

The Path to DPDK Speeds for AF_XDP

Magnus Karlsson and Björn Töpel

Intel, Inc.

Stockholm, Sweden

{magnus.karlsson,bjorn.topel}@intel.com

Abstract

AF_XDP is a new socket type for raw frames introduced in Linux 4.18. The current code base offers throughput numbers around 20 Mpps per application core for 64-byte packets on a typical Broadwell server, however, not much effort was spent on optimizations. The focus of this paper is the performance optimizations needed for AF_XDP to get it to the performance levels of user-space network driver packages such as DPDK.

In this paper, we present various optimizations that fall into two broad categories: ones that are seamless to the application and ones that requires additions to the uapi. With these optimizations, we can reach our goal of close to 40 Mpps of throughput for 64-byte packets for Rx and close to 70 Mpps for Tx. We end this paper by presenting further possible optimizations that would hopefully bring the Rx performance even higher.

Keywords Networking, Linux, AF_XDP, XDP, packet processing, zero-copy.

1. Introduction

In the beginning of August 2018, Linux 4.18 was released and with that a new socket type was introduced called AF_XDP. It is designed to pass network traffic from the driver in the kernel up to user space as fast and efficiently as possible, but still abiding by all the usual robustness, isolation and security properties that Linux provides. The performance target of AF_XDP has always been to be close to that of software packages with user space drivers (full or partial) and/or zero-copy semantics such as DPDK [5], Netmap [13], and PF_RING [4]. The initial release of AF_XDP in 4.18 targeted basic functionality and was not optimized for performance. While it did deliver quite good throughput performance between 15 and 22 Mpps [1, 9–11] for the benchmarks in the sample application, this is only around 50% or less of what the techniques above can deliver. And this is not enough.

In this paper, we present a number of optimization to AF_XDP that takes the performance up to levels that are closer to or even on par with what user-space driver techniques, such as DPDK, can deliver. With these optimizations, more than double the throughput performance: from 15 Mpps to 39 Mpps for Rx and from 25 Mpps to 68 Mpps for Tx. We have limited the optimization proposals to patch sets that we believe are acceptable to the networking community and non-intrusive to other component with the exception of XDP [8] in some cases, as AF_XDP uses XDP for its Rx data path.

To improve the performance of the Rx path, we propose three sets of improvements:

- Optimize the XDP path and XDP driver implementation for the post Spectre world with retpolines [14]. A performance drop of nearly 50% for XDP has been reported [3] and as AF_XDP uses XDP, we suffer from this too. This patch set optimizes indirect

calls and switch statements in the data path so that they perform better with retpolines.

- Introduce a new `bind` option in which the user does not have to supply an XDP program and all traffic on the specified queue id is sent up to the socket. This is realized in AF_XDP by loading a built-in XDP program and this program and the path leading up to it can be optimized leading to substantial performance improvements. Another benefit with this is that it improves ease of use and adoption of AF_XDP as an external XDP program is no longer required the configuration path becomes simpler.
- Introduce an execution context in the XDP code instead of using per-cpu state. While this improves performance on its own, more importantly, it becomes possible to implement a number of other performance improvements based on having information more readily available.

To reach these performance levels on the Tx side, we propose four new patch sets:

- Allow for multiple Tx sockets to be connected to one `umem`, so that we can spread the Tx load over multiple Tx HW queues. This patch is also required to support QoS and shaping features in NICs, as this usually requires one queue per class. So this feature is useful even without the performance improvements it gives rise to.
- Extend the driver so that AF_XDP gets its own HW queue. In the upstream version, XDP and AF_XDP shares one HW queue, but by giving AF_XDP its own queue we can make the Tx completion code much more efficient.
- Change the batch size and descriptor queue sizes in the user mode application. We have now tuned these to the new higher throughput levels. But note, that they are kept the same for all experiments, so we are not fine tuning anything.
- Introduce a new `setsockopt` that queries the device if the NIC supports in-order completion and if so stops using the completion queue and signals completions using the tail pointer of the Tx ring instead. This cuts down the coherency traffic between the user mode application on one core and the softirq processing on another core and also gets rid of the backpressure mechanism between the completion ring and the associated Tx rings.

When AF_XDP is executed, two cores are used: one for the user mode application and one for the Rx/Tx processing in kernel space. But with user-mode driver models, such as DPDK, the application and driver is usually executed on the same core. They can do that as both application and driver reside in the same program. This can give rise to a large performance increase since it eliminates the coherency traffic between the cores in the two core setup. If we co-located the application and kernel driver to the same core with

AF_XDP, there would be extensive mode and context switching between the two and performance would be poor even though we eliminated all coherency traffic. But there is a way to execute a networking application with AF_XDP using only a single core and not have to do any context switching between the application thread and any ksoftirqd thread, and that is by using *busy poll()* [7] (POLL_BUSY_LOOP) in conjunction with AF_XDP.

With busy poll(), the network driver is driven by the user space application through the poll() syscall, in contrast to the normal case where it is driven asynchronously by interrupts fired by the NIC. The driver is executed in the same context as the application, thus we do not require any context switching and the application and driver can be executed on the same core. The added overhead is the poll syscall and its associated mode switch into the kernel to execute the driver. With busy poll we get 30 Mpps for Rx and 51 Mpps for Tx, compared to 39 Mpps and 68 Mpps with the normal setup without busy poll. But note that the busy poll results are with a single core while the other results are with two, so if you look at what you get per core, the busy poll results are better.

In summary, the results look promising and make the performance of AF_XDP to be much closer to or even on par with user-space driver models. We will try to get these patches into mainline during the next 12 months. But even though we believe the performance is now in the “good enough” territory for a number of interesting applications using 40 Gbit/s devices, there are still many more performance optimizations that could be done, and should be, to cater for upcoming 100 Gbit/s and 200 Gbit/s network devices and applications with even higher performance requirements.

This paper is outlined as follows. In section 2, we first present the basics of AF_XDP followed by the proposed optimizations in section 3. Section 4 deals with the experimental methodology followed by the experimental results in section 5. The paper is ended (sections 6, 7 and 8) with some discussions and future work and finally the conclusions.

