Merging packets with System Events using eBPF

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About Us

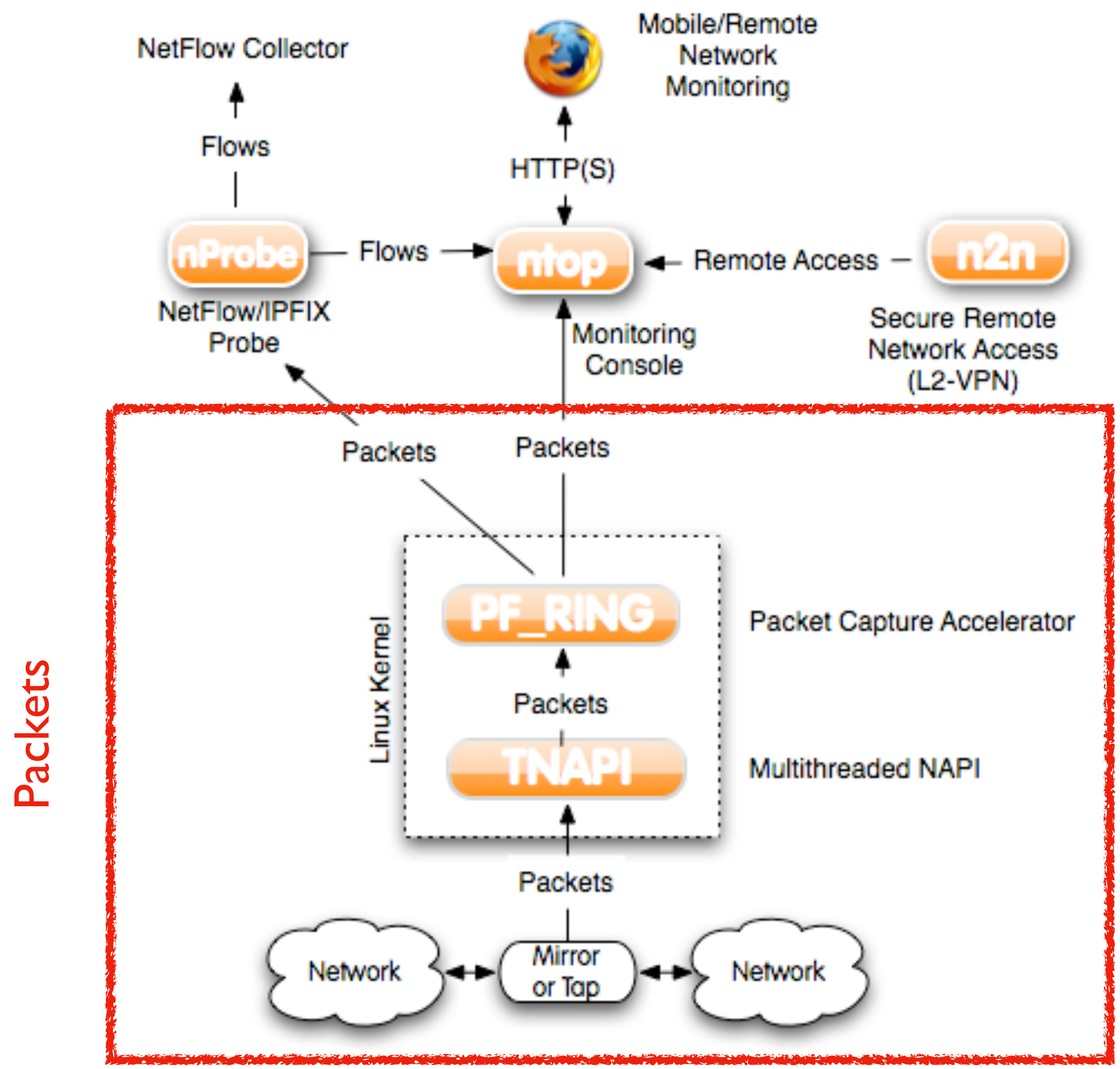
- Luca: lecturer at the University of Pisa, CS Department, founder of the ntop project.
- Samuele: student at Unipi CS Department, junior engineer working at ntop.
- ntop develops open source network traffic monitoring applications. ntop (circa 1998) is the first app we released and it is a web-based network monitoring application.
- Today our products range from traffic monitoring, high-speed packet processing, deep-packet inspection (DPI), IDS/IPS acceleration, and DDoS Mitigation.
- See http://github.com/ntop/

What is Network Traffic Monitoring?

- The key objective behind network traffic monitoring is to *ensure availability and smooth operations on a computer network*. Network monitoring incorporates network sniffing and packet capturing techniques in monitoring a network. Network traffic monitoring generally requires reviewing each incoming and outgoing packet.

