FOSDEM’17
Brussels, 2017-02-04

Stateful packet processing with eBPF: An implementation of OpenState interface

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@qeole

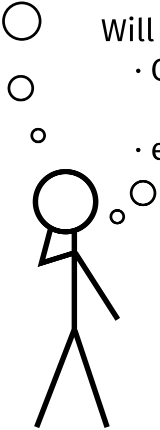
6WIND

Agenda

I'll speak at FOSDEM

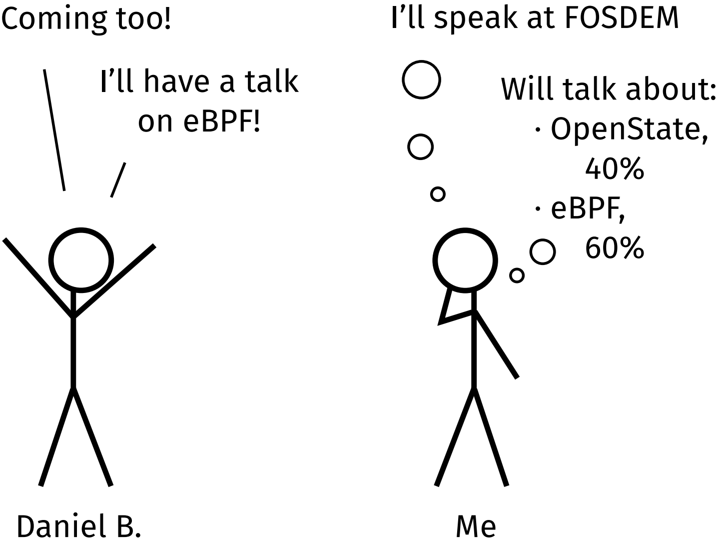
Will talk about:

- OpenState, 40%
- eBPF, 60%



Me

Agenda


Coming too!
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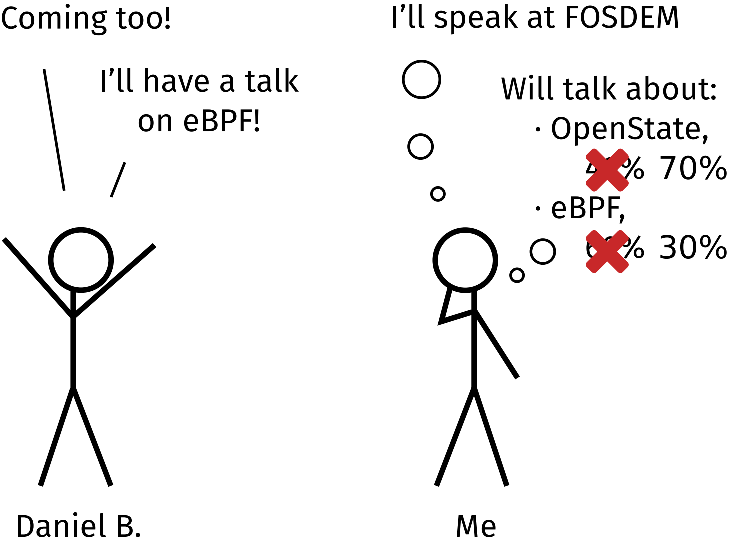
Will talk about:
· OpenState, 40%
· eBPF, 60%
Daniel B.
Me

