How to build a DDoS Mitigation Pipeline using XDP

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XDP in practice: integrating XDP into our DDoS mitigation pipeline

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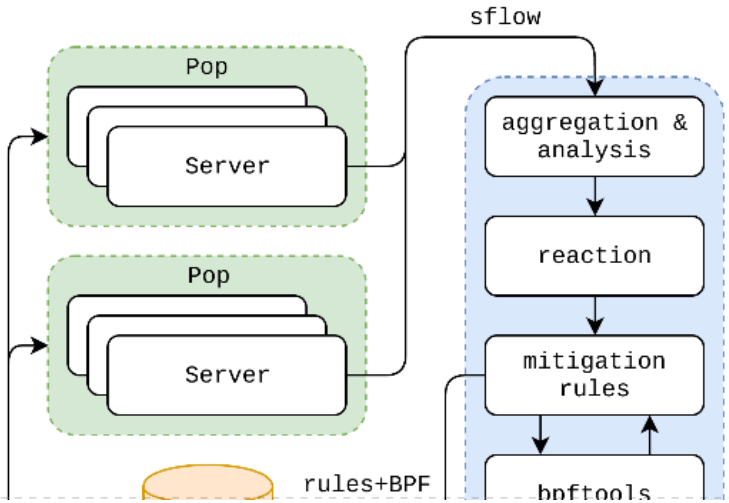
Abstract

To absorb large DDoS (distributed denial of service) attacks, the Cloudflare DDoS mitigation team has developed a solution based on kernel bypass and classic BPF. This allows us to filter network packets in userspace, skipping the usual packet processing done by Netfilter and the Linux network stack. This approach has solved performance issues that were experienced whilst handling large packet floods using solely the vanilla Linux kernel features.

In this paper we will first introduce our current architecture and then discuss a proposed solution based on XDP and eBPF. We will explain how XDP can be used in our infrastructure and which parts of our system need to be rewritten and adapted to make use of it. We will then conclude with the issues we have experienced so far with XDP.



Agenda

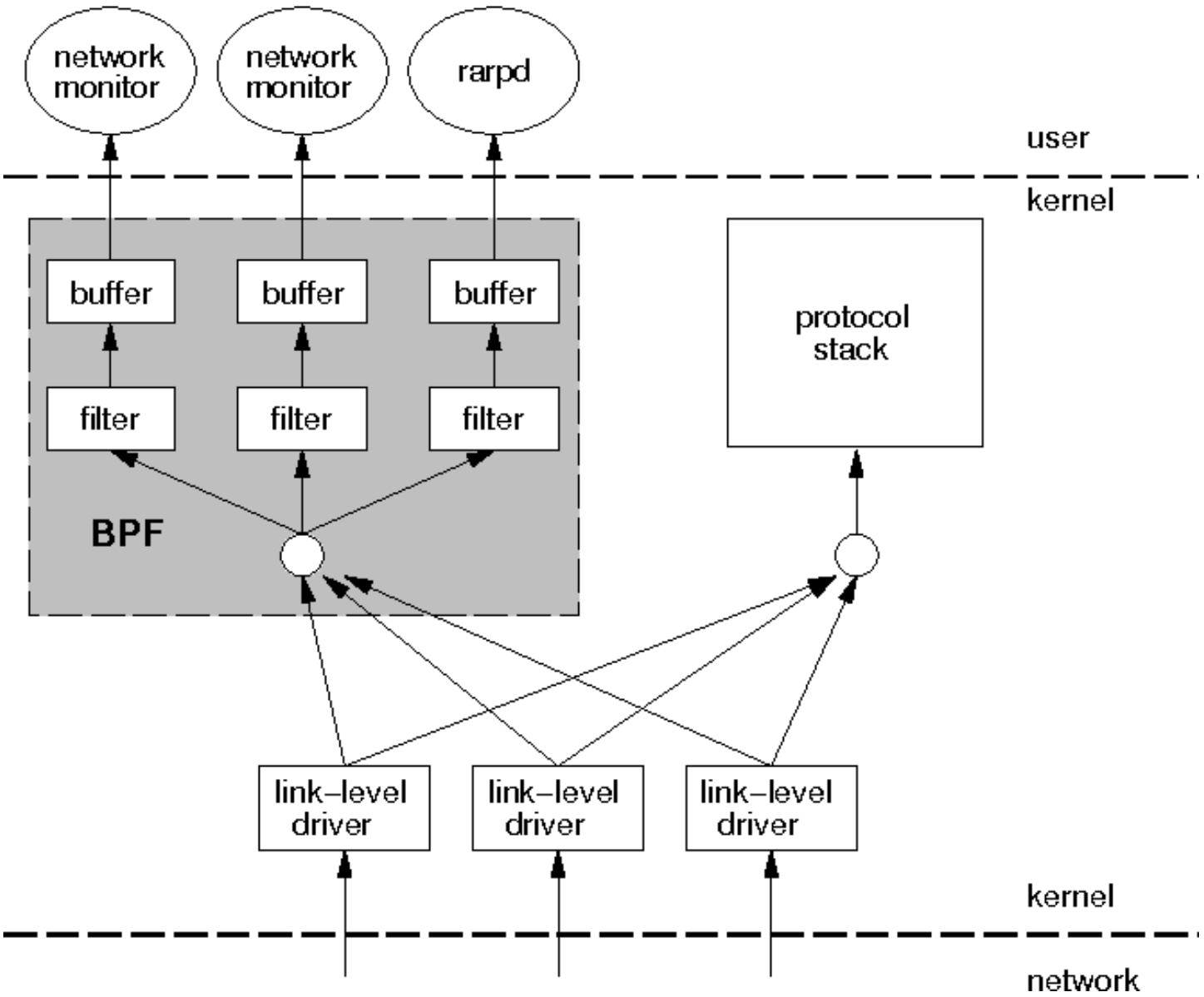
- cBPF
- eBPF
- XDP
- DDoS Mitigation Pipeline