2. AF_XDP

AF_XDP was designed to be able to deliver raw packets from networking cards (NIC) to a user space process with a performance comparable to solutions such as DPDK [5], Netmap [13], and PF_RING [4]. As AF_XDP is built as an extension to XDP (eXpress Data Path) [8], we need to explain some of its features first to see how AF_XDP builds on top of it.

XDP is a layer inside a Linux networking driver that for each packet will execute a piece of validated code loaded from user-space. This piece of code will then take actions on each packet. These actions are (somewhat simplified) to *drop* the packet, to *pass* it to the Linux networking stack or to *transmit* it out the same (XDP_TX) or another networking interface (XDP_REDIRECT) as seen in Figure 1. As the XDP program is executed in the driver, it can take these actions very quickly. But as the program is limited in size, there are only a limited set of actions that can be performed in XDP and if more complex processing is needed, the packet can be passed on to the Linux stack and perhaps even up to user space through one of the many socket types available such as raw sockets (AF_PACKET) or regular TCP/IP ones (AF_INET).

AF_XDP is a new socket type that permits raw packet data from the NIC to be delivered straight to user space from XDP without any copying and at significantly higher speeds than before [12]. It compares most closely with AF_PACKET in that it delivers raw packets to user space, however, it does so without sending a copy of the packet through the networking stack as it is zero-copy. AF_XDP works in three different modes from slowest to fastest: skb mode that works on any NIC, XDP copy mode that works on any NIC with XDP support in the driver, and zero-copy mode that only works on XDP enabled drivers that have been extended to support

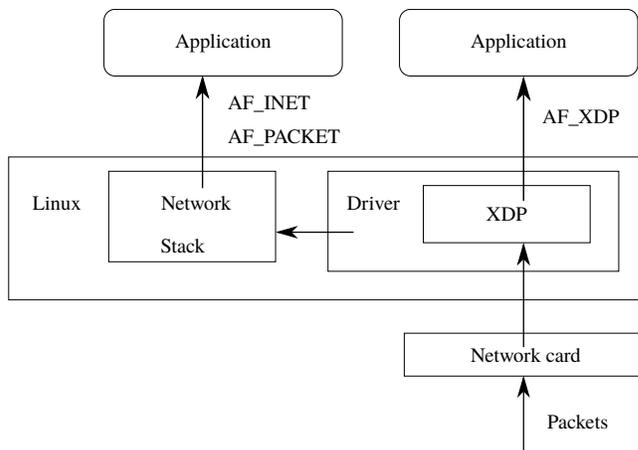


Figure 1: XDP can process special user space applications in the kernel driver. AF_XDP is the mechanism for which XDP can directly redirect packets up to an application in user-space with zero-copy semantics.

zero-copy mode. In this paper, we will only consider zero-copy mode as it has the best performance.

The XDP program decides to which AF_XDP socket the packet should be sent to. The sockets are put in the new XSKMAP map type and the XDP program can then pick which entry in this map a packet should be sent to. As XDP is a highly flexible program, the possible load balancing schemes for AF_XDP are also very flexible. Anything you can run in XDP is possible. For better performance, but less flexibility, you can use HW steering in the NIC instead. But note that in the current code base, an XDP program is mandatory even when you have HW steering.

From the application program point of view, all packets are located in an application allocated memory area called *umem* as seen in Figure 2. This is an area of equally sized chunks of memory called *packet buffers* in which packets can reside. Associated with a *umem* comes two rings: the *fill ring* and the *completion ring*. The fill ring is used to transfer ownership of a packet buffer from user space to the kernel, and conversely the completion buffer signals that ownership of a packet buffer has been transferred from the kernel to user space. The application indicates what packet buffer to transfer ownership of by putting the address of that packet buffer into the fill ring. Note, that this is the relative address from the start of the packet buffer, not the actual virtual address. In the same way, the kernel indicates ownership transfers in the completion ring by entering the relative address of the desired packet buffer into it.

```

/* Rx/Tx descriptor */
struct xdp_desc {
    __u64 addr;
    __u32 len;
    __u32 options;
};

/* Fill/Completion descriptor */
__u64 addr;

```

Listing 1: The descriptors of the Rx, Tx, Fill, and Completion rings.

Now we have a way to transfer ownership of packet buffers without sending or receiving any data. To be able to send and receive packet data, we need two more rings: the *Rx ring* and the *Tx ring*. As seen in Listing 1, the descriptor format of these are larger than the fill and completion rings. When a packet is received,

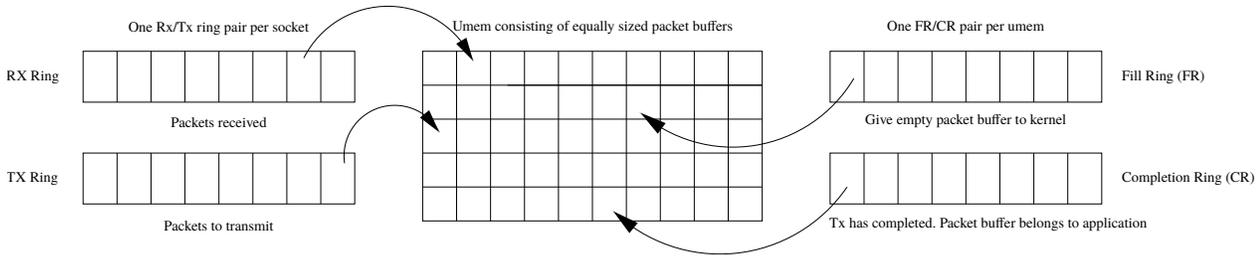


Figure 2: The four rings of AF_XDP and the umem containing all the packet buffers.

the kernel fills in a descriptor in the Rx ring, signifying what packet buffer contains the packet data by setting `addr` to the relative address of the packet buffer and indicating its length in `len`. There is also an options field, but it is reserved for future extensions. By checking the Rx ring, an application can find out if it has received a packet. Conversely, if the application wants to send a packet, it puts the same kind of information in the Tx ring, signaling to the kernel that this packet should be transmitted. Note that the Rx and Tx rings belong to the socket and each socket is bound to one umem which has only one fill ring and one completion ring. But many sockets can be bound to the same umem as long as they are bound to the same network device and queue id. In that case, there will be many Rx/Tx ring pairs.

