SKQ: Event Scheduling for Optimizing Tail Latency in a Traditional OS Kernel

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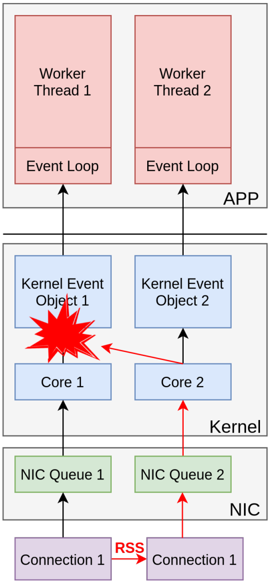
The Latency Problem

- Modern server applications require low tail latency
- Recent research proposed kernel-bypass/custom dataplanes
- Problem: most applications still on traditional OSes
- Solving the latency problem in kernel is challenging

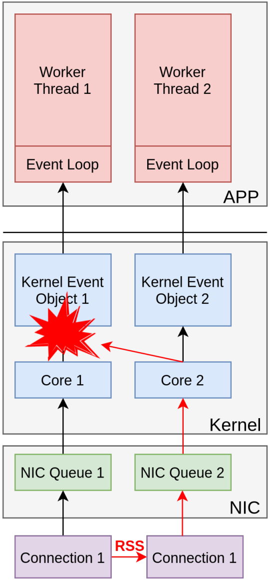
Sources of Latency

- Cache Misses
  - Connection migration from RSS & kernel
  - Applications do not detect any of this!
  - RPC server → 77% avoidable L2 misses



Sources of Latency

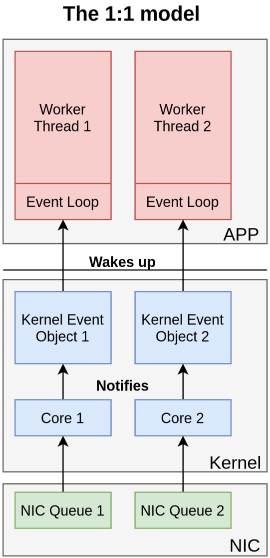
- Cache Misses
  - Connection migration from RSS & kernel
  - Applications do not detect any of this!
  - RPC server → 77% avoidable L2 misses
- Workload Imbalance
  - Over-saturated vs. under-saturated threads
  - Total processing time difference:
    - Memcached 1.4% vs. GIS application 46%



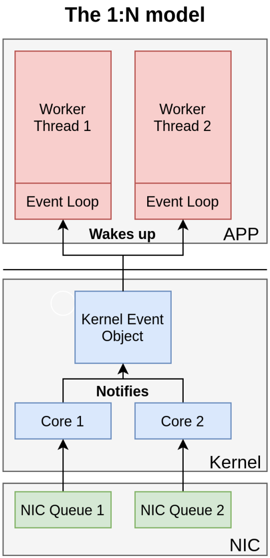
Event-Driven Programming Model

- Uses kernel event facility:
  - Older: `poll`, `select`, `/dev/poll`
  - Newer: FreeBSD Kqueue, Linux epoll, Windows IOCP
  - 20+ years old
- Maximum visibility into OS and applications
- Application workflow:
  - Applications register events to kernel event objects
  - Worker threads poll/listen on kernel event object

Event-Driven Programming Models



Model	1:1	1:N
Event Object	Private	Shared
Scalability	Good	Poor
Schedulability	Poor	Good
Affinity	Good	Poor
Popularity	High	Low



Our System: Scheduable Kqueue (SKQ)

- Efficient event scheduling on top of Kqueue
- Multicore scalability in the 1:N model
- Event scheduling to reduce latency
  - Cache misses & workload imbalance
- Event delivery control
  - Event prioritization & event pinning

SKQ Usage

Main thread

```
...
// Create a single SKQ instance
int skq = kqueue();

// Set scheduling policy
int sched = KQ_SCHED_CPU;
ioctl(skq, FKQMULTI, &sched);
...
```