cBPF

Berkeley Packet Filter

- *The BSD Packet Filter: A New Architecture for User-level Packet Capture*
- Avoid needless copying of packets
- Register-based VM in-kernel
- Filter packets as early as possible

cBPF


network monitor
network monitor
rarpd
user
kernel
buffer
buffer
buffer
filter
filter
filter
BPF
protocol stack
link–level driver
link–level driver
link–level driver
kernel
network

```
# lgian[~] tcpdump -i any tcp -d
(000) ldh      [14]
(001) jeq      #0x86dd          jt 2 jf 7
(002) ldb      [22]
(003) jeq      #0x6             jt 10 jf 4
(004) jeq      #0x2c            jt 5 jf 11
(005) ldb      [56]
(006) jeq      #0x6             jt 10 jf 11
(007) jeq      #0x800           jt 8  jf 11
(008) ldb      [25]
(009) jeq      #0x6             jt 10 jf 11
(010) ret      #262144
(011) ret      #0

# lgian[~] strace -e trace=setsockopt tcpdump -i any tcp
...
  setsockopt(3, SOL_SOCKET, SO_ATTACH_FILTER,
    {len=12, filter=0x5630ba569dd0}, 16) = 0
```

eBPF

eBPF

What changed

- Extended ISA for modern CPUs
- More registers (from 2 to 10)
- JIT compiler bytecode to native code

New concepts

- eBPF Maps shared between user and kernel space
- eBPF Verifier

eBPF Map Types

- Hash
- Array
- Tail Call Array
- Per-CPU Hash/Array
- Stack Trace
- LRU (per-CPU) Hash
- Longest-Prefix Matching Trie
- Array/Hash of Maps
- Net device Map
- Socket Map
- ...

eBPF Verifier

We essentially run userspace programs in the kernel.

How can we ensure an eBPF program won't cause a kernel panic or read/write arbitrary kernel memory?

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How can we ensure an eBPF program won't cause a kernel panic or read/write arbitrary kernel memory?

