Innovative R&D by NTT

Boost UDP Transaction Performance

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Today's topics

- Background
- Basic technologies for network performance
- How to improve UDP performance

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Who is Toshiaki Makita?

- Linux kernel engineer at NTT Open Source Software Center
- Technical support for NTT group companies
- Active patch submitter on kernel networking subsystem

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Background

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UDP transactions in the Internet

- **Services using UDP**
  - DNS
  - RADIUS
  - NTP
  - SNMP
  - …
- **Heavily used by network service providers**

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Ethernet Bandwidth and Transactions

- **Ethernet bandwidth evolution**
  - 10M -> 100M -> 1G -> 10G -> 40G -> 100G -> ...
  - 10G (or more) NICs are getting common on commodity servers

- **Transactions in 10G network**
  - In the shortest packet case:
    - Maximum 14,880,952 packets/s*1
  - Getting hard to handle in a single server...

*1 shortest ethernet frame size 64bytes + preamble+IFG 20bytes = 84 bytes = 672 bits
10,000,000,000 / 672 = 14,880,952

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How many transactions to handle?

- **UDP payload sizes**
  - DNS
    - A/AAAA query: 40~ bytes
    - A/AAAA response: 100~ bytes
  - RADIUS
    - Access-Request: 70~ bytes
    - Access-Accept: 30~ bytes
    - Typically 100~ bytes with some attributes
  - In many cases 100~ bytes
- **100 bytes transactions in 10G network**
  - Max 7,530,120 transactions/s*1
  - Less than shortest packet case, but still challenging

*1 100 bytes + IP/UDP/Ether headers 46bytes + preamble+IFG 20bytes = 166 bytes = 1328 bits
10,000,000,000 / 1328 = 7,530,120

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Basic technologies for network performance (not only for UDP)

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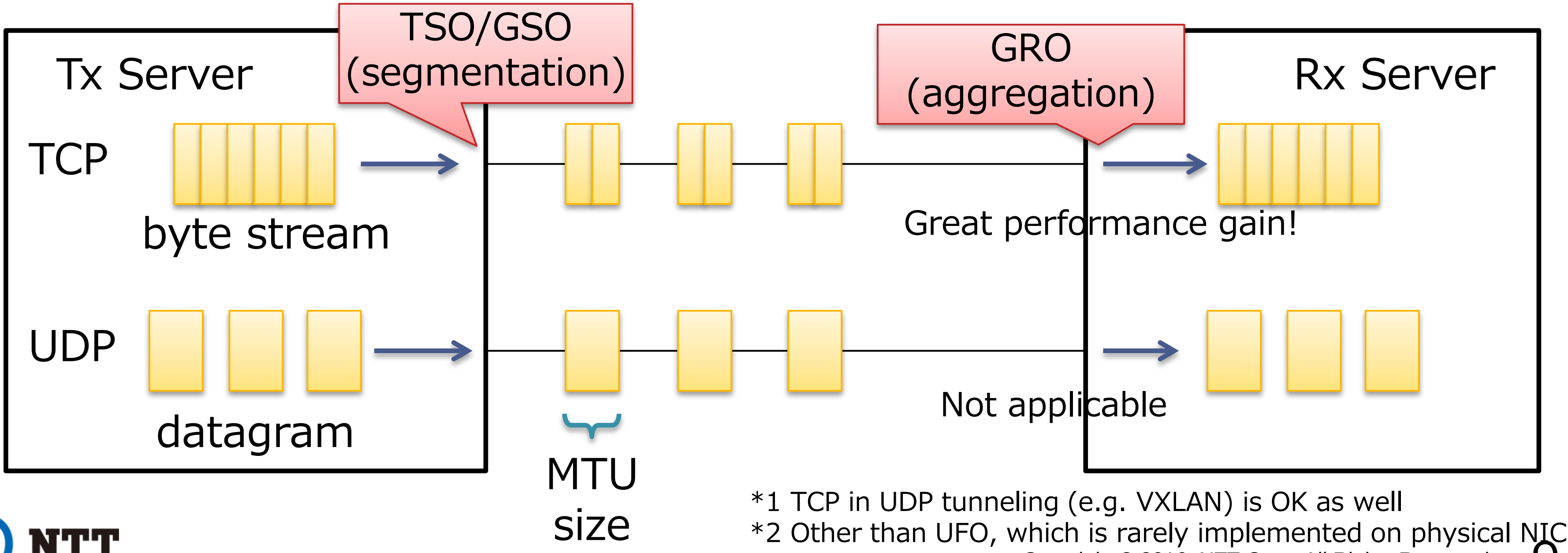
Basic technologies for network performance

- **TSO/GSO/GRO**
  - Packet segmentation/aggregation
  - Reduce packets to process within server
  - Applicable to TCP[*1] (byte stream)
  - Not applicable to UDP[*2] (datagram)☹
    - UDP has explicit boundary between datagrams
    - Cannot segment/aggregate packets



*1 TCP in UDP tunneling (e.g. VXLAN) is OK as well
*2 Other than UFO, which is rarely implemented on physical NICs

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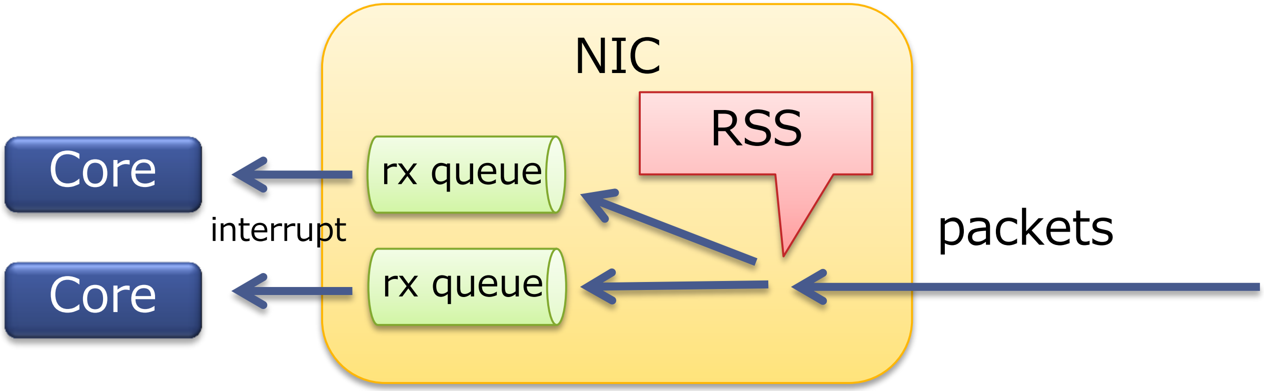
Basic technologies for network performance

- **RSS**
  - Scale network Rx processing in multi-core server
  - RSS itself is a NIC feature
    - Distribute packets to multi-queue in a NIC
    - Each queue has a different interrupt vector
      (Packets on each queue can be processed by different core)
  - Applicable to TCP/UDP ☺
  - Common 10G NICs have RSS



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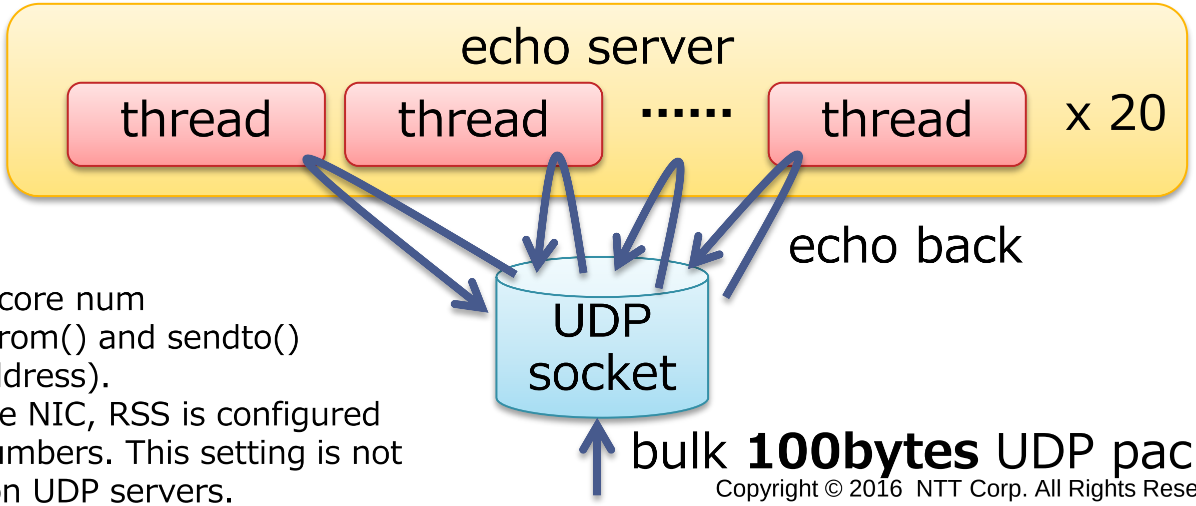
Performance with RSS enabled NIC

- **100 bytes UDP transaction performance**
  - Measured by simple*1 (multi-threaded) echo server
  - OS: **kernel 4.6.3** (in RHEL 7.2 environment)
  - Mid-range commodity server with **20 cores** and **10G** NIC:
    - NIC: Intel 82599ES (has RSS, **max 64 queues**)
    - CPU: Xeon E5-2650 v3 (2.3 GHz 10 cores) * 2 sockets
      Hyper-threading off (make analysis easy, enabled later)
  - Results: **270,000** transactions/s (tps) (approx. **360Mbps**)
    - **3.6%** utilization of 10G bandwidth



bulk **100bytes** UDP packets*1

*1 create as many threads as core num
each thread just calls recvfrom() and sendto()

*2 There is only 1 client (IP address).
To spread UDP traffic on the NIC, RSS is configured to see UDP port numbers. This setting is not needed for common UDP servers.

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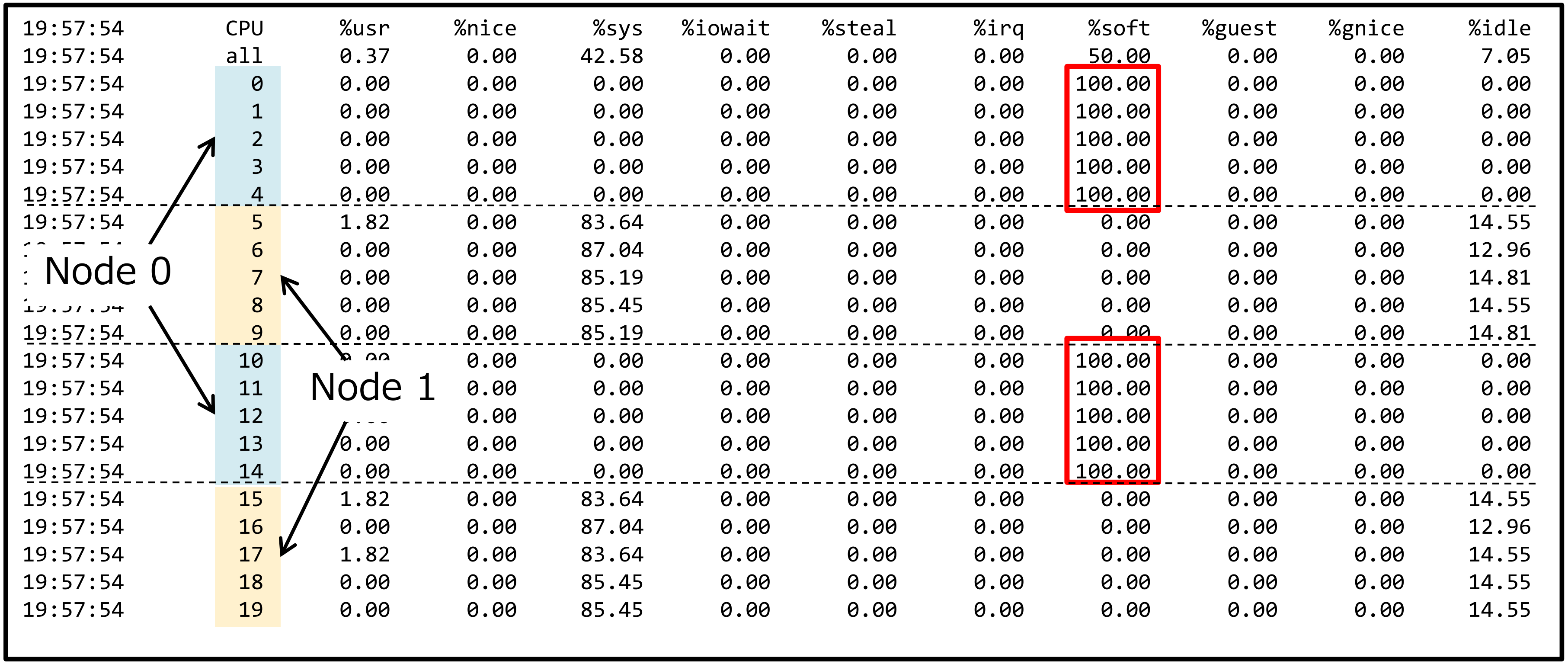
How to improve this?