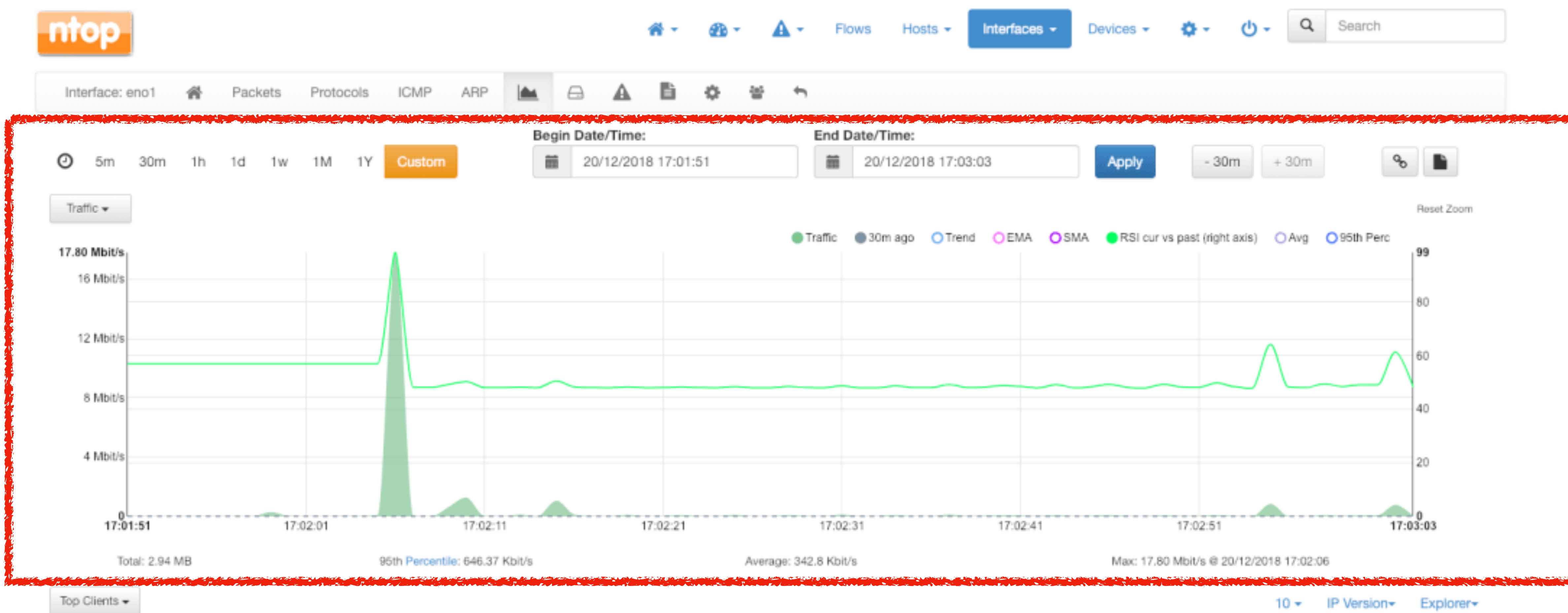
https://www.techopedia.com/definition/29977/network-traffic-monitoring

ntop Ecosystem (2009): Packets Everywhere



ntop Ecosystem (2019): Still Packets [1/2]