Worker threads

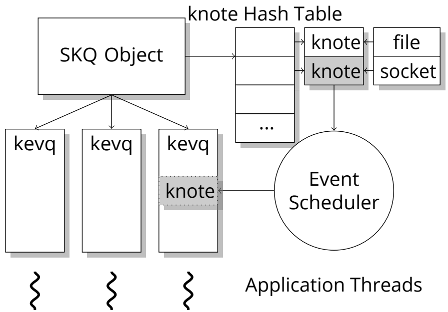
```
while (true) {
    const int maxev = 32;
    struct kevent evs[maxev];

    // Query events
    nev = kevent(skq, NULL, 0, &evs,
                 maxev, NULL);

    // Process events
    ...
}
```

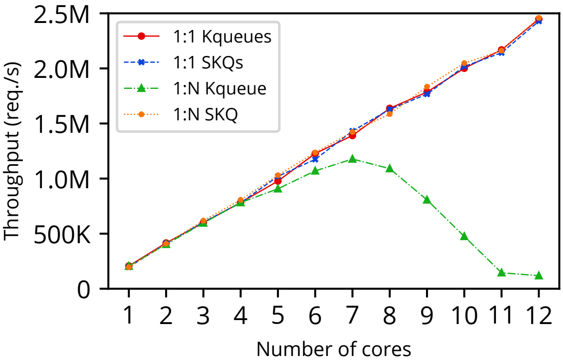
SKQ Architecture

- Scalability
  - Thread-private event queue *kevq*
  - Fine-grained locking
- Event scheduling and delivery control
  - The event scheduler
- Best of both worlds via scheduling
  - 1:N model to applications
  - 1:1 model internally



Scalability Showdown: SKQ vs. Kqueue

- POSIX pipes instead of sockets
- 1:N SKQ scales linearly
- 1:N Kqueue sees bottleneck

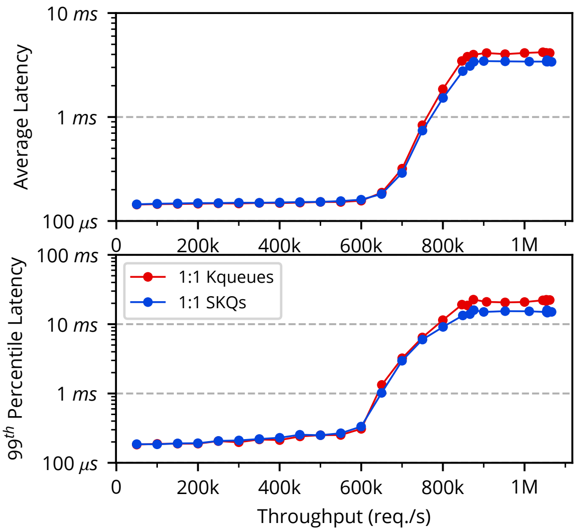


Performance Improvement: SKQ vs. Kqueue

- Memcached with 1:1 model
- Facebook Mutilate workload
- –33% tail latency at peak

Benchmark Baseline

We use *1:1 SKQs* throughout the talk to isolate the benefit of scheduling.



Scheduling Policies

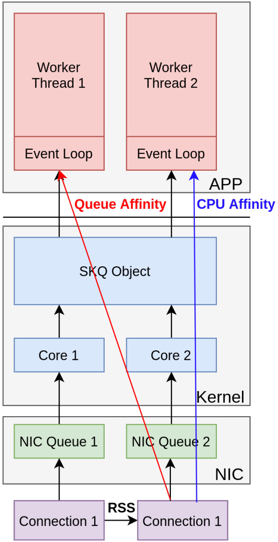
- Cache locality policies
- Load balancing policies
- Hybrid policies

Challenges of Efficient Event Scheduling

- Little overhead available for scheduling
  - Millions of events per second
- CPU cost, lock contention, and cache footprint
  - Statistics
  - Data structures
- Memcached:
  - 15k cycles per request (amortized)
  - L3 cache miss $\sim$ 400 cycles
  - 2.7% drop in throughput