Identify bottleneck

- **sar -u ALL -P ALL 1**



```
19:57:54        CPU     %usr     %nice      %sys   %iowait    %steal      %irq     %soft    %guest    %gnice     %idle
19:57:54        all     0.37      0.00     42.58      0.00      0.00      0.00     50.00      0.00      0.00      7.05
19:57:54          0     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54          1     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54          2     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54          3     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54          4     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54          5     1.82      0.00     83.64      0.00      0.00      0.00      0.00      0.00      0.00     14.55
19:57:54          6     0.00      0.00     87.04      0.00      0.00      0.00      0.00      0.00      0.00     12.96
[illegible]       7     0.00      0.00     85.19      0.00      0.00      0.00      0.00      0.00      0.00     14.81
19:57:54          8     0.00      0.00     85.45      0.00      0.00      0.00      0.00      0.00      0.00     14.55
19:57:54          9     0.00      0.00     85.19      0.00      0.00      0.00      0.00      0.00      0.00     14.81
19:57:54         10     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54         11 [illegible]   0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54         12     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54         13     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54         14     0.00      0.00      0.00      0.00      0.00      0.00    100.00      0.00      0.00      0.00
19:57:54         15     1.82      0.00     83.64      0.00      0.00      0.00      0.00      0.00      0.00     14.55
19:57:54         16     0.00      0.00     87.04      0.00      0.00      0.00      0.00      0.00      0.00     12.96
19:57:54         17     1.82      0.00     83.64      0.00      0.00      0.00      0.00      0.00      0.00     14.55
19:57:54         18     0.00      0.00     85.45      0.00      0.00      0.00      0.00      0.00      0.00     14.55
19:57:54         19     0.00      0.00     85.45      0.00      0.00      0.00      0.00      0.00      0.00     14.55
```

- **softirq (interrupt processing) is performed only on NUMA Node 0, why?**
  - although we have enough (64) queues for 20 cores...

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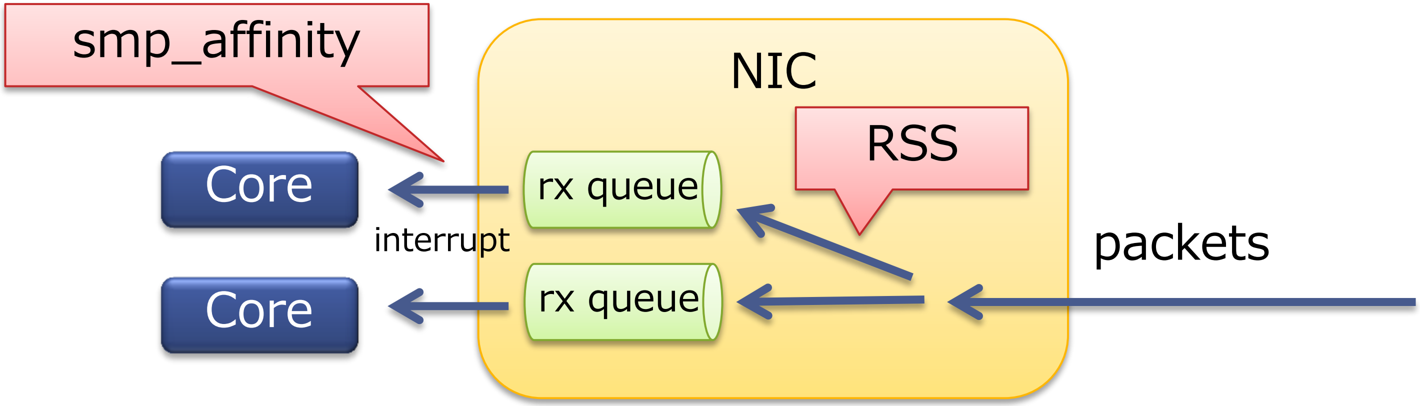
softirq (interrupt processing) with RSS

- RSS distributes packets to rx-queues
- Interrupt destination of each queue is determined by /proc/irq/<irq>/smp_affinity



- smp_affinity is usually set by irqbalance daemon

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Check smp_affinity

- **smp_affinity*1**

```
$ for ((irq=105; irq<=124; irq++)); do
>   cat /proc/irq/$irq/smp_affinity
> done
01000    -> 12    -> Node 0
00800    -> 11    -> Node 0
00400    -> 10    -> Node 0
00400    -> 10    -> Node 0
01000    -> 12    -> Node 0
04000    -> 14    -> Node 0
00400    -> 10    -> Node 0
00010    ->  4    -> Node 0
00004    ->  2    -> Node 0
02000    -> 13    -> Node 0
```

```
04000    -> 14    -> Node 0
00001    ->  0    -> Node 0
02000    -> 13    -> Node 0
01000    -> 12    -> Node 0
00008    ->  3    -> Node 0
00800    -> 11    -> Node 0
00800    -> 11    -> Node 0
04000    -> 14    -> Node 0
00800    -> 11    -> Node 0
02000    -> 13    -> Node 0
```

- **irqbalance is using only Node 0 (cores 0-4, 10-14)**
  - Can we change this?

*1 irq number can be obtained from /proc/interrupts

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Check affinity_hint

- Some NIC drivers provide affinity_hint

```
$ for ((irq=105; irq<=124; irq++)); do
>   cat /proc/irq/$irq/affinity_hint
> done
00001    -> 0
00002    -> 1
00004    -> 2
00008    -> 3
00010    -> 4
00020    -> 5
00040    -> 6
00080    -> 7
00100    -> 8
00200    -> 9
```

```
00400    -> 10
00800    -> 11
01000    -> 12
02000    -> 13
04000    -> 14
08000    -> 15
10000    -> 16
20000    -> 17
40000    -> 18
80000    -> 19
```

- affinity_hint is evenly distributed
- To honor the hint, add "-h exact" option to irqbalance (via /etc/sysconfig/irqbalance, etc.)*1

*1 If your NIC doesn't provide hint, you can use "-i" option or stop irqbalance to set their affinity manually

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Change irqbalance option

- **Added "-h exact" and restarted irqbalance**

```
$ for ((irq=105; irq<=124; irq++)); do
>   cat /proc/irq/$irq/smp_affinity
> done
00001    -> 0
00002    -> 1
00004    -> 2
00008    -> 3
00010    -> 4
00020    -> 5
00040    -> 6
00080    -> 7
00100    -> 8
00200    -> 9
```

```
00400    -> 10
00800    -> 11
01000    -> 12
02000    -> 13
04000    -> 14
08000    -> 15
10000    -> 16
20000    -> 17
40000    -> 18
80000    -> 19
```

- **With hint honored, irqs are distributed to all cores**

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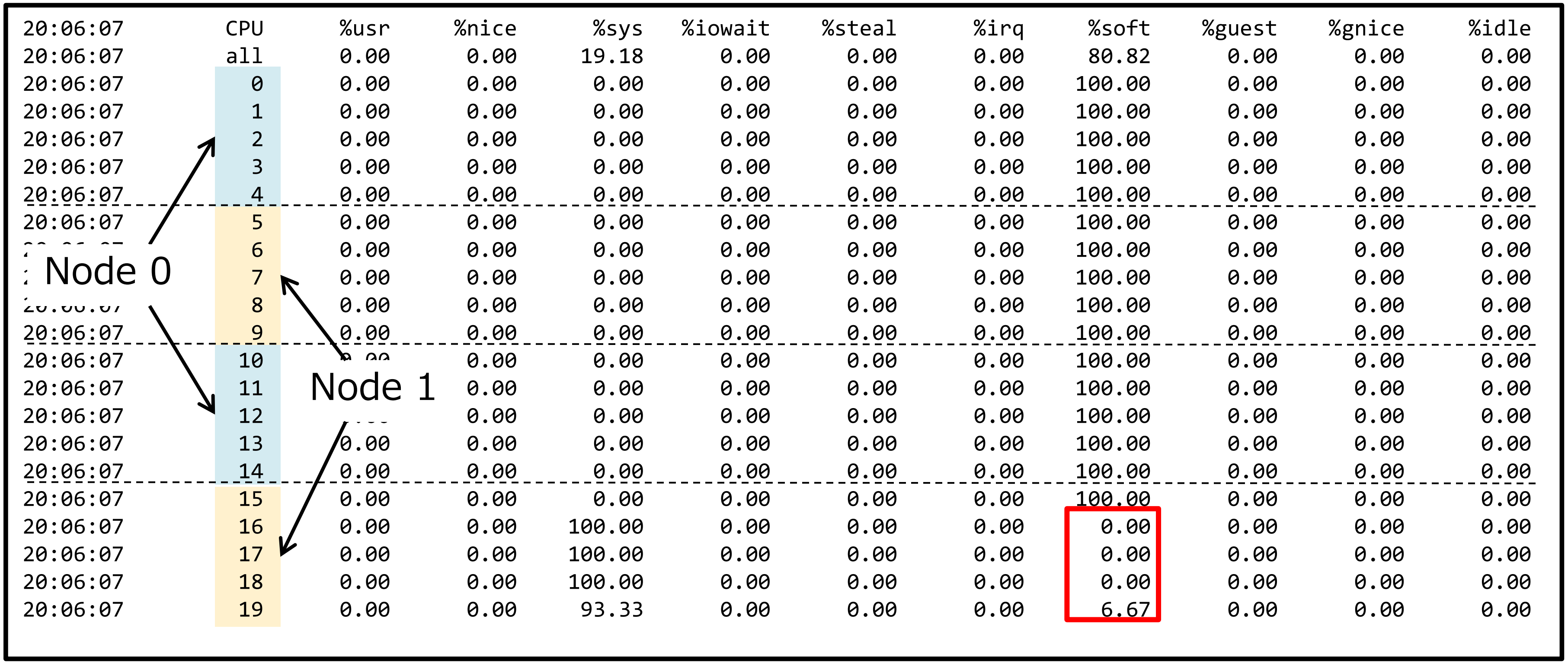
Change irqbalance option

- **sar -u ALL -P ALL 1**



```
20:06:07     CPU    %usr   %nice    %sys %iowait  %steal    %irq   %soft  %guest  %gnice   %idle
20:06:07     all    0.00    0.00   19.18    0.00    0.00    0.00   80.82    0.00    0.00    0.00
20:06:07       0    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       1    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       2    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       3    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       4    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
-----------------------------------------------------------------------------------------------------
20:06:07       5    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       6    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       7    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       8    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07       9    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
-----------------------------------------------------------------------------------------------------
20:06:07      10    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07      11    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07      12    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07      13    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07      14    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
-----------------------------------------------------------------------------------------------------
20:06:07      15    0.00    0.00    0.00    0.00    0.00    0.00  100.00    0.00    0.00    0.00
20:06:07      16    0.00    0.00  100.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
20:06:07      17    0.00    0.00  100.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
20:06:07      18    0.00    0.00  100.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00
20:06:07      19    0.00    0.00   93.33    0.00    0.00    0.00    6.67    0.00    0.00    0.00
```

- **Though irqs looks distributed evenly, core 16-19 are not used for softirq…**
- **Nodes look irrelevant this time**

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Check rx-queue stats

- ethtool -S*1

```
$ ethtool -S ens1f0 | grep 'rx_queue_.*_packets'
     rx_queue_0_packets: 198005155
     rx_queue_1_packets: 153339750
     rx_queue_2_packets: 162870095
     rx_queue_3_packets: 172303801
     rx_queue_4_packets: 153728776
     rx_queue_5_packets: 158138563
     rx_queue_6_packets: 164411653
     rx_queue_7_packets: 165924489
     rx_queue_8_packets: 176545406
     rx_queue_9_packets: 165340188
     rx_queue_10_packets: 150279834
     rx_queue_11_packets: 150983782
     rx_queue_12_packets: 157623687
     rx_queue_13_packets: 150743910
     rx_queue_14_packets: 158634344
     rx_queue_15_packets: 158497890
     rx_queue_16_packets: 4
     rx_queue_17_packets: 3
     rx_queue_18_packets: 0
     rx_queue_19_packets: 8
```

- **Revealed RSS has not distributed packets to queues 16-19**

*1 Output format depends on drivers

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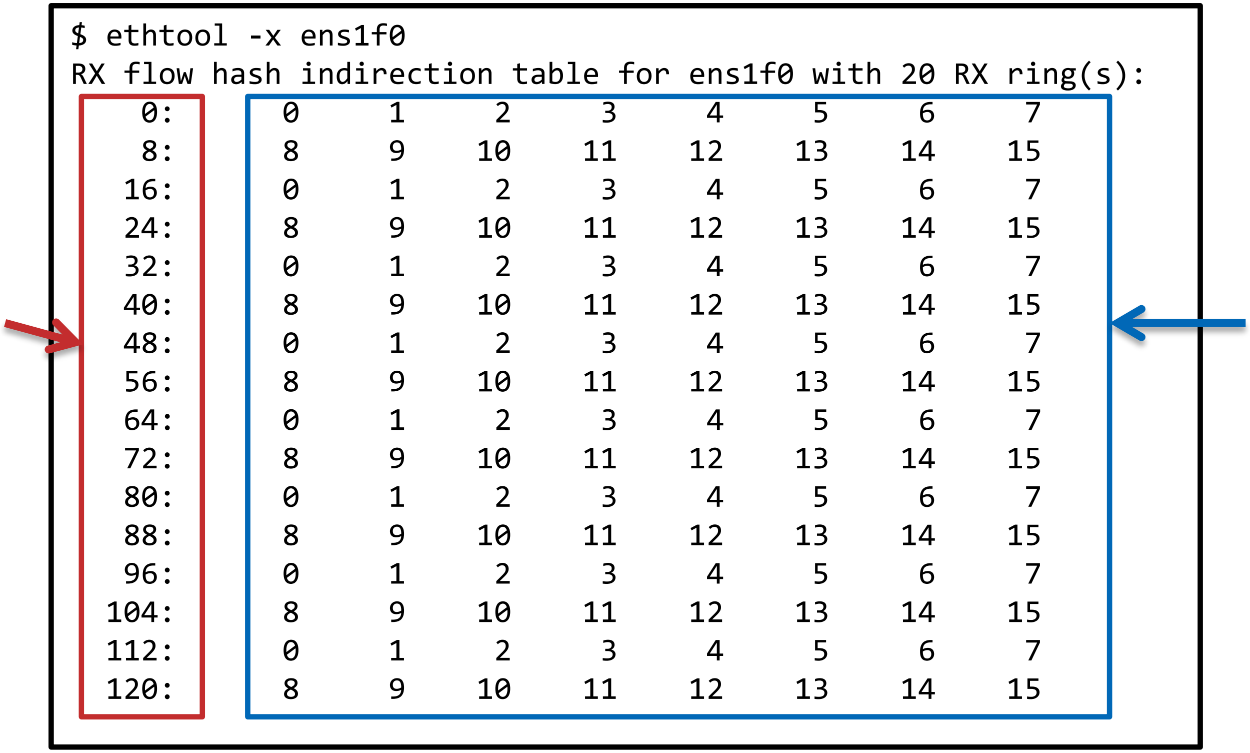
RSS Indirection Table