Restrictions:

- 4096 instructions per program
- No loops
- No unreachable instructions
- Cannot read uninitialized registers
- Cannot read any arbitrary memory
- No out-of-bounds jumps
- Everything needs to be inlined (no function calls or shared library calls)
- Only calls to BPF Helpers (BPF to BPF is also allowed on newer kernel versions)

(some) eBPF Helper Functions

uapi/linux/bpf.h

```
#define __BPF_FUNC_MAPPER(FN)   \
  FN(map_lookup_elem),    \
  FN(map_update_elem),    \
  FN(map_delete_elem),    \
  ...
  FN(ktime_get_ns),   \
  FN(trace_printk),   \
  FN(get_prandom_u32),    \
  FN(skb_store_bytes),    \
  FN(l3_csum_replace),    \
  FN(tail_call),      \
  FN(xdp_adjust_head),    \
  FN(xdp_adjust_meta),    \
  ...
```

Some use cases:

- Tracing (kprobes/uprobes/tracepoints)[1]
- Networking (tc/XDP)
- Security (seccomp/IDS/DDoS)

[1] https://www.youtube.com/watch?v=w8nFRoFJ6EQ

XDP

XDP

eXpress Data Path

- High-performance packet processing
- Runs eBPF programs at the earliest possible point (before sk_buffer allocations)
- In concert with the kernel (no userspace bypass or out-of-tree kernel modifications)
- Driver dependant
- Verdicts: XDP_DROP, XDP_PASS, XDP_TX, XDP_ABORTED, XDP_REDIRECT

Use cases:

- Firewalling (Cillium[1])
- DDoS
- Load balancing (Katran[2])
- Monitoring

[1] https://cilium.io/

[2] https://code.fb.com/open-source/open-sourcing-katran-a-scalable-network-load-balancer/

XDP Example

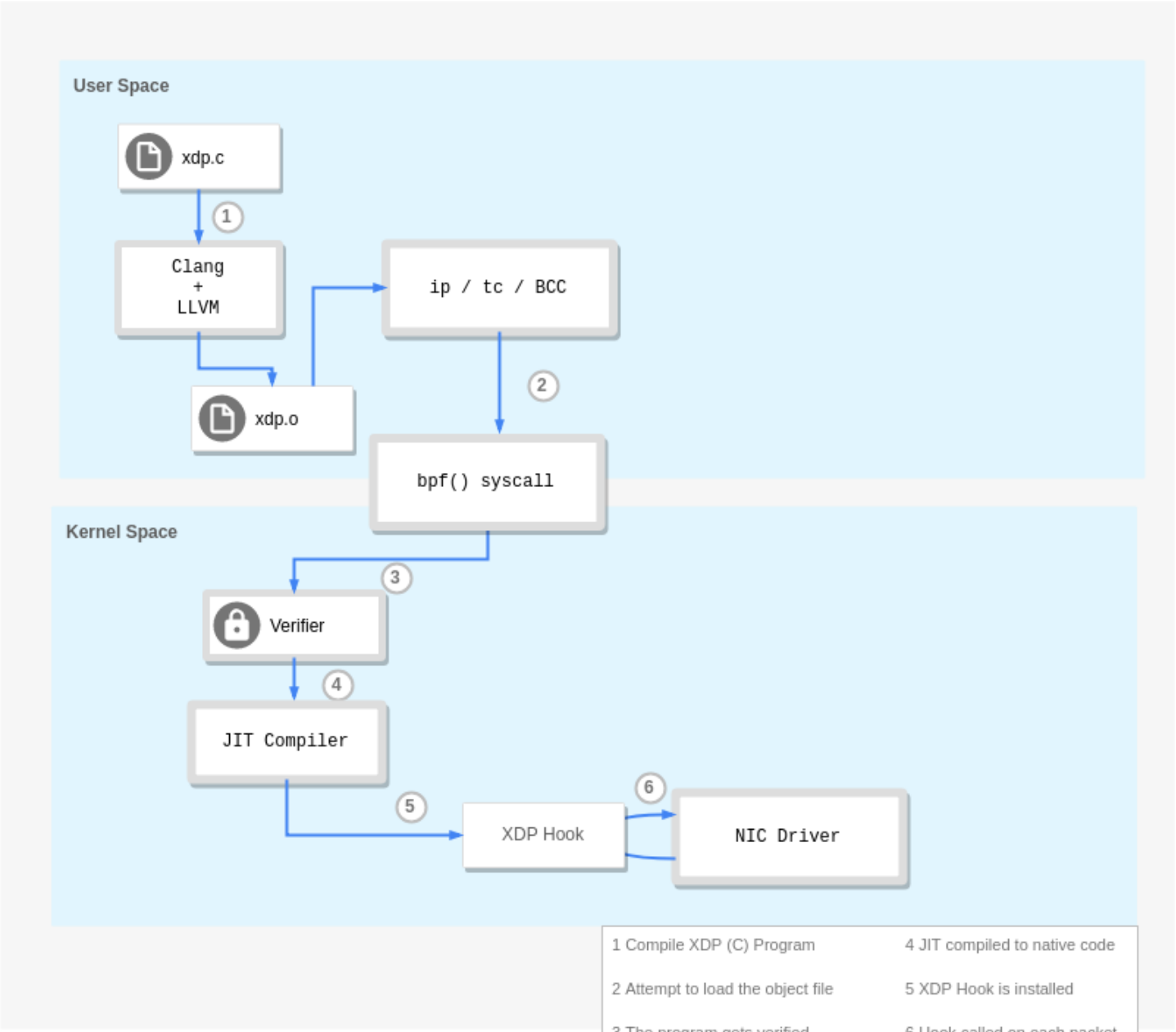
```
#include <linux/bpf.h>
#include <linux/if_ether.h>
#include <linux/ip.h>
#define SEC(NAME) __attribute__((section(NAME), used))

SEC("dropper")
int xdp(struct xdp_md *ctx)
{
    void *data = (void *)(long)ctx->data;
    void *data_end = (void *)(long)ctx->data_end;
    struct iphdr *ip = data + sizeof(struct ethhdr);

    // +1 is sizeof(struct iphdr)
    if (ip + 1 > data_end)
        return XDP_ABORTED;

    if(ip->saddr == 59017107){ // Binary format of "147.135.132.3"
        return XDP_DROP;
    }
    return XDP_PASS;
}
```