A typical life-of-a-packet for AF_XDP is the following. A packet enters the NIC and the Linux driver picks it up, executes the XDP program that decides if the packet should be sent to a specific AF_XDP socket. As AF_XDP is executing in zero-copy mode, the NIC has already put the packet in a packet buffer in the umem area so the only thing the kernel has to do is fill in the Rx descriptor to tell the application where this new packet resides and the length of it. The application will then check the Rx ring if it has received any packets. Once it has finished processing the packet, it can return it to the kernel via the fill ring so that a new packet can arrive in that packet buffer.

Tx works in a similar way but using the Tx and completion rings. When the application wants to send a packet, it fills out the next available descriptor in the Tx ring to point to the packet buffer it wants to send. The kernel will then pick up this request and send it to the hardware. Once the hardware has sent the packet, the kernel signals that it has indeed sent the packet by returning the packet buffer to the application via the completion ring.

Listing 2 shows the control path in pseudo-code. First we have to create an AF_XDP socket through the usual `socket()` call. After that some memory is allocated for the umem and register it through the `setsockopt` option `XDP_UMEM_REG`. The four rings are then created with the `setsockopts` `XDP_RX_RING`, `XDP_TX_RING`, `XDP_UMEM_FILL_RING`, and `XDP_UMEM_COMPLETION_RING`. The application then has to ask the kernel for the structure of these rings using the `setsockopt` `XDP_MAP_OFFSETS`. The reason for this is that the ring structures are highly optimized to minimize cache coherency traffic and might look different on various architectures. Now we have created all the structures we need and are ready to start receiving and/or sending traffic from a network device and this is indicated by issuing a `bind()` call providing the interface as well as the queue id of that interface from which we would like to receive traffic from and/or transmit traffic on. This concludes the control path of the set up.

The data path is simpler and is shown in Listing 3. It comes in two main flavors: either a run-to-completion-model or by calling `poll()` (or `select()`, `epoll()`, etc) to receive a packet. In the run-to-completion model, the application just busy polls the Rx

```
sfd = socket(PF_XDP, SOCK_RAW, 0);

start_of_umem = malloc(size_of_umem);
mr.addr = start_of_umem;
mr.len = length_of_umem;
mr.chunk_size = 2048;
mr.headroom = headroom;
setsockopt(sfd, SOL_XDP, XDP_UMEM_REG, &mr, sizeof(mr));

size = nr_descs_in_fill_queue;
ret = setsockopt(sfd, SOL_XDP, XDP_UMEM_FILL_RING,
                &size, sizeof(size));
size = nr_descs_in_completion_queue;
ret = setsockopt(sfd, SOL_XDP, XDP_UMEM_COMPLETION_RING,
                &size, sizeof(size));

size = nr_descs_in_rx_queue;
ret = setsockopt(sfd, SOL_XDP, XDP_RX_RING,
                &size, sizeof(size));
size = nr_descs_in_tx_queue;
ret = setsockopt(sfd, SOL_XDP, XDP_TX_RING,
                &size, sizeof(size));

/* Get the structure of the queues */
getsockopt(sfd, SOL_XDP, XDP_MAP_OFFSETS, &off, &optlen);

fill_q = mmap(NULL, off.fr.desc * nr_descs_in_fill_queue *
              sizeof(u64),
              PROT_READ | PROT_WRITE,
              MAP_SHARED | MAP_POPULATE,
              sfd, XDP_UMEM_PGOFF_FILL_RING);
/* ...and so on for all four queues */

sxdp.sxdp_family = PF_XDP;
sxdp.sxdp_ifindex = if_nametoindex(interface_name);
sxdp.sxdp_queue_id = queue_id;
bind(sfd, (struct sockaddr *)&sxdp, sizeof(sxdp));
```

Listing 2: The control path of AF_XDP in C-style pseudo-code.

ring in order to check if it has received a message. Once it receives a batch, it goes on to process them. In the `poll()` model, it calls `poll` when it has nothing to do, and when `poll` returns there is either a packet to receive or a timeout has occurred.

For the Tx path shown in Listing 4, a descriptor for the packet to be sent is put in the Tx ring. The kernel can pick this up to send it in two ways: either through a `sendmsg()` syscall from the application or through the transmit path NAPI context that might already be running. If the Tx ring is full, the application can call `poll()` to wait for the ring to have one or more free entries so that a packet can be sent, or just `poll` continuously using the run-to-completion model. The Tx code also needs to check the completion ring in order to be able to reuse packet buffers once the kernel has sent them.

When an AF_XDP program executes it usually consumes two cores: one for the application and one for `ksoftirqd` executing the Rx and Tx processing in a NAPI context as seen to the left in Figure 3. If the driver performs Rx and Tx processing in different NAPI

```

void process_batch(void)
{
    struct xdp_desc desc[BATCH_SIZE];

    rcvd = xq_deq(rx, desc, BATCH_SIZE);
    if (!rcvd)
        return;

    for (i = 0; i < rcvd; i++) {
        char *pkt = xq_get_data(desc[i].addr);
        process_packet(pkt, desc[i].len);
    }

    umem_fill_to_kernel(fq, desc, rcvd);
}

/* Run-to-completion model */
while (1) {
    process_batch();
}

/* With poll() */
fds[0].fd = sfd;
fds[0].events = POLLIN;

while (1) {
    ret = poll(fds, 1, 0);
    if (ret <= 0)
        continue;

    if (fds[0].fd != sfd ||
        !(fds[0].revents & POLLOUT))
        continue;

    process_batch();
}