- **RSS has indirection table which determines to which queue it spreads packets**
- **Can be shown by ethtool -x**



```
$ ethtool -x ens1f0
RX flow hash indirection table for ens1f0 with 20 RX ring(s):
    0:    0     1     2     3     4     5     6     7
    8:    8     9    10    11    12    13    14    15
   16:    0     1     2     3     4     5     6     7
   24:    8     9    10    11    12    13    14    15
   32:    0     1     2     3     4     5     6     7
   40:    8     9    10    11    12    13    14    15
   48:    0     1     2     3     4     5     6     7
   56:    8     9    10    11    12    13    14    15
   64:    0     1     2     3     4     5     6     7
   72:    8     9    10    11    12    13    14    15
   80:    0     1     2     3     4     5     6     7
   88:    8     9    10    11    12    13    14    15
   96:    0     1     2     3     4     5     6     7
  104:    8     9    10    11    12    13    14    15
  112:    0     1     2     3     4     5     6     7
  120:    8     9    10    11    12    13    14    15
```

flow hash (hash value from packet header)

rx-queue number

- **Only rx-queue 0-15 are used, 16-19 not used**

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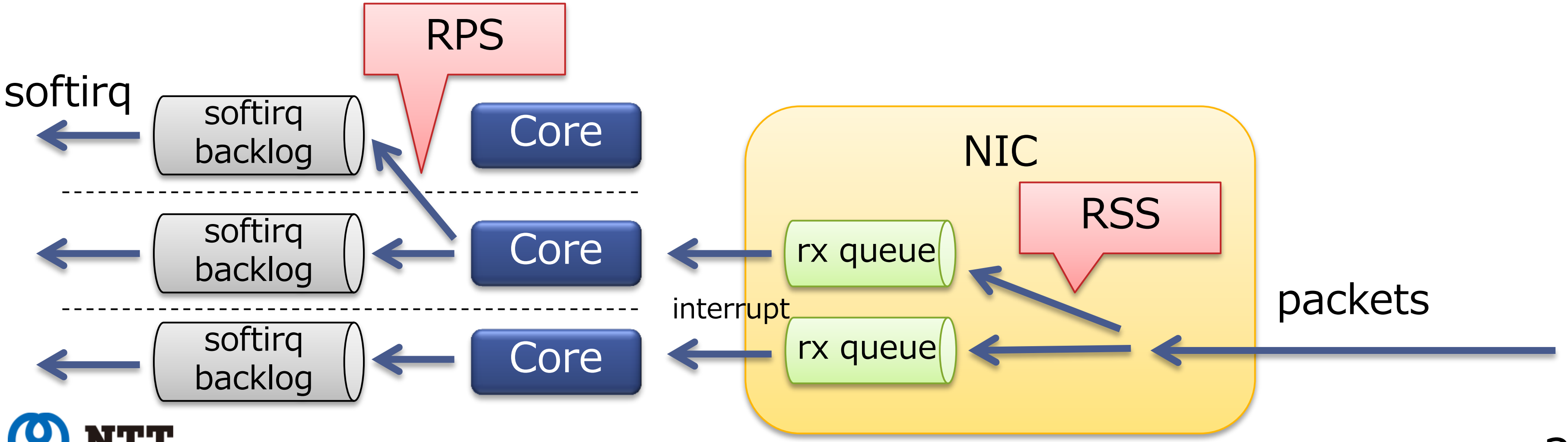
RSS Indirection Table

- **Change to use all 0-19?**

```
# ethtool -X ens1f0 equal 20
Cannot set RX flow hash configuration: Invalid argument
```

- **This NIC's max rx-queues in the indirection table is actually 16 so we cannot use 20 queues**
  - although we have 64 rx-queues...

- **Use RPS instead**
  - Software emulation of RSS



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Use RPS

- **This time I spread flows from rx-queue 6-9 to core 6-9 and 16-19**
  - Because they are all in Node 1
  - rx-queue 6 -> core 6, 16
  - rx-queue 7 -> core 7, 17
  - rx-queue 8 -> core 8, 18
  - rx-queue 9 -> core 9, 19

```
# echo 10040 > /sys/class/net/ens1f0/queues/rx-6/rps_cpus
# echo 20080 > /sys/class/net/ens1f0/queues/rx-7/rps_cpus
# echo 40100 > /sys/class/net/ens1f0/queues/rx-8/rps_cpus
# echo 80200 > /sys/class/net/ens1f0/queues/rx-9/rps_cpus
```

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Use RPS

- **sar -u ALL -P ALL 1**

```
20:18:53        CPU     %usr    %nice     %sys  %iowait   %steal     %irq    %soft   %guest   %gnice    %idle
20:18:54        all     0.00     0.00     2.38     0.00     0.00     0.00    97.62     0.00     0.00     0.00
20:18:54          0     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          1     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          2     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          3     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          4     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          5     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          6     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          7     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          8     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54          9     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         10     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         11     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         12     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         13     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         14     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         15     0.00     0.00     0.00     0.00     0.00     0.00   100.00     0.00     0.00     0.00
20:18:54         16     0.00     0.00    15.56     0.00     0.00     0.00    84.44     0.00     0.00     0.00
20:18:54         17     0.00     0.00     6.98     0.00     0.00     0.00    93.02     0.00     0.00     0.00
20:18:54         18     0.00     0.00    18.18     0.00     0.00     0.00    81.82     0.00     0.00     0.00
20:18:54         19     2.27     0.00     6.82     0.00     0.00     0.00    90.91     0.00     0.00     0.00
```

- **softirq is almost evenly distributed**

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RSS & affinity_hint & RPS

- **Now thanks to affinity_hint and RPS, we succeeded to spread flows almost evenly**

- **Performance change**
  - Before: **270,000** tps (approx. **360Mbps**)
  - After: **17,000** tps (approx. **23Mbps**)
    - Got worse...

- **Probably the reason is too heavy softirq**
  - softirq is almost 100% in total
  - Need finer-grained profiling than sar

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Profile softirq

- **perf**
  - Profiling tool developed in kernel tree
  - Identify hot spots by sampling CPU cycles

- **Example usage of perf**
  - perf record -a -g -- sleep 5
    - Save sampling results for 5 seconds to perf.data file

- **FlameGraph**
  - Visualize perf.data in svg format
  - https://github.com/brendangregg/FlameGraph

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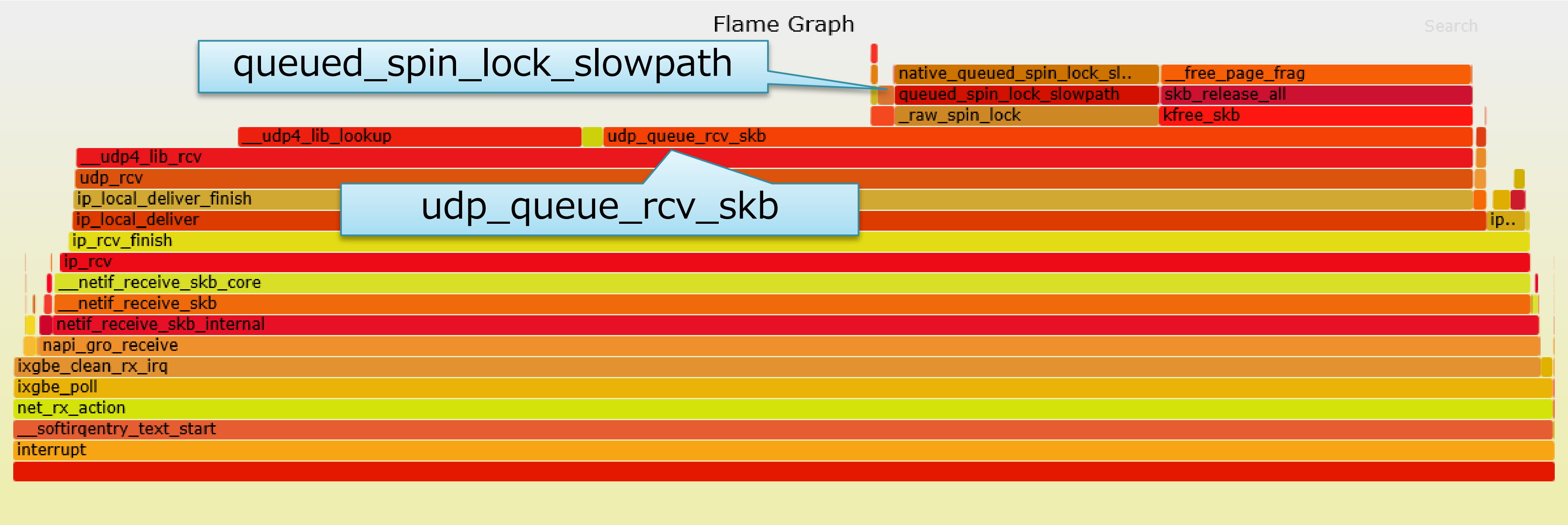
Profile softirq

- **FlameGraph of CPU0*1**
  - x-axis (width): CPU consumption
  - y-axis (height): Depth of call stack



queued_spin_lock_slowpath

udp_queue_rcv_skb

- **queued_spin_lock_slowpath: lock is contended**
- **udp_queue_rcv_skb: aquires socket lock**

*1 I filtered call stack under irq context from output of perf script to make the chart easier to see
irq context is shown as "interrupt" here

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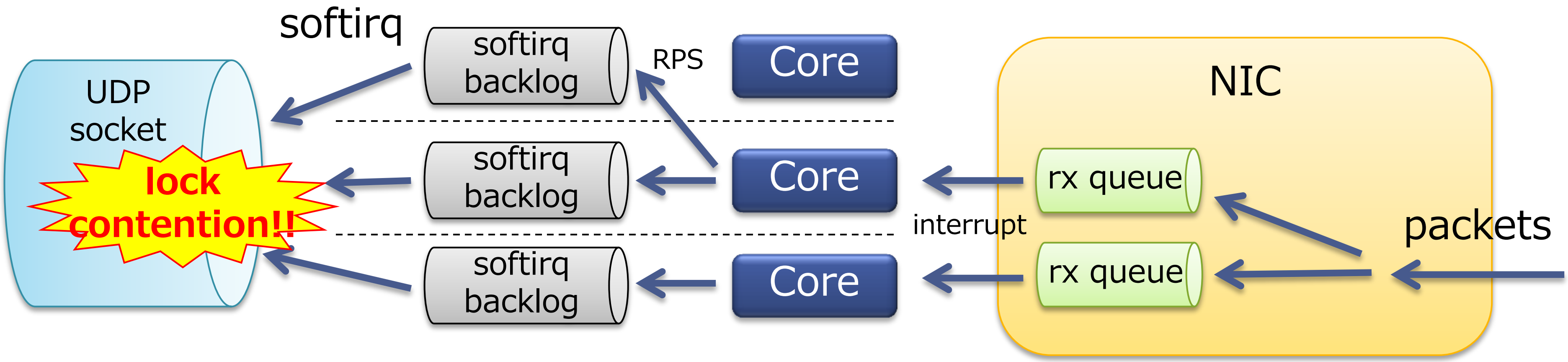
Socket lock contention

- Echo server has only one socket bound to a certain port
- softirq of each core pushes packets into socket queue concurrently



- socket lock gets contended

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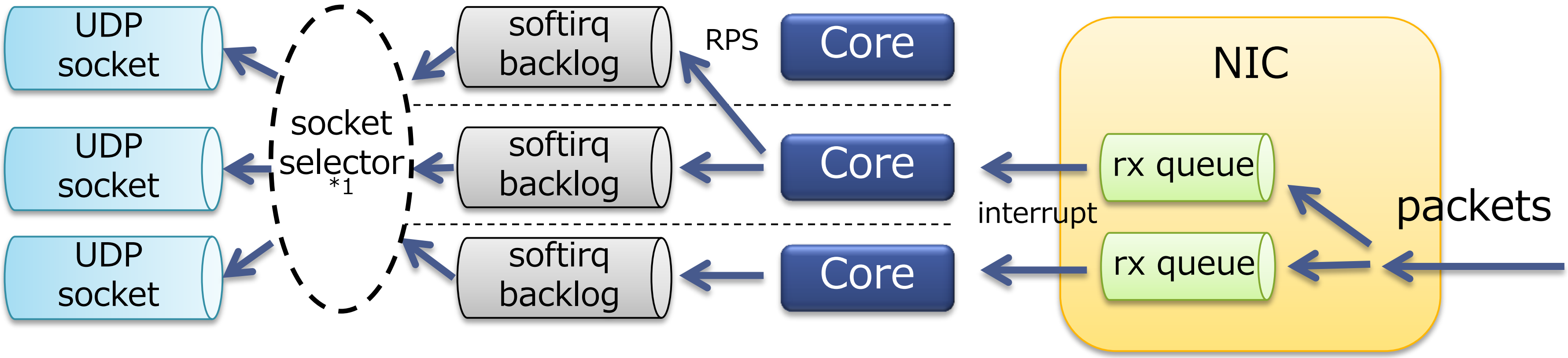
Avoid lock contention