XDP Load Program



XDP Load Program

- Write C Program
- clang -O2 -target bpf -c xdp.c -o xdp.o
- ip link set dev eth0 (xdpgeneric|xdpdrv|xdpoffload) obj xdp.o sec <section-name>

XDP vs Everything

What about IPtables?

XDP vs Everything

Test bench

- 10GbE Intel NIC
- 14Mpps tiny UDP packets
- Randomized source IP/Port
- Traffic is steered towards a single CPU
- Measure number of packets handled by the kernel on that CPU

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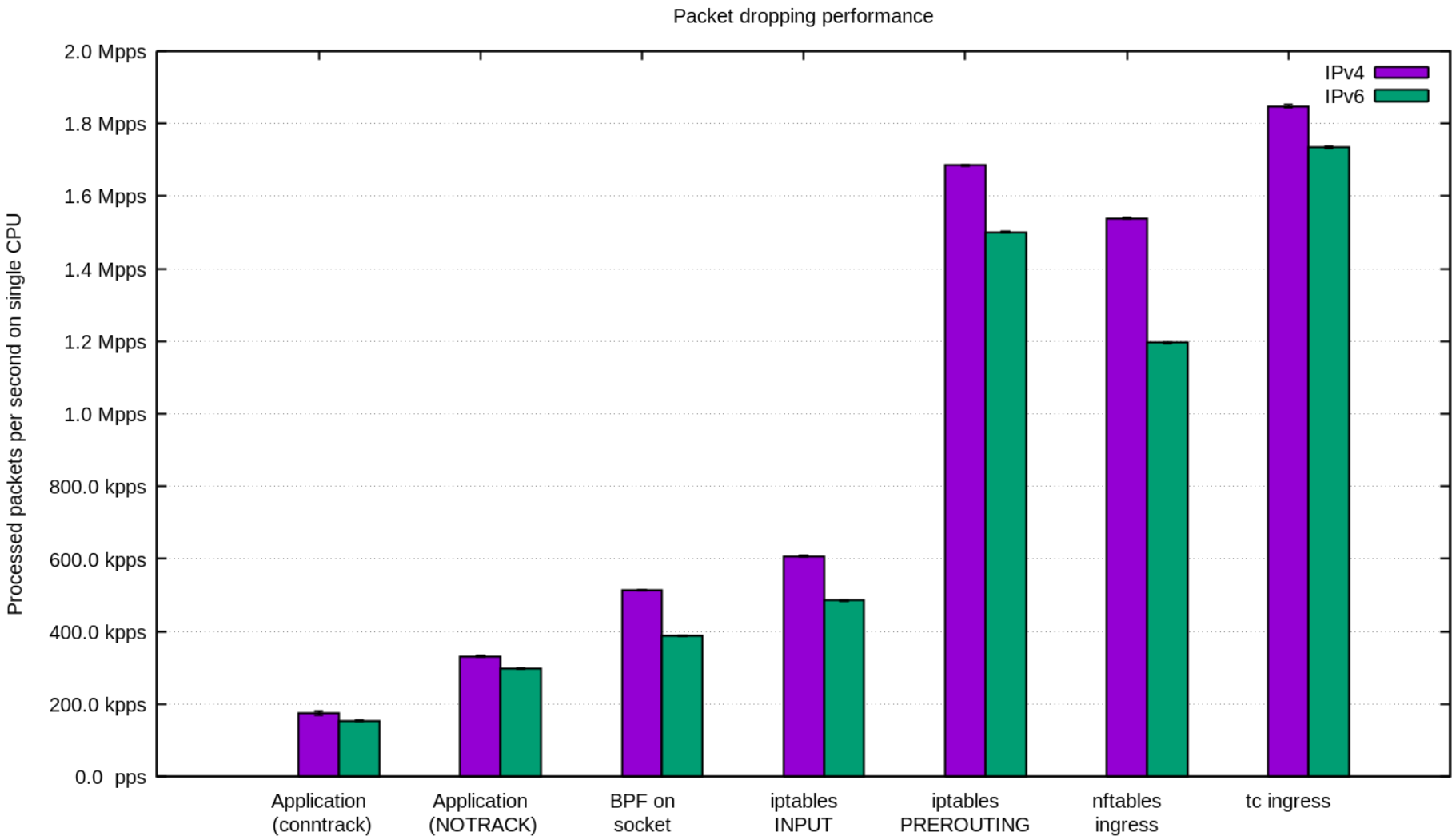
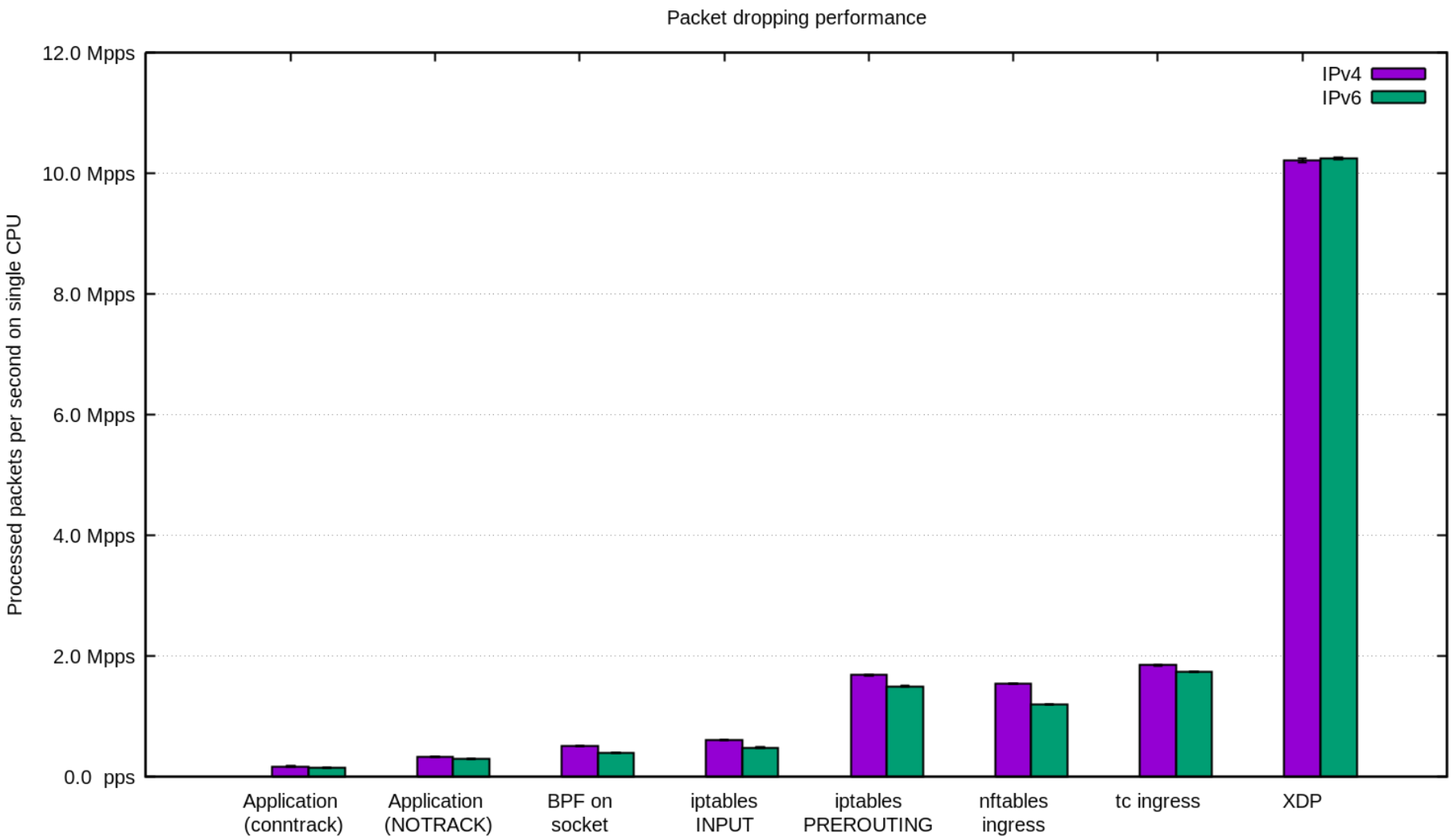
How fast can we drop packets?

