while shuffling the same total amount of data to obtain different workload characteristics: Smaller tuples result in more probe table inserts per transferred byte, leading to a large number of random memory accesses. Although not compute-bound like TPC-C, many hash-table inserts for small tuples can stall the CPU due to random memory accesses and therefore represent a challenging workload. In contrast, larger tuples lead to fewer insertions and fewer random memory accesses.

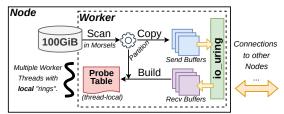


Figure 10: Overview of the shuffle architecture with scan & probe table. Workers use morsel-driven parallelism and handle scanning, probe table building and network I/O.

System conditions. We evaluate the shuffle workloads on a sixnode cluster with ConnectX-7 NICs, which provide 400Gbit/s bidirectional bandwidth, resulting in 4.8 Tbit/s of bisection bandwidth (6×2×400 Gbit/s). Since network round-trip latencies are orders of magnitude higher than SSD access latencies, even in traditional engines, it is common to adopt asynchronous strategies such as using dedicated I/O threads [3, 14, 29]. Batching tuples into larger chunks, e.g., 1 MiB, is also an often adopted approach to amortize network overhead and increase throughput [28]. Hence, we adopt an asynchronous design as a baseline from the beginning without discussing synchronous I/O in the context of the shuffle use case.

4.3 Using io_uring in the Shuffle Engine

Building on these insights and the results of the buffer manager use case in Section 3, we directly utilize io_uring's asynchronous I/O and batching capabilities for a first shuffle baseline.

Integrating io_uring into a shuffle. The asynchrony of io_uring enables us to avoid the approach of using dedicated I/O threads that use blocking I/O. As recommended with io_uring [8], we adopt a ring-per-thread architecture in which each worker thread possesses a thread-local io_uring ring. This architecture enables scanning data, while sending and receiving tuples asynchronously via io_uring within a single thread. While both approaches overlap computation and communication, increasing CPU utilization, colocating computation and I/O within the same thread avoids synchronization overhead with I/O workers and improves cache locality. Unlike in our buffer manager, we directly employ multithreading with the goal to saturate the 400 Gbit/s NICs.

Details of shuffle implementation. To avoid other system bottlenecks and isolate io_uring performance impacts, we adopt several state-of-the-art system optimizations in our shuffle implementation. For example, we use batched inserts into the probe table to improve access predictability and allow the prefetcher to issue concurrent loads [10]. We pin workers with their TCP/IP flows in a round-robin manner to CPU chiplets [17] to reduce overheads in io_uring for networking. Finally, we tune our network stack following industry best practices [31] and use Linux 6.17 for zero-copy recv support. Basic io_uring configuration. io_uring comes with multiple network-specific features, such as multi-shot receive (cf. Section 4.6), that can be used for data shuffling. As a baseline, we adopt the same DeferTR and single-issuer setup flags as used in the buffer manager use case to avoid preemptions and internal synchronization (cf. Section 2). For transfers, we use large buffer sizes of 1 MiB, which are more suitable than multi-shot receive or other mechanisms, as we show later in Section 4.6.

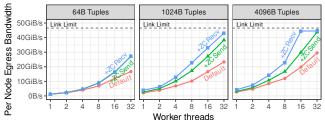


Figure 11: Per-node egress bandwidth for a six node shuffle with different tuple sizes using up to 32 worker threads.

Initial performance. Figure 11 shows the per-node egress bandwidth for small and large tuple sizes as the number of worker threads increases. The total bidirectional bandwidth is therefore twice these values. The baseline io_uring configuration (red) scales with more workers, mainly due to the morsel-based design, where workers can send and receive data independently. For small tuple sizes (e.g., 64 B), more frequent probe table inserts cause additional random memory accesses, which introduce stalls and limit network throughput. With larger tuples, the insertion rate decreases, reducing memory pressure and allowing the system to achieve higher bandwidths. However, even for larger tuples, the system reaches at most 30 GiB/s per node (Figure 11, red), well below the 400 Gbit/s link rate, indicating that the workload is not I/O-bound.