- **Split sockets by SO_REUSEPORT**
    - Introduced by kernel 3.9



- **SO_REUSEPORT allows multiple UDP sockets to bind the same port**
    - One of the sockets is chosen on queueing each packet

```
int on = 1;
int sock = socket(AF_INET, SOCK_DGRAM, 0);
setsockopt(sock, SOL_SOCKET, SO_REUSEPORT, &on, sizeof(on));
bind(sock, ...);
```

*1 select a socket by flow (packet header) hash by default

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Use SO_REUSEPORT

- **sar -u ALL -P ALL 1**

```
20:44:33        CPU     %usr    %nice     %sys  %iowait   %steal     %irq    %soft   %guest   %gnice    %idle
20:44:34        all     3.26     0.00    37.23     0.00     0.00     0.00    59.52     0.00     0.00     0.00
20:44:34          0     3.33     0.00    28.33     0.00     0.00     0.00    68.33     0.00     0.00     0.00
20:44:34          1     3.33     0.00    25.00     0.00     0.00     0.00    71.67     0.00     0.00     0.00
20:44:34          2     1.67     0.00    23.33     0.00     0.00     0.00    75.00     0.00     0.00     0.00
20:44:34          3     3.28     0.00    32.79     0.00     0.00     0.00    63.93     0.00     0.00     0.00
20:44:34          4     3.33     0.00    33.33     0.00     0.00     0.00    63.33     0.00     0.00     0.00
20:44:34          5     1.69     0.00    23.73     0.00     0.00     0.00    74.58     0.00     0.00     0.00
20:44:34          6     3.28     0.00    50.82     0.00     0.00     0.00    45.90     0.00     0.00     0.00
20:44:34          7     3.45     0.00    50.00     0.00     0.00     0.00    46.55     0.00     0.00     0.00
20:44:34          8     1.69     0.00    37.29     0.00     0.00     0.00    61.02     0.00     0.00     0.00
20:44:34          9     1.67     0.00    33.33     0.00     0.00     0.00    65.00     0.00     0.00     0.00
20:44:34         10     1.69     0.00    18.64     0.00     0.00     0.00    79.66     0.00     0.00     0.00
20:44:34         11     3.23     0.00    35.48     0.00     0.00     0.00    61.29     0.00     0.00     0.00
20:44:34         12     1.69     0.00    27.12     0.00     0.00     0.00    71.19     0.00     0.00     0.00
20:44:34         13     1.67     0.00    21.67     0.00     0.00     0.00    76.67     0.00     0.00     0.00
20:44:34         14     1.67     0.00    21.67     0.00     0.00     0.00    76.67     0.00     0.00     0.00
20:44:34         15     3.33     0.00    35.00     0.00     0.00     0.00    61.67     0.00     0.00     0.00
20:44:34         16     6.67     0.00    68.33     0.00     0.00     0.00    25.00     0.00     0.00     0.00
20:44:34         17     5.00     0.00    65.00     0.00     0.00     0.00    30.00     0.00     0.00     0.00
20:44:34         18     6.78     0.00    54.24     0.00     0.00     0.00    38.98     0.00     0.00     0.00
20:44:34         19     4.92     0.00    63.93     0.00     0.00     0.00    31.15     0.00     0.00     0.00
```

- **CPU consumption in softirq became some more reasonable**

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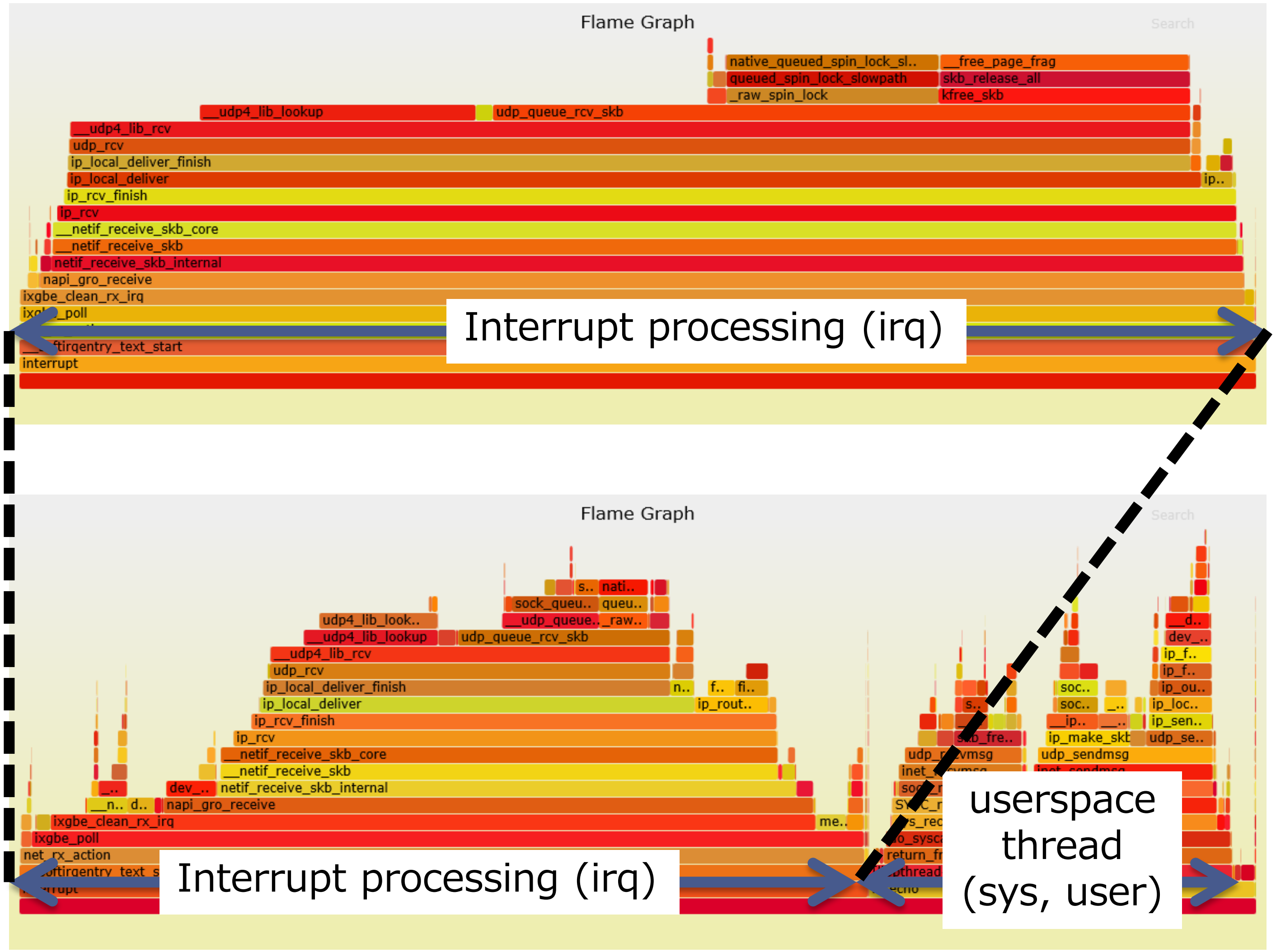
Use SO_REUSEPORT

- before
- after



Interrupt processing (irq)

Interrupt processing (irq)

userspace thread (sys, user)

Userspace starts to work

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Use SO_REUSEPORT

- **Perfomance change**
  - RSS: 270,000 tps (approx. 360Mbps)
  - +affinity_hint+RPS: 17,000 tps (approx. 23Mbps)
  - +SO_REUSEPORT: **2,540,000** tps (approx. **3370Mbps**)

    - Great improvement!
    - but...

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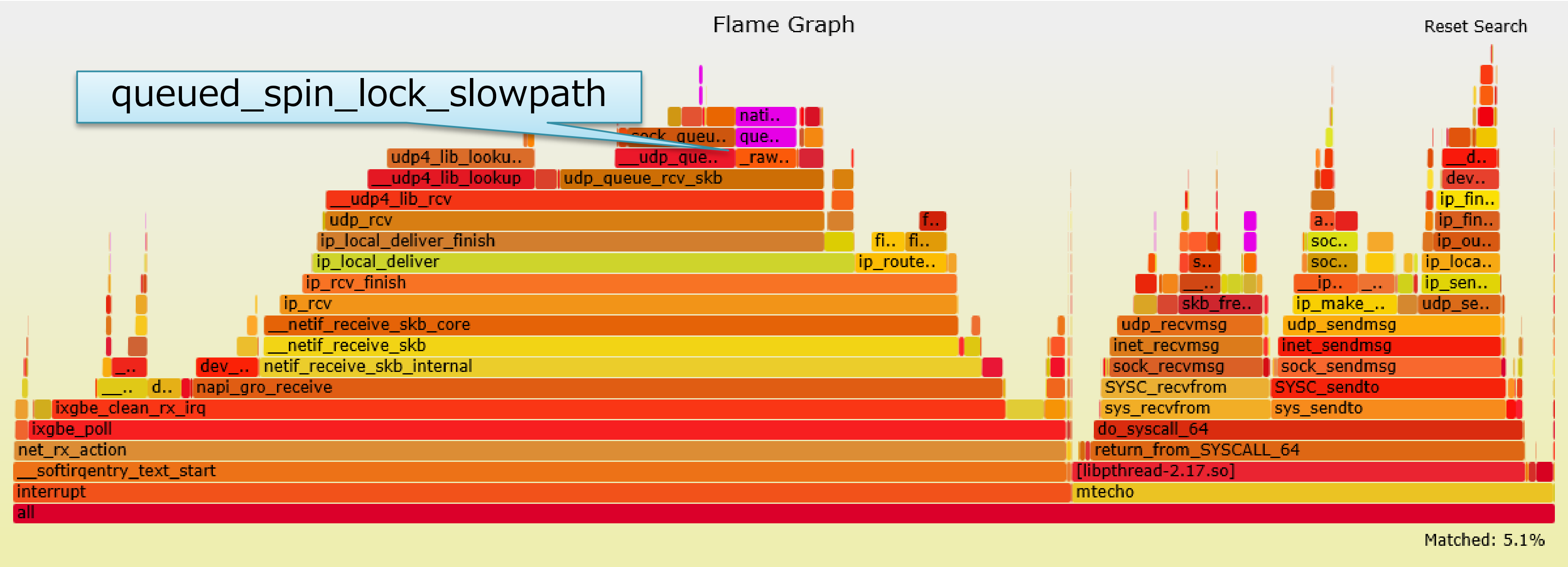
Use SO_REUSEPORT

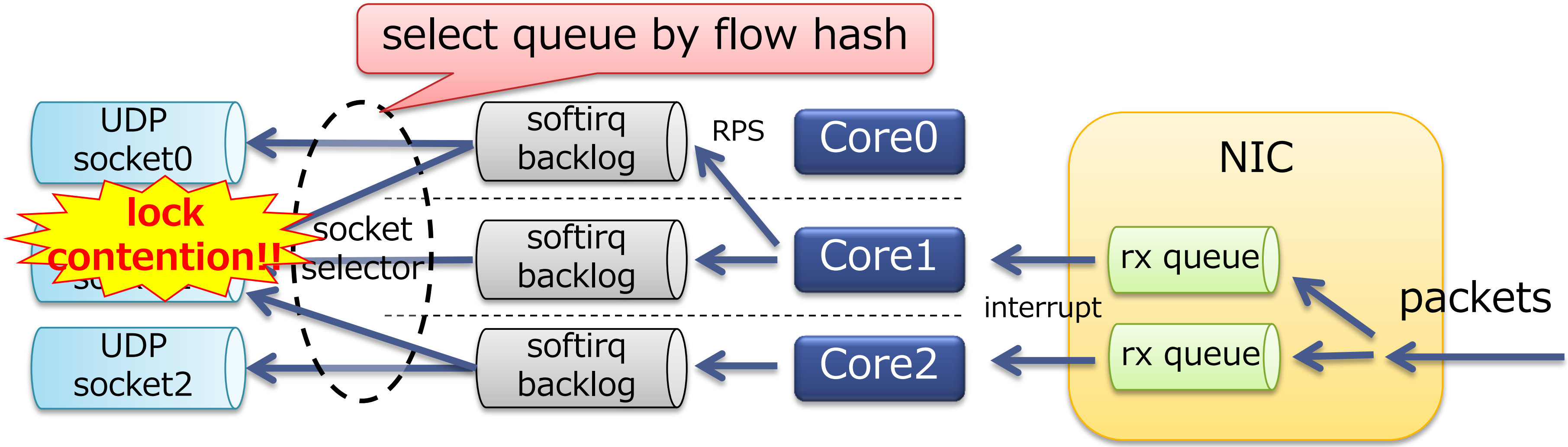
- **More analysis**



- **Socket lock is still contended**

Socket lock contention again

- SO_REUSEPORT uses flow hash to select queue by default
- Same sockets can be selected by different cores



