First INFN International School on Architectures, tools and methodologies for developing efficient large scale scientific computing applications

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Domenico Galli

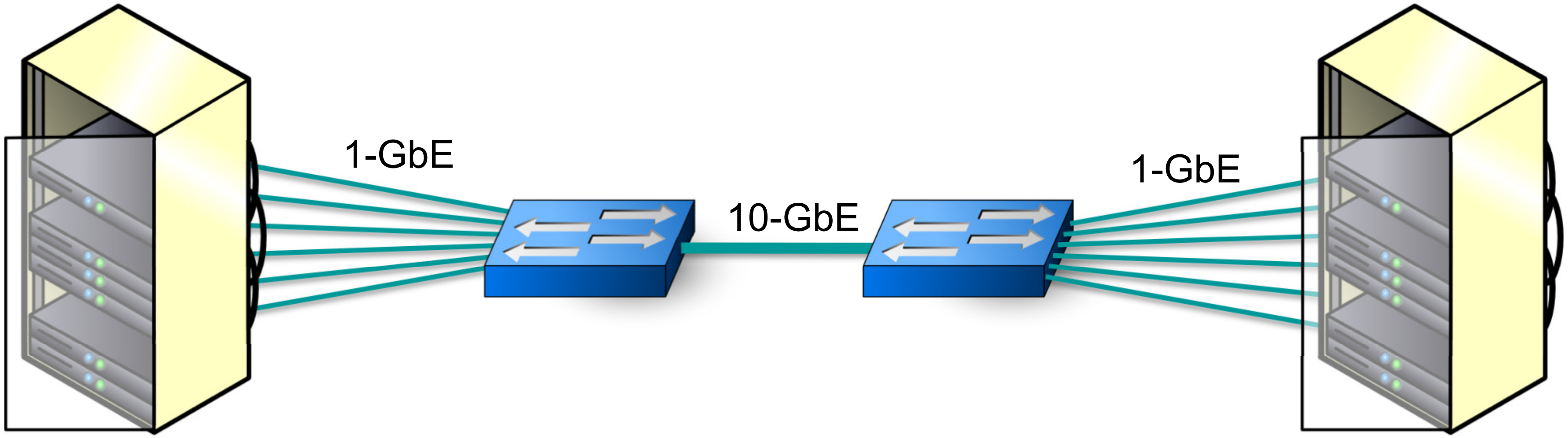
High Throughput Data Transmission Through Network Links

Outline

- **Need** of **High-Speed Links** in **HEP** applications:
  - 2 Use Cases.
- High speed data-link **technologies** in **HEP**:
  - Commodity links;
    - 10 Gb/s links.
- **Bottlenecks** in moving data through High-Speed Links.
- **Optimization**: Network **workload sharing** among **CPU cores**:
  - The Linux network layer:
    - Transmission and reception.
  - Process-to-CPU affinity;
  - IRQ-to CPU affinity;
- **Performances** of transmission through **10 Gb/s Ethernet**:
  - **UDP** transfer;
  - **TCP** transfer:
    - Nagle's algorithm;
    - Zero copy;
    - TCP hardware offload.

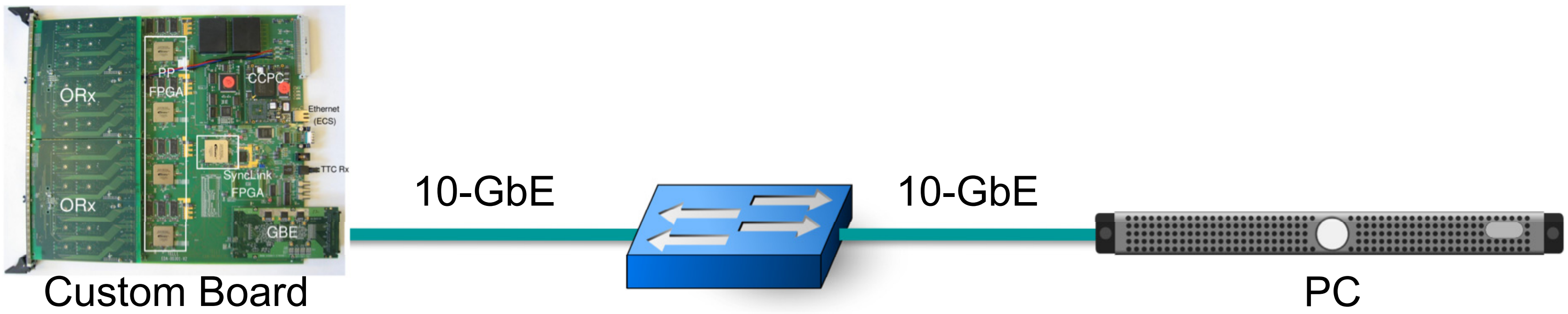
High Speed Network Links

- **Fastest available** network link technology in the market (e.g. 10-GbE at present) usually employed in LAN **backbones**:
  - Connecting **network devices** together:
    - E.g.: connecting together network switches in a LAN.
  - **Data flow** managed by Switch **Firmware**.
    - Switch manufacturer will care avoiding bottlenecks;
    - We only need to test the device…
- Front-end (PC, custom electronics) usually connected to lower speed devices.

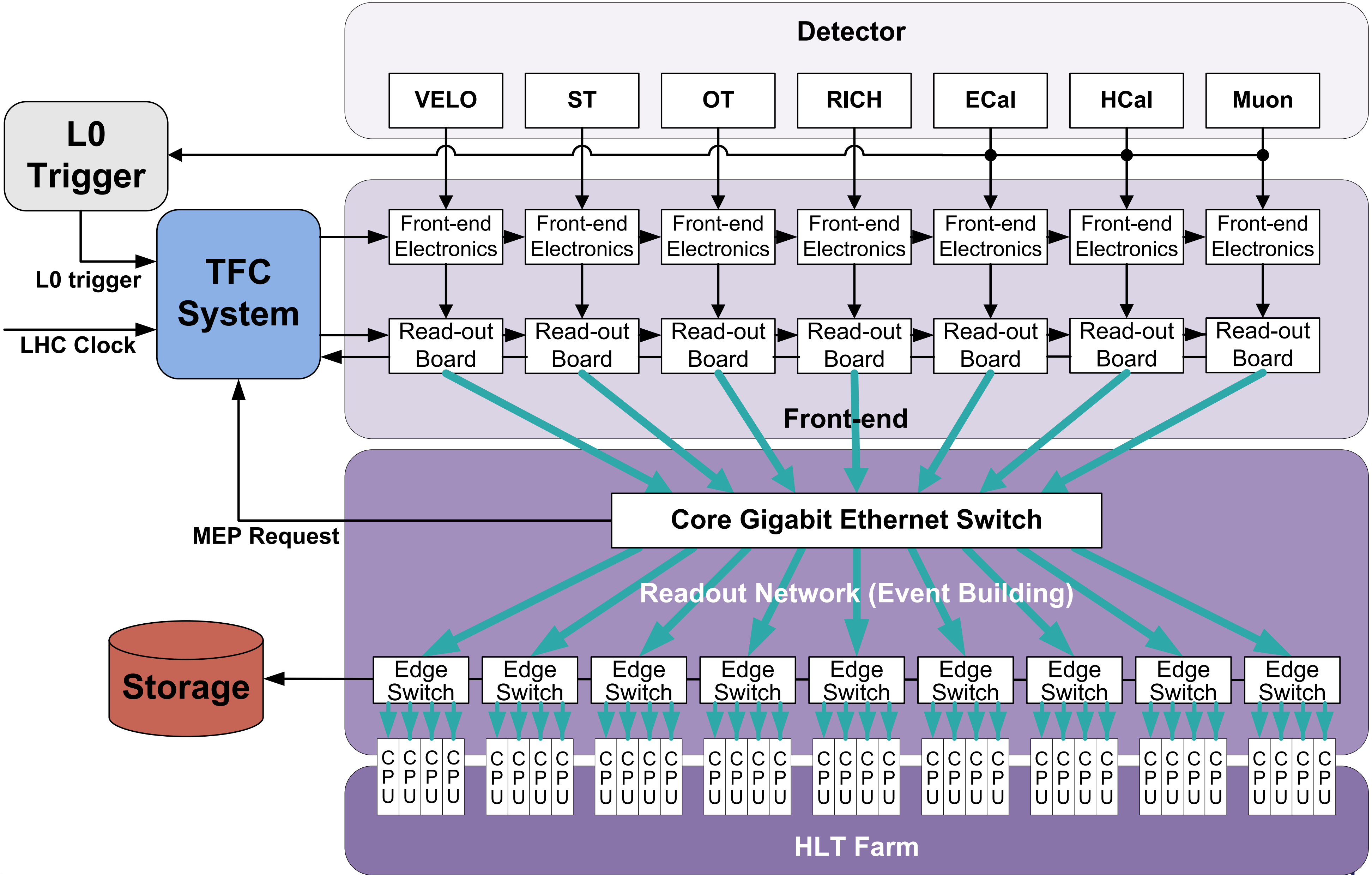


Front-end Access to High Speed Network

- **HEP applications** sometimes need High speed network links **directly connected to the front-end**:
  - PCs;
  - Custom electronic boards.
- **Data Flow** managed by **OS** or **FPGA software**.
  - Need to check **bottlenecks** which could limit the throughput.
- Use case 1: **On-line data path**:
  - Data Acquisition – Event Building – High Level Trigger.
- Use case 2: **Network Distributed Storage**:
  - Offline computing centers (Tier-1).