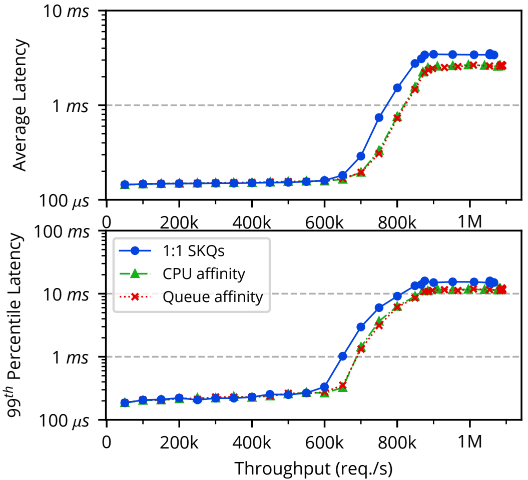
Cache Locality Policies

- CPU affinity
  - Delievers to the **triggering** core
  - Follows connection migration
  - Cache locality in the networking stack
- Queue affinity
  - Pins to the **first** core
  - Cache locality in userspace



Cache Locality Policies in Memcached

- A uniform workload
- Cache locality dominates latency
- Facebook Mutilate workload
  - $+9\%$ low-latency throughput
  - -26% tail latency at peak



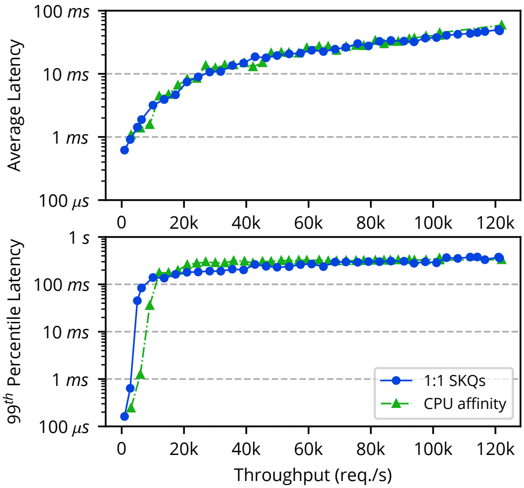
CPU Affinity vs. Queue Affinity

- L2 cache misses in a RPC server
- Uniform workload, Memcached-like
- CPU affinity –31.2% L2 cache misses

Policy	TCP input	TCP output	Event activation	Event query	Total
CPU	252k	15k	63k	166k	496k
Queue	343k	33k	95k	250k	721k
Vanilla	828k	76k	45k	1235k	2184k

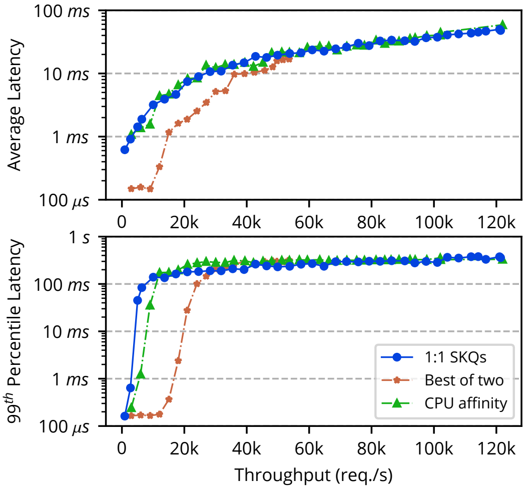
Imbalanced Workload: RocksDB

- Facebook ZippyDB workload
- Imbalanced – slow SEEK requests
- Cache locality policies don't help