Agenda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· OpenState, 70%
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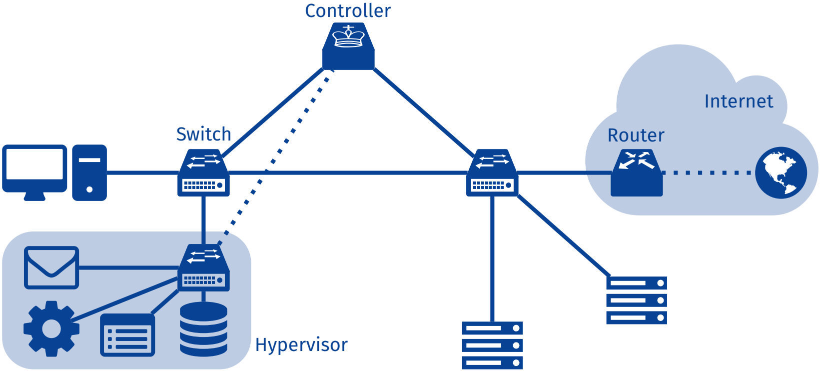
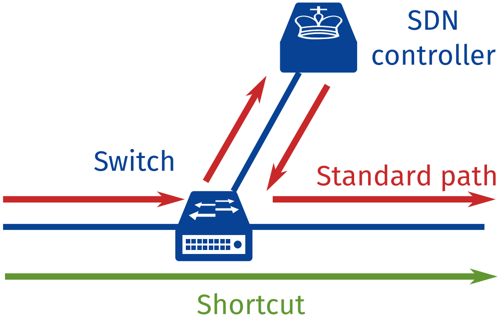
Daniel B.
Me

SDN: hosts, VMs, programmable switches, controllers...

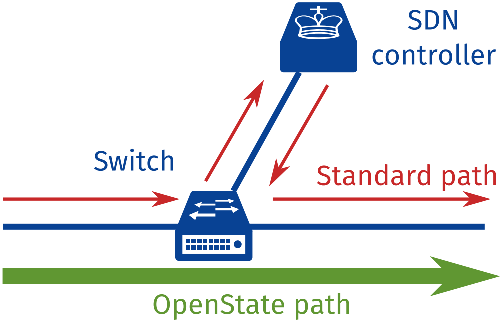


Two paths for dataplane



- Most packets goes through the “shortcut” dataplane
- Some packets are sent as exceptions—this generally includes stateful processing

What about: bringing back some control into the switch?



- Can we make the switch “smarter”, without loosing SDN benefits?
- How could we abstract stateful packet processing, in such a way the controller can easily set up the switches?

Beba
BEhavioural BAsed forwarding

European Commission
Horizon 2020

Objectives:

- Wire-speed-reactive control/processing tasks inside the switches
- Centralized control
- Scalability
- Platform-independent

From January 2015 to March 2017 (27 months)

More info at http://www.beba-project.eu/

BEBA: Who?

NEC

cnit consorzio nazionale interuniversitario per le telecomunicazioni

Beba

BEhavioural BAsed forwarding

THALES

KTH VETENSKAP OCH KONST

CESNET

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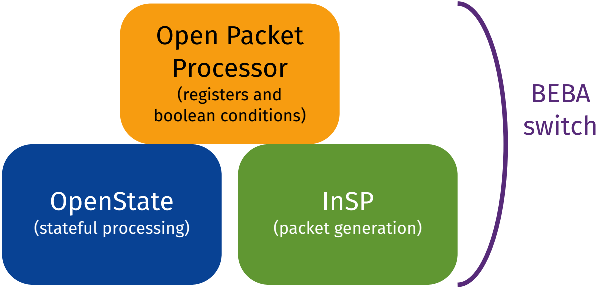
BEBA switch

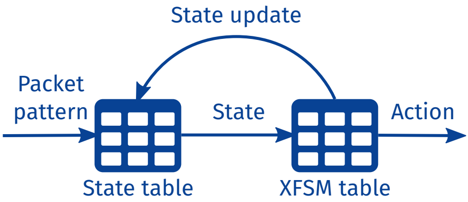

Open Packet Processor
(registers and boolean conditions)
OpenState
(stateful processing)
InSP
(packet generation)
BEBA switch

OpenState: stateful packet processing

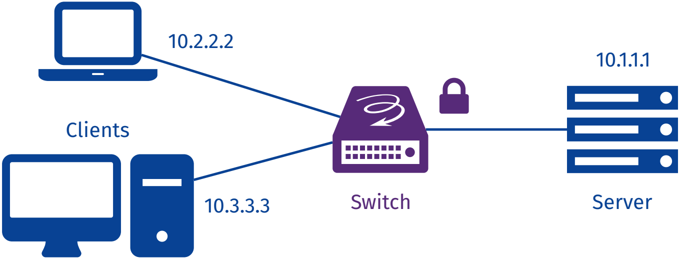
Forwarding depends on traffic previously observed

