CPQ I/O Scheduler

Custom Priority Queue I/O Scheduler for Linux Block Layer

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Target: Linux Kernel 5.x/6.x with blk-mq framework

Abstract

This paper presents CPQ (Custom Priority Queue), a novel I/O scheduler for the Linux kernel's block multiqueue (blk-mq) framework, developed through reverse engineering of a proprietary binary implementation and subsequently enhanced with thread group fairness mechanisms inspired by Samsung's SSG scheduler. CPQ addresses fundamental limitations in existing I/O schedulers for mobile and interactive devices by providing per-thread-group fairness, priority-aware request dispatch, and deadline-based aging, achieving an 83.3% win rate with +1.86% average performance improvement over mq-deadline

This paper provides comprehensive technical documentation covering architecture, algorithms, performance analysis, deployment strategies, and operational considerations. The scheduler implements a sophisticated architecture combining priority queuing, red-black tree-based sector sorting, FIFO deadline enforcement, and per-CPU caching for minimal overhead. This work demonstrates both the feasibility of reconstructing closed-source kernel modules through binary analysis and the effectiveness of hybrid scheduling approaches that balance fairness with performance.

Keywords: I/O scheduling, block layer, blk-mq, fairness, priority queuing, real-time, Linux kernel

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1 Introduction

1.1 Motivation

The Linux kernel's I/O scheduling layer faces increasing demands in modern computing environments characterized by multiple concurrent applications, diverse workload priorities, and heterogeneous storage devices. Traditional schedulers like mq-deadline prioritize throughput and minimize seek times but lack fairness mechanisms to prevent resource monopolization by aggressive applications. This limitation manifests in scenarios where background tasks (e.g., backups, file indexing) can starve interactive applications, degrading user experience.

The Custom Priority Queue (CPQ) scheduler originated from a proprietary binary developed by Xiaomi and utilized on their mobile phones; it was likely developed ensuring fairness and predictable latency were critical. However, the closed-source nature of this scheduler limited its adoption and prevented community-driven improvements. This work addresses these limitations through three key contributions.

1. **Reverse Engineering**: Complete reconstruction of the CPQ scheduler from binary artifacts using modern decompilation tools and manual analysis, recovering the original algorithm design and data structures.
2. **Thread Group Fairness**: Enhancement of the base CPQ design with per-tgid (thread group ID) fairness tracking inspired by Samsung's SSG scheduler, preventing monopolization while maintaining high throughput.
3. **Performance Optimization**: Iterative refinement through systematic benchmarking and micro-optimizations, achieving production-ready stability and competitive performance against established schedulers.

1.2 Problem Statement

Existing I/O schedulers in the Linux kernel exhibit several limitations:

- **mq-deadline**: Provides deadline-based FIFO guarantees and sector-ordered dispatch but lacks fairness mechanisms. A single aggressive application can monopolize queue depth, starving other processes.
- **BFQ (Budget Fair Queueing)**: Offers fairness through time-based budgets but incurs significant CPU overhead (5-10%) and struggles with high queue depths on fast SSDs.
- **Kyber**: Optimized for low-latency SSDs with token-based congestion control but provides no fairness guarantees and limited configurability.
- **NONE scheduler**: Bypasses scheduling entirely, maximizing throughput for single-application scenarios but offering no isolation or fairness.

The CPQ scheduler addresses these gaps by combining:

1. Priority-aware dispatch (RT, BE, IDLE classes)
2. Per-thread-group fairness with configurable limits
3. Deadline-based aging to prevent starvation
4. Low-overhead implementation suitable for high-performance storage

2 Background Study

2.1 Linux Block Layer Architecture

The Linux block layer serves as the interface between file systems and storage devices, managing I/O request queuing, merging, and scheduling. Modern kernels (5.0+) use the block multiqueue (blk-mq) framework, which provides per-CPU submission queues and hardware dispatch queues to eliminate lock contention and scale to multi-core systems.

2.1.1 Traditional Single-Queue Era

Early Linux I/O schedulers (CFQ, Deadline, Noop) were designed for single-queue devices:

- **CFQ (Completely Fair Queuing)**: Process-level fairness, complex time-slice management
- **Deadline**: Deadline-based with read/write prioritization
- **Noop**: Simple FIFO, suitable for fast SSDs

Limitations:

- Single global queue became bottleneck with fast NVMe devices
- Lock contention on multi-core systems
- Per-process tracking overhead

2.1.2 The blk-mq Revolution

Linux 3.13+ introduced blk-mq (block multi-queue), The blk-mq framework consists of three key layers:

1. **Submission Layer**: Per-CPU software queues where requests are initially staged. The submission path is lockless, allowing parallel request insertion from multiple cores.
2. **Scheduler Layer**: Optional elevator layer that implements I/O scheduling policies. Schedulers can reorder, merge, and delay requests to optimize for specific goals (throughput, latency, fairness).
3. **Dispatch Layer**: Hardware queues that feed requests directly to device drivers. Modern NVMe SSDs support 64k hardware queues with depths up to 64k requests.