4.4 Tuning io_uring for Network I/O

As with storage, io_uring also provides multiple network optimizations to reduce per-I/O overhead. In the following, we discuss our findings on how to best use them for efficient network shuffling. Reducing memory pressure. In the Linux networking stack, send and receive operations typically copy data between user-space and kernel buffers. While these copies are negligible at moderate speeds, they become costly at high network speeds, as even a single extra copy can consume precious memory bandwidth. To address this, io_uring supports zero-copy operations, eliminating redundant data copies between kernel and user space. Zero-copy send transmits data directly from pinned user-space buffers, avoiding intermediate copies. Zero-copy receive, a more recent io_uring addition, writes received data directly into registered user-space memory. It requires NIC support to separate the TCP header (still handled by the kernel) from the payload, so it may not be available on all network devices. **Zero-copy I/O reduces memory load.** As shown in Figure 11, enabling zero-copy send (green) and zero-copy receive (blue) yields visible throughput improvements across different tuple sizes compared to the default setting. For 4 KiB tuples, link bandwidth is saturated with only 16 workers per node when both zero-copy paths are active, achieving full bidirectional 400 Gbit/s utilization with modest CPU usage. However, for 64B tuples, zero-copy receive does not provide additional benefits beyond zero-copy send. We suspect that contention between NIC traffic and CPU-driven random memory accesses, along with resulting stalls, diminishes the potential gains. Since zero-copy receive is a recent kernel addition, a deeper investigation is left for future work.

Analyzing memory bandwidth. To understand why shuffle performance is limited without zero-copy operations, we analyze system memory bandwidth during the scale-out experiment described

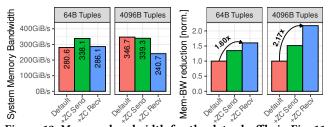


Figure 12: Memory bandwidth for the data shuffle in Fig. 11 (32 Workers). Left: absolute bandwidth; right: Bandwidth reduction normalized by achieved network throughput.

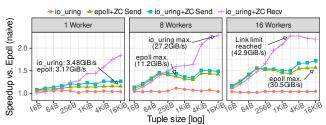


Figure 13: Speedup of io_uring and zero-copy send epoll vs. plain epoll for data shuffling across six nodes and different tuple sizes. Zero-copy receive is only available with io_uring.

above. Figure 12 shows measurements for both the default and zerocopy configurations. On the left, we present the system memory bandwidth, calculated as the sum of read and write traffic from hardware performance counters. For both workloads, peak system bandwidth approaches 400 GiB/s. Zero-copy configurations typically show equal or higher absolute memory bandwidth, primarily due to their higher network throughput, which increases overall memory traffic. To account for this effect, we normalize the measured bandwidth by the achieved network throughput. The normalized plot (cf. Figure 12, right) shows that using zero-copy for send and receive reduces effective memory bandwidth by about half, as expected, since data copies are eliminated in both directions. End-to-end comparison with epoll. Similar to the buffer manager, we compare our optimized io_uring-enabled implementation to state-of-the-art approaches. For the shuffle, we use epoll as a baseline, a readiness-based I/O interface commonly used in existing systems. Figure 13 shows the speedup of different io_uring variants and an epoll-based zero-copy send implementation against a naive epoll baseline without optimizations. We vary tuple sizes (smaller tuples result in more random inserts into the probe table per byte transferred) and scale up to sixteen workers to avoid link saturation and ensure a fair comparison. Without zero-copy, epoll is only marginally slower than io_uring despite issuing more system calls. This behavior stems from both implementations transferring tuples in large 1 MiB chunks, which amortizes syscall and I/O-path overhead. With zero-copy send, io_uring achieves substantially better performance, with the gap widening as the number of workers increases. Unlike epoll, io_uring also supports zero-copy receive, further improving performance and providing up to a 2.5× speedup. Overall, io_uring offers a more efficient and unified interface for network I/O, supporting batching, and zero-copy send and receive.