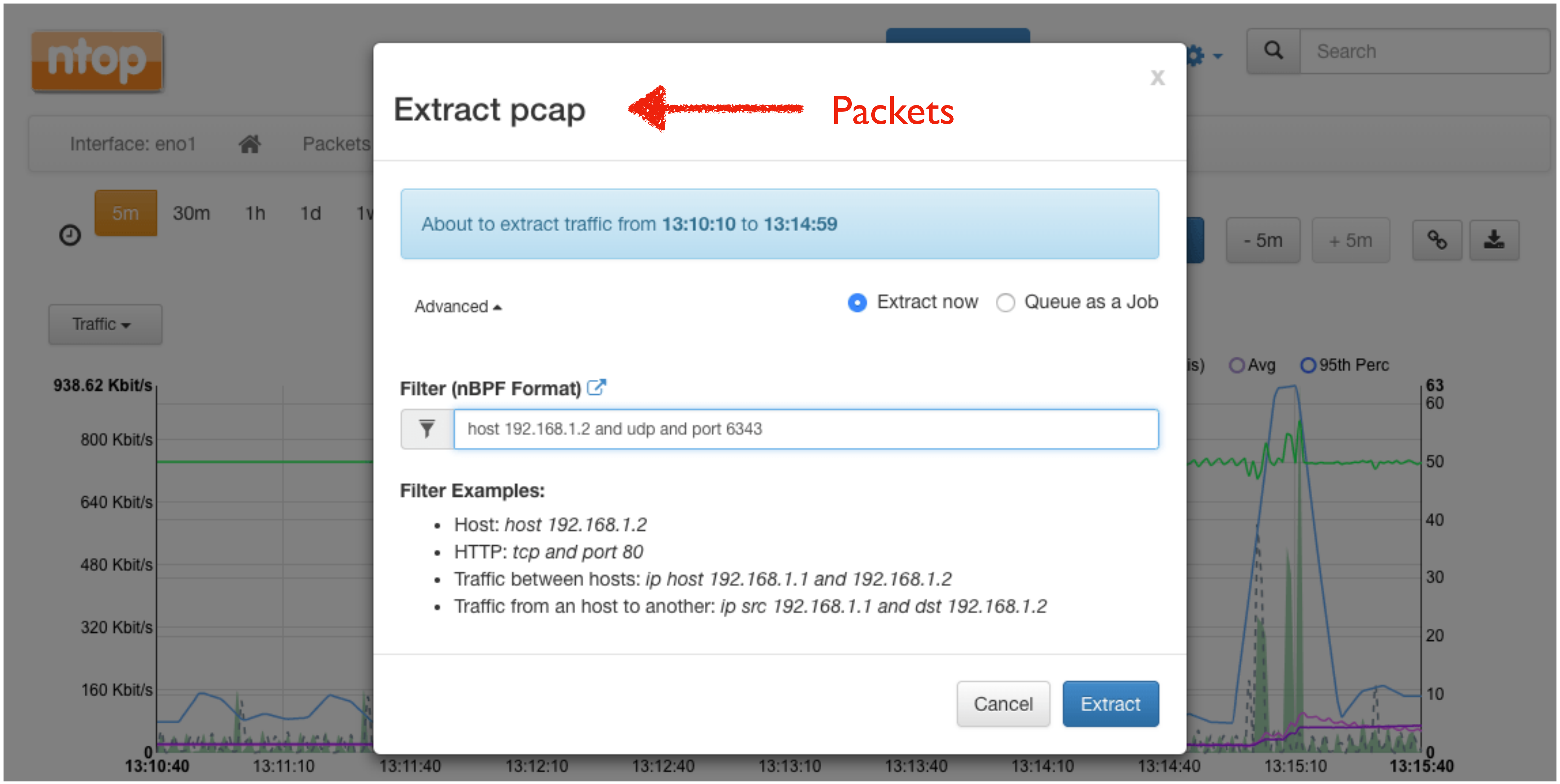
Packets



Flows

Host Name	IP Address	Bytes Sent to Servers	Throughput	Actions
192.168.2.130	192.168.2.130	193.51 KB	22.02 kbit/s	
devel	192.168.2.222	10.18 KB	1.16 kbit/s	
192.168.2.136	192.168.2.136	1.26 KB	143.22 bit/s	
192.168.2.126	192.168.2.126	864 Bytes	96 bit/s	
192.168.2.182	192.168.2.182	860 Bytes	95.56 bit/s	
192.168.2.142	192.168.2.142	258 Bytes	28.67 bit/s	
192.168.1.100	192.168.1.100	258 Bytes	28.67 bit/s	
NoIP	0.0.0.0	98 Bytes	10.89 bit/s	

ntop Ecosystem (2019): Still Packets [2/2]



What’s Wrong with Packets?

- Nothing in general but…
  - It is a paradigm good for monitoring network traffic from outside of systems on a passive way.
  - Encryption is challenging DPI techniques (BTW ntop maintains an open source DPI toolkit called nDPI).
  - Virtualisation techniques reduce visibility when monitoring network traffic as network manager are blind with respect to what happens inside systems.
  - Developers need to handle fragmentation, flow reconstruction, packet loss/retransmissions… metrics that would be already available inside a system.

From Problem Statement to a Solution

- Enhance network visibility with system introspection.
- Handle virtualisation as first citizen and don't be blind (yes we want to see containers interaction).
- Complete our monitoring journey and…
  - System Events: processes, users, containers.
  - Flows
  - Packets
- …bind system events to network traffic for enabling continuous drill down: system events uncorrelated with network traffic are basically useless.

Early Experiments: Sysdig [1/3]

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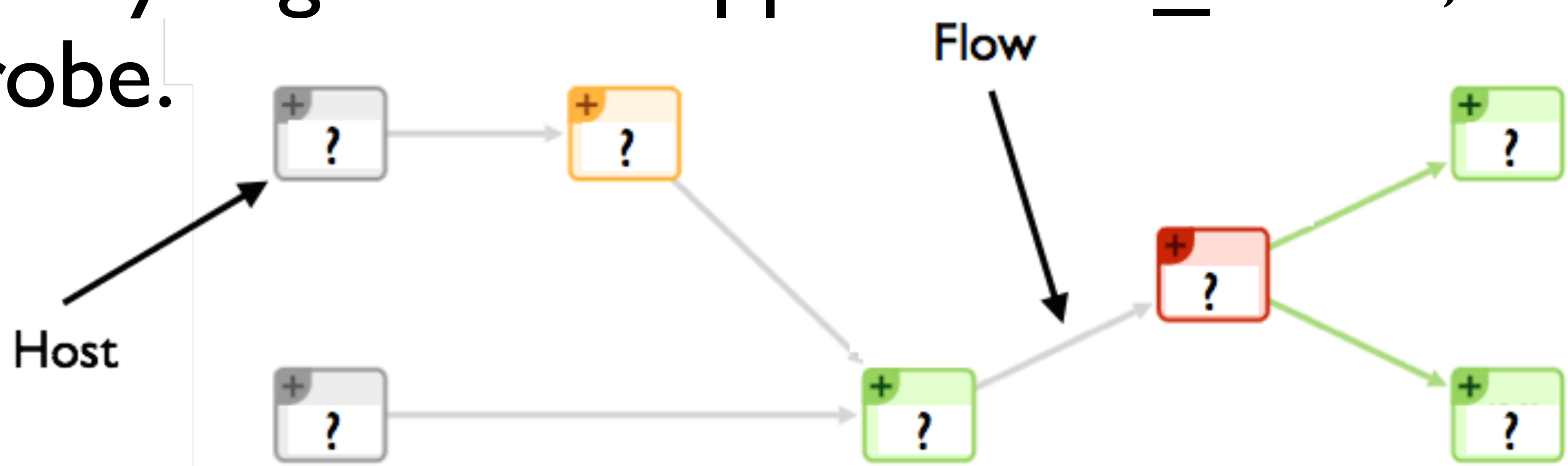
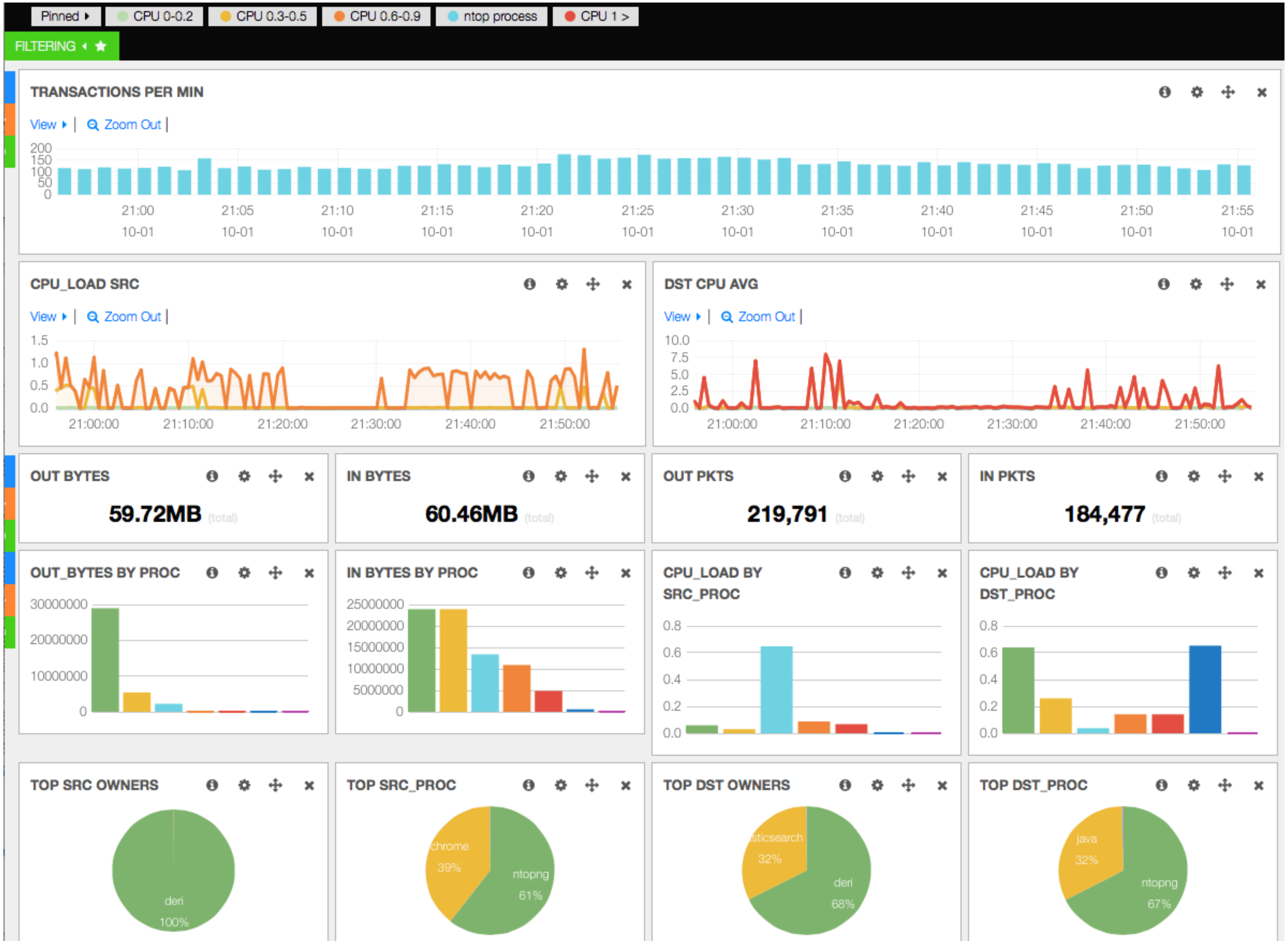
Combining System and Network Visibility using nProbe and Sysdig