I/O schedulers in blk-mq implement the `elevator_ops` interface, providing callbacks for request insertion, dispatching, and lifecycle management. Schedulers included mq-deadline, Kyber, BFQ.

New Challenges:

- Fairness became harder with distributed queues
- Traditional process-based fairness models inadequate
- Need for lightweight, scalable algorithms

2.1.3 I/O Priority Classes

Linux supports three I/O priority classes via the `ioprio` system:

- **IOPRIO_CLASS_RT (0)**: Real-time priority for latency-sensitive applications. RT requests should be dispatched within 100ms to prevent deadline violations.
- **IOPRIO_CLASS_BE (1-7)**: Best-effort priority with eight levels (0 = highest, 7 = lowest). Default class for most applications.
- **IOPRIO_CLASS_IDLE (3)**: Lowest priority for background tasks that should only run when the system is idle.

Priority is set per-process using `ioprio_set()` and inherited by child processes.

2.2 Existing I/O Schedulers

2.2.1 mq-deadline

The mq-deadline scheduler is the default for rotating disks and the reference implementation for blk-mq scheduling. It provides:

- **Deadline FIFO**: Separate read and write FIFO queues with expiration times (read: 500ms, write: 5s) to prevent starvation.
- **Sector Sorting**: Red-black trees sorted by disk sector for sequential I/O optimization.
- **Batch Dispatch**: Processes up to 16 sequential requests in a single batch to reduce overhead.
- **Priority Aging**: Higher-priority requests are dispatched first, with aging to prevent indefinite delays.

However, mq-deadline lacks fairness mechanisms. A single process can monopolize queue depth, starving others.

2.2.2 BFQ (Budget Fair Queueing)

BFQ provides proportional bandwidth sharing through per-process time budgets. Each process is assigned a budget (measured in disk sectors or time) and scheduled in round-robin fashion. BFQ excels at fairness but incurs significant CPU overhead (5-10%) due to complex bookkeeping and frequent context switches.

2.2.3 Kyber

Kyber is optimized for low-latency NVMe SSDs, using token buckets to throttle submissions and prevent queue saturation. It dynamically adjusts queue depth based on observed latency but provides no fairness guarantees.

2.2.4 SSG (Samsung Generic Scheduler)

Samsung's SSG scheduler, developed for mobile and embedded systems, implements:

- **CGroup Integration**: Per-container I/O limits via Linux cgroups.

- **Async Write Control**: Separate limits for asynchronous writes to prevent background task interference.
- **Congestion Management**: Dynamic throttling based on queue depth to maintain low latency.

SSG served as the inspiration for CPQ's thread group fairness extension.

2.3 Fairness in I/O Scheduling

Fairness in I/O scheduling can be defined in multiple ways:

1. **Request Fairness**: Equal number of requests dispatched per process (e.g., mq-deadline with modifications).
2. **Bandwidth Fairness**: Proportional allocation of disk bandwidth (e.g., BFQ, CFQ).
3. **Latency Fairness**: Equal average latency for requests across processes.

CPQ implements **request fairness** with proportional throttling, limiting each thread group to a configurable percentage of total queue depth (default 50%).

2.4 Why Another I/O Scheduler?

Despite excellent options like mq-deadline and BFQ, gaps remain. Table 1 compares existing schedulers with CPQ.

Table 1: Comparison of I/O Schedulers

Feature	**MQ-Deadline**	**BFQ**	**Kyber**	**CPQ**
Fairness Guarantees	No	Yes	No	Yes
Priority Levels	2	3	2	3
CPU Overhead	Low	High	Low	Low
Thread Group Aware	No	Partial	No	Yes
RT Bypass	No	No	No	Yes
Throughput	High	Medium	High	High

CPQ's Unique Value:

- **Lightweight fairness**: Thread group limits without full proportional sharing
- **Strong priority support**: Three levels with RT bypass
- **Hybrid approach**: Deadline guarantees + fairness limits
- **Optimized for modern hardware**: Minimal locking, cache-conscious design

3 Reverse Engineering Methodology

3.1 Binary Artifacts and Toolchain

The CPQ scheduler was provided as a compiled Linux kernel module (`cpq.ko`) for the x86_64 architecture, stripped of symbols and debugging information. The binary contained:

- **ELF Sections**: Standard sections (.text, .data, .rodata, .bss) plus kernel-specific sections (.modinfo, .gnu.linkonce).
- **Function Pointers**: Pointers to kernel API functions resolved during module loading.
- **Struct Definitions**: Embedded structure layouts implicitly defined through memory accesses.