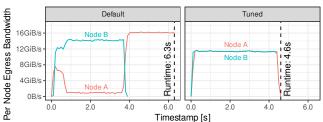


Figure 14: Careful tuning of the networking setup is required to achieve equal bandwidth sharing. Workload: 100 GiB table shuffle between 2 nodes using eight workers (no probe table).

4.5 Take-aways and Summary

When to use io_uring. Our shuffle use case shows that io_uring provides benefits in high-throughput settings where memory bandwidth becomes a bottleneck. In the setup with large tuples, where probe table inserts are rare, and workers mainly stream tuples and perform simple partitioning, zero-copy networking enables us to saturate 400 Gbit/s links with relatively few cores. For smaller tuple sizes, random memory accesses during hash-table inserts dominate and limit the achievable throughput; network-path optimizations have a relatively less significant impact but are still important for achieving optimal bandwidth.

How to integrate it. Treating io_uring as a drop-in replacement in a traditional I/O-worker design is inadequate. Instead, io_uring requires a ring-per-thread design that overlaps computation and I/O within the same thread. Together with careful placement of workers across CPU chiplets and an optimized networking stack, this architecture keeps cores busy and exposes sufficient concurrent I/O for io_uring to be effective.

How to tune it. Once the engine operates asynchronously with large batched transfers, tuning io_uring can reduce data movement and CPU overhead per I/O. Registered buffers and zero-copy send/receive eliminate kernel-user copies, reducing memory bandwidth consumption per unit of network throughput by $\approx 2\times$.

4.6 Detailed Analysis of io_uring

In this section, we focus on important aspects of io_uring for tuning network interfaces of database systems, which we could not cover before through targeted microbenchmarks.

Impact of network-stack configuration. To quantify the effect of suboptimal network settings on io_uring performance, we conduct a microbenchmark using the shuffle workload. The experiment transfers 100 GiB bidirectionally between two machines, each running eight worker threads, and measures end-to-end throughput over time. In the default configuration, we disable Nagle's algorithm (TCP_NODELAY) and pin NIC queues to CPU cores. Despite these settings, persistent flow imbalance occurs, with one peer dominating the bandwidth and starving the other (Figure 14), resulting in a total runtime of 6.3 s. Such behavior masks potential io_uring gains at the system level. For the shuffle evaluation above we therefore used a tuned network stack. Specifically, using fairer queue discipline (qdisc) and configuring socket buffers for 400 Gbit/s according to [31] balance bandwidth utilization. As shown in Figure 14, the total runtime is reduced by over 25%, from 6.3s to 4.6s.

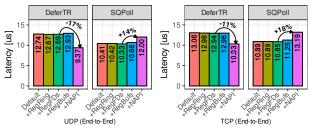
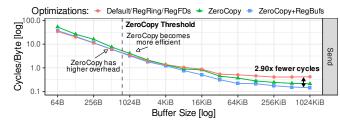


Figure 15: UDP and TCP latency ping-pong with 8 -byte messages and incrementally enabled optimizations. NAPI polling reduces latency for DeferTR, but increases it with SOPoll.

Reducing latency with io_uring. Network latency is crucial for distributed latency-sensitive database protocols, such as transaction coordination or replication, where microsecond-level delays accumulate at scale. We measure one-way and round-trip latencies for TCP and UDP using 8-byte messages to capture the minimum cost of message delivery. Both modes - deferred taskrun (DeferTR) and SQPoll - are evaluated, along with optimizations such as registered file descriptors, registered buffers, and NAPI (the networking counterpart of IOPoll). As shown in Figure 15, SQPoll achieves lower latency than DeferTR, but the advantage disappears once NAPI is enabled. DeferTR with NAPI yields the best overall latency, outperforming SOPoll, while registered buffers have a negligible impact for small messages and increase latency slightly. When the NIC queue is pinned to a remote chiplet, cross-chiplet interrupt handling increases latency by 14 % for UDP and 21 % for TCP. With NAPI enabled, however, remote queues cause only a negligible increase of less than 1 %. For reference, a DPDK-based implementation reaches 7 µs, providing a lower bound for userspace networking.