XDP vs Everything



XDP vs Everything



XDP

Overview of Pipeline

- Traffic sampling
- Traffic aggregation and analysis
- Attack reaction
- Attack mitigation

Some things to note

- DDoS Attacks that our uplink can handle
- If that's not the case:
  - Anycast with different PoPs
  - Flowspec
- Flowspec has its limitations
- Software and not hardware limitations

Traffic sampling

In contrast with an IDS, sampling instead of working on the whole traffic is crucial here.

- Use *NFLOG (+Statistic)*
- Userspace daemon and Sflow packets to central server

Traffic sampling

The problem with the above is that you have no visibility in the dropped traffic

- Once a packet arrives use *xdp_event_output* to copy packet to a perf event ring buffer
- Then use a userspace daemon to obtain the packet

Traffic aggregation and analysis

How do we categorize traffic?

Traffic aggregation and analysis

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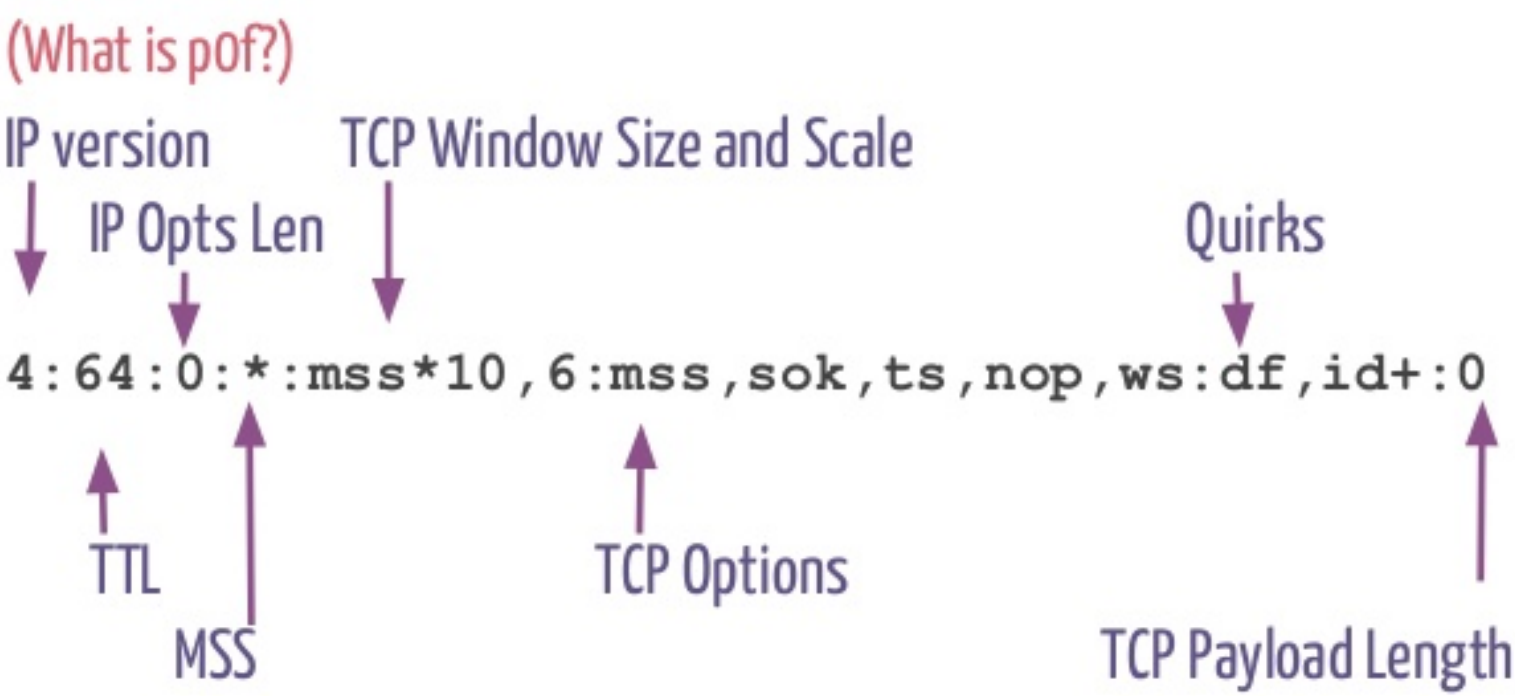