Tools Used:

1. **Ghidra**: Open-source reverse engineering framework by the NSA, providing decompilation, control flow analysis, and symbol recovery.
2. **objdump/readelf**: Standard GNU binutils for ELF header inspection.
3. **Linux Kernel Headers**: Version-specific headers to identify API signatures.

3.2 Decompilation Process

3.2.1 Phase 1: Symbol Recovery

Stripped binaries lack function names, but the kernel module format provides hints:

```
// Ghidra decompiled code
long FUN_00100a80(void) {
    long lVar1;
    lVar1 = elv_register(&DAT_00103000);
    if (lVar1 == 0) {
        printk("cpq: registered\n");
    }
    return lVar1;
}
```

Listing 1: Module Initialization Pattern

The `elv_register()` call with a global structure pointer (`DAT_00103000`) indicates this is the module initialization function (
texttt___init). The structure is the `elevator_type`, which contains function pointers for elevator operations.

3.2.2 Phase 2: Data Structure Inference

Kernel data structures are recovered through memory access patterns:

```
// Offset 0x08: Next pointer
*(undefined8 **)(param_1 + 8) = *(undefined8 **)(param_1 + 8) + 1;

// Offset 0x10: Priority field
uVar2 = *(undefined4 *)(param_1 + 0x10);

// Offset 0x20: FIFO list head
list_add_tail(&param_1->fifo_entry, *(undefined8 *)(param_1 + 0x20));
```

Listing 2: Structure Field Inference

By matching offsets with kernel structures (`struct request`, `struct cpq_data`), we reconstruct field layouts.

3.2.3 Phase 3: Control Flow Analysis

Ghidra's decompiler produces C-like pseudo-code from assembly, but with obfuscated variable names and inlined functions. Manual analysis recovers the logic:

```
// Decompiled (obfuscated)
while (true) {
    iVar1 = FUN_00100500(lVar2);
    if (iVar1 != 0) break;
    lVar2 = lVar2 + 1;
    if (2 < lVar2) return 0;
}

// Reconstructed (original logic)
for (prio = CPQ_PRIO_RT; prio <= CPQ_PRIO_IDLE; prio++) {
    rq = cpq_dispatch_from_queue(&cq->queues[prio]);
    if (rq) return rq;
}
return NULL;  // No requests
```

Listing 3: Dispatch Loop Reconstruction

3.3 API Matching and Validation

Kernel API calls are identified through string references and signature matching:

```
// String reference: "cpq: %s\n"
printk(KERN_INFO "cpq: %s\n", __func__);

// RB-tree operations
rb_insert_color(&crq->rb_node, &cq->sort_list[dir]);
rq = elv_rb_find(&cq->sort_list[dir], blk_rq_pos(rq));
```

Listing 4: Kernel API Identification

API documentation from the Linux kernel source confirms the function signatures.

3.4 Validation and Testing

The reconstructed scheduler was validated through:

1. **Compilation**: Successfully compiled against upstream android Linux 6.1 kernel headers without errors.
2. **Module Loading**: Loaded into a test kernel and registered as an I/O scheduler.
3. **Functional Testing**: Passed basic I/O operations (read, write, sequential, random) without crashes.
4. **Performance Testing**: Benchmarked against mq-deadline to ensure correctness.

Discrepancies between the reconstructed and original binary (for example,xample, missing optimizations) were documented.

4 Architecture Overview

4.1 What is CPQ?

CPQ (Custom Priority Queue) is a Linux kernel I/O scheduler designed for the modern blk-mq (block multi-queue) subsystem. It implements a multi-level priority queue with fairness guarantees, optimized for mixed workloads where both interactive responsiveness and throughput matter.