Send path optimizations. As shown in Figure 15, registered buffers have little effect for very small messages, in contrast to their positive impact in the storage setting (Section 3.4.1). To better understand which optimizations are most effective for different database workloads, we vary the transfer size and report the effective cycle cost per transmitted byte. Figure 16 (left) shows a clear threshold around 1 KiB: below this size, zero-copy send performs worse than plain io_uring due to buffer-management overheads, whereas for larger messages registered buffers amortize this cost and consistently reduce per-byte CPU time. Registering rings and file descriptors yields only marginal improvements but introduces no observable drawbacks. Overall, zero-copy with registered buffers is the most efficient configuration for large messages, achieving up to 3.5× fewer cycles per transmitted byte than default io_uring.

Receive path optimizations. We observe analogous thresholds for the receive path (Figure 16, right). Multishot receive operations repeatedly generate completions from a single submission and are most efficient for workloads with small messages. Once message sizes exceed roughly 1 KiB, zero-copy receive becomes more efficient, and for very large messages (e.g., 13 KiB and above) even the normal single-shot receive path outperforms multishot due to reduced per-message overheads. io_uring can also draw receive buffers from a kernel-managed pool (RingBufs), but these perform worse than user-supplied buffers and are only useful in multishot scenarios. Exact thresholds vary with capabilities and available offloads of the NIC, but the overall pattern remains consistent.



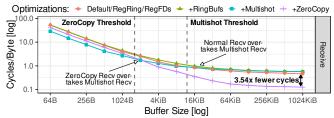


Figure 16: Impact of incremental io_uring optimizations on the cycle cost for a single TCP connection. The best-performing configuration depends on the shown thresholds. Registered file descriptors offer minimal benefit and are therefore omitted.

Optimizing kernel execution for sockets. Recall how io_uring executes *task_work* inside the kernel. By default, it first attempts to complete an I/O operation inline in non-blocking mode and falls back to internal polling only if the call returns -EAGAIN (see Figure 3). For socket operations, this speculative attempt can be wasteful when the application already knows the socket is empty (for receive) or full (for send), causing unnecessary kernel work. Such cases commonly occur in RPC-style communication, where the response is expected only after the request. To handle this efficiently, io_uring provides the RECVSEND_POLL_FIRST flag, which skips the speculative attempt and directly uses the poll set. Using PollFirst reduces the number of instructions executed and kernel work, resulting in up to 1.5× reduction in CPU cycles spent.

5 Insights for System Builders

In our study, we focused on three research questions: when to use io_uring, how to integrate it, and how to tune it. Exploring these questions provided key insights for effectively using io_uring in database systems. We summarize these insights as actionable guidelines for engineers, and then validate their practicality by applying them to enhance PostgreSQL's I/O performance.

5.1 Guidelines

Based on our system case studies, we draw four practical guidelines for using io_uring effectively in database systems:

- (1) **Determine if I/O is a system bottleneck.** When I/O accounts for only a small fraction of execution time, as in CPU-bound or cache-resident workloads, potential io_uring gains are limited. Our use cases in Section 3 and Section 4 show that io_uring is most effective when it reduces or amortizes the CPU cost of I/O operations, or when it lowers the memory bandwidth consumption. As demonstrated in the buffer manager case study, simple latency or cycle models help to model such bottlenecks.
- (2) Align the architecture with io_uring capabilities. io_uring enables asynchronous execution, system call batching, and a unified interface for storage and network I/O. Our buffer manager (Section 3.1) shows that architectural changes, such as overlapping I/O and computation via asynchronous execution or amortizing per-I/O cost through batching, can yield large improvements. The network shuffle (Section 4.1) shows how applications can use the *ring-per-thread* architecture to scale beyond a single core and enable internal io_uring optimizations.
- (3) Choose and tune the execution mode deliberately. The recommended io_uring configuration uses DeferTR with *single-issuer* for predictable task execution and controlled completion reaping