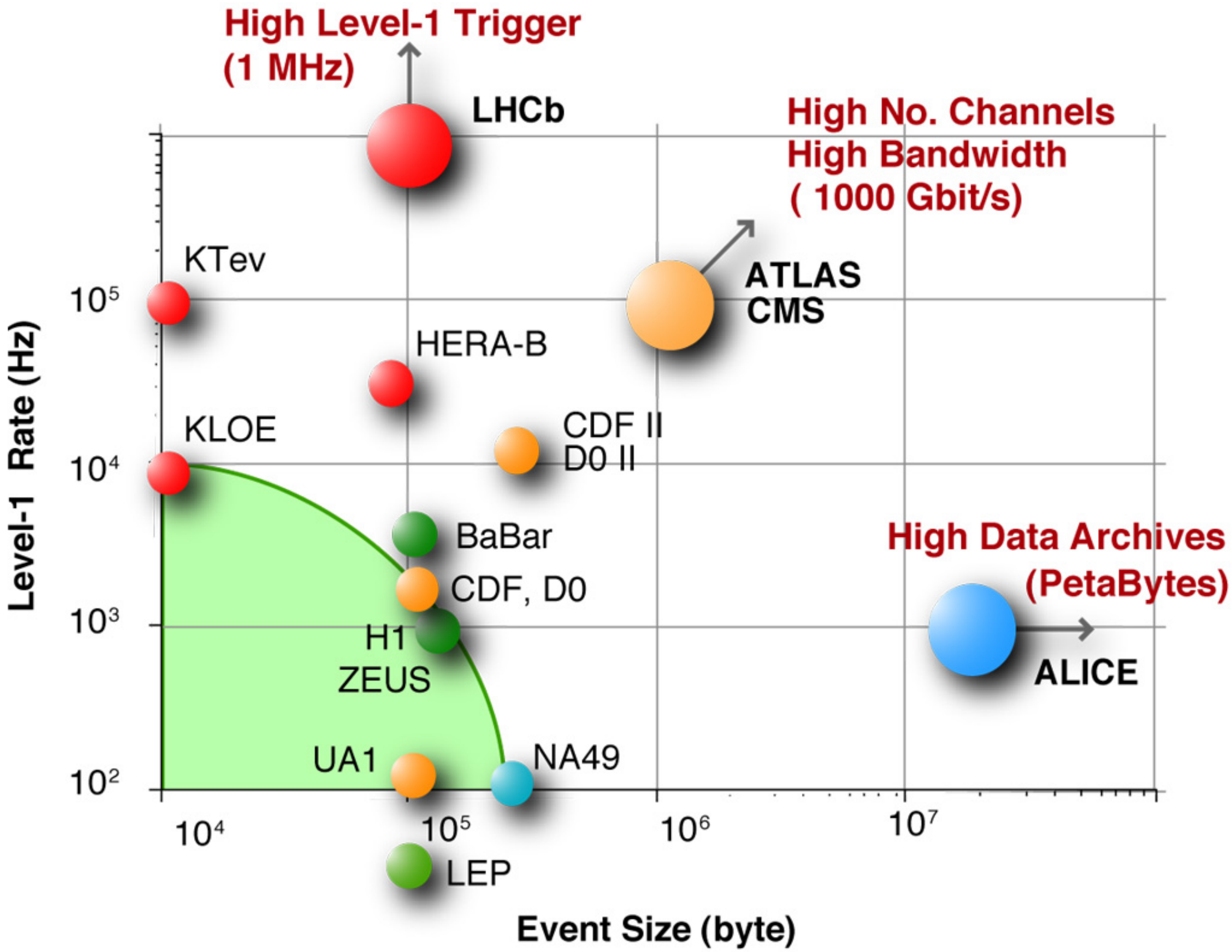


Use case 1: The On-Line Data Path



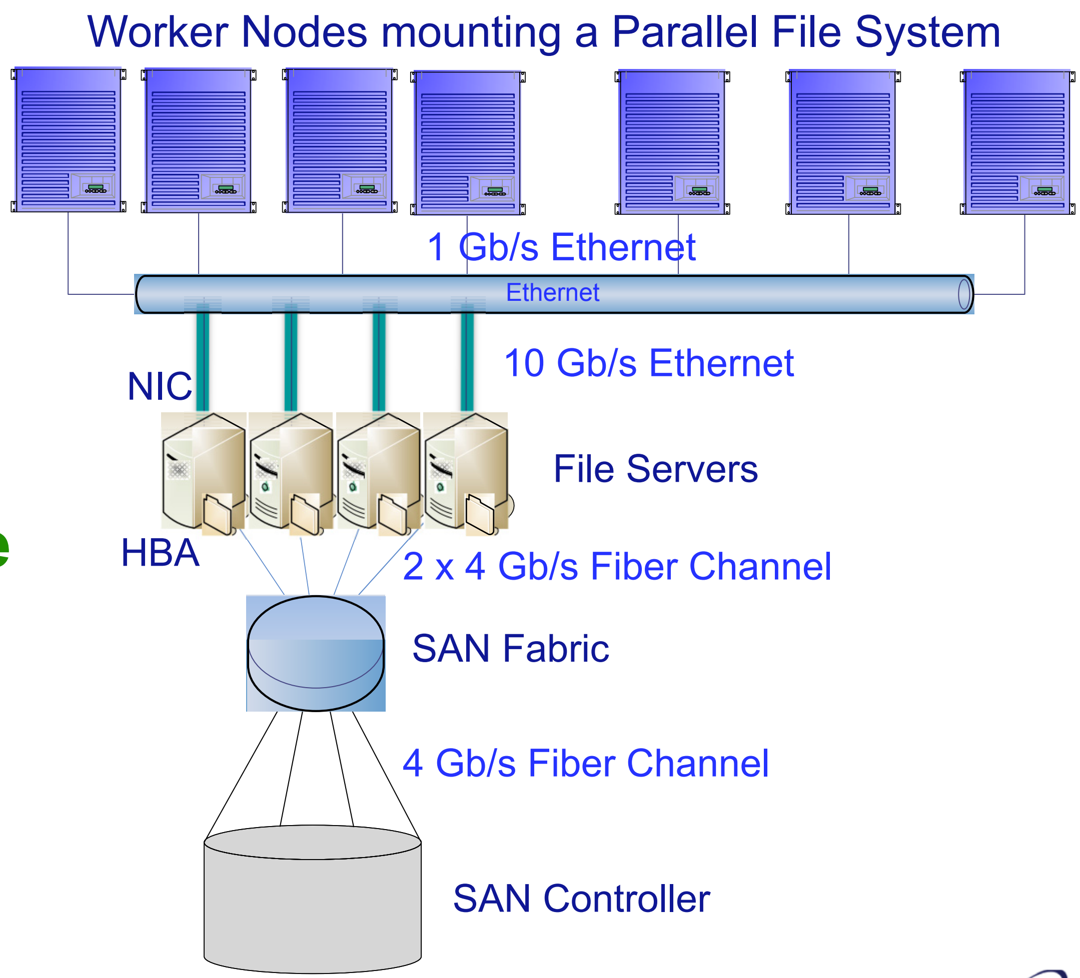
Use case 1: The On-Line Data Path (II)

- Trend in data packet rate and size.



Use Case 2: Network Storage in a SAN

- **File servers** in a **Storage Area Network** (SAN) which exports data to client nodes via Ethernet.
- Common situation in case of large computing farms:
  - Computing nodes access the mass storage through a pool of **Parallel File System** disk-servers:
    - E.g.: GPFS or Lustre.



High Speed Data Link Technology

- **Trend toward COTS technologies**:
  - HERA-B:
    - **Shark link** (proprietary, by Analog Devices) until level 2, than **Fast Ethernet**.
  - BaBar:
    - **Fast Ethernet**.
  - DØ:
    - **Fast Ethernet** / **Gigabit Ethernet**.
  - CDF:
    - **ATM** / **SCRAMnet** (proprietary, by Systran, low latency replicated non-coherent shared memory network).
  - CMS:
    - **Myrinet** (proprietary, Myricom) / **Gigabit Ethernet**.
  - Atlas / LHCb / Alice:
    - **Gigabit Ethernet**.
  - Possible new experiments:
    - **10-Gigabit Ethernet** (soon also on copper), **16-48-Gigabit infiniBand**, **100-Gigabit Ethernet**.