- Socket lock still gets contended

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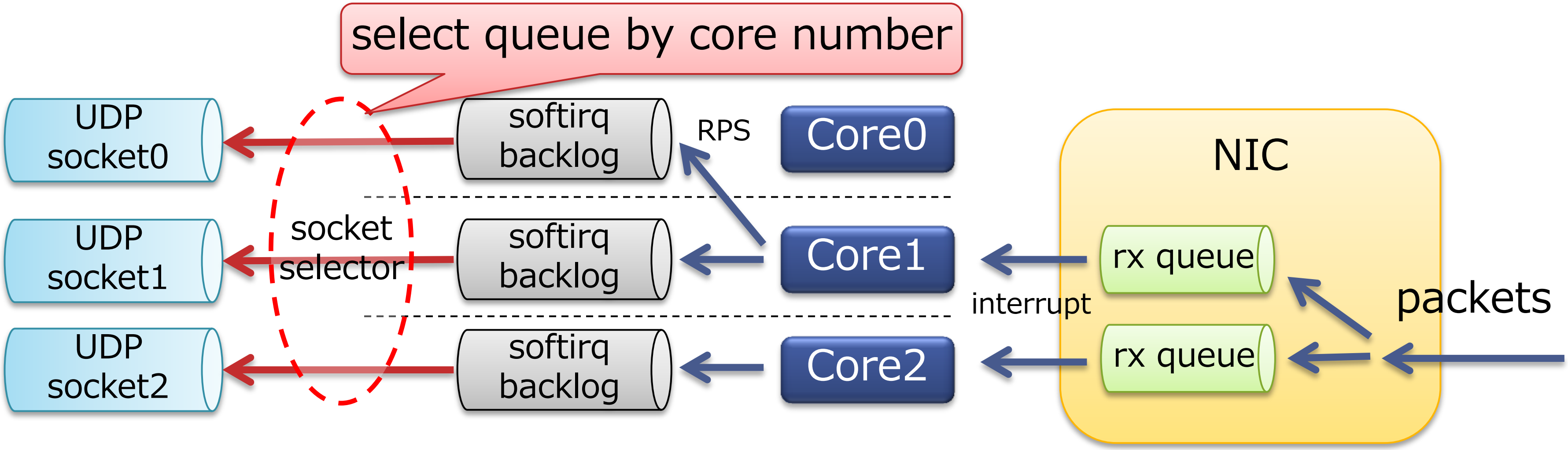
Avoid socket lock contention

- **Select socket by core number**
  - Realized by SO_ATTACH_REUSEPORT_CBPF/EBPF[*1]
  - Introduced by kernel 4.5



- **No lock contention between softirq**
- **Usage**
  - See example in kernel source tree
    - tools/testing/selftests/net/reuseport_bpf_cpu.c

[*1] BPF allows much more flexible logic but this time only cpu number is used

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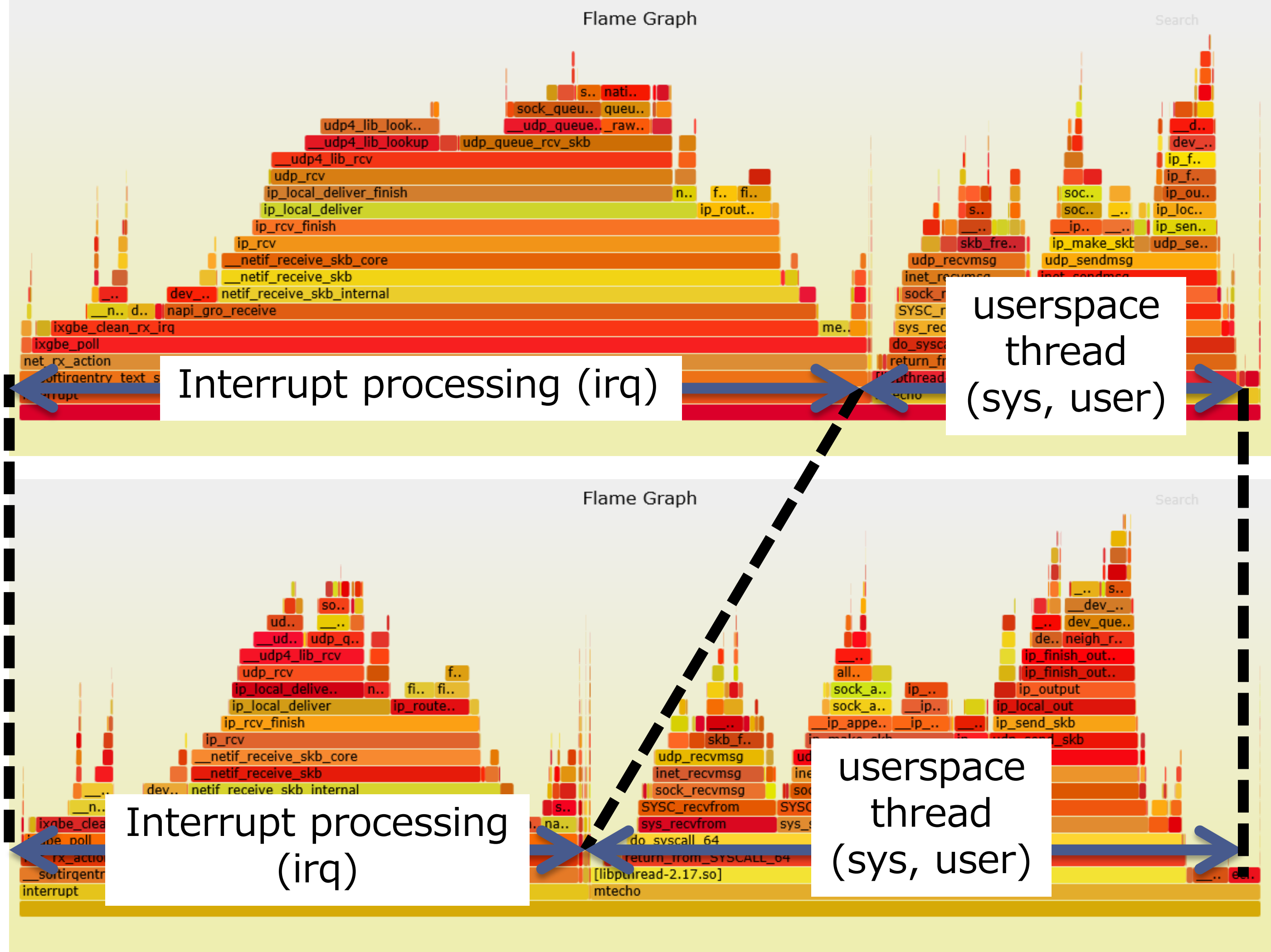
Use SO_ATTACH_REUSEPORT_EPBF

- before

- after



irq overhead gets less

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Use SO_ATTACH_REUSEPORT_EBPF

- **Perfomance change**

• RSS:	270,000 tps	(approx. 360Mbps)
• +affinity_hint+RPS:	17,000 tps	(approx. 23Mbps)
• +SO_REUSEPORT:	2,540,000 tps	(approx. 3370Mbps)
• +SO_ATTACH_...:	**4,250,000** tps	(approx. **5640Mbps**)

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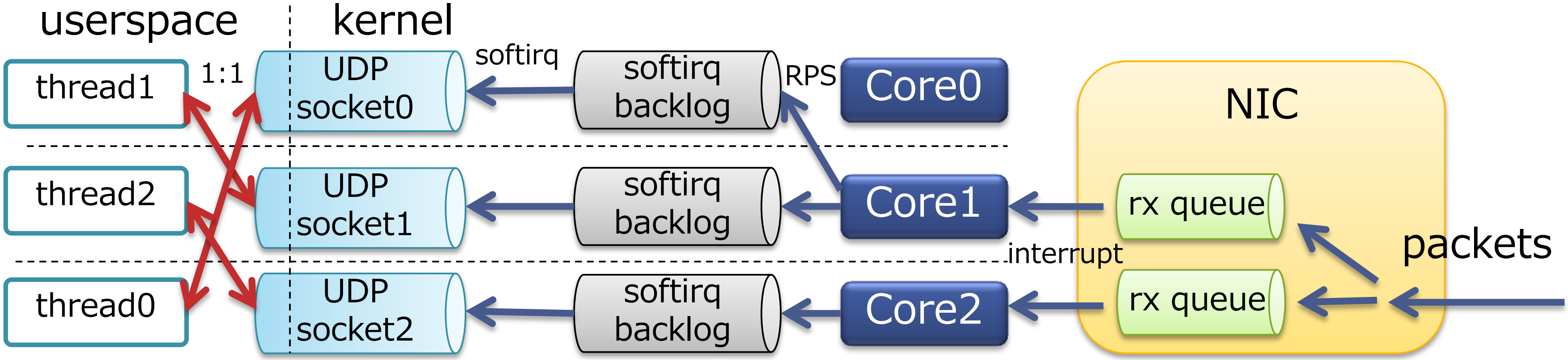
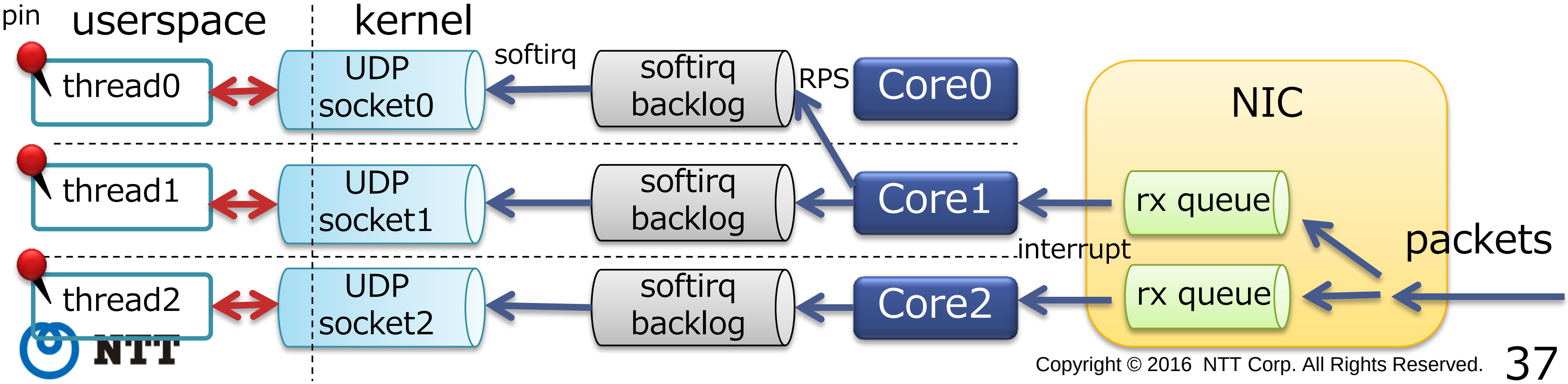
Pin userspace threads

- **Userspace threads : sockets == 1 : 1**
  - No lock contention
- **But not necessarily on the same core as softirq**



- **Pin userspace thread on the same core for better cache affinity**
  - cgroup, taskset, pthread_setaffinity_np(), ... any way you like



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Pin userspace threads

- **Perfomance change**
  - RSS: 270,000 tps (approx. 360Mbps)
  - +affinity_hint+RPS: 17,000 tps (approx. 23Mbps)
  - +SO_REUSEPORT: 2,540,000 tps (approx. 3370Mbps)
  - +SO_ATTACH_...: 4,250,000 tps (approx. 5640Mbps)
  - +Pin threads: **5,050,000** tps (approx. **6710Mbps**)

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Tx lock contention?

- So far everything has been about Rx
- No lock contention on Tx?

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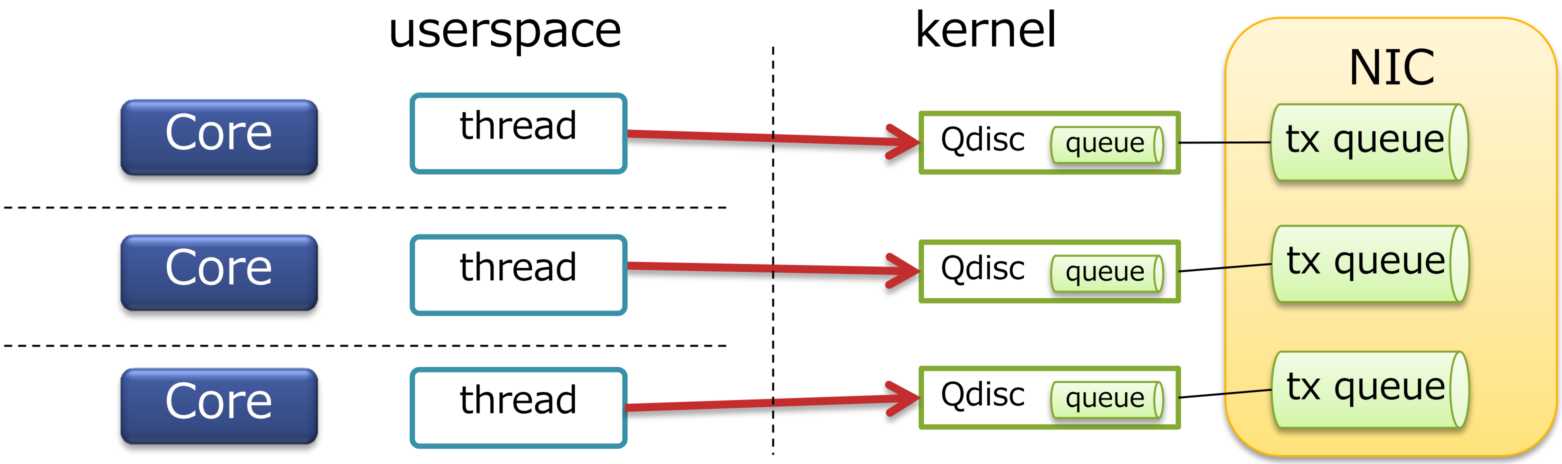
Tx queue