(Section 2). SQPoll can improve performance when dedicating a polling core is amortized, and latency or IOPS targets justify the additional CPU cost. Falling back to io_workers should be avoided by ensuring that all operations, including fsync and large I/Os, can execute fully asynchronously (cf. Figure 8). Tuning the execution mode to the underlying hardware helps avoid costly effects, such as cross-chiplet traffic or non-local interrupt handling (Section 4.3). (4) Use io_uring optimizations. io_uring offers a range of general, storage-specific, and networking-specific optimizations for I/O-intensive systems. Carefully selecting these optimizations can reduce the per-I/O cycle cost. Some optimizations, such as registered FDs or fixed buffers for 4 KiB page-aligned storage I/O, do not negatively impact performance (see Section 3.4.1). However, mechanisms like zero-copy or multishot receive are only effective when payloads exceed device-specific thresholds (cf. Figure 16). Other optimizations, such as NVMe passthrough or IOPoll, apply only when no filesystem or a compatible filesystem is used.

5.2 Optimizing PostgreSQL using Guidelines

PostgreSQL recently added support for io_uring in version 18, enabling asynchronous I/O for data and WAL access [19]. We use this integration to illustrate how our guidelines can be used in a production-grade engine and where PostgreSQL's architecture imposes constraints.

- GL (1): Determine if I/O is a system bottleneck. Even without tuning io_uring parameters or enabling additional features, PostgreSQL's new io_uring backend achieves up to 3× higher performance in I/O-intensive workloads than the previous synchronous design based on blocking calls and OS readahead [19]. This shows that I/O has been a dominant bottleneck and validates guideline (1) in a real system: once I/O is identified as limiting, adopting io_uring yields measurable gains. This baseline forms the starting point for the guideline-driven improvements in Figure 17. We use 1–8 backend workers scanning a 32 GiB cold table via direct I/O to show how PostgreSQL's I/O bottleneck improves.
- GL (2): Align the architecture with io_uring capabilities. Post-greSQL already partially aligns with guideline (2). Backend processes overlap computation and I/O by issuing multiple asynchronous reads and writes, aligning with io_uring's batching capability. However, PostgreSQL uses a multi-process model in which a backend may wait on I/O submitted through rings owned by other processes. Rings are therefore not exclusively used by a single issuer, which prevents using DeferTR, as it requires per-thread ring ownership. A more io_uring-friendly design would use one ring

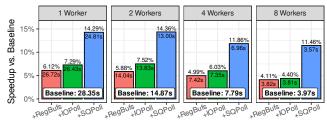


Figure 17: PostgreSQL speedup from io_uring optimizations. Sharing the SQPoll kernel thread between rings has negligible performance impact. Improvements remain limited by the filesystem and PostgreSQL's multi-process architecture.

per thread with exclusive ownership and no cross-process sharing. PostgreSQL also relies on filesystems for data storage, which prevents low-level optimizations for guideline (4), such as NVMe passthrough and IOPoll. Filesystem traversal adds CPU overhead and constrains effective utilization of modern storage hardware.

GL (3): Choose and tune the execution mode deliberately. Given PostgreSQL's architecture, DeferTR cannot be used without substantial refactoring. We therefore configure io_uring with CoopTR as the next-best alternative. CoopTR disables kernel-driven task_work preemptions but still processes completions on each kernel-user transition, providing more predictable execution while remaining compatible with PostgreSQL's process model. Still following guideline (3), we extend the backend to support SQPol1 by enabling the respective setup flag during ring creation and allowing multiple backend processes to share a single SQPol1 kernel thread. For WAL durability, PostgreSQL invokes fsync() directly (or via O_DATASYNC) rather than through io_uring, consistent with guideline (3). This avoids spawning io_workers for blocking fsync() calls and keeps the critical path fully asynchronous.