```

Listing 3: The Rx data path of AF_XDP in C-style pseudo-code.

```

static struct xdp_desc desc[BATCH_SIZE];

int send_batch(desc)
{
    u64 comp_desc[BATCH_SIZE];

    if (xq_nb_free(tx, BATCH_SIZE) >= BATCH_SIZE)
        xq_enq(tx, desc, BATCH_SIZE) == 0);
    else
        return 0;

    sendto(sfd, NULL, 0, MSG_DONTWAIT, NULL, 0);
    rcvd = umem_complete_from_kernel(cq,
                                     comp_desc,
                                     BATCH_SIZE);

    if (rcvd > 0)
        process_completions(desc, rcvd);

    return rcvd;
}

/* Run-to-completion model */
while (1) {
    produce_packets(desc);
    (void)send_batch();
}

/* With poll() */
fds[0].fd = sfd;
fds[0].events = POLLOUT;

while (1) {
    produce_packets(desc);
    nr_pkts_sent = send_batch();

    if (nr_pkts_sent == 0) {
        ret = poll(fds, 1, 0);
    }
}

```

Listing 4: The Tx data path of AF_XDP in C-style pseudo-code.

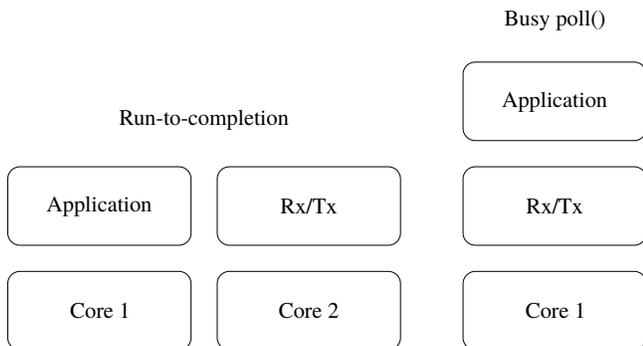


Figure 3: When run normally, AF_XDP will consume two cores in our experiments, but if busy poll() support is used both application and Rx/Tx processing can run efficiently on a single core.

contexts, then they can execute on different cores for a total of three cores. But this is not the case for the driver we are using in our experimental evaluation. This is in contrast with DPDK and other user-mode driver packages which can, with good performance, execute both Rx/Tx processing and the application on a single core. If we did this, the performance would drop by orders of magnitude due to context switching. But there is a solution for this in Linux and that is to use the *busy poll()* support (BUSY_POLL_LOOP) in the kernel. With this feature, and the corresponding enablement in the AF_XDP code, only one core is needed as the application will drive the NAPI context from the poll() syscall. With this busy poll()

support, we can achieve a set up that is similar to DPDK, if desired. We will evaluate this support in the results section.

AF_XDP was introduced in Linux 4.18 and the source code can be found in the net/xdp directory and the headers in include/net/xdp_sock.h. Note that some of the Rx path is in the XDP path and that code is in net/core/filter.c. An example sample program can be found in samples/bpf/xdpsock_user.c and the XDP program used to route the packets are in samples/bpf/xdpsock_kern.c.

3. Optimizations

This section presents the proposed optimizations that require some changes to non AF_XDP components and/or can generate architectural design discussions. The optimizations that we think are trivial are not mentioned here. Instead they will be mentioned briefly in the results section.

3.1 Built-In XDP Program

In the current code base, it is mandatory to install an XDP program that routes packets to one or more AF_XDP sockets. Without this program, the AF_XDP sockets will not receive any traffic at all. But when the application writer only wants to use the simplest possible XDP program that sends all packets from a queue id to a single socket bound to that queue id, we propose to provide a built-in XDP program that the user does not have to load. This will nearly half the amount of setup code required for an XDP program. More importantly for this paper, if we provide this built-in XDP program, we can implement a faster path through the XDP code up

to the AF_XDP code that significantly improves performance for this simple case.

We propose to add this support by adding a new flag to the `bind` call called `XDP_ATTACH`. When this flag is set, the AF_XDP code will load a built-in XDP program for you. This XDP program behaves like an ordinary XDP program: you can dump it or replace it with another XDP program on top of it. A change that we would like to propose is that this built-in XDP program forms a hitch with any regular, loaded XDP program. If an XDP program is loaded on top of the built-in, the externally loaded program will replace the built-in one. But if the externally loaded XDP program is unloaded, then the built-in program will become active again. The reason for this is that we think this is a good way to get it back. Another option would have been to just have no XDP program running once the external one is unloaded (as it is today), but in that case we would have to kill all sockets on that interface and restart them to get traffic back or provide a new XDP program with the basic functionality, but that would defeat the whole purpose of this optimization.

We envision that at least one more built-in program would be useful in the future and that would be an XDP program that copies the packet and passes the copy to the Linux stack and the original to user space. This could be used by applications that today use AF_PACKET such as `tcpdump`, `wireshark` and some DPI applications.

3.2 Retpoline Optimizations

The retpoline mechanism that mitigates Spectre v2 type of attacks can cut the performance of XDP by up to 50% [3]. As AF_XDP is based on XDP, it has a negative effect on it too, but only for the Rx part as the Tx part does not use the XDP Tx code at this point in time. Retpoline degrades the performance of indirect function calls, so that is something we would like to avoid.

The built in XDP program that was introduced in the previous section can be used to cut down the number of indirect function calls in the XDP path as we now know exactly what path it will take and that this program will not be replaced under our feet. We also optimized the XDP path in the NIC driver by replacing switch statements on the XDP actions with if statements, as the switch statements generated jump tables with indirect function calls.

3.3 XDP Optimizations

One more optimization we tried on the XDP Rx path was to replace the per-cpu state with an explicit context that is passed between functions. While this makes the function calls longer (and uglier), it provides a number of performance benefits. Retrieving data from the stack allocated explicit state is cheap compared to using the per-cpu state. This explicit context is also used to cut down the number of look-ups in the XDP code, which also improves performance.