1. **Lookup** for flow **state**
2. **Lookup** for **action** associated to flow state, perform action
3. **Update state** to new value

So we need two tables: a **state table** and a table for actions: **XFSM table** (eXtended Finite State Machine)



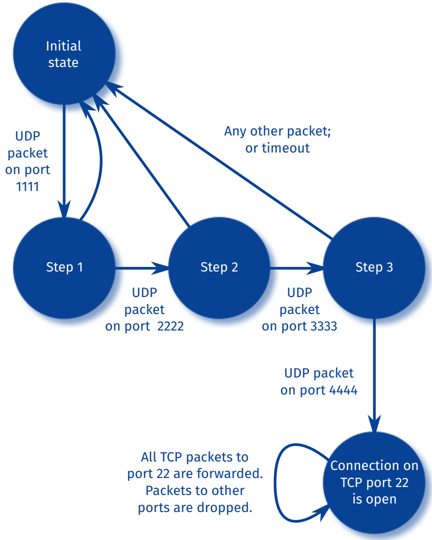
Case study: port knocking



- Clients see port 22 of the server as closed
- To access port 22, they first have to send a secret packet sequence to that port

Our example secret sequence: UDP packet on port 1111, 2222, 3333 then 4444

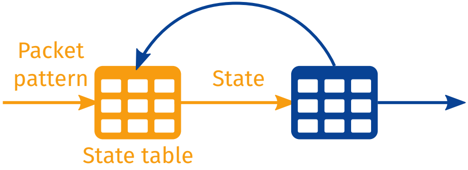
Case study: port knocking



State table

- Tracks current state for each flow

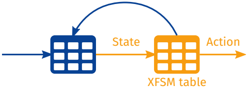
Flow matching pattern	State
...	...
IP src = any	DEFAULT



XFSM table

- To state and “event” pattern, associates action and “next state”

Flow matching pattern		Actions	
State	**Event**	**Action**	**Next state**
...	...	...	...
DEFAULT	UDP dst port = 1111	Drop	STEP_1
STEP_1	UDP dst port = 2222	Drop	STEP_2
STEP_2	UDP dst port = 3333	Drop	STEP_3
STEP_3	UDP dst port = 4444	Drop	OPEN
OPEN	TCP dst port 22	Forward	OPEN
OPEN	Port = *	Drop	OPEN
...	...	...	...
*	Port = *	Drop	DEFAULT

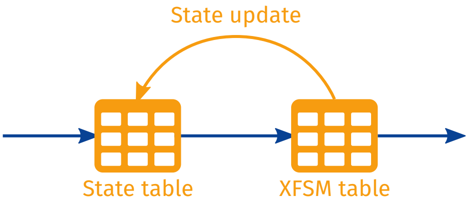


- “Next state” is used to update the entry for this flow in the state table

State table update

- The state of the flow is updated for each packet, thus unrolling the port knocking sequence

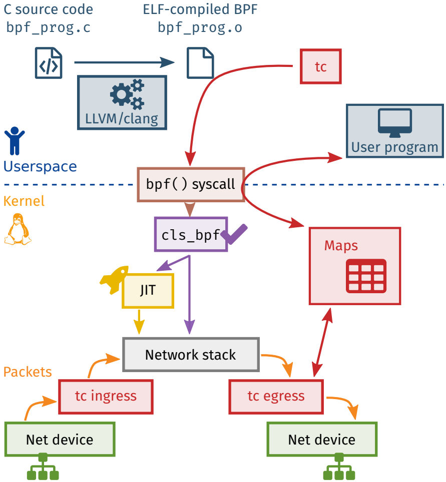
Flow matching pattern	State
...	...
IP src = 10.3.3.3, IP dst = 10.1.1.1	STEP_1
...	...
IP src = any	DEFAULT



Can we implement that with eBPF?

eBPF ~ extended Berkeley Packet Filter

- Assembly-like language, based on cBPF (packet filtering)
- Programs come from user space, run in the kernel



Stateful eBPF

- Default behavior: program is run to process a packet, no state preserved on exit
- However: eBPF Maps (kernel 3.18+):
  - Memory area accessible from eBPF program through specific kernel helpers
  - Arrays, hash maps (and several other kinds)
  - **Persistent** across multiple runs of an eBPF program
  - Can be shared with other eBPF programs
  - Can be shared with userspace applications

→ Let's use hash maps for OpenState tables!