Commodity Links

- More and more often used in **HEP** for **DAQ**, **Event Building** and **High Level Trigger Systems**:
  - Limited costs;
  - Maintainability;
  - Upgradability.
- **Demand of data throughput** in **HEP** is **increasing** following:
  - Physical event rate;
  - Number of electronic channels;
  - Reduction of the on-line event filter (trigger) stages.
- **Industry** has **moved on** since the design of the DAQ for the LHC experiments:
  - **10 Gigabit/s Ethernet** well established;
  - **48 Gigabit/s InfiniBand** available;
  - **96 Gigabit/s InfiniBand** is being actively worked on;
  - **100 Gigabit/s Ethernet** is being actively worked on.

10 Gb/s Technologies

- **Ethernet**:
  - **10 Gb/s** well established
    - Various **optical** standards, short range **copper** (**CX4**), long range **copper** over **UTP CAT6A** standardised), widely used as aggregation technology.
  - Begins to conquer MAN and WAN market (succeeding SONET).
  - Large market share, vendor independent IEEE **standard** (802.3x).
  - Very active R&D on **100 Gigabit/s** and 40 Gigabit/s (will probably die).
- **Myrinet**:
  - Popular cluster-interconnect technology, **low latency**.
  - **10 Gb/s standard** (**optical** and **copper** (CX4) exist)
  - **Single vendor** (Myricom).
- **InfiniBand**:
  - Cluster interconnect technology, **low latency**.
  - **8 Gb/s** and **16 Gb/s** standards (**optical** and **copper**).
  - **Open** industry **standard**, **several vendors** (OEMs) but **very few chipmakers** (Mellanox).
  - Powerful protocol/software stack (reliable/unreliable datagrams, QoS, out-of-band messages etc…).

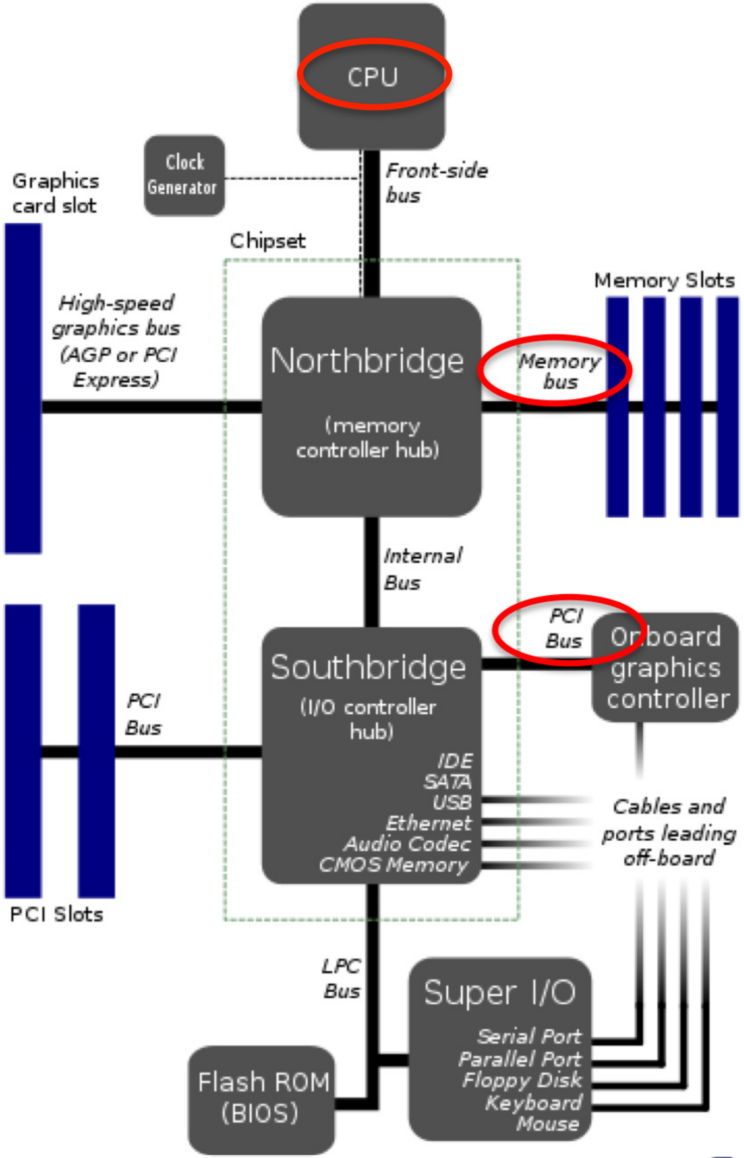
10 Gb/s Technologies (II)

Ethernet
1260 port switch

InfiniBand
3456 port switch

Bottlenecks

- **Direct access** to a high-speed network from a device can incur in 3 major system **bottlenecks**:
  - The **peripheral bus bandwidth**:
    - PCI, PCI-X, PCI-e.
  - The **memory bus bandwidth**:
    - Front Side Bus, AMD HyperTransport, Intel QuickPath Interconnect.
  - The **CPU utilization**.
- "**Fast network**, **slow host**" scenario:
  - **Moore's law**: "Every 18-24 months, computing power doubles…";
  - **Gilder's law**: "Every 12 months, optical fiber bandwidth doubles…".

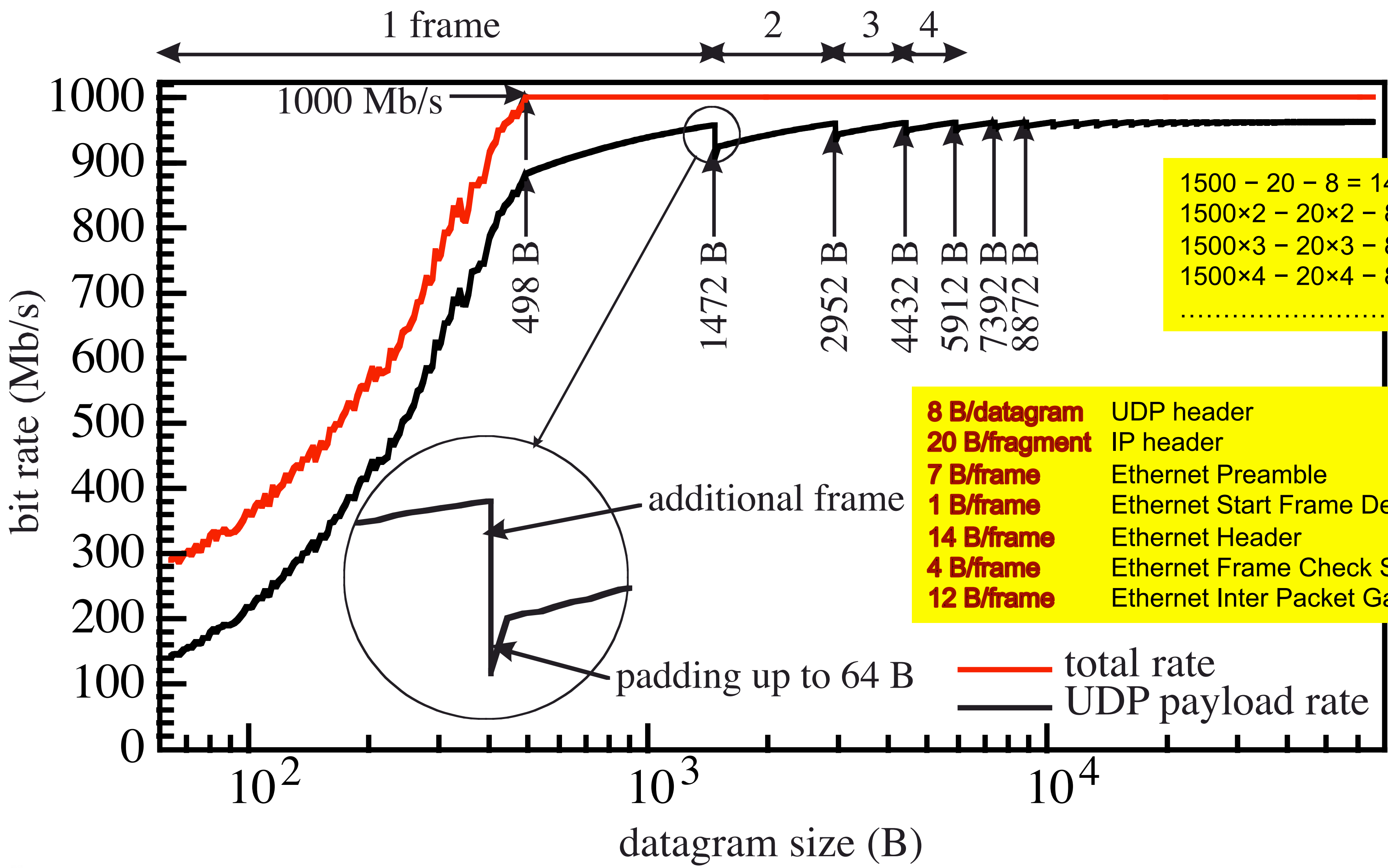


Nomenclature

- **Frame**: **Ethernet** Data Packet:
  - **Standard** Frames: 46 B – 1500 B payload size;
  - **Jumbo** Frames: 46 B – 9000 B payload size.
- **Datagram**: **IP**/**UDP** Data Packet:
  - 20 B – 64 KiB (65535 B) total size.
- **Fragment**: fragment of IP Datagram which fits into an Ethernet frame.
- **Segment**: **TCP** Data Packet:
  - Usually fits into the maximum Ethernet payload size (1500/9000 B).