- kernel has Qdisc (Queueing discipline)
- Each Qdisc is linked to NIC tx-queue
- Each Qdisc has its lock



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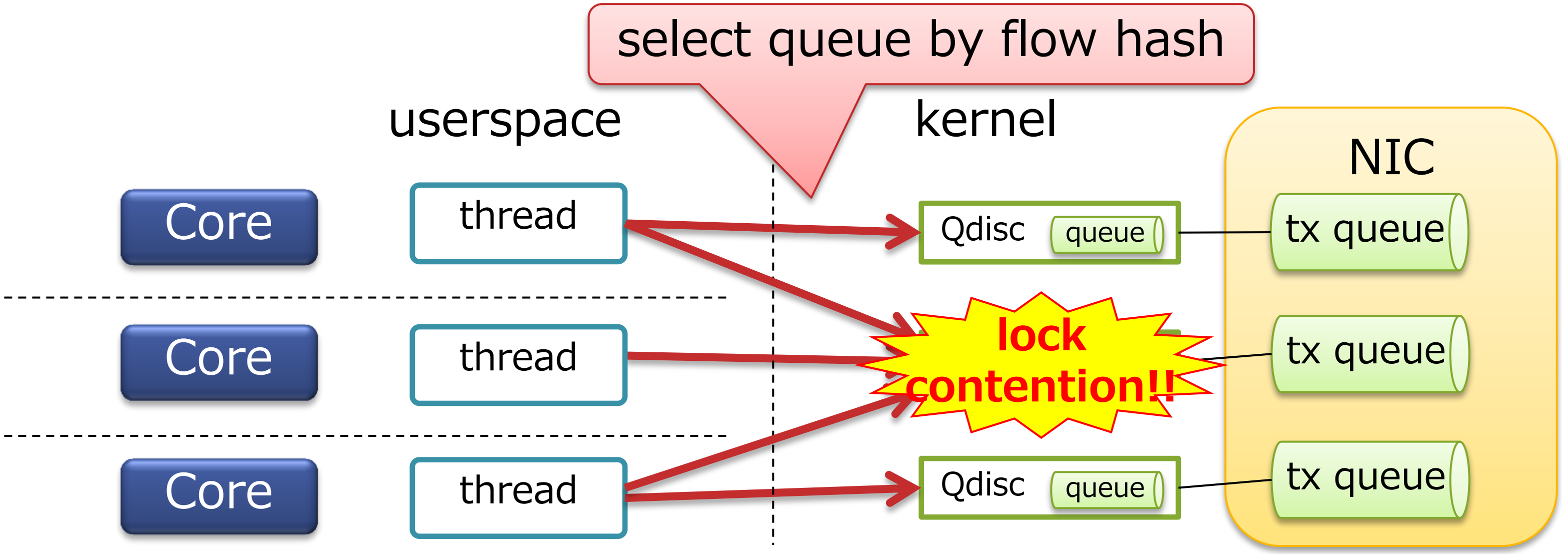
Tx queue lock contention

- By default Qdisc is selected by flow hash
- Thus lock contention can happen



- We haven't seen contention on Tx, why?

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Avoid Tx queue lock contention

- **Because ixgbe (Intel 10GbE NIC driver) has an ability to set XPS automatically**

```
$ for ((txq=0; txq<20; txq++)); do
>   cat /sys/class/net/ens1f0/queues/tx-$txq/xps_cpus
> done
00001    -> core 0
00002    -> core 1
00004    -> core 2
00008    -> core 3
00010    -> core 4
00020    -> core 5
00040    -> core 6
00080    -> core 7
00100    -> core 8
00200    -> core 9
```

```
00400    -> core 10
00800    -> core 11
01000    -> core 12
02000    -> core 13
04000    -> core 14
08000    -> core 15
10000    -> core 16
20000    -> core 17
40000    -> core 18
80000    -> core 19
```

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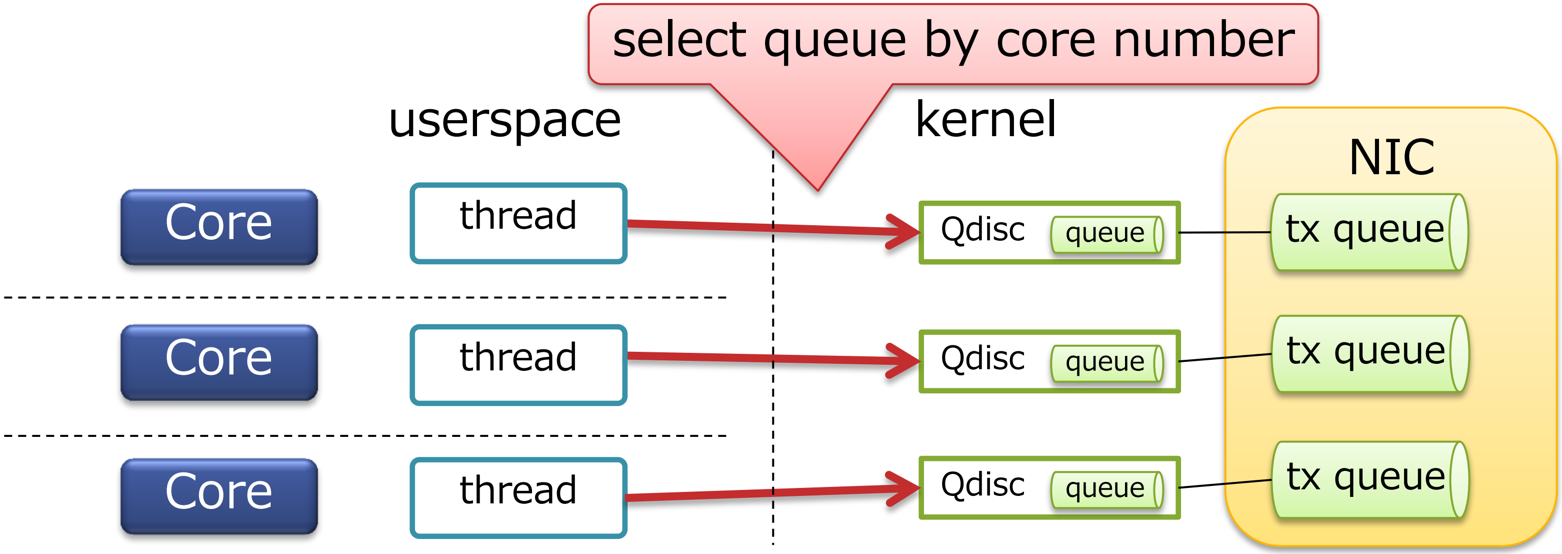
XPS

- **XPS allows kernel to select Tx queue (Qdisc) by core number**



- **Tx has no lock contention**

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How effective is XPS?

- **Try disabling it**

```
# for ((txq=0; txq<20; txq++)); do
>   echo 0 > /sys/class/net/ens1f0/queues/tx-$txq/xps_cpus
> done
```

  - Before: **5,050,000** tps (approx. **6710Mbps**)
  - After: **1,086,000** tps (approx. **1440Mbps**)

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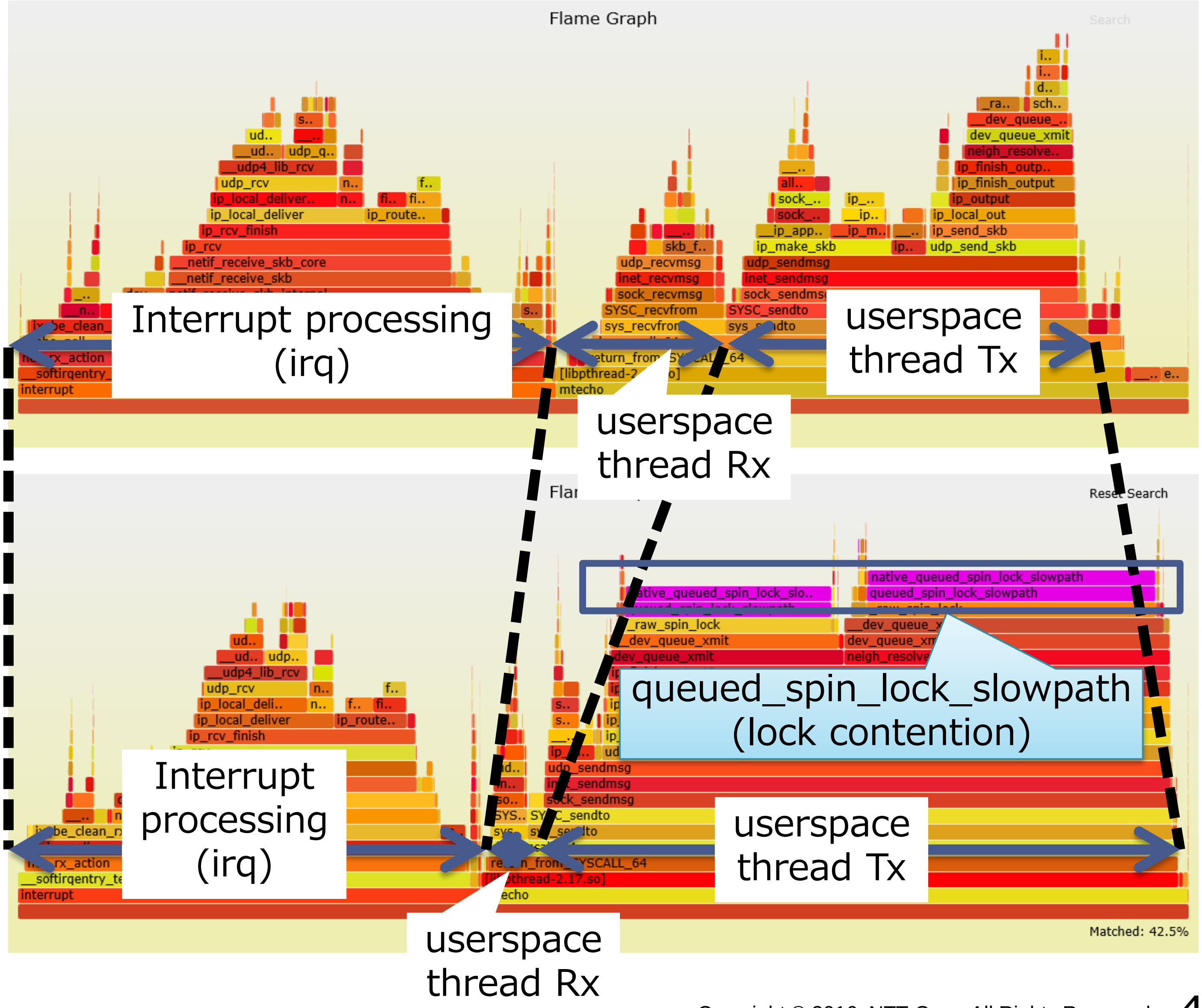
Disabling XPS

- **XPS enabled**

- **XPS disabled**



Interrupt processing (irq)

userspace thread Rx

userspace thread Tx

Interrupt processing (irq)

userspace thread Rx

userspace thread Tx

queued_spin_lock_slowpath (lock contention)

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Enable XPS

- **Enable XPS again**

```
# echo 00001 > /sys/class/net/<NIC>/queues/tx-0/xps_cpus
# echo 00002 > /sys/class/net/<NIC>/queues/tx-1/xps_cpus
# echo 00004 > /sys/class/net/<NIC>/queues/tx-2/xps_cpus
# echo 00008 > /sys/class/net/<NIC>/queues/tx-3/xps_cpus
...
```

- **Although ixgbe can automatically set XPS, not all drivers can do that**
- **Make sure to check xps_cpus is configured**

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Optimization per core

- **By making full use of multi-core with avoiding contention, we achieved**
  - **5,050,000** tps (approx. **6710Mbps**)