(`https://github.com/qmonnet/pkpoc-bpf`)

openstate.h

```c
/* State table */

struct StateTableKey {
    uint16_t ether_type;
    uint32_t ip_src;
    uint32_t ip_dst;
};

struct StateTableVal {
    int32_t state;
};

/* XFSM table */

struct XFSMTableKey {
    int32_t  state;
    uint8_t  l4_proto;
    uint16_t src_port;
    uint16_t dst_port;
};

struct XFSMTableVal {
    int32_t action;
    int32_t next_state;
};
```

portknocking.c: State table lookup

```c
/* [Truncated]
 * Parse headers and make sure we have an IP packet, extract src and dst
 * addresses; since we will need it at next step, also extract UDP src and dst
 * ports.
 */

state_idx.ether_type = ntohs(ethernet->type);
struct StateTableKey state_idx;
state_idx.ip_src = ntohl(ip->src);
state_idx.ip_dst = ntohl(ip->dst);

/* State table lookup */

struct StateTableVal *state_val = map_lookup_elem(&state_table, &state_idx);

if (state_val) {
    current_state = state_val->state;
    /* If we found a state, go on and search XFSM table for this state and
     * for current event.
     */
    goto xfsmlookup;
}
goto end_of_program;
```

portknocking.c: XFSM table lookup, state table update, action

```
/* Set up the key */
xfsm_idx.state    = current_state;
xfsm_idx.l4_proto = ip->next_protocol;
xfsm_idx.src_port = 0;
xfsm_idx.dst_port = dst_port;

/* Lookup */
struct XFSMTableVal *xfsm_val = map_lookup_elem(&xfsm_table, &xfsm_idx);

if (xfsm_val) {

    /* Update state table entry with new state value */
    struct StateTableVal new_state = { xfsm_val->next_state };
    map_update_elem(&state_table, &state_idx, &new_state, BPF_ANY);

    /* Return action code */
    switch (xfsm_val->action) {
        case ACTION_DROP:
            return TC_ACT_SHOT;
        case ACTION_FORWARD:
            return TC_ACT_OK;
        default:
            return TC_ACT_UNSPEC;
    }
}
```

Compile and run

- One would compile the complete program into eBPF with:

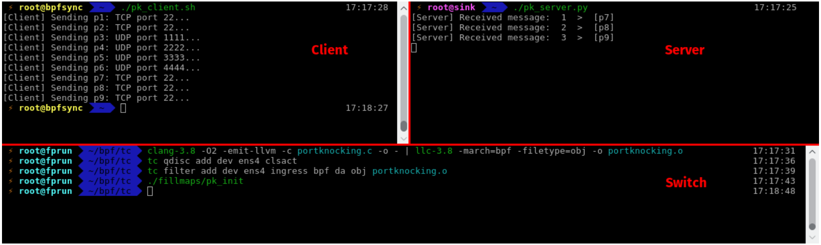
```
$ clang -O2 -emit-llvm -c openstate.c -o - | \
    llc -march=bpf -filetype=obj -o openstate.o
```

- ... and attach it with, for example:

```
# tc qdisc add dev eth0 clsact
# tc filter add dev eth0 ingress bpf da obj openstate.o
```