3.4 Multiple Tx Rings for one umem

In applications that use QoS and shaping support present in many NICs, it is important to support multiple Tx sockets bound to different queue ids but the same umem. Each one of these sockets will then be treated differently by the NIC according to the QoS and shaping set up. One example of such an area is the radio access and core network of the mobile phone infrastructure. It is not uncommon to have more than 10 classes of service in these systems since a lot of the traffic goes over pay per use, shared transport networks. We also observed that spreading the Tx load over multiple queues increased performance

This feature can be supported without any extensions or changes to the uapi. Tx-only sockets can now be bound to a umem that has other sockets and queue ids bound to it. But note that there can still only be one Rx ring id associated with the umem. In order to preserve the Single-Producer Single-Consumer semantics of the

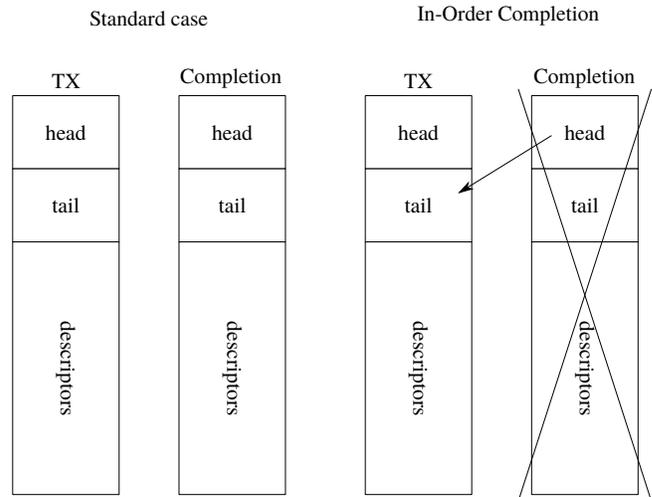


Figure 4: Normally, the head pointer in the completion ring signals that packet buffers have completed and which one have to be read out from the completion ring itself. With the in-order optimization, the completion ring can be skipped completely and the tail pointer in the Tx ring will now signify completions in the same order as in the Tx ring.

rings, the AF_XDP code will ask the driver if it can support this mutual exclusion by for example running the handling of the rings in the same NAPI context or by some HW mechanism. If so, this is left up to the driver. If the driver replies no, then the synchronization will occur in the AF_XDP code using a spinlock which is usually more expensive, but will work for any driver.

3.5 In-Order Completion

The current uapi assumes that completions can be delivered out-of-order by the underlying NIC and AF_XDP code. That is the reason why there is a completion ring with entries stating what packet buffers that have completed. But what if the NIC can only deliver packets in-order? In that case we actually do not need the completion ring entries as they would be in the exact same order as the entries in the Tx ring, as seen in Figure 4. We only need a mechanism to signal that entries up to a certain point in the Tx ring have completed, and that can be done with the tail pointer of the Tx ring.

To support this feature, we introduce a new `setsockopt` called `XDP_INORDER_COMPLETION`. When called it will return an error code if in-order completion cannot be guaranteed by the driver and 0 if it can be supported. In that case, the application only needs to check the Tx ring and can completely ignore the completion ring. It does not even have to exist. From a performance perspective, not having to populate or use the completion ring cuts the amount of coherency traffic between the two cores. We can also stop running the backpressure mechanism between the completion ring and the Tx ring. This mechanism guarantees that there is always space in the completion ring once we send a packet to the NIC, so that we do not have to buffer anything in our code path. But without the completion ring, there is no need for this, cutting down the coherency traffic even further.

3.6 Busy Poll() for AF_XDP

During the past couple of years, a number of people have added busy poll() support [7] to poll(), epoll() and select(). In this mode,

the NAPI context associated with receiving and sending messages to and from a socket can be driven by the syscall itself. This happens if the NAPI context is not already running because it has gotten for example an interrupt.

The main advantage of busy poll() is that we can run the application and its associated Rx and Tx actions on a single core as depicted in Figure 3. This will eliminate the coherency traffic between the two cores completely but the cost of this is the poll syscall itself that we do not need to use in the run-to-completion model that uses two cores.

4. Experimental Methodology

We run on a dual socket system with two Broadwell E5-2660 @ 2.7 GHz with hyper-threading turned off. Each socket has 14 cores which gives a total of 28. The memory is DDR4 @ 2133 MT/s (1067 MHz) and the size of each DIMM is 8192MB and with 8 of those DIMMs in the system we have 64 GB of total memory. We run Linux version v4.19-rc6-2008-g438363c0feb8 from the bpf-next tree with all Meltdown and Spectre mitigations turned on. The distribution we use is Ubuntu 18.04.1 LTS, and the compiler used is gcc version 7.3.0. We use two Intel I40E 40Gbit/s networking cards version 2.3.2-k with firmware version 6.01. Only a single interface/port is used on the card but we use two queues on each interface (in all experiments except the first one in the Tx section). Both NICs are served by the same core. The BIOS is from Intel and has version number GRRFCRB1.86B.0261.R01.1507240936 and the microcode has signature 0x000406f0. Power save has been turned off to provide more stable performance numbers. All the four types of HW prefetchers are turned on. Packets are generated by commercial packet generator HW that is generating 64-byte packets at full 40 Gbit/s line rate to each NIC.

The micro-benchmarks used in this study are shown in Table 1. All of them are part of the xdpsock.user.c sample application. Rxdrop and txpush does not touch packet data while l2fwd touches every packet by swapping the MAC addresses. Each benchmark runs for 60 seconds and each application process executes on its own core with cpu affinity. All processes are run on the same socket as the NIC is plugged into.

Benchmark	Description
rxdrop	RX only without packet data touch
txpush	TX only without packet data touch
l2fwd	RX + swap MAC headers + TX

Table 1: The micro-benchmarks used in this paper.