1-Gigabit Ethernet UDP Bit-Transfer Rate

- **Year 2005**, bus **PCI-X** (**bottleneck**).

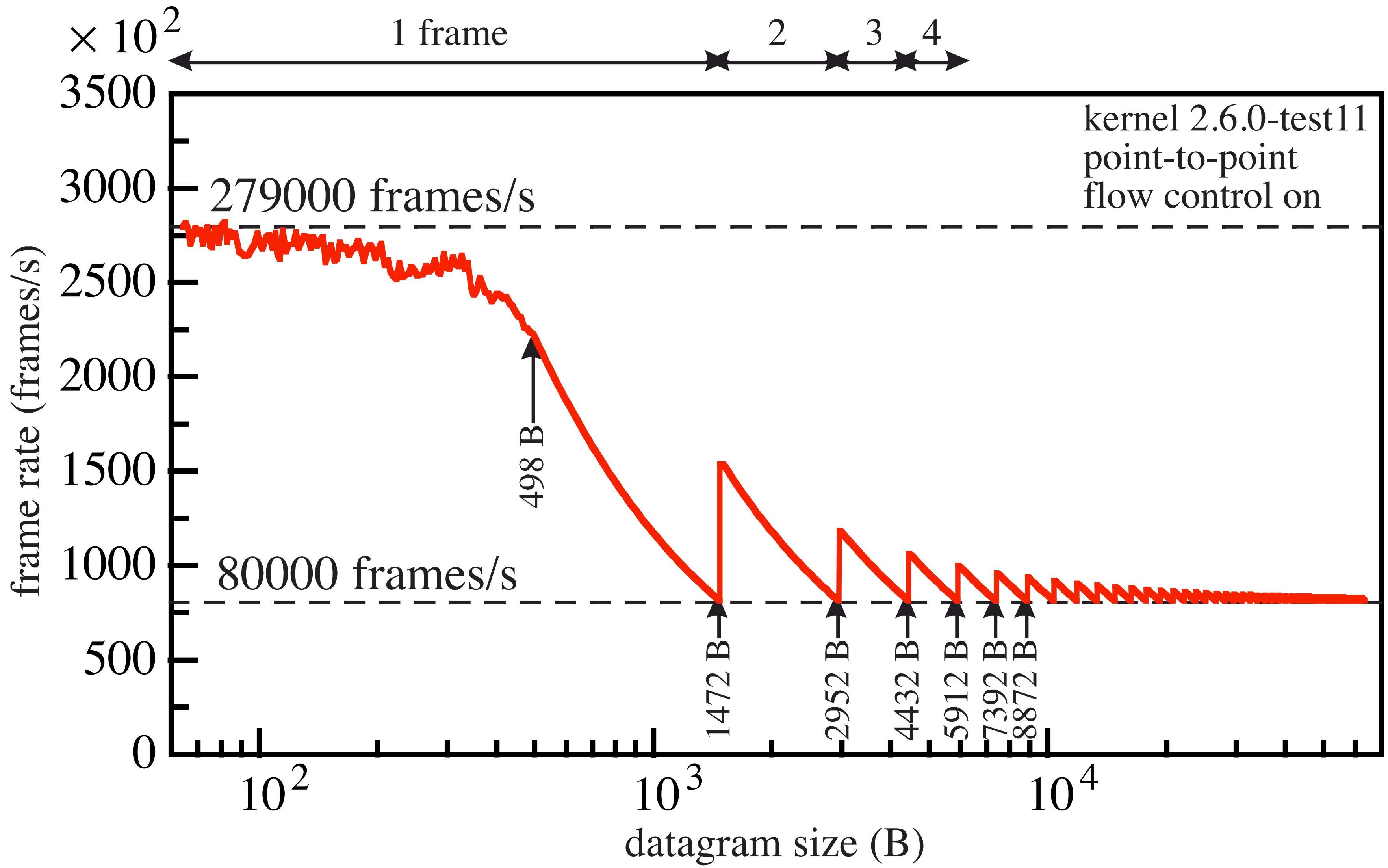


1500 − 20 − 8 = 1472
1500×2 − 20×2 − 8 = 2952
1500×3 − 20×3 − 8 = 4432
1500×4 − 20×4 − 8 = 5912
…………………………

8 B/datagram	UDP header
20 B/fragment	IP header
7 B/frame	Ethernet Preamble
1 B/frame	Ethernet Start Frame Delimiter
14 B/frame	Ethernet Header
4 B/frame	Ethernet Frame Check Sequence
12 B/frame	Ethernet Inter Packet Gap

1-Gigabit Ethernet Frame Transfer Rate

- **Year 2005**, bus **PCI-X** (**bottleneck**).



10-GbE Network I/O

- "Fast network, slow host" scenario.
- **Bottlenecks** in I/O performance:
  - The PCI-X **bus bandwidth** (peak throughput 8.5 Gbit/s in 133 MHz flavor):
    - Substituted by the **PCI-E**, (20 Gbit/s peak throughput in x8 flavor).
  - The **memory bandwidth**:
    - **FSB** has increased the clock from 533 MHz to 1600 MHz.
    - New Memory Architectures:
      - AMD **HyperTransport**;
      - Intel **QuickPath Interconnect**.
  - The **CPU utilization**:
    - **Multi-core** architectures.