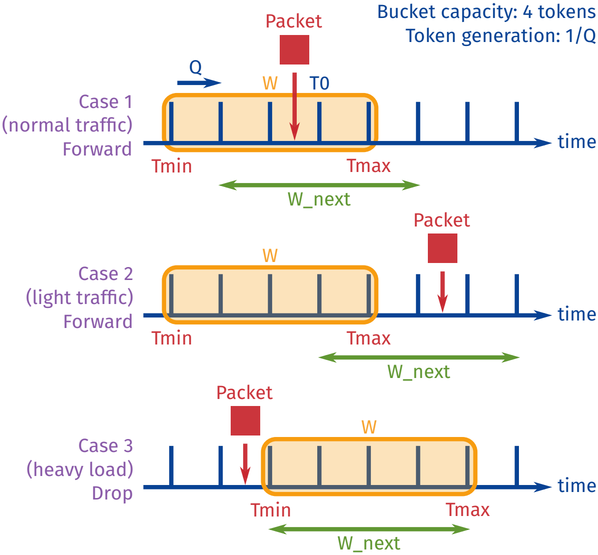
- One more thing: initialize the maps (user-space program with `bpf()` syscall)
- Alternative method: bcc's Python wrappers provide an easier way to initialize maps, to compile and to inject programs

Result


root@bpfsync ~ ./pk_client.sh 17:17:28
[Client] Sending p1: TCP port 22...
[Client] Sending p2: TCP port 22...
[Client] Sending p3: UDP port 1111...
[Client] Sending p4: UDP port 2222...
[Client] Sending p5: UDP port 3333...
[Client] Sending p6: UDP port 4444...
[Client] Sending p7: TCP port 22...
[Client] Sending p8: TCP port 22...
[Client] Sending p9: TCP port 22...
root@bpfsync ~ 17:18:27
Client
root@sink ~ ./pk_server.py 17:17:25
[Server] Received message: 1 > [p7]
[Server] Received message: 2 > [p8]
[Server] Received message: 3 > [p9]
Server
root@fprun ~/bpf/tc clang-3.8 -O2 -emit-llvm -c portknocking.c -o - | llc-3.8 -march=bpf -filetype=obj -o portknocking.o 17:17:31
root@fprun ~/bpf/tc tc qdisc add dev ens4 clsact 17:17:36
root@fprun ~/bpf/tc tc filter add dev ens4 ingress bpf da obj portknocking.o 17:17:39
root@fprun ~/bpf/tc ./fillmaps/pk_init 17:17:43
root@fprun ~/bpf/tc 17:18:48
Switch

Second case study: token bucket

Token bucket algorithm

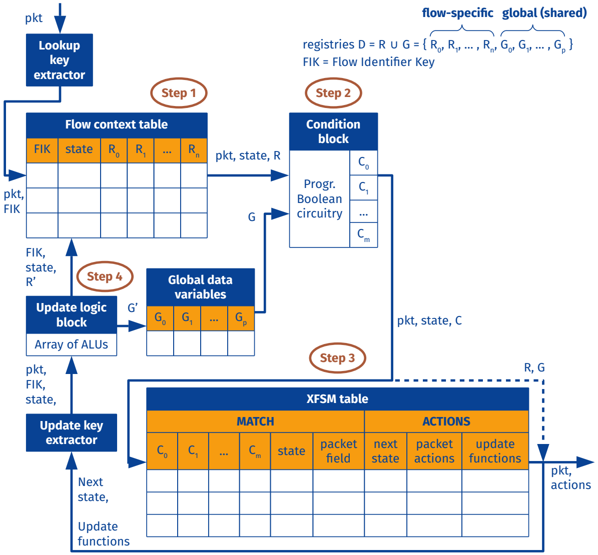


Model side: Open Packet Processor

- Extension of OpenState:
  - With global and per-flow registers
  - Registers evaluated with a set of conditions
  - XFSM table lookup must also match on conditions
- For token bucket: registers for `Tmin` and `Tmax`, then evaluate conditions:
  - `cond1 = (t ≥ Tmin);  cond2 = (t ≤ Tmax)`
  - `cond1 == true && cond2 == true` → Case 1
  - `cond1 == true && cond2 == false` → Case 2
  - `cond1 == false` → Case 3

(https://github.com/qmonnet/tbpoc-bpf)

