

# Linux Zero-Copy High-Throughput Networking Engineering Handbook

Deep Implementation Guide: `io_uring` Fixed Buffers, `splice()` Rings, and `AF_XDP` at 100GbE Line Rate

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## 1. The Performance Collapse of POSIX Sockets at 100GbE

At 100 Gigabit Ethernet (100GbE), network cards process up to 148 million packets per second. Traditional POSIX socket interfaces (`recv()`, `send()`, `read()`, `write()`) incur catastrophic overhead: every packet involves memory allocation (`sk_buff`), multiple user-to-kernel memory copies, CPU context switches, and softirq interrupt storms. At 100Gbps line rate, CPU cores spend 80% of their cycles copying bytes rather than processing payload logic.

## 2. Evolution of Linux Zero-Copy: `splice()` and `vmsplice()`

Linux introduced `splice()` to move data between file descriptors and pipe buffers without copying data through user space. While effective for proxying TCP streams directly to disk or other sockets, `splice()` still requires kernel-space synchronization, pipe allocations, and synchronous system calls, limiting maximum packet throughput to roughly 10-20 million packets per second.

## 3. Modern `io_uring` with Registered Fixed Buffers and Polled I/O

Linux 5.1+ and 6.x revolutionized socket performance with `io_uring`. By utilizing shared memory Submission Queue (SQ) and Completion Queue (CQ) ring buffers, user-space applications submit thousands of I/O requests without entering a single syscall. When combined with registered buffers (`IORING_REGISTER_BUFFERS`) and kernel polling (`IORING_SETUP_SQPOLL`), `io_uring` delivers true zero-copy asynchronous networking with sub-microsecond latency.

## 4. `AF_XDP`: Kernel-Bypass Architecture at Line Rate

For ultimate performance, Address Family XDP (`AF_XDP`) routes raw Ethernet frames directly from the NIC driver's eXpress Data Path (XDP) into a shared user-space memory arena (UMEM) via Lockless Ring Buffers (Fill, RX, TX, Completion rings). `AF_XDP` achieves 35+ million packets per second per CPU core, bypassing the entire kernel TCP/IP stack while preserving Linux security models.

## Key Engineering Metrics & Reference Specifications

| Networking Paradigm                        | Memory Copy Overhead            | Syscall Cost per Batch      | Max Pkt/sec per Core | Implementation Complexity |
|--------------------------------------------|---------------------------------|-----------------------------|----------------------|---------------------------|
| Standard POSIX ( <code>read/write</code> ) | 2 Copies (Driver->Kernel->User) | 1 Syscall per Packet/Vector | 1.5 - 2.5 Mpps       | Low (Standard POSIX)      |

|                                                 |                                 |                              |                   |                                   |
|-------------------------------------------------|---------------------------------|------------------------------|-------------------|-----------------------------------|
| <b>Pipe Splice</b><br>( <code>splice()</code> ) | Zero User Copy (Pipe buffer)    | 1 Syscall per Batch          | 8.0 - 14.0 Mpps   | Medium (Pipe management)          |
| <b>io_uring (Fixed Buffers)</b>                 | True Zero-Copy (Pre-registered) | 0 Syscalls (SQPOLLMode)      | 18.0 - 26.0 Mpps  | Medium-High (Ring queues)         |
| <b>AF_XDP (Kernel Bypass)</b>                   | Zero-Copy via Direct UMEM DMA   | 0 Syscalls (Polled NIC Ring) | 35.0 - 50.0+ Mpps | High (Custom driver/packet logic) |

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