Posted October 7, 2014 ·

- ntop has been an early sysdig adopter adding in 2014 sysdig events support in PF_RING, ntopng, nProbe.



Early Experiments: Sysdig [2/3]



Early Experiments: Sysdig [3/3]

- Despite all our efforts, this activity has NOT been a success for many reasons:
  - Too much CPU load (in average +10-20% CPU load) due to the design of sysdig (see later).
  - People do not like to install agents on systems as this might create interferences with other installed apps.
  - Sysdig requires a new kernel module that sometimes is not what sysadmins like as it might invalidate distro support.
  - Containers were not so popular in 2014, and many people did not consider system visibility so important at that time.

How Sysdig Works

- As sysdig focuses on system calls for tracking a TCP connections we need to:
  - Discard all non TCP related events (sockets are used for other activities on Linux such as Unix sockets)
  - Track socket() and remember the socketId to process/thread
  - Track connect() and accept() and remember the TCP peers/ports.
  - Collect packets and bind each of them to a flow (i.e. this is packet capture again, using sysdig instead of libpcap).
- This explains the CPU load, complexity…

Welcome to eBPF

From	Alexei Starovoitov <>
Subject	[RFC PATCH tip 0/5] tracing filters with BPF
Date	Mon, 2 Dec 2013 20:28:45 -0800

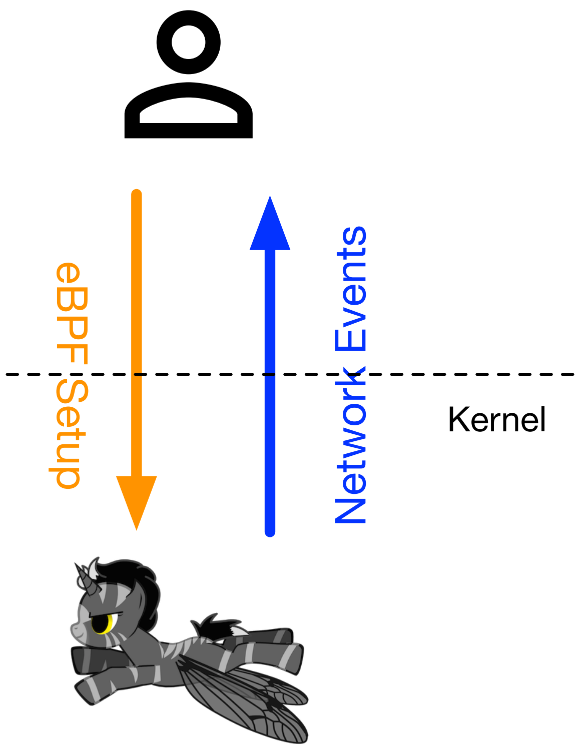
share

```
Hi All,

the following set of patches adds BPF support to trace filters.

Trace filters can be written in C and allow safe read-only access to any
kernel data structure. Like systemtap but with safety guaranteed by kernel.

The user can do:
cat bpf_program > /sys/kernel/debug/tracing/.../filter
if tracing event is either static or dynamic via kprobe_events.
```

eBPF is great news for ntop as

- It gives the ability to avoid sending everything to user-space but perform in kernel computations and send metrics to user-space.
- We can track more than system calls (i.e. be notified when there is a transmission on a TCP connection without analyzing packets).
- It is part of modern Linux systems (i.e. no kernel module needed).