For the DPDK experiments, we use the same system and kernel as for the AF_XDP experiments. We use DPDK version 18.08 and compile it using the standard supplied options and that is without any retpoline support. We use both vectorized and scalar drivers in the experiments. The same two NICs are used with two queues active on a single port per NIC. We use the DPDK I40E PMD with 32-byte descriptors as that is what is used in the Linux driver, however both DPDK and AF_XDP will get a performance boost (2% for DPDK) by moving to 16-byte descriptors. But this has not been implemented in the Linux driver. The testpmd application is used for all benchmarks and the command line is testpmd -l 14-15 -n 4 -w 0000:81:00.1 -w 0000:86:00.0 -- -i --portmask=0x3 --rxd=512 --txd=512 --txq=1 --rxq=1 and the prompts that follows for the different applications can be found in Table 2. We modified the txonly code to use pregenerated packets to improve its perfor-

mance and to make it comparable to the AF_XDP txonly that also uses pregenerated packets¹.

Benchmark	Testpmd Command Line
rxdrop	set fwd rxonly
txpush	set fwd txonly
l2fwd	set fwd macswap

Table 2: The DPDK testpmd command lines used for the benchmarks in this paper.

5. Experimental Results

This section starts by first reporting the results of the Rx optimizations in section 5.1, followed by the Tx optimizations in section 5.2. We then put all the optimizations together when the results for the busy poll() implementation are reported in section 5.3. In section 5.4, we show how the optimizations improve the performance of the XDP path and finally section 5.5 compares AF_XDP's performance to DPDK's.

5.1 RX Results

Figure 5 shows the results of the proposed Rx optimizations. "Baseline" refers to the performance of the code without any of our optimizations in it, what you would get if you would compile the latest bpf-next or net-next tree. "XDP_ATTACH" introduces the XDP_ATTACH option and by doing that we can use a simpler built-in XDP program that gives rise to faster xdp_do_redirect, xdp_do_flush_map and a specialized version of bpf_redirect_map called bpf_xsk_redirect that improves performance. The next two categories are self explanatory, but the "various driver opts" inlines a number of functions in the data path of the driver, restructures struct to be more cache friendly, increases the tail bump interval from 32 to 128 and other optimizations. The "Explicit context in XDP path" was explained in its own section.

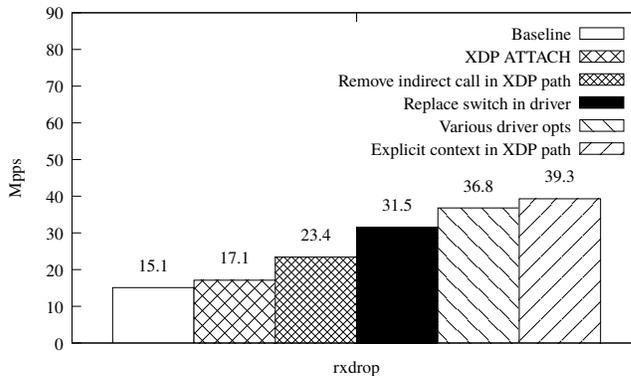


Figure 5: Results for rxdrop and the various Rx optimizations.

As can be seen the performance after all the optimizations is increased by 131% from 15.1 Mpps to 39.3 Mpps. This is mainly due to the shorter code path that can be gained by the built-in XDP program and especially by the retpoline optimizations.

¹Performance results are based on testing as of October 17, 2018 and may not reflect all publicly available security updates. See configuration disclosure for details. No product can be absolutely secure.

5.2 TX Results

Figure 6 shows the results of the proposed Tx optimizations. “Baseline” is the same build as the one for Rx, while “Batch size and descriptor changes” is when the batch size of the application is increased from 16 to 64 and the ring sizes are increased from 1024 to 2048. The other ones should be self explanatory and/or covered in the optimization section.

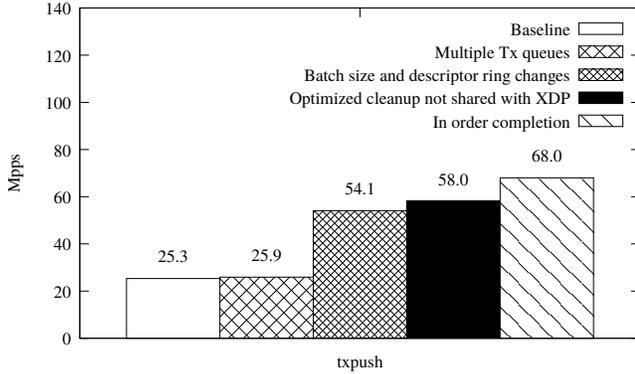


Figure 6: Results for txpush and the various Tx optimizations.

From the figure, we can see that the performance is increased by 169% or from 25.3 Mpps to 68.0 Mpps with all the Tx optimizations. (Note that we can get more than 59.5 Mpps because we are using two 40 Gbit/s NIC cards.) The highest performance gain is found by just tuning the sample application slightly. We had not given this much love before, but by just increasing the batch size and ring sizes we could gain a substantial performance increase. Without the prior optimizations, increasing these would not have mattered that much. It is the cumulative effect of all three optimizations that is seen here. The in-order completion mode can increase the throughput even more up to 68.0 Mpps.

5.3 Combined Results and Busy Poll()

Figure 7 shows a comparison between the run-to-completion model that we have used in the experiments so far and using the poll() syscall in the busy poll() mode. The main difference between these modes is that the first mode uses two cores, one for the application and one for Rx/Tx processing, while the busy poll() mode uses only one core driving both the application and all Rx/Tx processing in a manner much more similar to a typical DPDK setup. All the Rx and Tx optimizations from the previous sections are used in these measurements.