Credit: *https://www.slideshare.net/InfoQ/xdp-in-practice-ddos-mitigation-cloudflare*

Traffic aggregation and analysis

Traffic aggregated into groups

- TCP SYNs, TCP ACKs, UDP/DNS
- Destination IP/Port
- Known attack vectors and other heuristics

p0f -> XDP

```
$ ./p0f2ebpf.py --ip 1.2.3.4 --port 1234
    '4:64:0:*:mss*10,6:mss,sok,ts,nop,ws:df,id+:0'

static inline int match_p0f(void *data, void *data_end) {
    struct ethhdr *eth_hdr;
    struct iphdr *ip_hdr;
    struct tcphdr *tcp_hdr;
    u8 *tcp_opts;

    eth_hdr = (struct ethhdr *)data;
    if (eth_hdr + 1 > (struct ethhdr *)data_end)
        return XDP_ABORTED;
    if_not (eth_hdr->h_proto == htons(ETH_P_IP))
        return XDP_PASS;
```

p0f -> XDP

```
ip_hdr = (struct iphdr *)(eth_hdr + 1);
if (ip_hdr + 1 > (struct iphdr *)data_end)
    return XDP_ABORTED;
if_not (ip_hdr->daddr == htonl(0x1020304))
    return XDP_PASS;
if_not (ip_hdr->version == 4)
    return XDP_PASS;
if_not (ip_hdr->ttl <= 64)
    return XDP_PASS;
if_not (ip_hdr->ttl > 29)
    return XDP_PASS;
if_not (ip_hdr->ihl == 5)
    return XDP_PASS;
if_not ((ip_hdr->frag_off & IP_DF) != 0)
    return XDP_PASS;
if_not ((ip_hdr->frag_off & IP_MBZ) == 0)
    return XDP_PASS;
```