OPP: architecture



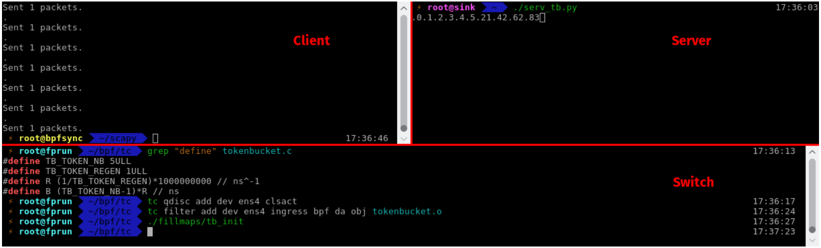
eBPF side

- Arrival time of the packet: there is a helper (`ktime_get_ns()`)
- Conditions: can be defined in each program, we need to encode the result to store it in the tables

```
uint64_t tnow = ktime_get_ns();

/* State table lookup */
state_val = map_lookup_elem(&state_table, &state_idx);

current_state = state_val->state;
tmin          = state_val->r1;
tmax          = state_val->r2;

/* Evaluate conditions */
int32_t cond1 = check_condition(GE, tnow, tmin);
int32_t cond2 = check_condition(LE, tnow, tmax);
if (cond1 == ERROR || cond2 == ERROR)
  goto error;

/* XFSM table lookup */
xfsm_idx.state = current_state;
xfsm_idx.cond1 = cond1;
xfsm_idx.cond2 = cond2;
xfsm_val = map_lookup_elem(&xfsm_table, &xfsm_idx);
```

- Tables: just add the registers, we have everything else already

Result


Sent 1 packets.
Sent 1 packets.
Sent 1 packets.
Sent 1 packets.
Sent 1 packets.
Sent 1 packets.
Sent 1 packets.
root@bpfsync ~/scapy
17:36:46
Client
root@sink ~ ./serv_tb.py
17:36:03
.0.1.2.3.4.5.21.42.62.83
Server
root@fprun ~/bpf/tc grep "define" tokenbucket.c
17:36:13
#define TB_TOKEN_NB 5ULL
#define TB_TOKEN_REGEN 1ULL
#define R (1/TB_TOKEN_REGEN)*1000000000 // ns^-1
#define B (TB_TOKEN_NB-1)*R // ns
root@fprun ~/bpf/tc tc qdisc add dev ens4 clsact
17:36:17
root@fprun ~/bpf/tc tc filter add dev ens4 ingress bpf da obj tokenbucket.o
17:36:24
root@fprun ~/bpf/tc ./fillmaps/tb_init
17:36:27
root@fprun ~/bpf/tc
17:37:23
Switch

Additional use cases for OpenState and OPP

- QoS, load balancer
- DDoS detection and mitigation as middle box application or at network level
- In-switch ARP handling in datacenter
- Forwarding consistency
- Failure detection and recovery
- ...

Conclusion

- eBPF makes a nice target for BEBA architecture (OpenState, Open Packet Processor)
- Some limitations:
  - no wildcard mechanism for map lookup (yet)
  - locks for concurrent access?
- Next step:
  - With XDP (hook in the driver instead of tc interface)?
  - High-level description language to generate the program
- More implementations, by other project partners:
  - Reference implementation: ofsoftswitch
  - Acceleration with PFQ (controller: Ryu)
  - Acceleration with DPDK, running on a FPGA

Thank you!

Resources

BEBA project web page
http://www.beba-project.eu/

BEBA repositories: reference implementations of BEBA switch and controller
https://github.com/beba-eu

OpenState article (SIGCOMM 2014)
http://openstate-sdn.org/pub/openstate-ccr.pdf

Open Packet Processor article (TBP)
https://arxiv.org/abs/1605.01977

Code for the port knocking proof-of-concept in eBPF
https://github.com/qmonnet/pkpoc-bpf

Code for the token bucket proof-of-concept in eBPF
https://github.com/qmonnet/tbpoc-bpf

Resources on BPF — *Dive into BPF: a list of reading material*
https://qmonnet.github.io/whirl-offload/2016/09/01/dive-into-bpf/

GitHub repository of the IO Visor project (bcc tools, documentation, and more)
https://github.com/iovisor/