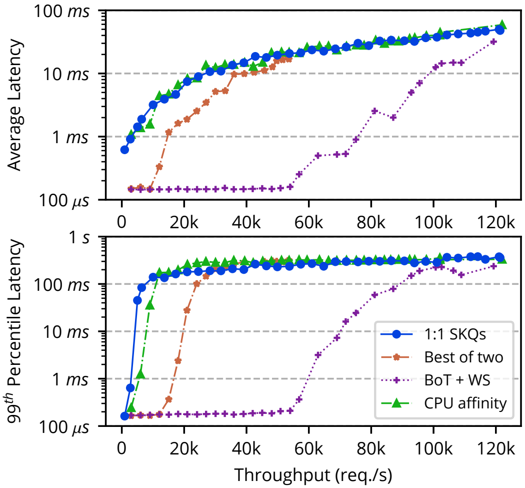
Load Balancing Policies

- Best of two
  - Selects the better of two random kevqs
  - Statistics keeping
    - Number of events
    - Average processing time per event



Load Balancing Policies

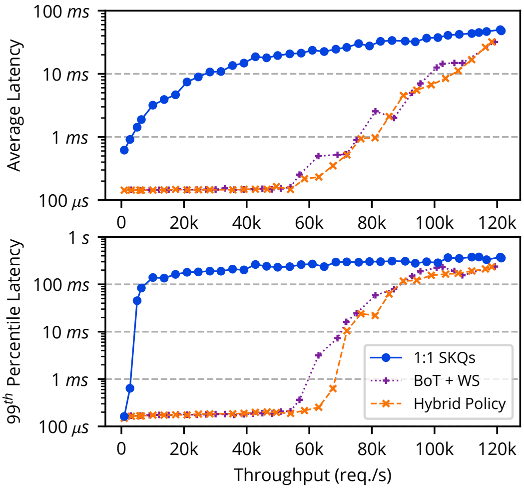
- Best of two
  - Selects the better of two random kevqs
  - Statistics keeping
    - Number of events
    - Average processing time per event
- Work stealing
  - Idle threads steal work
  - Minimal interference
- Best of two + work stealing



Hybrid Policies

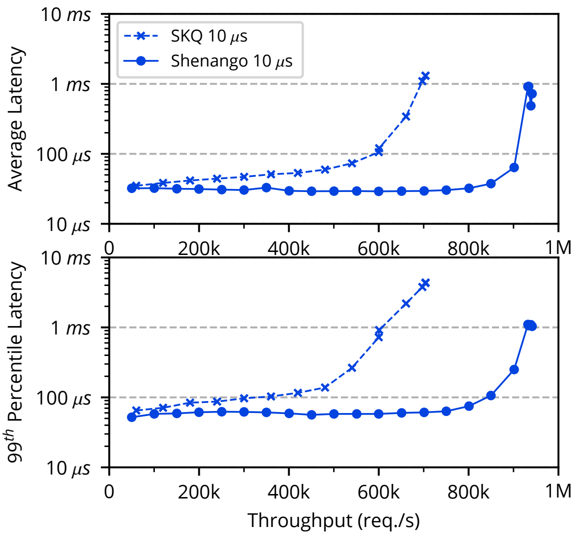
- Load balancing + cache locality
  - Best of two vs. cache-local kevq
  - Cache miss penalty

- Hybrid Policy
  - CPU affinity + best of two + work stealing
  - 27.4× low-latency throughput
  - Up to 1022× lower tail latency



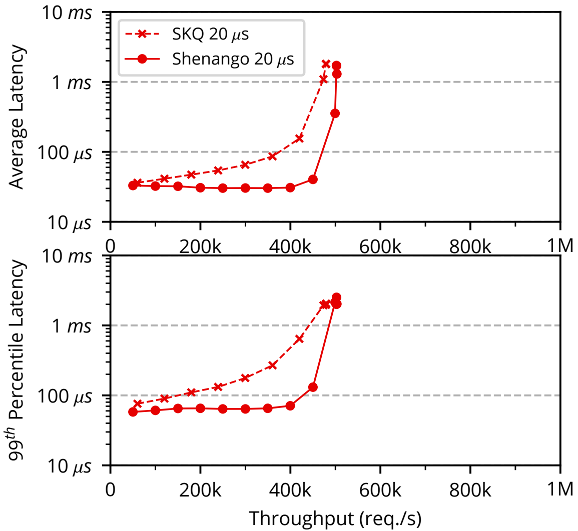
SKQ vs. Kernel Bypass: Uniform 10 µs Workload