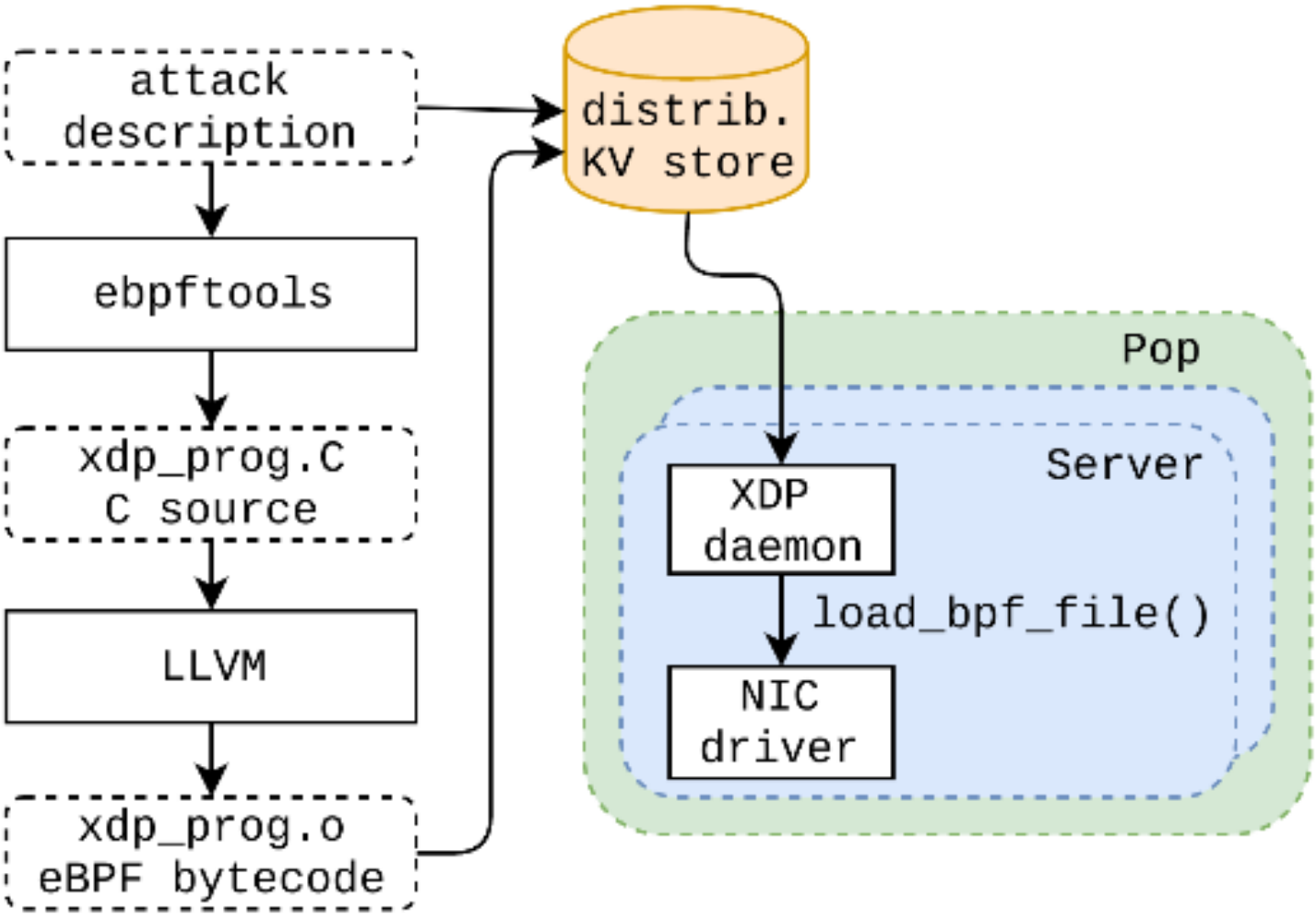
p0f -> XDP

```
    tcp_hdr = (struct tcphdr*)((u8 *)ip_hdr +
    ip_hdr->ihl * 4);
    if (tcp_hdr + 1 > (struct tcphdr *)data_end)
        return XDP_ABORTED;
    if_not (tcp_hdr->dest == htons(1234))
        return XDP_PASS;
    if_not (tcp_hdr->doff == 10)
        return XDP_PASS;
    if_not ((htons(ip_hdr->tot_len) - (ip_hdr->ihl * 4) - (tcp_hdr->dof
        return XDP_PASS;

    ...

    return XDP_DROP;
}
```

Attack Reaction/Mitigation

- Once we have a p0f signature of a specific attack
- Based on the signature generate an XDP program to drop the malicious traffic
- Push it to a distributed KV store
- Userspace daemon on each edge server that polls distributed KV store
- Update the XDP program deployed

Attack Reaction/Mitigation



Credit: *https://netdevconf.org/2.1/papers/Gilberto_Bertin_XDP_in_practice.pdf*

Thank you!

Questions?