As can be seen from the results, busy poll() decreases the performance by between 20% and 25%. But note that busy poll() only uses a single core instead of two (one fully loaded Rx/Tx core and a very lightly loaded application core), so on a per core basis the performance of busy poll() is between 50% and 59% better than the run-to-completion model. This is mainly due to the fact that we do not have to communicate any data between cores since it is all local to a single core and this eliminates any coherency traffic leading to better performance. The performance drawback with busy poll() is that incurs a system call overhead for the poll() call itself. This is something that the run-to-completion model avoids as it directly polls the relevant rings without any system call. But it is good to be able to pick between both these models. There are workloads and systems where one would be preferable to the other. E.g., for multi-stage pipelined workloads, using several cores for just application processing makes sense. But a workload for which the packets can

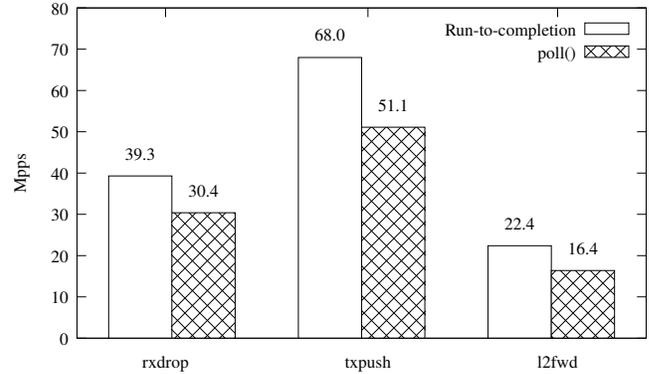


Figure 7: Results with and without busy poll(). Note that run-to-completion uses two cores but busy poll() only one.

be easily distributed between cores by a NIC, the busy poll() model is usually a better fit.

5.4 XDP Results

Some of the performance improvements we made to AF_XDP are also beneficial to the regular XDP path. Table 3 shows the performance increase of the xdp_drop micro-benchmark found in the samples/bpf directory in Linux. This benchmark when run with the notouch option is the same as rxdrop but implemented in XDP. As can be seen from the table, the throughput is increased by 23%. So our optimizations of AF_XDP that touches the XDP path has not decreased the performance. On the contrary.

Benchmark	Before	After optimizations
xdp_drop	19.9	24.5

Table 3: The performance improvement to XDP as a result of the AF_XDP targeted optimizations in this paper.

5.5 Comparison with DPDK

The benchmark for highly optimized drivers and SW interfaces for packet processing is today DPDK [5]. It is frequently used together with switching software to show really high throughput numbers in the range of 1 Tbit/s worth of switching [6]. The question is then, how does AF_XDP with these new set of optimizations compare to DPDK?

Figure 8 shows the performance of AF_XDP and DPDK for three benchmarks: rxdrop, txpush and l2fwd. For DPDK we have used both scalar drivers (not using any vector or floating point instructions) and vectorized drivers. As far as we know, there are no vectorized networking drivers available in Linux at the time of writing.

In summary, when we compare the busy poll() mode, that uses the same amount of cores as DPDK, to DPDK with scalar drivers then AF_XDP is only around half the performance of DPDK. The run-to-completion mode fares better and is even faster than DPDK (running a scalar driver) for Tx but around 30% slower for Rx. So we need to put more effort in optimizing the Rx path and the busy poll() path. More interestingly, when we actually start to touch the data in l2fwd, which is the normal case for pretty much all non toy-applications, the difference between AF_XDP and DPDK becomes much smaller. The run-to-completion mode of AF_XDP is faster than the scalar DPDK driver but slower than the vectorized one and busy poll() is only 16% slower when both DPDK and AF_XDP

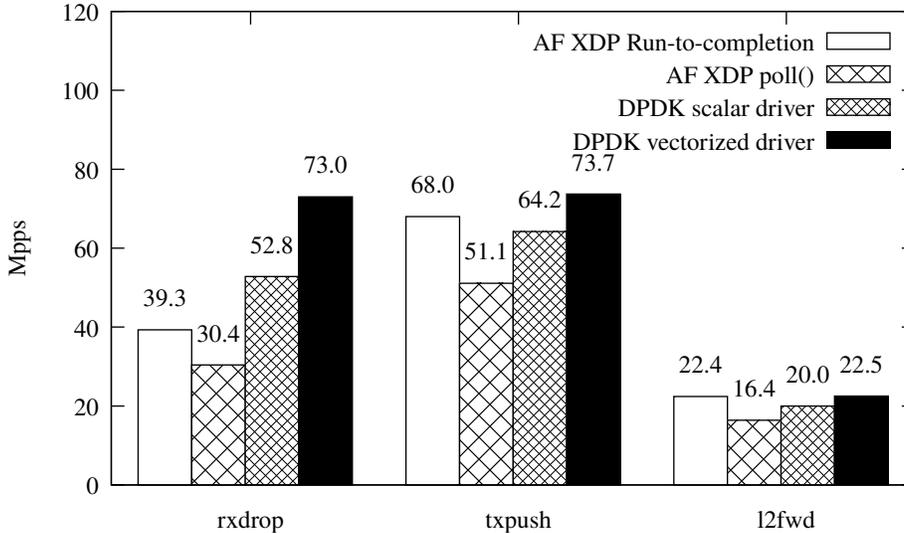


Figure 8: Results comparing AF_XDP with DPDK for three micro benchmarks.

are running scalar drivers. The more we actually use the data, the less the performance difference will be. It would be interesting to evaluate the performance difference for some real workloads and see how they compare and where we need to focus our efforts. What we have here are just micro-benchmarks.

We can also see from the results that vectorized drivers do offer a performance boost, between 12% and 38% for the DPDK micro-benchmarks used in this paper. The question is how much performance increase this translates to for realistic workloads and if this increase offsets the lowered maintainability and flexibility of such drivers.

6. Future Work and Discussion

It is clear from the initial user feedback we have gotten that the setup and data plane usage of AF_XDP need to become simpler to lower the bar of entry. Currently, it seems that users are just copying the code from the sample program, which is not a good solution in the mid to long term. The XSK_ATTACH optimization presented in this paper is the way we propose to facilitate the setup of an AF_XDP socket. But to make the data path simpler to use, we need something else. We would like to propose to add a lean and mean access library for AF_XDP sockets to libbpf, in the same manner as XDP has added helper functions to facilitate adoption of XDP programs. The library could present a libc interface (or at least libc-like) to the user with familiar functions such as `recv`, `recvmsg`, and `sendmsg`. This would go well with the control plane usage of pure libc functions and the already existing usage of `poll`, `select`, `read`, `write` and `sendto` in the data plane. The library could also be used to implement a really simple DPDK PMD for AF_XDP.