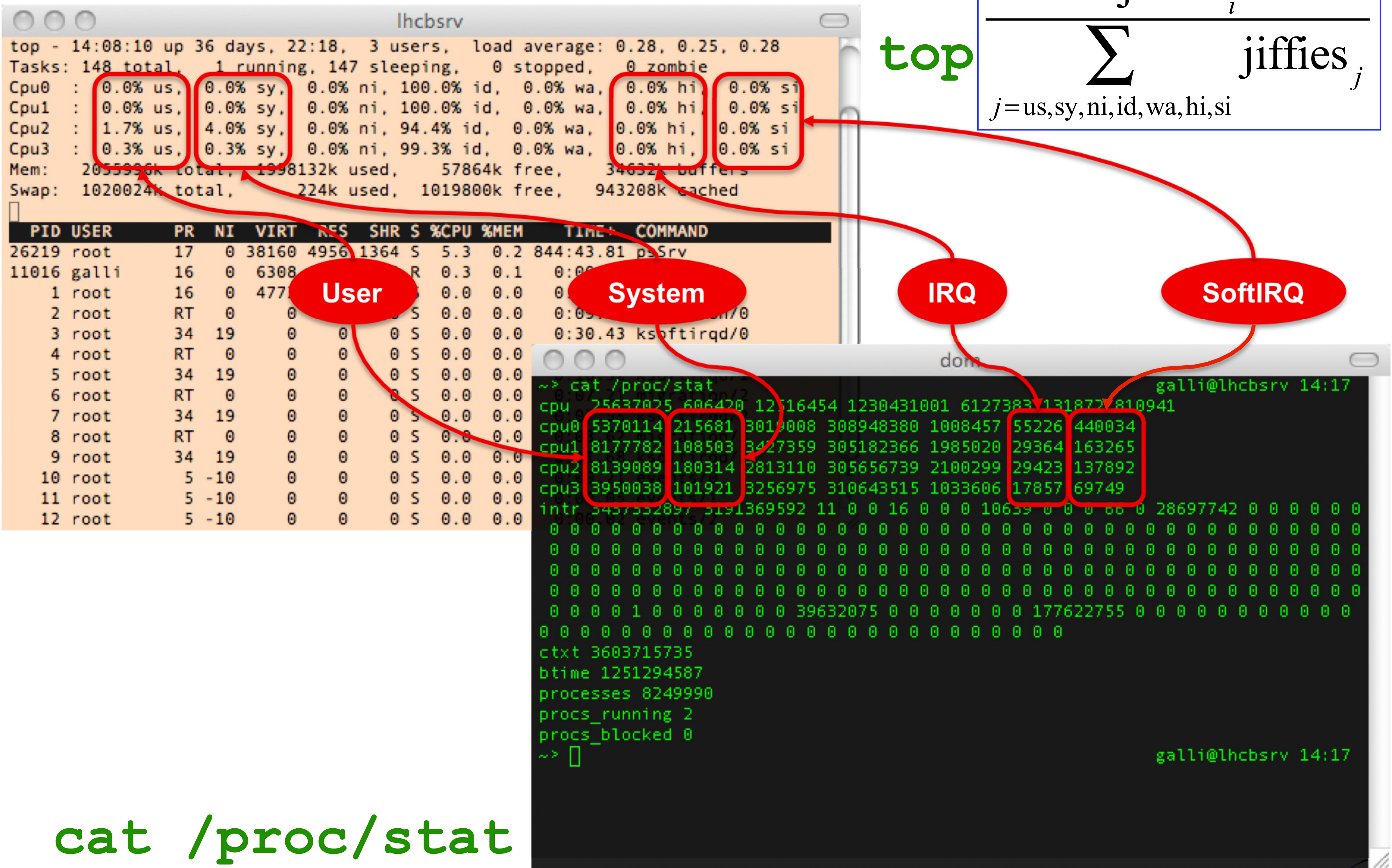
Sharing Workload among CPU Cores

- To take advantage of the **multiple cores** of recent CPUs, **workload** should be **shared** among different cores.
- The Linux Kernel splits the process of **sending/receiving** data packets into **different tasks**:
  - **Differently scheduled** and **accounted**;
  - Can be **partially distributed** over several CPU cores.
- Statistics of **kernel accounting** partitions accessible through the `/proc/stat` pseudo-file:
  - Data relative to **each CPU core**;
  - Partitions relevant to network processing: **User**, **System**, **IRQ** and **SoftIRQ**;
  - Number of **jiffies** (1/1000th of a second) spent by CPU core in each different mode.

Linux Kernel Accounting

$$\frac{\text{jiffies}_i}{\sum_{j=\text{us,sy,ni,id,wa,hi,si}} \text{jiffies}_j}$$

top



cat /proc/stat

Linux Kernel Accounting (II)

- **User**: User applications which send/receive data packets are typically **ordinary processes** which run in **user mode**:
  - **Non-privileged** execution mode;
  - **No access** to portions of memory allocated by the kernel or by other processes.
- **System**: to access a network device, the applications execute **system calls**, where the execution is switched to **kernel mode**:
  - **Privileged** execution mode (code assumed to be fully trusted);
  - **Any instruction** can be executed and **any memory address** can be referenced;
  - The **portion of the kernel** which is responsible of the required service is actually executed.

Linux Kernel Accounting (III)

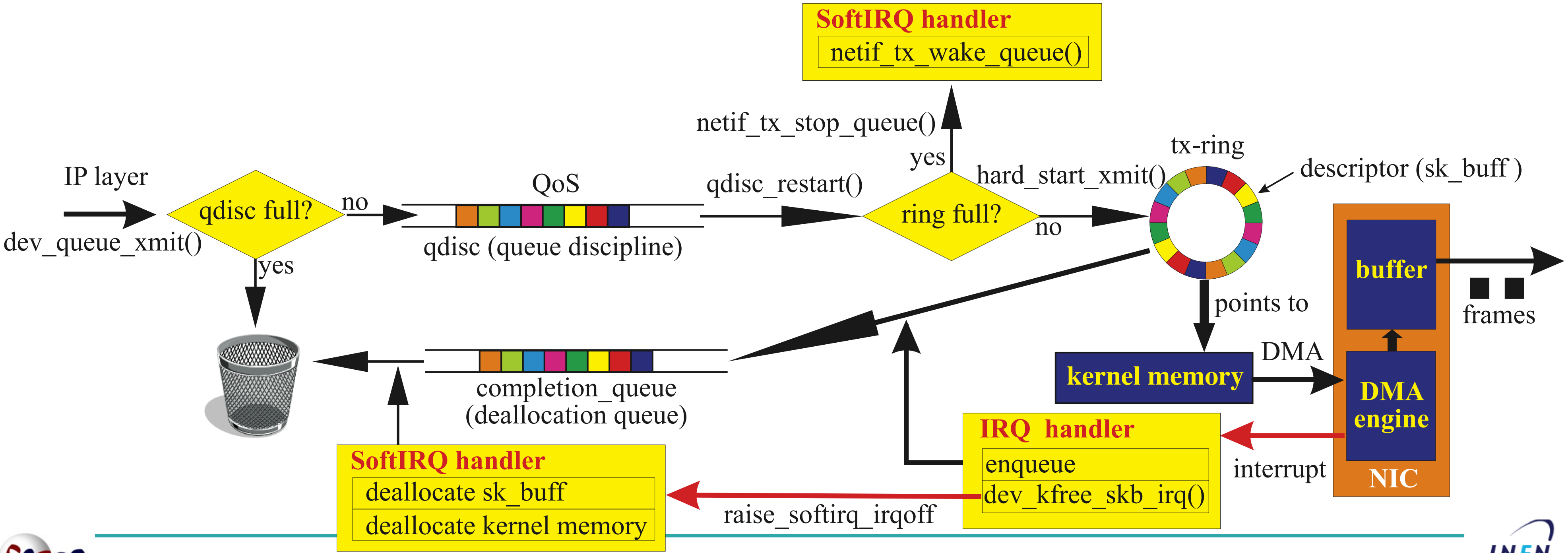
- **IRQ**: Transmission/reception code executed **out of the logical execution flow** of the applications:
  - **Driven by the motion of data packets** through the network.
    - E.g.: when new data packets reach the Network Interface Card (NIC) of a PC through a network cable, a procedure must be executed in order to process the received data and forward them to the appropriate user application which is waiting for data.
  - To this aim the kernel provides **hardware interrupt handlers**, which are **software routines executed upon the reception of hardware interrupt** signals, in our case raised by the NIC.

Linux Kernel Accounting (IV)

- **SoftIRQ**: Code executed **out of interrupt context** (interrupt reception enabled), **scheduled by hardware interrupt** handlers:
  - While the kernel is processing hardware interrupts (**interrupt context**), the interrupt reception is disabled, hence **interrupts** received in the meantime are **lost**.
  - To avoid such a situation, the hardware interrupt handlers perform **only the work which must be accomplished immediately** (**top half**), so **limiting to the minimum the amount of time spent with interrupts disabled**.
  - The **real work** is instead **deferred** to the execution of so-called **software interrupt handlers** (**bottom half**), which are usually scheduled by hardware interrupt handlers;
  - Always executed **on the same CPU** where they were originally raised.

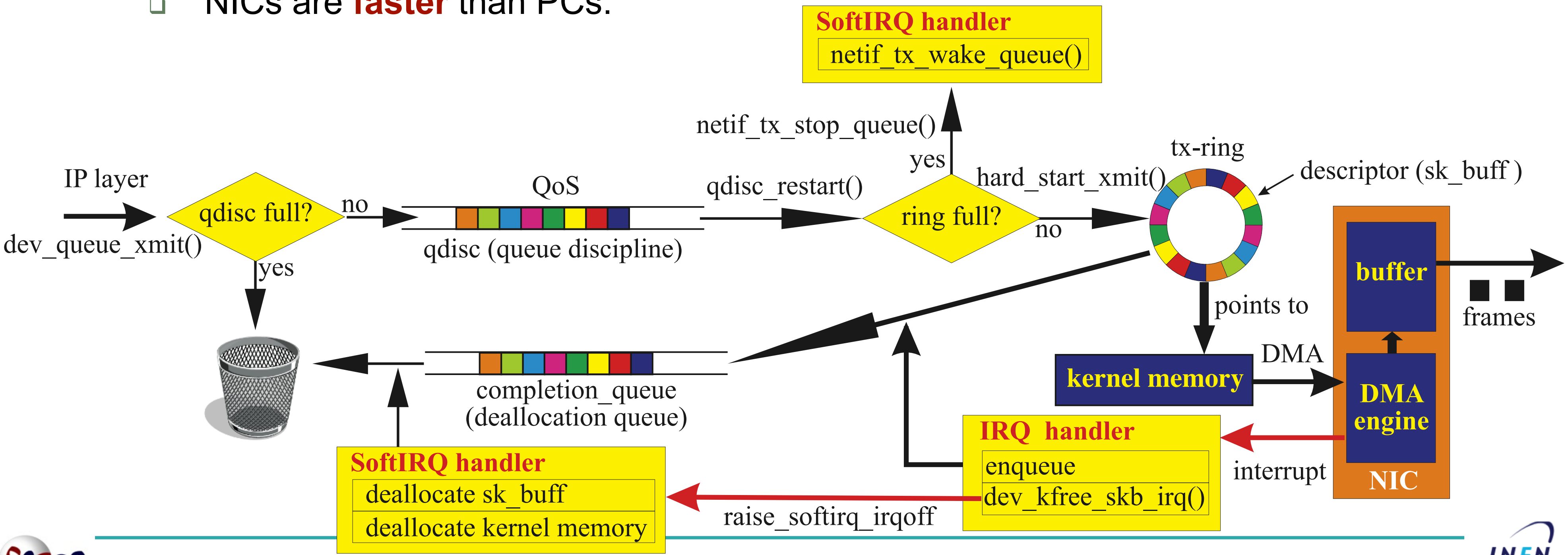
Packet Transmission

- Packet sent from IP layer to Queue Discipline (**qdisc**).
- Any appropriate **Quality of Service** (QoS) in **qdisc**:
  - **pfifo_fast** (packet fifo);
  - **RED** (Random Early Drop);
  - **CBQ** (Class Based Queuing).
- **qdisc** notifies network driver when it's **time to send**: it calls **hard_start_xmit()**:
  - Place all ready **sk_buff** pointers in **tx_ring**;
  - Notifies NIC that packets are ready to send.