libebpfflow Overview [1/2]




```
struct netInfo {
  __u16 sport;
  __u16 dport;
  __u8  proto;
  __u32 latency_usec;
};

struct taskInfo {
  __u32 pid; /* Process Id */
  __u32 tid; /* Thread Id  */
  __u32 uid; /* User Id    */
  __u32 gid; /* Group Id   */
  char task[COMMAND_LEN], *full_task_path;
};
```

```
// ----- ----- STRUCTS AND CLASSES ----- ----- //
struct ipv4_kernel_data {
  __u64 saddr;
  __u64 daddr;
  struct netInfo net;
};

struct ipv6_kernel_data {
  unsigned __int128 saddr;
  unsigned __int128 daddr;
  struct netInfo net;
};

typedef struct {
  __u64 ktime;
  char ifname[IFNAMSIZ];
  struct timeval event_time;
  __u8  ip_version:4, sent_packet:4;

  union {
    struct ipv4_kernel_data v4;
    struct ipv6_kernel_data v6;
  } event;

  struct taskInfo proc, father;

  char cgroup_id[CGROUP_ID_LEN];
} eBPFevent;
```

libebpfflow Overview [2/2]

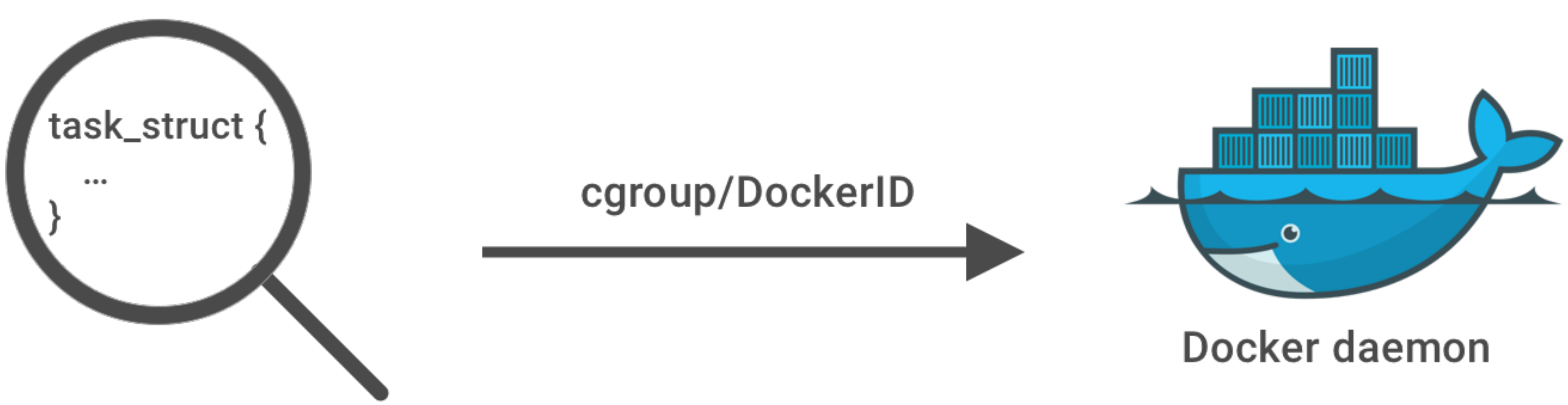
```
// Attaching probes ----- //
if (userarg_eoutput && userarg_tcp) {
  // IPv4
  AttachWrapper(&ebpf_kernel, "tcp_v4_connect",  "trace_connect_entry",     BPF_PROBE_ENTRY);
  AttachWrapper(&ebpf_kernel, "tcp_v4_connect",  "trace_connect_v4_return", BPF_PROBE_RETURN);
  // IPv6
  AttachWrapper(&ebpf_kernel, "tcp_v6_connect",  "trace_connect_entry",     BPF_PROBE_ENTRY);
  AttachWrapper(&ebpf_kernel, "tcp_v6_connect",  "trace_connect_v6_return", BPF_PROBE_RETURN);
}

if (userarg_einput && userarg_tcp)
  AttachWrapper(&ebpf_kernel, "inet_csk_accept", "trace_accept_return",     BPF_PROBE_RETURN);

if (userarg_retr)
  AttachWrapper(&ebpf_kernel, "tcp_retransmit_skb", "trace_tcp_retransmit_skb", BPF_PROBE_ENTRY);

if (userarg_tcpclose)
  AttachWrapper(&ebpf_kernel, "tcp_set_state", "trace_tcp_close", BPF_PROBE_ENTRY);

if (userarg_einput && userarg_udp)
  AttachWrapper(&ebpf_kernel, "inet_recvmsg",    "trace_inet_recvmsg_entry",  BPF_PROBE_ENTRY);
  AttachWrapper(&ebpf_kernel, "inet_recvmsg",    "trace_inet_recvmsg_return", BPF_PROBE_RETURN);

if (userarg_eoutput && userarg_udp) {
  AttachWrapper(&ebpf_kernel, "udp_sendmsg",     "trace_udp_sendmsg_entry",   BPF_PROBE_ENTRY);
  AttachWrapper(&ebpf_kernel, "udpv6_sendmsg",   "trace_udpv6_sendmsg_entry", BPF_PROBE_ENTRY);
}
```

Gathering Information Through eBPF

- In linux every task has associated a struct (i.e. task_struct) that can be retrieved by invoking the function bpf_get_current_task provided by eBPF. By navigating through the kernel structures it can be gathered:
  - uid, gid, pid, tid, process name and executable path
  - cgroups associated with the task.
  - connection details: source and destination ip/port, bytes send and received, protocol used.