GL (4): Use io_uring optimizations. We apply guideline (4) by enabling io_uring optimizations that fit PostgreSQL's access patterns and architectural constraints. We register the entire buffer pool as fixed buffers, eliminating PostgreSQL's heuristic of enabling IO_ASYNC after four outstanding I/Os. Given PostgreSQL's 8 KiB page size, this optimization aligns with the findings from Figure 8. In Figure 17, fixed buffers alone provide a 4–6% improvement. Because we use ext4, we additionally enable IOPol1, improving performance up to 7.5% over the baseline. Combined with SQPol1, total throughput improves by 11–15% over upstream PostgreSQL, despite the architectural constraints discussed above.

Summary. Applying the guidelines yields consistent improvements even in a mature DBMS. Although PostgreSQL already incorporates optimizations such as coalescing small reads and using OS readahead, and although its process model and filesystem dependence limit the applicability of several io_uring features, the remaining optimizations still yield measurable gains. Despite these factors, we observe speedups of 11–15% for the scan workload.

6 Related Work

Although io_uring is a relatively recent addition to the Linux kernel, it has already been studied in various contexts, primarily focusing on storage I/O and its impact on data-intensive systems.

Storage interfaces and NVMe systems. Initial systematic comparisons of io_uring with established interfaces such as libaio and SPDK were conducted using the fio benchmark to evaluate typical storage workloads [13]. Ren and Trivedi extended this analysis for Intel Optane SSDs, characterizing microarchitectural behavior, instruction-level overheads, and Linux block I/O scheduler performance [39]. In the context of database systems, Haas et al. explored io_uring and other asynchronous I/O mechanisms for NVMe SSD arrays. They identified improvements in throughput and latency associated with various io_uring features [21–23].

Application-level and system integrations. Several works integrated io_uring into production systems to evaluate application-specific benefits. Chen et al. applied io_uring to Redis, reporting significant reductions in overhead for medium and large payloads [12]. Durner et al. used io_uring to accelerate cloud object storage access, achieving lower latency and higher throughput [15]. However, systematic analyses of network-specific aspects and end-to-end effects on distributed systems remain absent.

Security and advanced feature analyses. From a security perspective, He et al. proposed RingGuard, an eBPF-based framework that monitors and restricts io_uring operations to prevent kernel-level vulnerabilities. It extends eBPF with new io_uring-specific hooks and verifier logic, enforcing safety policies at runtime while maintaining low overhead [25]. The most comprehensive exploration of io_uring features to date is the work by Ingimarsson, who integrated basic functionality into RocksDB [26]. However, detailed evaluations of advanced io_uring features, such as registered buffers for zero-copy operations and linked requests to minimize system calls, are still lacking.

Our research addresses these gaps, offering detailed empirical evaluations in the context of data-intensive workloads and providing practical guidelines to use io_uring's capabilities effectively.

7 Conclusion and Outlook

The modern Linux io_uring interface provides powerful mechanisms for efficient asynchronous I/O, but achieving measurable gains requires more than simply enabling its features. Our case studies show that performance depends on understanding system bottlenecks and integrating io_uring into the overall design, including leveraging asynchronous execution to hide latency, batching to amortize kernel interactions, and applying targeted optimizations to reduce CPU cost per byte. We further used focused microbenchmarks to highlight trade-offs and subtleties of specific optimizations, such as the effects of buffer size on zero-copy and the importance of aligning polling strategies with hardware and workload characteristics. From this analysis, we distilled practical guidelines for I/O-intensive systems and validated them through an integration into PostgreSQL, improving table-scan throughput by 11-15% over its baseline io_uring implementation. As io_uring continues to evolve, it offers a path towards scalable I/O in Linux. Adopting it today also makes systems future-ready, allowing applications to benefit from new capabilities, such as recently added zero-copy receive and upcoming features, without requiring architectural changes.

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