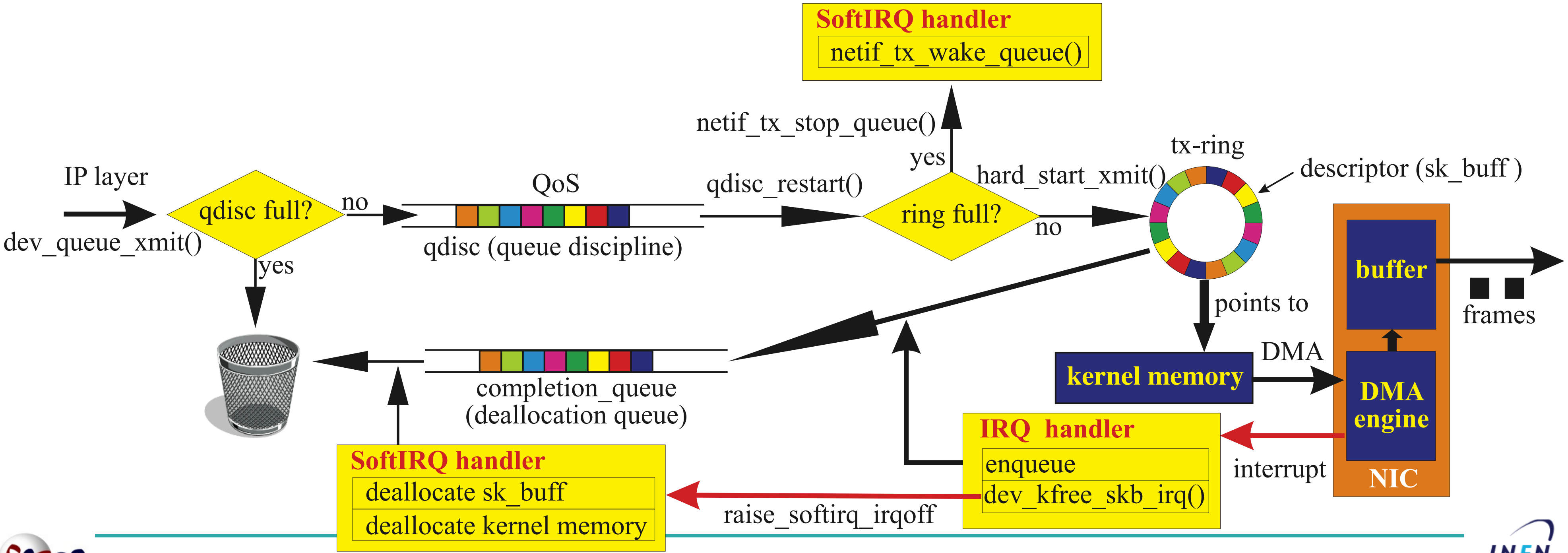
Packet Transmission (II)

- If **immediate sending** is **not possible**:
  - The driver **stops the queuing** of packets by calling `netif_tx_stop_queue()`:
    - **No more calls** to `hard_start_xmit()` **allowed**.
      - Until the queue is woken up by a call to **netif_tx_wake_queue()**.
  - A **SoftIRQ** is scheduled and the packet **transmission** "over the wire" is **deferred** to a later time.
- Could happen if the **device** is running **out of resources**.
- System could in principle generate packets for transmission **faster** than the device can handle.
- Using recent PCs and NICs, **in practice**, this **never happens**:
  - NICs are **faster** than PCs.



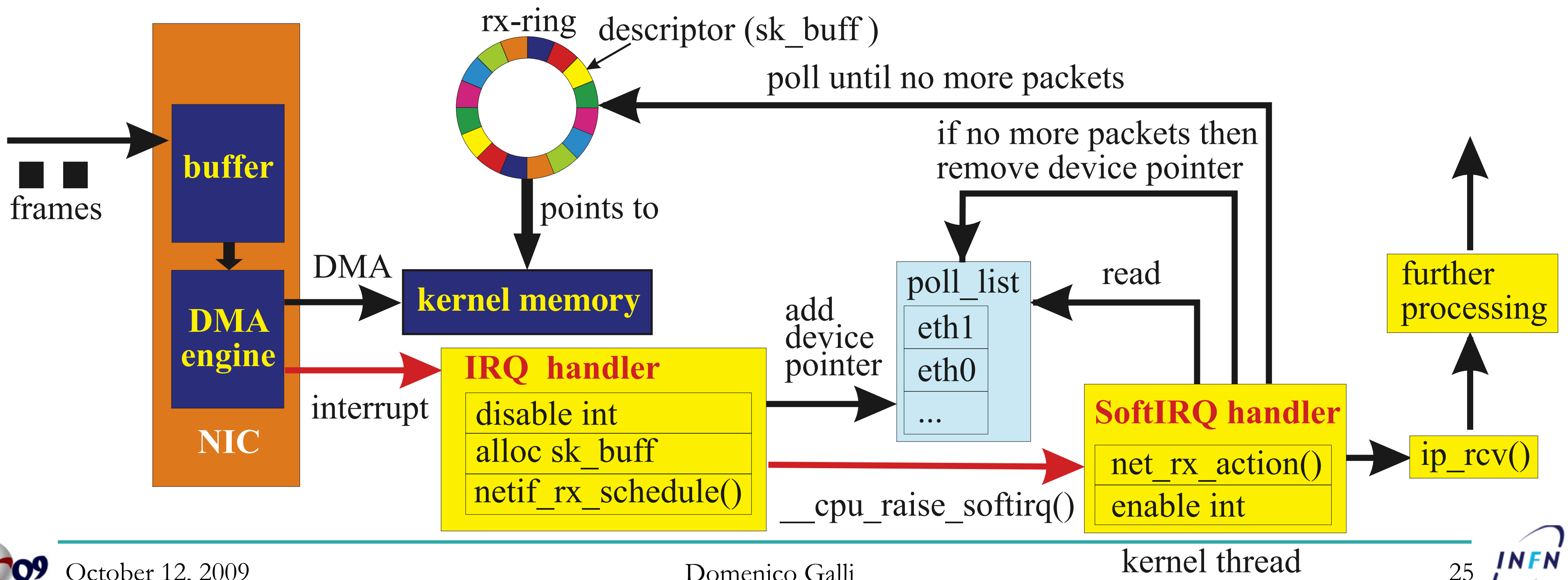
Packet Transmission (III)

- The NIC signals the kernel (via **interrupt**) when packets are **successfully** transmitted:
  - **Highly variable on when interrupt is sent!**
- Interrupt handler **enqueues** transmitted packets **for deallocation** (`completion_queue`);
- At next **`softirq`**, all packets in the `completion_queue` are deallocated:
  - Meta-data contained in the `sk_buff` struct;
  - Packet data not needed anymore.



