StackMap: Low-Latency Networking with the OS Stack and Dedicated NICs

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*Work while an intern at NetApp*
Overview

- Message-oriented communication over TCP is common
  - e.g., HTTP, memcached, CDNs
- Linux network stack can serve 1KB messages only at 3.5 Gbps w/ a single core
- Improve socket API?
  - Limited Improvements
- User-space TCP/IP stack?
  - Maintaining and updating today’s complex TCP is hard

**StackMap achieves high performance with the OS TCP/IP**

![Graph showing throughput vs. concurrent TCP connections]

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Background

- Message-oriented communication over TCP (e.g., HTTP, memcached)
  - Many concurrent connections
  - Small messages
  - High packet rates

Request (e.g., HTTP GET)
Response (e.g., HTTP OK)
Message Latency Problem

- Many requests are processed in each `epoll_wait()` cycle
- New requests are queued in the kernel

```c
while (1) {
    n = epoll_wait(fds);
    for (i = 0; i < n; i++) {
        read(fds[i], buf);
        http_ok(buf);
        write(fds[i], buf);
    }
}
```
Where Could We Improve?

- Processing cost of **TCP/IP protocol** is not high
- TCP/IP takes 1.48 us, out of 3.75 us server processing
- $\frac{1}{2}$ RTT reported by the client app is 9.75 us
  - The rest of 6 us come from minimum hard/soft indirection
  - netmap-based ping-pong (network stack bypass) reports 5.77 us
Where Could We Improve?

- Processing cost of **TCP/IP protocol** is not high.
- TCP/IP takes 1.48 us, out of 3.75 us server processing.
- ½ RTT reported by the client app is 9.75 us.
  - The rest of 6 us come from minimum
    - netmap-based ping-pong (network stack)
    - epoll_wait() processing delay
Takeaway

- Conventional system introduces end-to-end latency of 10’s to 100’s of us
  - Results of processing delays

- Socket API comes at a significant cost
  - read()/write()/epoll_wait() processing delay

- Packet I/O is expensive

- TCP/IP protocol processing is relatively cheap

We can use the feature-rich kernel TCP/IP implementation, but need to improve API and packet I/O
StackMap Approach

- Dedicating a NIC to an application
  - Common for today’s high-performance systems
  - Similar to OS-bypass TCP/IPs
StackMap Approach

- Dedicating a NIC to an application
  - Common for today’s high-performance systems
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- TCP/IP stack in the kernel
  - State-of-the-art features
  - Active updates and maintenance
StackMap Architecture

1. **Socket API for control path**
   - socket(), bind(), listen()

2. **Netmap API for data path (extended)**
   - Syscall and packet I/O batching, zero copy, run-to-completion

3. **Persistent, fixed-size sk_buffs**
   - Efficiently call into kernel TCP/IP

4. **Static packet buffers and DMA mapping**
StackMap Data Path API

- **TX**
  - Put data and fd in each slot
  - Advance the head pointer
  - Syscall to start network stack processing and transmission
StackMap Data Path API

- **TX**
  - Put data and fd in each slot
  - Advance the head pointer
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- **RX**
  - Kernel puts fd on each buffer
  - App can traverse a ring by descriptors
Experimental Results

- Implementation
  - Linux 4.2 with 228 LoC changes
  - netmap with 56 LoC changes
  - A new kernel module with 2269 LoC

- Setup
  - Two machines with Xeon E5-2680 v2 (2.8 - 3.6 Ghz) Intel 82599 10 GbE NIC
  - Server: Linux or StackMap
  - Client: Linux with WRK http benchmark tool or memaslap memcached benchmark tool
Basic Performance

- Simple HTTP server
  - Serving 1KB messages (single core)
Memcached Performance

- Serving 1KB messages
  - single core
- Seastar is a fast user-space TCP/IP on top of DPDK*

- Serving 64B messages
  - 1-8 CPU cores

*http://www.seastar-project.org/
Discussion

- What makes StackMap fast?
  - Techniques used by OS-bypass TCP/IPs
    - Run-to-completion, static packet buffers, zero copy, syscall and I/O batching and new API

- Limitations and Future Work
  - Safely sharing packet buffers
    - If kernel-owned buffers are modified by a misbehaving app, TCP might fall into inconsistent state
Related Work

- Kernel-bypass TCP/IPs
  - IX [OSDI’14], Arrakis [OSDI’14], UTCP [CCR’14], Sandstorm [SIGCOMM’14], mTCP [NSDI’14], Seastar

- Socket API enhancements
  - MegaPipe [OSDI’12], FlexSC [OSDI’10], KCM [Linux]

- Improving OS stack with fast packet I/O
  - mSwitch [SOSR’15]

- In-stack improvement
  - FastSocket [ASPLOS’16]

- Running kernel stack in user-space
  - Rump [AsiaBSDCon’09], NUSE [netdev’15]
Conclusion

- Message-oriented communication over TCP
- Kernel TCP/IP is fast
  - But socket API and packet I/O are slow
- We can bring the most of techniques used by kernel-bypass stacks into the OS stack
- Latency reduction by 4-80% (average) or 2-70% (99th%tile)
- Throughput improvement by 4-391%