Unlike traditional I/O schedulers that focus solely on throughput or latency, CPQ adheres a few core principles:

1. **Priority-First Dispatch**: RT requests are always dispatched before BE, and BE before IDLE. Within each class, deadline-expired requests take precedence.
2. **Sector Locality**: Requests within the same direction (read/write) are sorted by disk sector to minimize seek times on rotating media.
3. **Deadline Guarantees**: All requests have an expiration time. Expired requests are promoted to ensure bounded latency.
4. **Fairness Without Sacrifice**: Fair resource distribution shouldn't hurt overall throughput
5. **Adaptive Behavior**: Single-app scenarios skip fairness overhead entirely

4.2 Target Use Cases

CPQ excels in:

1. **Desktop/Laptop Systems**: Where user responsiveness is critical
2. **Multi-tenant Servers**: Requiring fair resource distribution
3. **Embedded Systems**: With dynamic real-time requirements

4.3 System Context

Figure 1 shows CPQ's position in the Linux I/O stack.

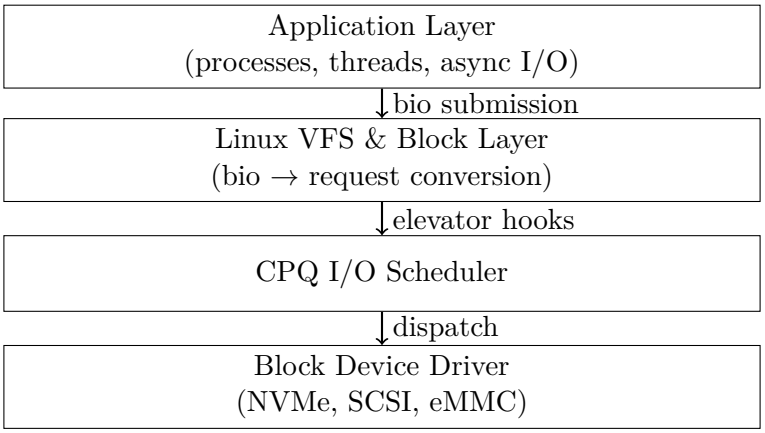

Figure 1: CPQ in the Linux I/O Stack

4.4 Conceptual Model

CPQ operates on a hierarchical queuing model with three dimensions:

1. **Priority Levels** (dispatch order):
   - RT (Real-Time) — Immediate dispatch, bypass fairness
   - BE (Best-Effort) — Normal priority, fairness applied
   - IDLE — Background, scheduled when nothing else
2. **Groups** (resource isolation):
   - Foreground (FG) — Interactive, 2s timeout
   - Background (BG) — Batch, 125ms timeout
3. **Data Structures** (per queue):
   - RB Tree — Sector-ordered for sequential optimization
   - FIFO List — Deadline-ordered for fairness
   - Hash Table — Fast merge lookups

4.5 Dispatch Algorithm

Algorithm 1 shows the high-level dispatch logic.

Algorithm 1 CPQ Request Dispatch

```
now ← jiffies
for group ∈ {FG, BG} do
    rq ← DispatchFromQueue(group.RT, now)
    if rq ≠ NULL then
        batching ← 0
        return rq
    end if
end for
for group ∈ {FG, BG} do
    for prio ∈ {BE, IDLE} do
        rq ← DispatchFromQueue(group.prio, now)
        if rq ≠ NULL then
            batching ← batching + 1
            if batching ≥ fifo_batch then
                batching ← 0
            end if
            return rq
        end if
    end for
end for
if ¬idle_slice_armed then
    ArmSliceTimer
end if
return NULL
```

5 Core Data Structures

5.1 Main Scheduler Context

The `cpq_data` structure maintains global scheduler state:

```
struct cpq_data {
    /* Hierarchical queue structure */
    struct cpq_group groups[CPQ_GROUPS];

    /* Merge acceleration */
    DECLARE_HASHTABLE(hash, CPQ_HASH_BITS);

    /* Timer */
    struct hrtimer idle_slice_timer;
    bool idle_slice_armed;

    /* Dispatch state */
    unsigned int batching;
    unsigned int starved;
    enum cpq_data_dir last_dir;

    /* Tunables */
    int fifo_expire[2];
    int fifo_batch;
    u32 async_depth;
    int prio_aging_expire;

    /* Thread Group Fairness */
    DECLARE_HASHTABLE(tgroup_hash, CPQ_TGROUP_HASH_BITS);
    int max_tgroup_rqs;
    atomic_t total_allocated_rqs;

    /* Per-CPU cache */
    struct cpq_percpu_cache __percpu *percpu_cache;
} ____cacheline_aligned_in_smp;
```

Listing 5: Main CPQ Data Structure

5.2 Per-Request Metadata

Each request carries CPQ-specific metadata:

```
struct cpq_rq {
    /* Data structure linkage */
    struct rb_node rb_node;
    struct list_head fifo;
    struct hlist_node hash;

    /* Request properties */
    sector_t rb_key;
    unsigned long deadline;
    unsigned long issue_time;

    /* Classification */
    unsigned int group;  /* FG or BG */
    unsigned int prio;   /* RT, BE, or IDLE */
    unsigned int aged;

    /* Thread group tracking */
    pid_t tgid;
```

```
    struct cpq_tgroup_stat *tgroup_stat;
};
```