- **To get more performance, reduce overhead per core**

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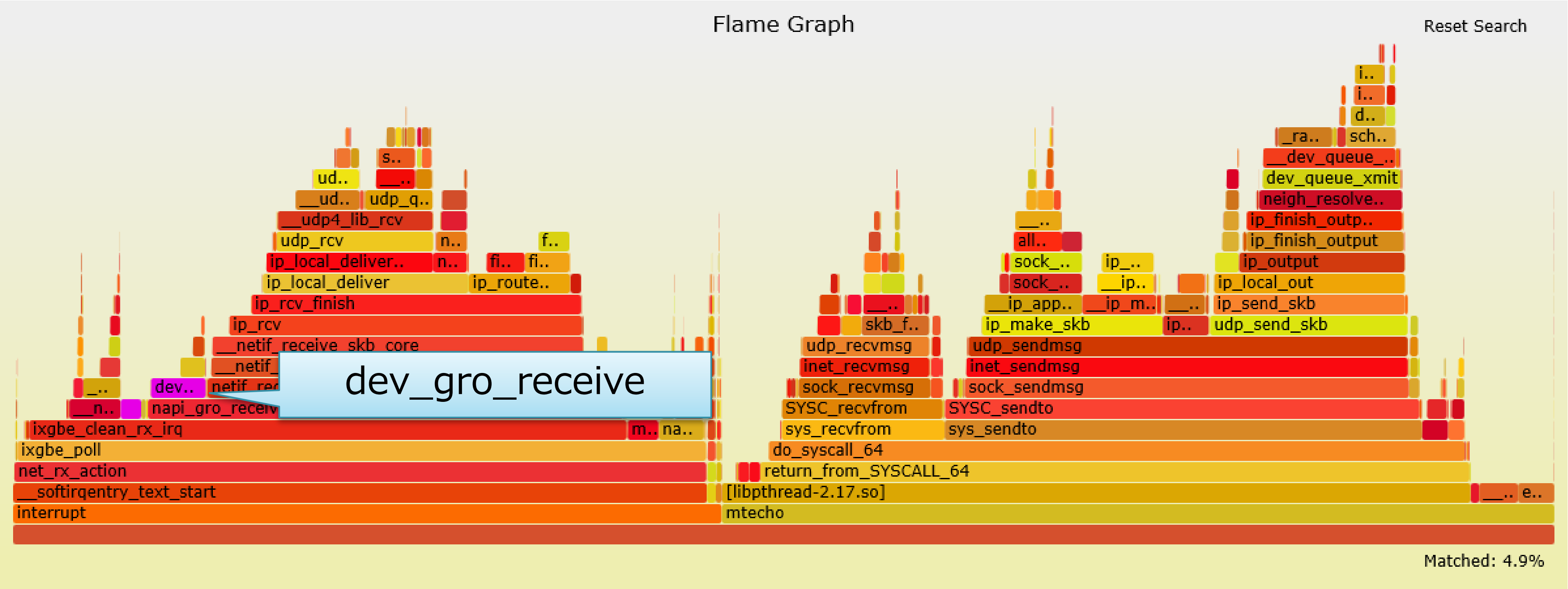
Optimization per core



- GRO is enabled by default
- Consuming 3.57% of CPU time

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GRO

- **GRO is not applicable to UDP[*1]**
- **Disable it for UDP servers**

```
# ethtool -K <NIC> gro off
```

- **WARNING:**
  - Don't disable it if TCP performance matters
    - Disabling GRO makes TCP rx throughput miserably low
  - Don't disable it on KVM hypervisors as well
    - GRO boost throughput of tunneling protocol traffic as well as guest's TCP traffic on hypervisors

[*1] Other than UDP tunneling, like VXLAN

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Disable GRO

- **Perfomance change**

RSS (+XPS):	270,000 tps (approx. 360Mbps)
+affinity_hint+RPS:	17,000 tps (approx. 23Mbps)
+SO_REUSEPORT:	2,540,000 tps (approx. 3370Mbps)
+SO_ATTACH_...:	4,250,000 tps (approx. 5640Mbps)
+Pin threads:	5,050,000 tps (approx. 6710Mbps)
+Disable GRO:	**5,180,000** tps (approx. **6880Mbps**)

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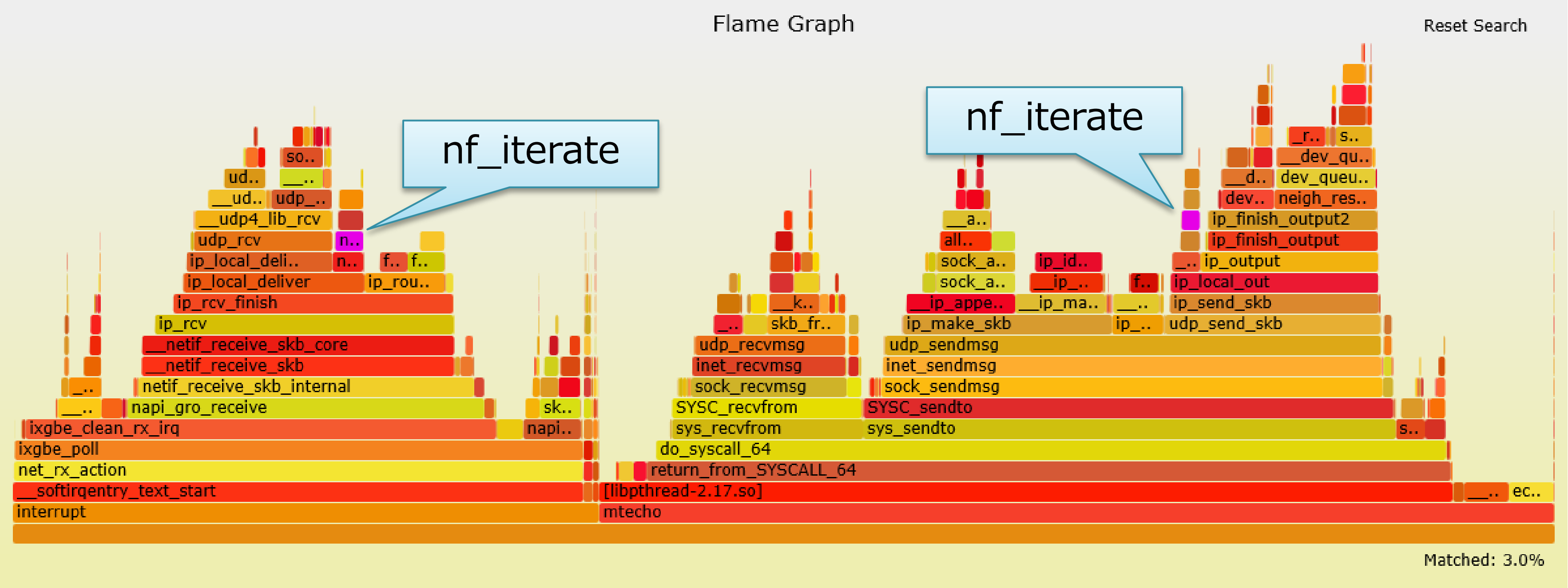
Optimization per core



- **iptables-related processing (nf_iterate) is performed**
  - Although I have not added any rule to iptables
- **Consuming 3.00% of CPU time**

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iptables (netfilter)

- With iptables kernel module loaded, even if you don't have any rules, it can incur some overhead
- Some distributions load iptables module even when you don't add any rule
- If you are not using iptables, unload the module

```
# modprobe -r iptable_filter
# modprobe -r ip_tables
```

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Unload iptables

- **Perfomance change**

RSS (+XPS):	270,000 tps (approx. 360Mbps)
+affinity_hint+RPS:	17,000 tps (approx. 23Mbps)
+SO_REUSEPORT:	2,540,000 tps (approx. 3370Mbps)
+SO_ATTACH_...:	4,250,000 tps (approx. 5640Mbps)
+Pin threads:	5,050,000 tps (approx. 6710Mbps)
+Disable GRO:	5,180,000 tps (approx. 6880Mbps)
+Unload iptables:	**5,380,000** tps (approx. **7140Mbps**)

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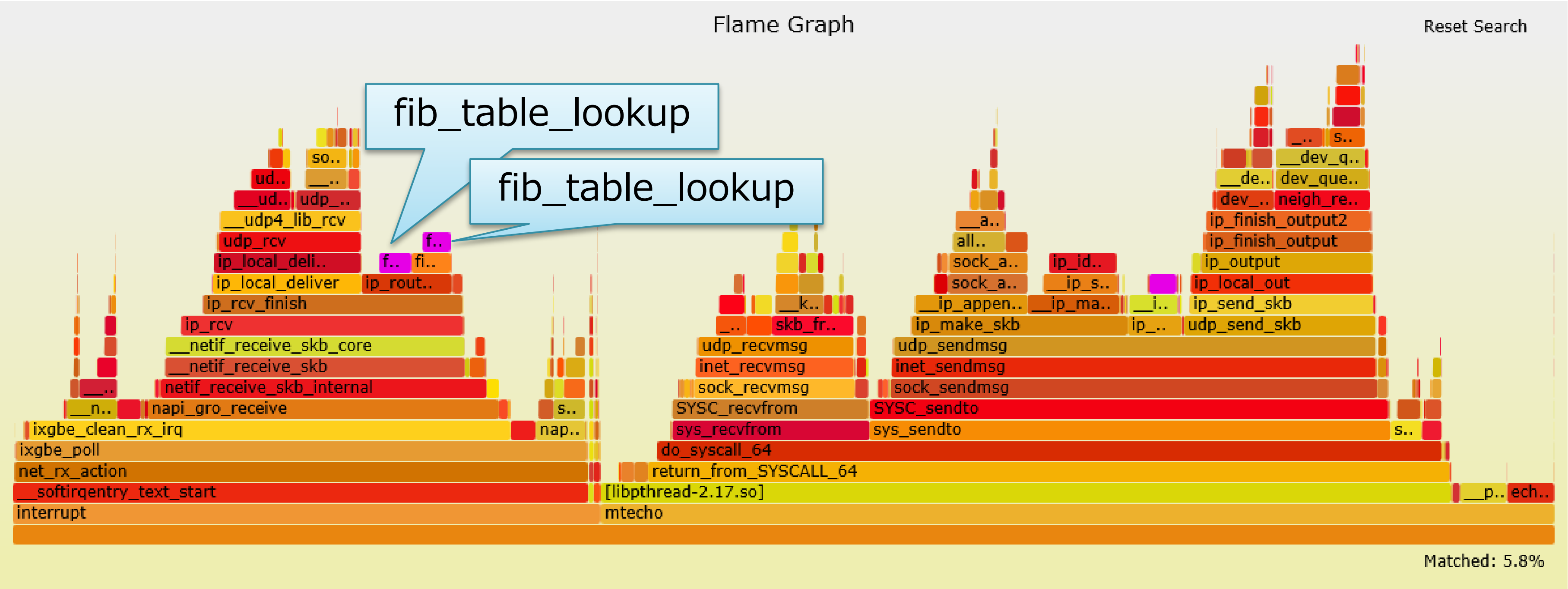
Optimization per core



fib_table_lookup

fib_table_lookup

- On Rx, FIB (routing table) lookup is done twice
- Each is consuming 1.82%~ of CPU time

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FIB lookup on Rx

- **One of two times of table lookup is for validating source IP addresses**
  - Reverse path filter
  - Local address check
- **If you really don't need source validation, you can skip it**

```
# sysctl -w net.ipv4.conf.all.rp_filter=0
# sysctl -w net.ipv4.conf.<NIC>.rp_filter=0
# sysctl -w net.ipv4.conf.all.accept_local=1
```

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Disable source validation

- **Perfomance change**

• RSS (+XPS):	270,000 tps (approx. 360Mbps)
• +affinity_hint+RPS:	17,000 tps (approx. 23Mbps)
• +SO_REUSEPORT:	2,540,000 tps (approx. 3370Mbps)
• +SO_ATTACH_...:	4,250,000 tps (approx. 5640Mbps)
• +Pin threads:	5,050,000 tps (approx. 6710Mbps)
• +Disable GRO:	5,180,000 tps (approx. 6880Mbps)
• +Unload iptables:	5,380,000 tps (approx. 7140Mbps)
• +Disable validation:	**5,490,000** tps (approx. **7290Mbps**)

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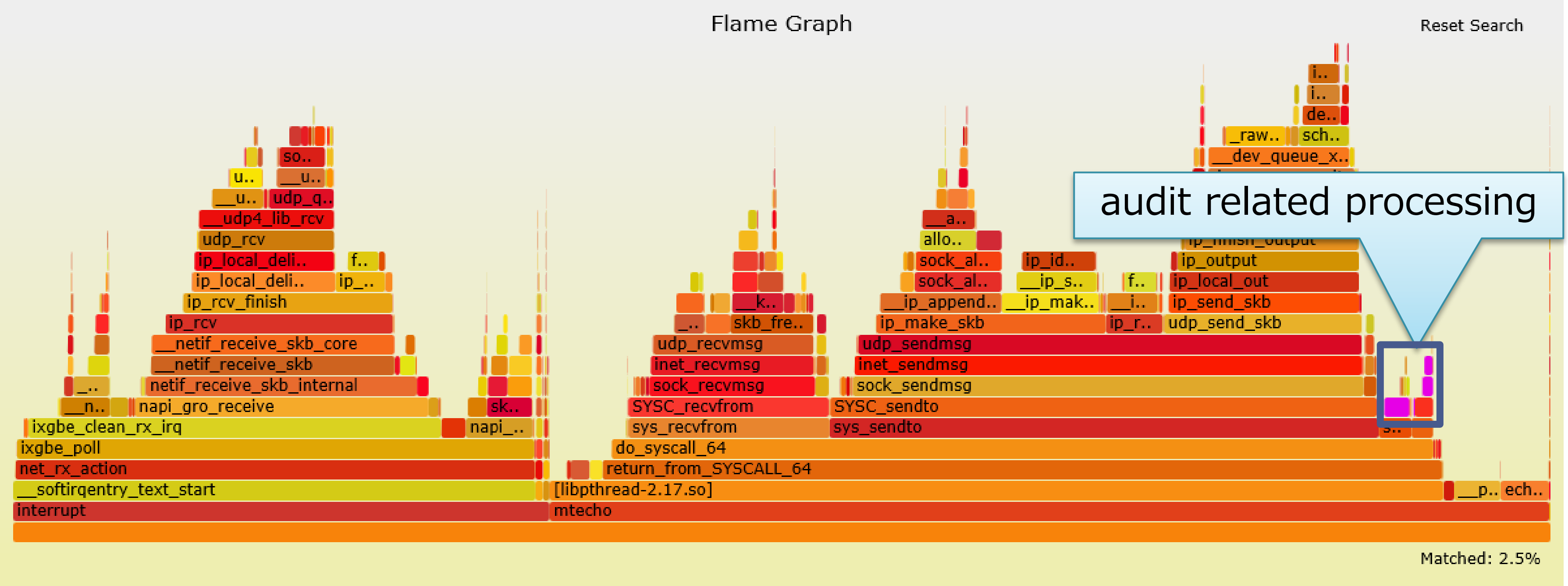
Optimization per core



audit related processing

- Audit is a bit heavy when heavily processing packets
- Consuming 2.31% of CPU time