It would be beneficial to add hugepage support to AF_XDP, not only because it will cut down the TLB miss rate, but more so because it can cut down the communication rate on the fill ring. In the fill ring we indicate which page buffers should be returned by indicating what chunk it belongs to. In the current implementation the chunk size can be 2K or 4K, but with huge pages this could be for example 64K. So indicating the ownership transfer of 32 consecutive 2K page buffers to the kernel can be accomplished with just one write to the fill ring when the chunk size is 64K,

instead of 32 writes with a chunk size of 2K. This should improve performance.

Another avenue worth pursuing is to optimize the driver for “XDP first”. Currently we use the standard skb path, but there are many things in that path that cannot happen because they are not supported in XDP or AF_XDP. We could, for example, register a special NAPI handler that only deals with XDP Rx and/or Tx rings and provide a slim and highly optimized path from there. Another example would be to go to 16-byte descriptors for those queues as these can be handled faster by the I40E NIC and also consumes less memory which could lead to better performance.

One idea that we had for this paper, but had no time to implement, was to batch the XDP processing so that a batch of packets is first received, then that batch is processed in the XDP program and their corresponding actions recorded, then after this the actions are performed as a batch. When we implemented AF_PACKET V4, we experimented with this and it provided better throughput as it used the instruction cache more efficiently. But we have not had the time to implement this in the latest Linux kernel with AF_XDP. Jesper Dangaard Brouer has also posted interesting suggestions [2] on how to batch more in XDP.

We would like to encourage users out there to try out AF_XDP on real commercial workloads to see how it performs instead of our micro-benchmarks that we have gotten. Please report any performance problems, bugs and improvement suggestions on the mailing list so that we can address them.

7. Conclusions

This paper presented a number of possible performance optimizations to both the Rx and Tx paths of AF_XDP. Most of them are transparent to the user with the exception of the XSK_ATTACH bind option and the XSK_INORDER_COMPLETION setsockopt extension that require application changes to take advantage of them.

The performance evaluation shows that the performance compared to the current baseline in bpf-next and net-next is improved by 160% from 15.1 Mpps to 39.3 Mpps for Rx and by 169% or from 25.3 Mpps to 68.0 Mpps for Tx. We also evaluate the support of the busy poll() feature in conjunction with AF_XDP and while it reduces the total performance by between 20% and 25%, it also

cuts down the number of used cores to one. Measured on a per core basis, busy poll() actually increases performance with another 50% compared to the optimized Rx and Tx results. We also compare AF_XDP against DPDK and while there is still substantial work required on the Rx side to reach the same performance levels, Tx and an application that actually touches the data, l2fwd, offers comparable performance to DPDK when we run in run-to-completion mode.

8. Acknowledgments

We would really like to thank the reviewers on the mailing list and all the people that have taken AF_XDP for a spin and reported issues, bugs and improvement suggestions: Ilias Apalodimas, Daniel Borkmann, Jesper Dangaard Brouer, Willem De Bruijn, Eric Dumazet, Alexander Duyck, Mykyta Iziuntsev, Jakub Kicinski, Song Liu, David S. Miller, Pavel Odintsov, Sridhar Samudrala, Yonghong Song, Alexei Starovoitov, William Tu, Anil Vasudevan, Jingjing Wu, and Qi Zhang. We owe you one.

References

- [1] J. Corbet. Accelerating networking with AF_XDP. URL <https://lwn.net/Articles/750845/>, 2018.
- [2] J. Dangaard Brouer. Focusing the XDP project. URL <https://lists.openwall.net/netdev/2017/02/20/29>, 2018.
- [3] J. Dangaard Brouer. XDP performance regression due to CONFIG_RETPOLINE Spectre V2. URL <https://lkml.org/lkml/2018/4/12/285>, 2018.
- [4] L. Deri. Improving passive packet capture: Beyond device polling. In *International System Administration and Network Engineering Conference (SANE)*, Amsterdam, The Netherlands, 2004.
- [5] DPDK Community. DPDK - DataPlane Development Kit. URL <http://www.dpdk.org/>, 2018.
- [6] J. Duman. FD.io Doubles Packet Throughput Performance to Terabit Levels. URL <https://fd.io/2017/07/fdio-doubles-packet-throughput-performance-terabit-levels/>, 2017.
- [7] E. Dumazet. BUSY POLLING: past, present, future. In *Netdev Conference 2.1*, 2017. URL <https://netdevconf.org/2.1/slides/apr6/dumazet-BUSY-POLLING-Netdev-2.1.pdf>.
- [8] T. Høiland-Jørgensen, J. Dangaard Brouer, D. Borkmann, J. Fastabend, T. Herbert, D. Ahern, and D. Miller. The eXpress Data Path: Fast Programmable Packet Processing in the Operating System Kernel. In *Proceedings of the ACM CoNEXT Conference*, 2018. URL <https://github.com/tohojo/xdp-paper/blob/master/xdp-the-express-data-path.pdf>.
- [9] M. Karlsson and B. Töpel. The AF_XDP patch set. URL <https://lwn.net/Articles/750293/>, 2018.
- [10] M. Karlsson and B. Töpel. AF_XDP zero-copy support for I40E. URL <https://patchwork.ozlabs.org/cover/962906/>, 2018.
- [11] M. Karlsson and B. Töpel. Zero-copy support for AF_XDP. URL <https://lwn.net/Articles/756549/>, 2018.
- [12] M. Karlsson, B. Töpel, and J. Fastabend. AF_PACKET V4 and PACKET_ZEROCOPY. In *Netdev Conference 2.2*, 2017. URL <https://www.netdevconf.org/2.2/papers/karlsson-afpacket-talk.pdf>.
- [13] L. Rizzo. netmap: A novel framework for fast packet i/o. In *2012 USENIX Annual Technical Conference (USENIX ATC 12)*, pages 101–112, Boston, MA, 2012. USENIX Association. ISBN 978-931971-93-5. URL <https://www.usenix.org/conference/atc12/technical-sessions/presentation/rizzo>.
- [14] P. Turner. Retpoline: a software construct for preventing branch-target-injection. URL <https://support.google.com/faqs/answer/7625886>, 2018.