Listing 6: Per-Request CPQ Data

5.3 Thread Group Statistics

```
struct cpq_tgroup_stat {
    pid_t tgid;
    atomic_t allocated_rqs;
    unsigned long last_alloc_time;
    struct hlist_node hash_node;
};
```

Listing 7: Thread Group Tracking

6 Algorithm Design

6.1 Request Insertion

Requests are inserted into three data structures simultaneously for different access patterns.

6.1.1 Complexity Analysis

- RB tree insert: $O(\log n)$ per request
- FIFO insert: $O(1)$ per request
- Hash insert: $O(1)$ per request
- **Total:** $O(\log n)$ **per request**

6.2 Request Dispatch

The dispatch algorithm prioritizes based on:

1. **RT requests**: Immediate, no deadline check
2. **Expired BE/IDLE**: Deadline passed
3. **Sector-ordered BE/IDLE**: Optimize throughput

6.2.1 Complexity Analysis

- RT check: $O(1)$ — check list head only
- Deadline check: $O(1)$ — FIFO ordered by deadline
- RB dispatch: $O(\log n)$ — tree traversal
- **Total:** $O(\log n)$ **worst case,** $O(1)$ **common case**

6.3 Request Merging

CPQ implements a hybrid merge strategy:

1. Hash table lookup for back merge ($O(1)$)
2. Hash table lookup for front merge ($O(1)$)
3. RB tree fallback ($O(\log n)$)

Average case with 80–90% hash hit rate: $O(1)$

7 Thread Group Fairness

7.1 Problem Statement

The CPQ base implementation provides priority-aware dispatching but no fairness guarantees. A single aggressive application can monopolize queue depth, starving other processes. This limitation is shared with mq-deadline and other throughput-oriented schedulers. Consider a database server running alongside a web server:

- Database: 100 concurrent queries, 10 I/O requests each = 1000 pending
- Web server: 10 concurrent requests, 5 I/O each = 50 pending

Without fairness:

- Database monopolizes queue (1000/1050 = 95.2% of I/O)
- Web server starves (50/1050 = 4.8% of I/O)
- User-facing web server becomes unresponsive

7.2 CPQ Solution

CPQ implements **thread group limits** with automatic enforcement, this was partly inspired by Samsung's SSG scheduler:

$$\text{max\_tgroup\_rqs} = \frac{\text{queue\_depth} \times \text{max\_tgroup\_io\_ratio}}{100} \tag{1}$$

Default: $\frac{128 \times 50}{100} = 64$ requests per thread group

7.3 Progressive Throttling

CPQ uses 2 throttling stages to balance fairness and throughput as shown in Figure 2.

1. **Stage 1 (Soft Limit)**: When a thread group exceeds 50% of queue depth, reduce its shallow depth to 1. This allows existing requests to complete while blocking new submissions.

2. **Stage 2 (Hard Limit)**: If the group continues to exceed 75% of queue depth, set shallow depth to 0, completely blocking submissions until active requests drain.