Containers Visibility: cgroups and Docker

- For each container Docker creates a cgroup whose name corresponds to the container identifier.
- Therefore by looking at the task cgroup the docker identifier can be retrieved and further information collected.



TCP Under the Hood: accept

A kprobe has been attached to inet_csk_accept

- Used to accept the next outstanding connection.
- Returns the socket that will be used for the communication, NULL if an error occurs.
- Information is collected both from the socket returned and from the task_struct associated with the process that triggered the event.

In a similar fashion events concerning retransmissions and socket closure can be monitored.

TCP Under the Hood: connect

An hash table, indexed with thread IDs, has been used:

- When connect is invoked the socket is collected from the function arguments and stored together with the kernel time.
- When the function terminates the execution, the return value is collected and the thread ID is used to retrieve the socket from the hash table.
- The kernel time is used to calculate the connection latency.

Using libebpfflow from CLI

```
deri@ubuntu18 205> sudo ./ebpflow
kProbes attached
Output buffer opened
[ktime: 0][pid: 11443][uid: 0][gid: 1000][sudo]
|__ parent: [pid: 11318][uid: 1000][gid: 1000][tcsh]
|__ netinfo: [UDP/snd][IPv4][addr: 127.0.0.1:56452 <-> 127.0.0.1:53]
|__ [minor_faults: 213][major_faults: 0]
[ktime: 1][pid: 10215][uid: 997][gid: 997][pihole-FTL]
|__ parent: [pid: 1][uid: 0][gid: 0][systemd]
|__ netinfo: [UDP/rcv][IPv4][addr: 127.0.0.1:56452 <-> 127.0.0.1:53]
|__ [minor_faults: 5849][major_faults: 0]
[ktime: 6][pid: 11443][uid: 0][gid: 1000][sudo]
|__ parent: [pid: 11318][uid: 1000][gid: 1000][tcsh]
|__ netinfo: [UDP/snd][IPv4][addr: 127.0.0.1:43457 <-> 127.0.0.1:53]
|__ [minor_faults: 216][major_faults: 0]
[ktime: 7][pid: 10215][uid: 997][gid: 997][pihole-FTL]
|__ parent: [pid: 1][uid: 0][gid: 0][systemd]
|__ netinfo: [UDP/rcv][IPv4][addr: 127.0.0.1:43457 <-> 127.0.0.1:53]
|__ [minor_faults: 5849][major_faults: 0]
[ktime: 31308][pid: 1136][uid: 114][gid: 117][chronyd]
|__ parent: [pid: 1][uid: 0][gid: 0][systemd]
|__ netinfo: [UDP/snd][IPv4][addr: 127.0.0.1:34324 <-> 127.0.0.1:123]
|__ [minor_faults: 147][major_faults: 2]
[ktime: 31437][pid: 1136][uid: 114][gid: 117][chronyd]
|__ parent: [pid: 1][uid: 0][gid: 0][systemd]
|__ netinfo: [UDP/rcv][IPv4][addr: 213.251.52.250:123 <-> 192.168.1.87:34324]
|__ [minor_faults: 147][major_faults: 2]
[ktime: 52712][pid: 1136][uid: 114][gid: 117][chronyd]
|__ parent: [pid: 1][uid: 0][gid: 0][systemd]
|__ netinfo: [UDP/snd][IPv4][addr: 127.0.0.1:34751 <-> 127.0.0.1:123]
|__ [minor_faults: 147][major_faults: 2]
```

Integrating eBPF with ntopng

- We have done an early integration of eBPF with ntopng using the libebpflow library we developed:
  - Incoming TCP/UDP events are mapped to packets monitored by ntopng.
  - We've added user/process/flow integration and partially implemented process and user statistics.
- Work in progress
  - Container visibility (including pod), retransmissions… are reported by eBPF but not yet handled inside ntopng.
  - To do things properly we need to implement a system interface in ntopng where to send all system events.
  - Decide how/if netlink will be part of the equation.