- RPC server
  - Uniform
  - 10 µs request service time
  - CPU affinity policy
- Compared 150 µs tail latency
- Shenango
  - 1.67× low-latency throughput
- Bottleneck: system call overhead



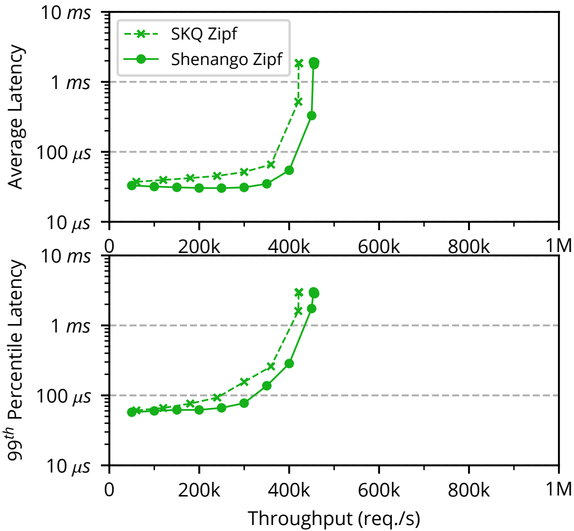
SKQ vs. Kernel Bypass: Uniform 20 µs Workload

- RPC server
  - Uniform
  - 20 µs request service time
  - CPU affinity policy
- Compared 150 µs tail latency
- Shenango
  - 1.5× low-latency throughput
- Bottleneck: system call overhead



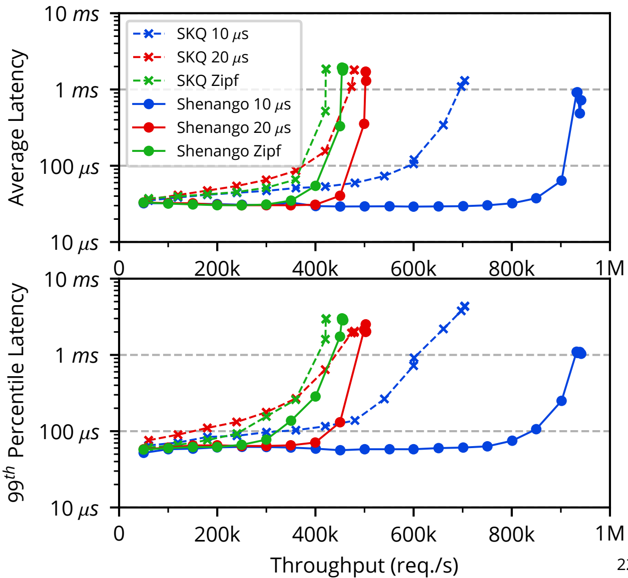
SKQ vs. Kernel Bypass: Zipf-like Workload

- RPC server
  - Zipf-like
  - 20.5 μs average service time
  - Hybrid policy
- Compared 150 μs tail latency
- Shenango
  - 1.17× low-latency throughput
- Benefit from event scheduling



SKQ vs. Kernel Bypass

- Kernel bypass:
  - Short and uniform
- Kernel event scheduling:
  - Long and imbalanced
- Unfair comparison
  - Different OSes
  - Different TCP stack



Policy Selection Guidelines

- Uniform workloads
  - CPU affinity
- Imbalanced or IO-heavy workloads
  - Hybrid policy (CPU affinity + Best of two + Work stealing)

Conclusion

- A practical solution to the latency problem
- More optimization opportunities in kernel
- See paper for:
  - Event prioritization and pinning
  - Cache miss analysis and more benchmarks
  - Design details and optimizations
- Source code available:
  - `https://rcs.uwaterloo.ca/skq/`