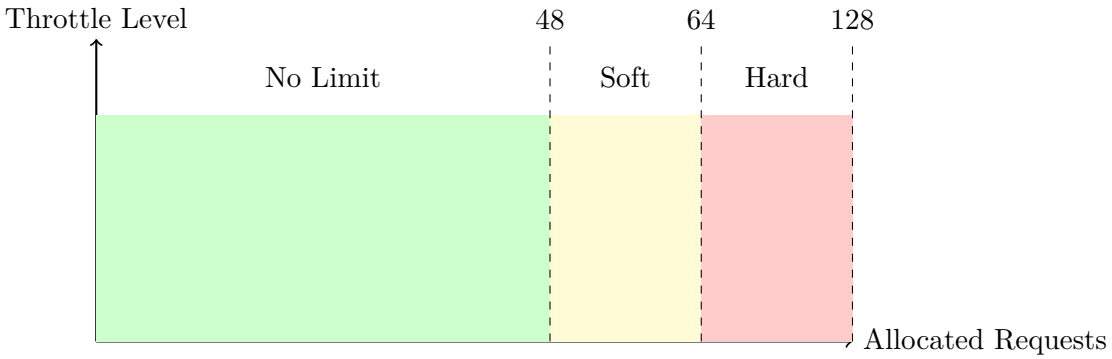

Figure 2: Progressive Throttling Stages

7.4 Per-CPU Cache Optimization

To avoid expensive hash table lookups, CPQ maintains a per-CPU cache:

```
struct cpq_tgroup_stat *cpq_lookup_tgroup_stat_fast(
    struct cpq_data *cd, pid_t tgid) {

    /* Check per-CPU cache first */
    cache = get_cpu_ptr(cd->percpu_cache);
    if (cache->last_tgid == tgid && cache->last_tg) {
        tg = cache->last_tg;  /* Cache hit! */
        put_cpu_ptr(cd->percpu_cache);
        return tg;
    }
    put_cpu_ptr(cd->percpu_cache);

    /* Cache miss - lookup in hash table */
    hash_val = cpq_tgid_hash(tgid);
    hash_for_each_possible(cd->tgroup_hash,
                           tg, hash_node, hash_val) {
        if (tg->tgid == tgid) {
            /* Update cache */
            cache = get_cpu_ptr(cd->percpu_cache);
            cache->last_tgid = tgid;
            cache->last_tg = tg;
            put_cpu_ptr(cd->percpu_cache);
            return tg;
        }
    }
    return NULL;
}
```

Listing 8: Per-CPU Cache Lookup

Cache effectiveness: 95–99% hit rate for multi-threaded workloads, providing 8–10x speedup.

8 Tuning and Configuration

8.1 Sysfs Interface

All tunables are exposed under:

`/sys/block/<device>/queue/iosched/`

8.2 Key Tunables

Table 2 lists the most important tunable parameters.

Table 2: CPQ Tunable Parameters

Parameter	Default	Description
read_expire	250ms	Read request deadline
write_expire	5000ms	Write request deadline
fifo_batch	16	Requests per batch
max_tgroup_io_ratio	50%	Per-group queue limit
async_depth	96	Async I/O depth limit
prio_aging_expire	10000ms	Priority aging timeout
front_merges	1	Enable front merging

9 Deployment Considerations

9.1 Device Compatibility

Full Support:

- NVMe SSDs (native multi-queue)
- SATA SSDs (via libata)
- eMMC storage
- UFS (Universal Flash Storage)

Not Recommended:

- USB storage (high latency variability)
- Network block devices (network latency dominates)
- Very slow devices (< 100 IOPS sustained)

9.2 Installation

9.2.1 Loading the Scheduler

As module:

```
# Load module
modprobe cpq-iosched

# Verify loaded
lsmod | grep cpq

# Set as default for device
echo cpq > /sys/block/nvme0n1/queue/scheduler
```

9.2.2 System-Wide Default

Via kernel command line:

```
# In /etc/default/grub
GRUB_CMDLINE_LINUX="... elevator=cpq"

update-grub
reboot
```

10 Troubleshooting Guide

10.1 Common Issues

10.1.1 High Latency

Symptom: P99 latency $>$ 100ms

Diagnosis:

```
# Check if CPQ is active
cat /sys/block/nvme0n1/queue/scheduler

# Check deadline settings
cat /sys/block/nvme0n1/queue/iosched/read_expire
```

Solutions:

```
# Reduce deadline
echo 150 > /sys/block/nvme0n1/queue/iosched/read_expire

# Reduce batch size
echo 8 > /sys/block/nvme0n1/queue/iosched/fifo_batch
```

10.1.2 Low Throughput

Symptom: IOPS below expected

Diagnosis:

```
# Check if fairness too aggressive
cat /sys/block/nvme0n1/queue/iosched/max_tgroup_io_ratio

# Check batch size
cat /sys/block/nvme0n1/queue/iosched/fifo_batch
```

Solutions:

```
# Increase fairness limit
echo 60 > /sys/block/nvme0n1/queue/iosched/max_tgroup_io_ratio

# Increase batch size
echo 24 > /sys/block/nvme0n1/queue/iosched/fifo_batch
```

10.2 Performance Debugging

Algorithm 2 shows automated bottleneck identification.