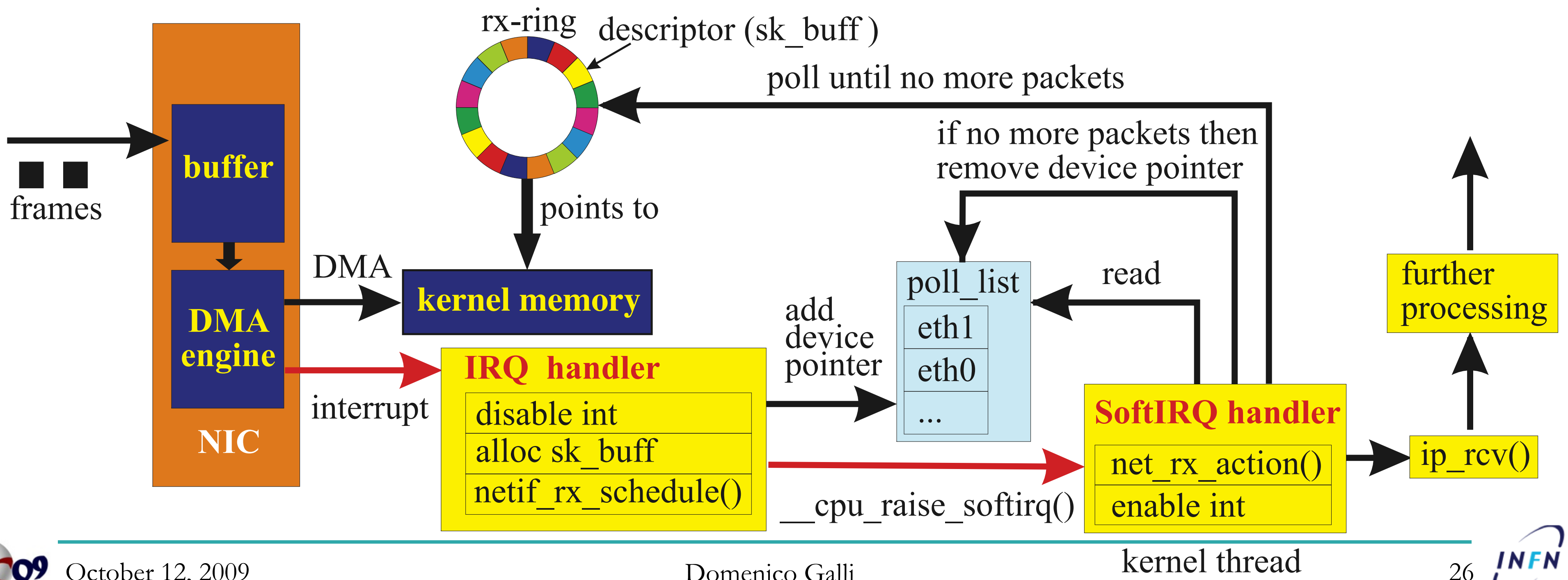
Packet Reception

- NIC **accumulates** a bunch of frames in an **internal buffer**.
- NIC start a **bus-mastered DMA transfer** from the buffer to a reserved space in the **kernel memory**.
  - Packet descriptors (metadata, sk_buff) pointing to data are stored in a circular ring (`rx-ring`).
- As soon as the **DMA transfer has terminated**, the NIC **notifies the kernel** of the new available packets:
  - By means of an **interrupt** signal raised on a **dedicated IRQ line**.
- The **Interrupt Controller** issues an interrupt to the dedicated **processor pin**.



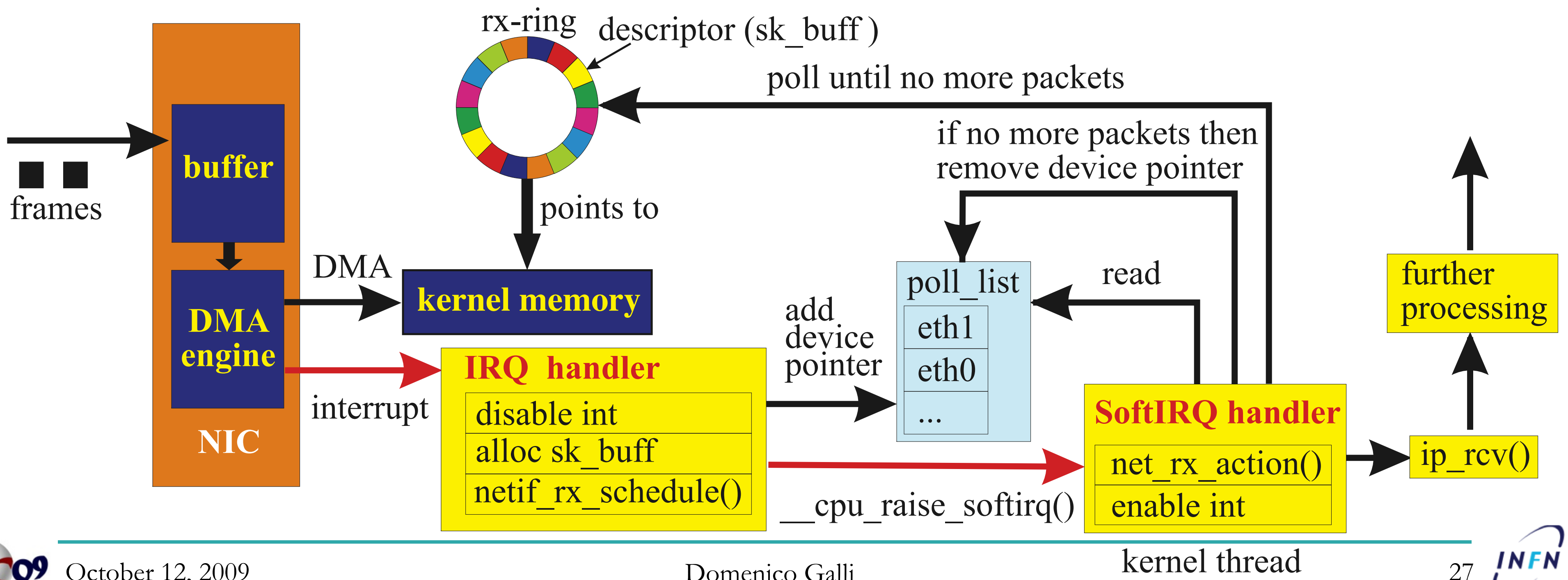
Packet Reception (II)

- The kernel reacts to the IRQ by executing *a* hardware **interrupt handler**.
- The handler **leaves** the packets in the **`rx_ring`** and **enables polling** mode for the originating NIC:
  - By **disabling the *IRQ* reception** for that NIC and **putting a reference to the NIC** in a **poll-list** attached to the interrupted CPU, and finally schedules a **SoftIRQ**.
- The SoftIRQ handler polls all the NICs registered in the poll-list to **draw packets** from the **`rx_ring`** (in order to process them) until a configurable number of packets at maximum, known as **quota** and controlled by the parameter **`netdev_max_backlog`**, is reached.



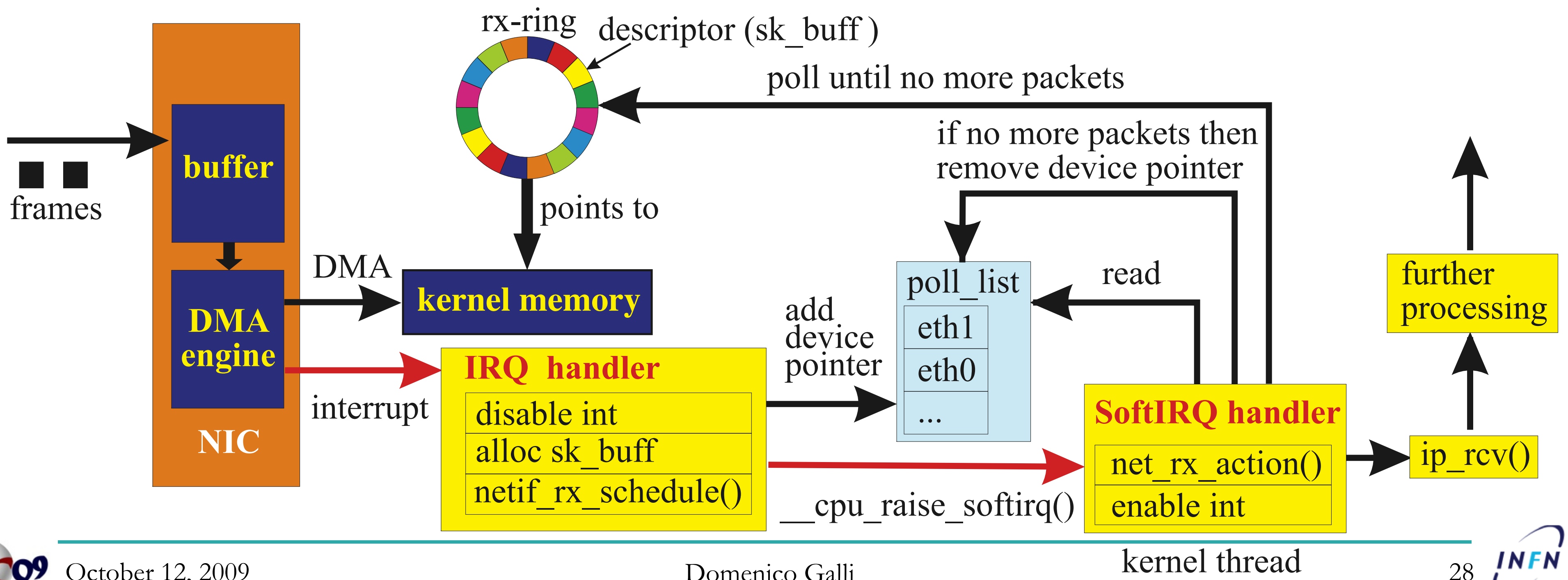
Packet Reception (III)

- If the **quota** is **reached**, but the NIC has **still packets to offer**:
  - Then the NIC is **put at the end of the poll-list**.
- If the **quota** is **reached**, but the NIC has **no more packets to offer**:
  - The NIC is **deleted from the poll-list** and the **IRQ reception** for that NIC is **enabled again**.