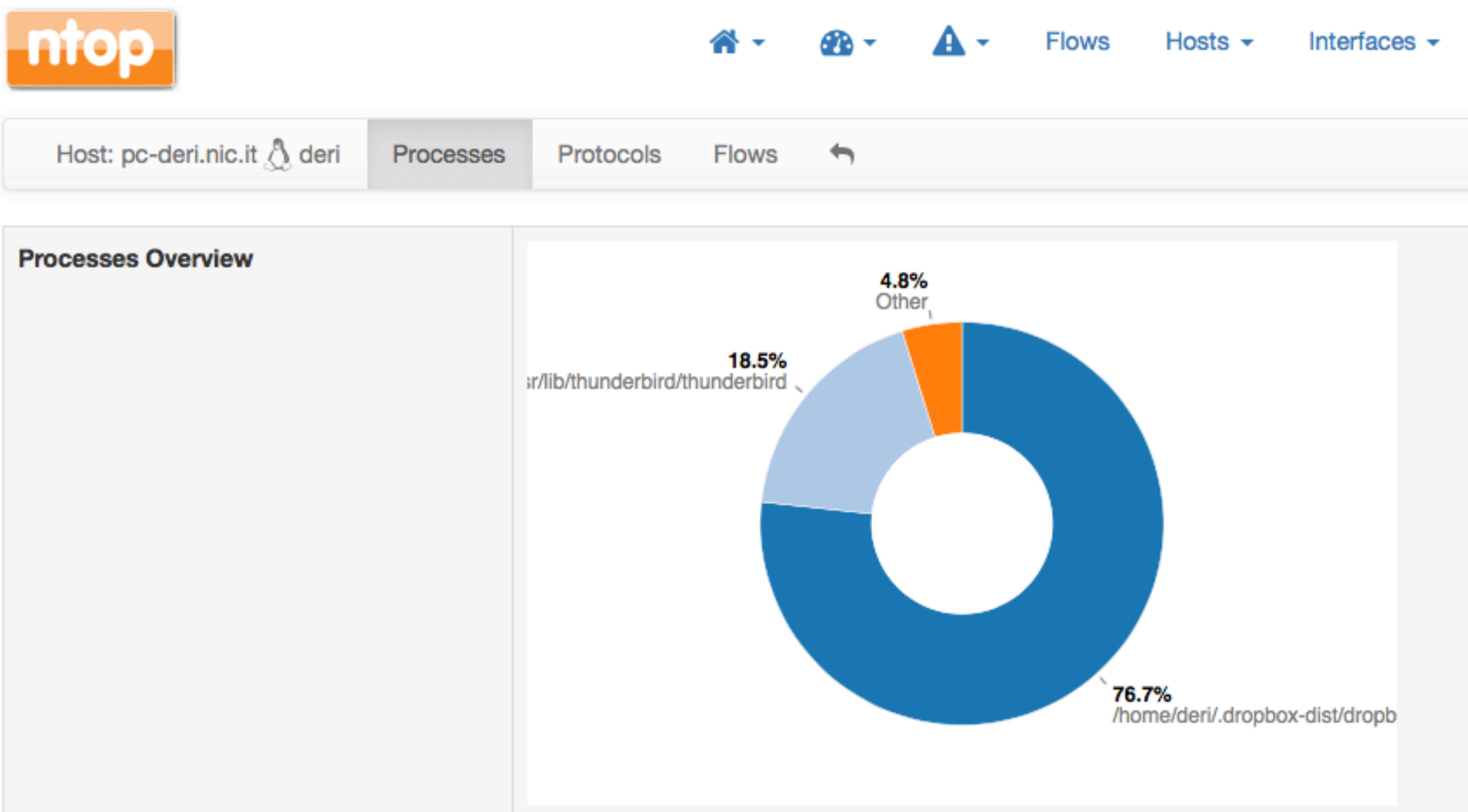
ntopng with eBPF: Flows

Active Flows

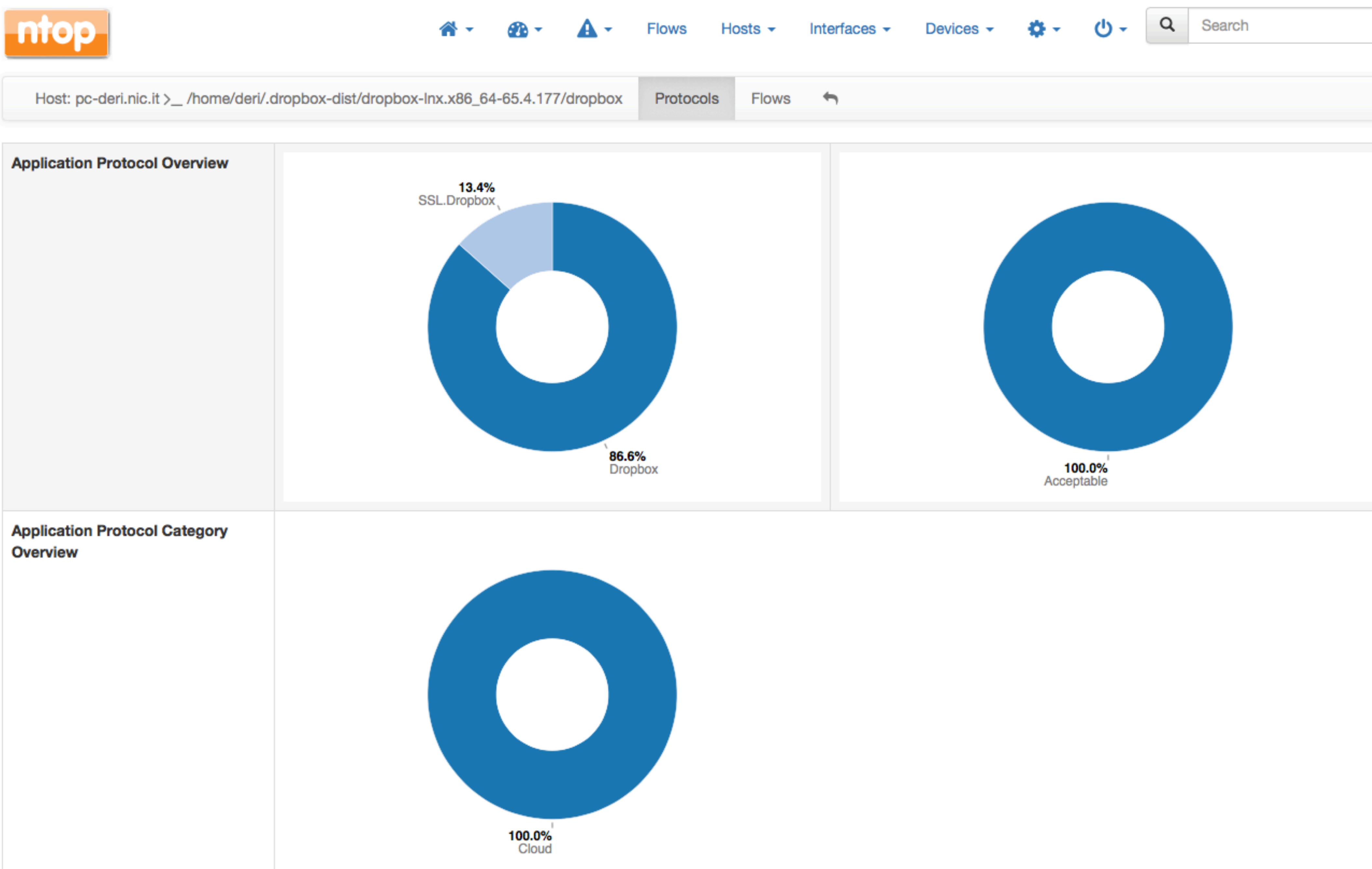
10 ▾ Hosts ▾ Status ▾ Direction ▾ Applications ▾ Categories ▾ IP Version ▾