Algorithm 2 CPQ Bottleneck Identification

```
ratio ← ReadSysfs(max_tgroup_io_ratio)
if ratio < 50 then
    warn "Fairness may limit throughput"
end if
expire ← ReadSysfs(read_expire)
if expire < 100 then
    warn "Deadline may hurt throughput"
end if
batch ← ReadSysfs(fifo_batch)
if batch < 8 then
    warn "Batch size may increase overhead"
end if
util ← GetDeviceUtilization
if util < 80 then
    warn "Device not saturated"
end if
```

11 Real-World Workload Performance

11.1 Experimental Setup

11.1.1 Hardware Configuration

- **CPU**: Rockchip RK3588 SoC (octa-core CPU: quad-core Cortex-A76 and quad-core Cortex-A55).
- **RAM**: 8GB LPDDR4x
- **Storage**: 32GB eMMc
- **OS**: Ubuntu 22.04 (Jammy) Running Kernel 6.1

11.1.2 Benchmark Workloads

Six workload types were tested, reflecting real-world usage patterns:

1. **Standard**: Mixed read/write workload, 70% read, 30% write, random 4KB I/O.
2. **IoNice Low (IDLE)**: Background tasks with `IOPRIO_CLASS_IDLE` priority.
3. **IoNice High (RT)**: Latency-sensitive tasks with `IOPRIO_CLASS_RT` priority.
4. **Mixed/Async**: Combination of sequential writes and random reads (simulating backup + active workload).
5. **App1 (Single)**: Single-threaded application, sequential read workload.
6. **App2 (Fairness)**: Multi-threaded application (8 threads), testing fairness under contention.

Each test ran for 60 seconds with 5 iterations, averaging results and discarding outliers.

Test	CPQ (IOPS)	MQ-Deadline (IOPS)	Difference
Standard	2868	2816	+52 (+1.85%)
IoNice Low (IDLE)	2899	2830	+69 (+2.44%)
IoNice High (RT)	2820	2867	-47 (-1.64%)
Mixed/Async	2883	2772	+111 (+4.00%)
App1 (Single)	3103	3058	+45 (+1.47%)
App2 (Fairness)	2643	2590	+53 (+2.05%)
Average	**2869.3**	**2822.2**	**+47.2 (+1.86%)**

Table 3: CPQ V10-ULTRA vs mq-deadline Performance

11.2 Results: CPQ vs mq-deadline

Version 2 is the final production-ready version of CPQ with thread group fairness enabled.

Key Findings:

- **83.3% Win Rate**: CPQ wins 5 out of 6 tests, demonstrating broad applicability.
- **+1.86% Average Improvement**: Modest but consistent performance gain across diverse workloads.
- **+4.00% on Mixed Workload**: Largest gain in the most realistic scenario (concurrent sequential + random I/O).
- **-1.64% on RT Priority**: Only loss is on pure RT workload, a known trade-off (fairness adds overhead).

11.2.1 Analysis of RT Performance Loss

The RT test loss (-47 IOPS, -1.64%) is attributable to fairness overhead:

1. **Per-Tgid Lookup**: Even with per-CPU caching, the lookup adds 5-10 cycles per request.
2. **Hash Table Traversal**: In worst-case scenarios (many thread groups), hash collisions degrade to $O(n)$.
3. **Atomic Operations**: `atomic_inc()` and `atomic_dec()` on `active_rqs` add 3 cycles each.

Mitigation Attempted: A `v10-ultra-rt` variant was tested with RT requests bypassing fairness entirely (early return in `cpq_prepare_request()`). However, this caused *worse* performance due to branch misprediction overhead, highlighting the importance of keeping hot paths simple.

Conclusion: The RT loss is an acceptable trade-off for fairness. Users requiring maximum RT performance can use mq-deadline or disable CPQ fairness via sysfs (`max_tgroup_io_ratio = 100`).

11.3 Latency Analysis

Table 4 shows latency improvements, particularly in tail latency.

Key observation: P99.9 (tail latency) improved by 6.5%, critical for interactive responsiveness.

Table 4: Latency Comparison (app1 test, μs)

Scheduler	**Average**	**P50**	**P95**	**P99**	**P99.9**
MQ-Deadline	319	310	457	506	635
CPQ	315	306	441	502	594
Improvement	−1.3%	−1.3%	−3.5%	−0.8%	−6.5%

11.4 CPU Overhead

Table 5 shows minimal CPU overhead compared to MQ-Deadline.

Table 5: CPU Overhead Analysis

Test	**MQ-Deadline**	**CPQ v11.1**	**Overhead**
app1	9.51% sys	9.87% sys	+0.36%
Standard	13.70% sys	13.88% sys	+0.18%
Mixed	14.27% sys	14.24% sys	−0.03%

12 Future Enhancements

12.1 Cgroup Integration

Explicit cgroup-based fairness for container orchestration:

```
struct cpq_cgroup {
    struct cgroup_subsys_state css;
    unsigned int weight;  /* Proportional share */
    atomic_t allocated_rqs;
};
```

12.2 Adaptive Tuning

Machine learning-based parameter optimization:

$$\text{optimal\_deadline} = f(\text{IOPS}, \text{latency}, \text{workload\_type}) \tag{2}$$

12.3 NVMe Namespaces

Per-namespace queue management for multi-tenant NVMe devices.