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Audit

- **If you don't need audit, disable it**

```
# systemctl disable auditd
# reboot
```

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Disable audit

- **Perfomance change**

RSS (+XPS):	270,000 tps (approx. 360Mbps)
+affinity_hint+RPS:	17,000 tps (approx. 23Mbps)
+SO_REUSEPORT:	2,540,000 tps (approx. 3370Mbps)
+SO_ATTACH_...:	4,250,000 tps (approx. 5640Mbps)
+Pin threads:	5,050,000 tps (approx. 6710Mbps)
+Disable GRO:	5,180,000 tps (approx. 6880Mbps)
+Unload iptables:	5,380,000 tps (approx. 7140Mbps)
+Disable validation:	5,490,000 tps (approx. 7290Mbps)
+Disable audit:	**5,860,000** tps (approx. **7780Mbps**)

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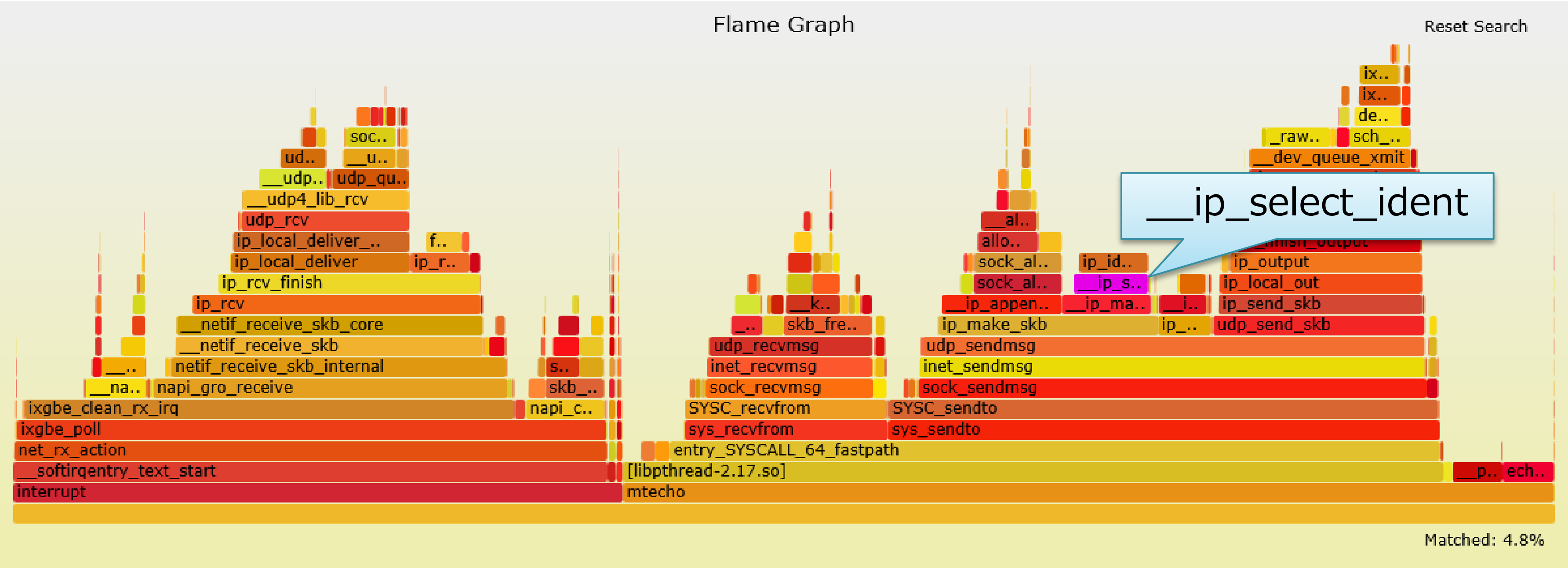
Optimization per core



__ip_select_ident

- **IP ID field calculation (__ip_select_ident) is heavy**
- **Consuming 4.82% of CPU time**

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IP ID field calculation

- **This is an environment-specific issue**
  - This happens if many clients has the same IP address
    - Cache contention by atomic operations
  - It is very likely you don't see this amount of CPU consumption without using tunneling protocol

- **If you really see this problem…**
  - You can skip it only if you never send over-mtu-sized packets
    - Though it is very strict

```
int pmtu = IP_PMTUDISC_DO;
setsockopt(sock, IPPROTO_IP, IP_MTU_DISCOVER, &pmtu, sizeof(pmtu));
```

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Skip IP ID calculation

- **Perfomance change**

RSS (+XPS):	270,000 tps (approx. 360Mbps)
+affinity_hint+RPS:	17,000 tps (approx. 23Mbps)
+SO_REUSEPORT:	2,540,000 tps (approx. 3370Mbps)
+SO_ATTACH_...:	4,250,000 tps (approx. 5640Mbps)
+Pin threads:	5,050,000 tps (approx. 6710Mbps)
+Disable GRO:	5,180,000 tps (approx. 6880Mbps)
+Unload iptables:	5,380,000 tps (approx. 7140Mbps)
+Disable validation:	5,490,000 tps (approx. 7290Mbps)
+Disable audit:	5,860,000 tps (approx. 7780Mbps)
+Skip ID calculation:	**6,010,000** tps (approx. **7980Mbps**)

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Hyper threading

- **So far we have not enabled hyper threading**
- **It makes the number of logical cores 40**
  - Number of physical cores are 20 in this box

- **With 40 cores we need to rely on RPS more**
  - Remind: Max usable rx-queues == 16

- **Enable hyper-threading and set RPS on all rx-queues**
  - queue 0 -> core 0, 20
  - queue 1 -> core 1, 21
  - ...
  - queue 10 -> core 10, 16, 30
  - queue 11 -> core 11, 17, 31
  - ...

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Hyper threading

- **Perfomance change**

RSS (+XPS):	270,000 tps (approx. 360Mbps)
+affinity_hint+RPS:	17,000 tps (approx. 23Mbps)
+SO_REUSEPORT:	2,540,000 tps (approx. 3370Mbps)
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+Disable validation:	5,490,000 tps (approx. 7290Mbps)
+Disable audit:	5,860,000 tps (approx. 7780Mbps)
+Skip ID calculation:	6,010,000 tps (approx. 7980Mbps)
+Hyper threading:	**7,010,000** tps (approx. **9310Mbps**)

  - I guess more rx-queues would realize even better performance number

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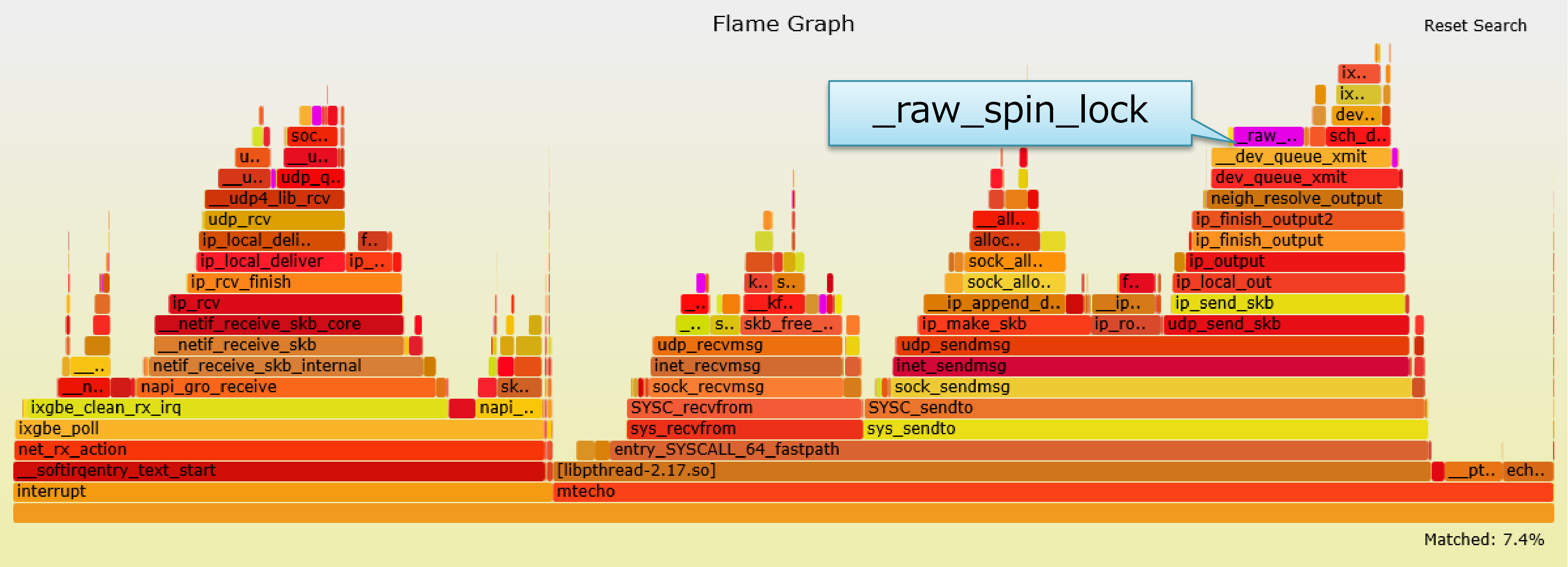
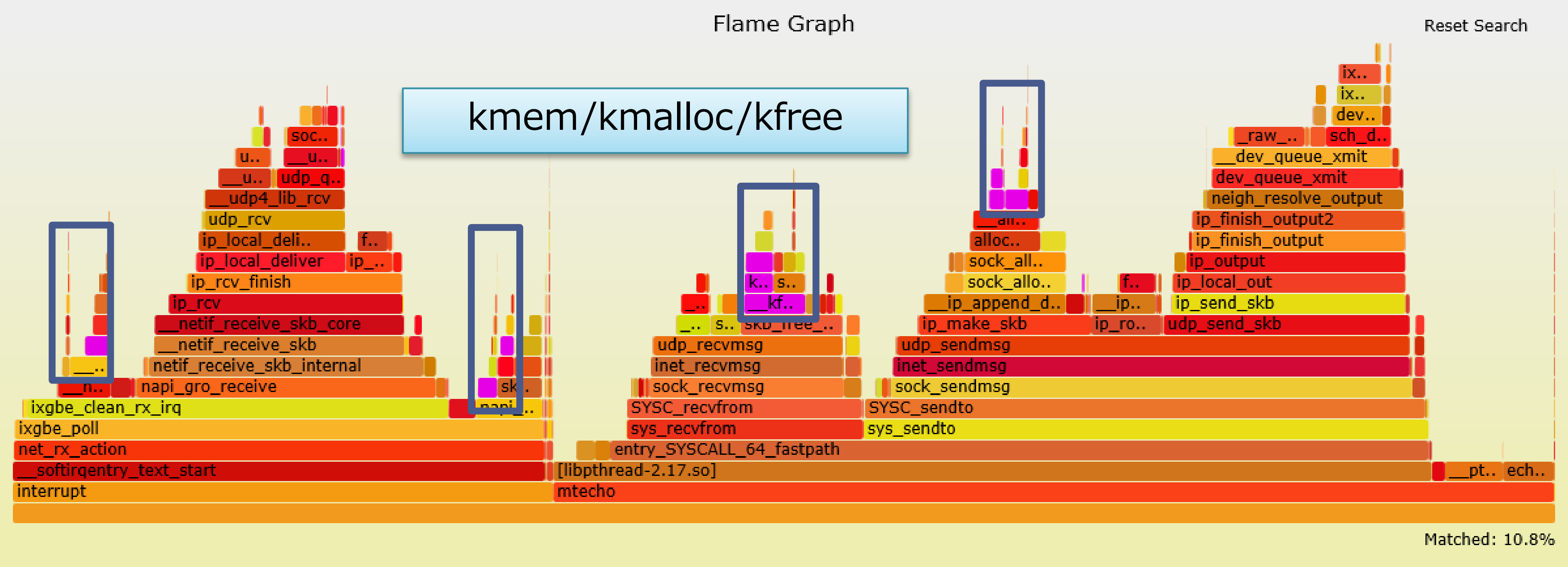
More hot spots



- Tx Qdisc lock (_raw_spin_lock) is heavy
- Not contended but involves many atomic operations
- Being optimized in Linux netdev community

More hot spots



kmem/kmalloc/kfree

- Memory alloc/free (slab)
- Being optimized in netdev community as well

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Other challenges

- **Virtualization**
  - UDP servers as guests
  - Hypervisor can saturate CPUs or drop packets
  - We are going to investigate ways to boost performance in virtualized environment as well

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Summary

- **For 100bytes, we can achieve almost 10G**
  - From: 270,000 tps (approx. 360Mbps)
  - To: 7,010,000 tps (approx. 9310Mbps)
    - Of course we need to take into account additional userspace work in real applications so this number is not applicable as is

- **To boost UDP performance**
  - Applications (Most important!)
    - implement SO_REUSEPORT
    - implement SO_ATTACH_REUSEPORT_EBPF/CBPF
    - These are useful for TCP listening sockets as well

  - OS settings
    - Use RPS if rx-queues are not enough
    - Make sure XPS is configured
    - Consider other tunings to reduce per-core overhead
      - Disable GRO
      - Unload iptables
      - Disable source IP validation
      - Disable auditd

  - Hardware
    - Use NICs which have enough RSS rx-queues if possible (as many queues as core num)

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Thank you!

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