	Application	L4 Proto	Client	Server	Duration	Breakdown	Actual Thpt	Total Bytes	Info
Info	ICMP	ICMP	217.29.76.4	pc-deri.nic.it	19:04:30	Client Server	0 bit/s	1.32 MB	*Echo Reply*
Info	IMAPS	TCP	pc-deri.nic.it :44580 [deri >_ thunderbird]	93.62.150.157 :imaps	12:16:18	Client Server	0 bit/s	370.53 KB	
Info	IMAPS	TCP	pc-deri.nic.it :43902 [deri >_ thunderbird (deleted)]	146.48.98.155 :imap2	04:47:03	Client Server	0 bit/s	407.69 KB	
Info	SSL.Dropbox	TCP	pc-deri.nic.it :37908 [deri >_ dropbox]	bolt.dropbox.com :https	01:27:35	Client S	0 bit/s	788.7 KB	bolt.dropbox.com
Info	SSL.Dropbox	TCP	pc-deri.nic.it :60530 [deri >_ dropbox]	bolt.dropbox.com :https	47:38	Client Serve	0 bit/s	93.08 KB	bolt.dropbox.com
Info	MDNS	UDP	misure.nic.it :mdns	224.0.0.251:mdns	06:53	Client	0 bit/s	7.24 KB	
Info	MDNS	UDP	mauk :mdns	224.0.0.251:mdns	01:37	Client	0 bit/s	1.21 KB	
Info	SSL.Telegram	TCP	pc-deri.nic.it :58480 [deri >_ Telegram]	149.154.167.91 :https	01:42	Client Server	0 bit/s	3.27 KB	
Info	SSL.ntop	TCP	80.181.77.107 :58539	i7.ntop.org :300 [root >_ ntopng]	00:06	Clier Server	0 bit/s	6.3 KB	i7.ntop.org
Info	SSL.ntop	TCP	80.181.77.107 :63143	i7.ntop.org :300 [root >_ ntopng]	00:06	Clier Server	0 bit/s	6.29 KB	i7.ntop.org

ntopng with eBPF: Users + Processes



ntopng with eBPF: Processes + Protocols

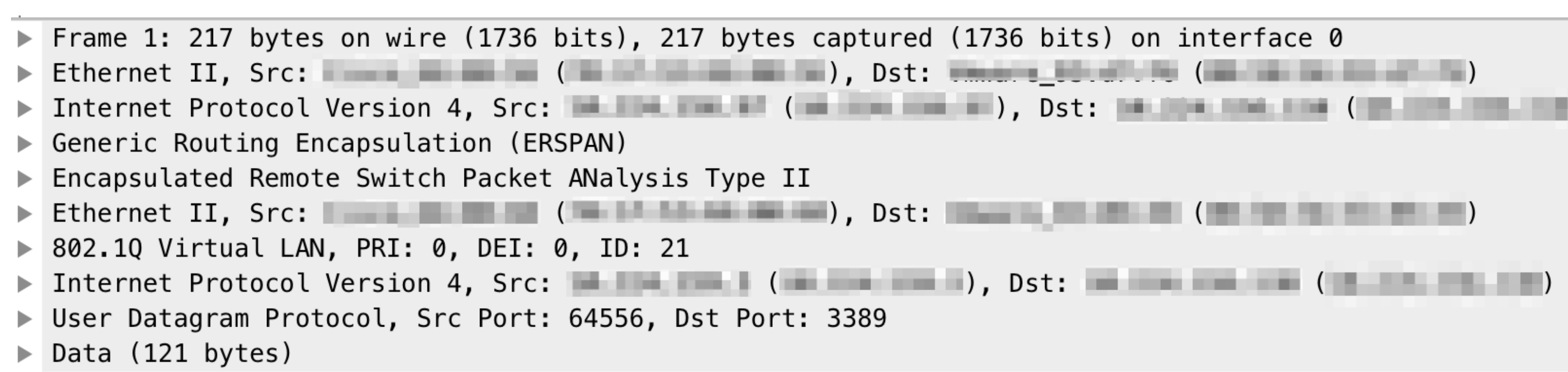


Current eBPF Work Items: UDP

- Contrary to TCP, in UDP we need to handle packets. To avoid overloading the system we are using an in-kernel LRU to minimise load: is there a better option available that avoids us playing with packets at all?
- As in UDP each packet can have a different destination, intercepting up in the stack some metadata info are missing (local IP/Ethernet is computed after routing decision).
- Better multicast handling.

BCC/eBPF Pitfalls

- BCC (BPF Compiler Collection) has limitations in terms of:
  - Function complexity/length: memory/stack and loop unroll are limited and this might be a problem in some cases (e.g. decoding).
  - Sometimes its behaviour is non deterministic and the same code works with the dev but fails to compile with the stable version.
  - No ability to read the BCC API version (functions prototypes change cross versions).
- Inability to read message drops number.
- Packet decoding can be a nightmare due to restrictions on function calls



Conclusions

- With eBPF it is now possible to have full system and network visibility in an integrated fashion.
- Contrary to Sysdig, eBPF load on the system is basically unnoticeable and no kernel module is necessary (i.e. issues of early work are now solved).
- Container/user/process information allows us to enhance network communications with metadata that is great not just for visibility but also for spotting malicious system activities.
- System visibility will be integrated in ntopng 4.x due later this year.