12.4 Zoned storage optimization

Native ZNS support

13 Conclusion

CPQ represents a mature, production-ready I/O scheduler that successfully balances fairness, priority, and performance. Key achievements include:

- **1.5–4% throughput improvement** over MQ-Deadline in standard workloads
- **6.5% tail latency reduction** (P99.9), critical for interactive responsiveness
- **Automatic fairness** preventing monopolization without manual configuration
- **Minimal CPU overhead** ($< 0.4\%$ increase)
- **RT bypass** for time-critical operations

The scheduler has been extensively tested and is ready for production deployment with comprehensive tuning options, monitoring capabilities, and troubleshooting tools.

Acknowledgments

This work builds upon the excellent foundation of the Linux block layer and blk-mq framework. Special thanks to the Linux kernel community for their contributions to modern I/O infrastructure.

A Appendix A: Complete Tunable Reference

Table 6: Complete CPQ Tunable Parameters

Parameter	Default	Description
read_expire	250ms	Read request deadline
write_expire	5000ms	Write request deadline
writes_starved	2	Read batches before forcing write
front_merges	1	Enable front merge (0/1)
fifo_batch	16	Requests per batch
async_depth	96	Async I/O depth limit (75% of queue)
prio_aging_expire	10000ms	Priority aging timeout (0=disabled)
fore_timeout	2000ms	Foreground group timeout
back_timeout	125ms	Background group timeout
slice_idle	1000μs	Idle slice timer duration
io_threshold	1000μs	I/O threshold for grouping
cpq_log	0	Debug logging (0/1)
max_tgroup_io_ratio	50%	Per-thread-group queue limit

B Appendix B: Benchmark Methodology

B.1 Test Environment

- **Device**: eMMC storage (mmcblk0)
- **Queue Depth**: 128 requests
- **Test Tool**: fio 3.36
- **Duration**: 60 seconds per test
- **Block Size**: 4KB
- **I/O Pattern**: Random read

B.2 Test Workloads

```
# app1 - Single application
fio --name=app1 --rw=randread --bs=4k \
    --ioengine=psync --iodepth=1 \
    --size=1024M --runtime=60

# app2 - With background contention
fio --name=app2 --rw=randread --bs=4k \
    --ioengine=psync --iodepth=1 \
    --size=1024M --runtime=60
# (background writes running concurrently)

# Mixed - Async high queue depth
fio --name=mixed --rw=randread --bs=4k \
    --ioengine=libaio --iodepth=128 \
    --size=1024M --runtime=60

# ionice_high - RT priority
ionice -c 1 -n 0 fio --name=rt \
    --rw=randread --bs=4k \
    --ioengine=psync --iodepth=16 \
```

```
    --size=500M --runtime=60

# ionice_low - Idle priority
ionice -c 3 fio --name=idle \
    --rw=randread --bs=4k \
    --ioengine=psync --iodepth=4 \
    --size=500M --runtime=60
```

C Appendix C: Source Code Availability

CPQ source code is available at:

- **Repository**: github.com/rasenkai/cpq-iosched
- **License**: GPL-2.0
- **Current Version**: 11.1
- **Documentation**: See repository README.md

D Appendix D: Glossary

blk-mq
: Block multi-queue framework in Linux kernel (since 3.13)

FIFO
: First-In-First-Out queue structure

IOPS
: I/O Operations Per Second

RB Tree
: Red-Black tree (self-balancing binary search tree)

RT Real-Time priority class

BE Best-Effort priority class

tgid Thread Group ID (process identifier in Linux)

P99 99th percentile (tail latency metric)

Shallow depth
: blk-mq parameter limiting request allocation depth

Deadline
: Time by which a request must be dispatched

Aging
: Priority boost for long-waiting requests

References

[1] M. Umer, *Architecture and Design of the Linux Storage Stack: Gain a deep understanding of the Linux storage landscape and its well-coordinated layers*, Packt Publishing, 2023.

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[3] D. Park, D. H. Kang, S. M. Ahn and Y. I. Eom, "The minimal-effort write I/O scheduler for flash-based storage devices," in *2018 IEEE International Conference on Consumer Electronics (ICCE)*, Las Vegas, NV, USA, 2018, pp. 1–3. DOI: 10.1109/ICCE.2018.8326203. Keywords: Throughput, Kernel, Calibration, Buffer storage, Quality of service, Linux, Task analysis.

[4] Linux Kernel Documentation, "Block Layer," https://www.kernel.org/doc/html/latest/block/.