Packet Reception (IV)

- Reception mechanism, known as **NAPI** (New Network Application Program Interface):
  - Introduced in the **2.6 kernel** series.
- Main feature:
  - Converge to an **interrupt-driven mechanism** under **light network traffic**:
    - Reducing both latency and CPU load.
  - Converge to to a **poll mechanism** under **high network traffic**:
    - Avoiding **live-lock** conditions:
      - Packets are accepted only **as fast as the system is able process them**.



Setting the Process-to-CPU Affinity

- **Library calls**:
  - `#include <sched.h>`
  - `int` **`sched_setaffinity`** `(pid_t` **`tgid`**`, unsigned int` **`cpusetsize`**`, cpu_set_t *`**`mask`**`)`
  - `int` **`sched_getaffinity`** `(pid_t` **`tgid`**`, unsigned int` **`cpusetsize`**`, cpu_set_t *`**`mask`**`)`
- **Macro** to set/get the CPU mask:
  - `void` **`CPU_CLR`**`(int` **`cpu`**`, cpu_set_t *`**`mask`**`)`
  - `int` **`CPU_ISSET`**`(int` **`cpu`**`, cpu_set_t *`**`mask`**`)`
  - `void` **`CPU_SET`**`(int` **`cpu`**`, cpu_set_t *`**`mask`**`)`
  - `void` **`CPU_ZERO`**`(cpu_set_t *`**`mask`**`)`
- **Parameters**:
  - **`tgid`**: thread group identifier (was pid);
  - **`cpusetsize`**: length (in bytes) of the data pointed to by mask. Normally: `sizeof(cpu_set_t)`.
  - **`mask`**: CPU mask (structure).

Setting the Process-to-CPU Affinity

- **Shell commands**:
  - `taskset [mask] -- [command] [arguments]`
  - `taskset -p [tgid]`
  - `taskset -p [mask] [tgid]`
- **Parameters**:
  - `tgid`: thread group identifier (was pid);
  - `mask`: bitmask, with the lowest order bit corresponding to the first logical CPU and the highest order bit corresponding to the last logical CPU:
    - `0x00000001` is processor #0;
    - `0x00000002` is processor #1;
    - `0x00000003` is processors #0 and #1;
    - `0x0000000f` is processor #0 through #3;
    - `0x000000f0` is processors #4 through #7;
    - `0xffffffff` is all processors (#0 through #31).

Setting the Interrupt-to-CPU Affinity

- Usually `irqbalance` daemon running in Linux distributions:
  - `irqbalance` **automatically distributes interrupts** over the processors and cores;
  - Design goal of `irqbalance`: find a **balance** between **power savings** and **optimal performance**.
- To **manually** optimize network workload distribution among CPU core `irqbalance` has to be **switched off**:
  - `service irqbalance status`
  - `service irqbalance stop`

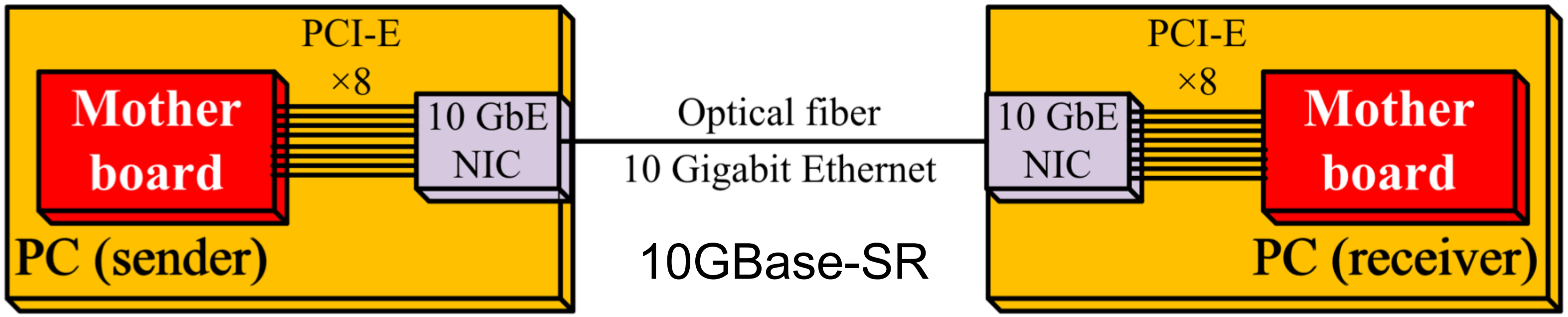
Setting the Interrupt-to-CPU Affinity (II)

- **To find IRQ #:**
  - `cat /proc/interrupts`
- **To set CPU Affinity for the handler of IRQ N:**
  - `echo ⟨mask⟩ >/proc/irq/⟨N⟩/smp_affinity`

```
[root@lhcbsrv ~]# cat /proc/interrupts
           CPU0       CPU1       CPU2       CPU3
  0:  764171426  782928855  772144125  783044446    IO-APIC-edge  timer
  1:          0          0          0         11    IO-APIC-edge  i8042
  4:          0          0          4         12    IO-APIC-edge  serial
  8:       2614       2531       2642       2556    IO-APIC-edge  rtc
  9:          0          0          0          0   IO-APIC-level  acpi
 12:          0          0          0         66    IO-APIC-edge  i8042
 14:    3240199   10456731   10598289    3601451    IO-APIC-edge  ide0
169:          0          0          0          0   IO-APIC-level  uhci_hcd
177:          0          0          0          0   IO-APIC-level  uhci_hcd
185:          0          0          0          1   IO-APIC-level  ehci_hcd
193:    8267699   10522243   10674619    9203133   IO-APIC-level  libata
201:  172756650       2317          0       1352   IO-APIC-level  eth0
NMI:     235372     226427     235290     226286
LOC: 3101981654 3102143482 3101981635 3102143484
ERR:          0
MIS:          0
[root@lhcbsrv ~]# cat /proc/irq/201/smp_affinity
02
[root@lhcbsrv ~]# echo 01 >/proc/irq/201/smp_affinity
[root@lhcbsrv ~]# cat /proc/irq/201/smp_affinity
01
[root@lhcbsrv ~]#
```

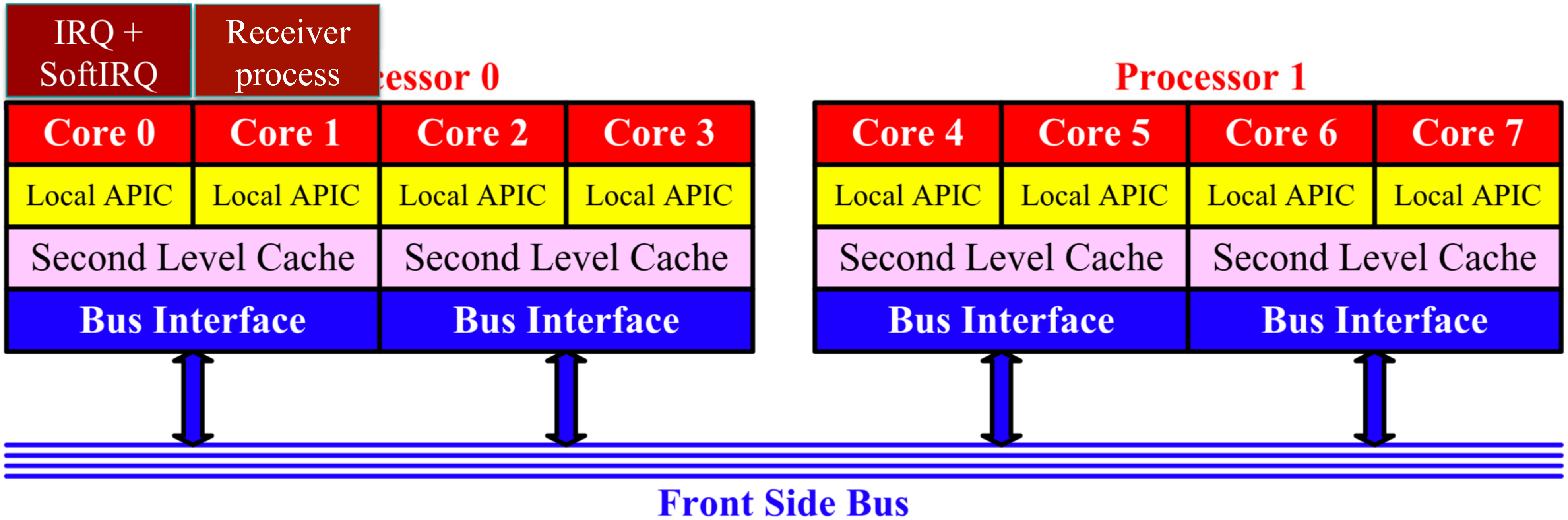
10-GbE Point-to-Point Throughput

- In real operating condition, maximum transfer rate **limited** not only by the capacity of the link itself, but also:
  - By the capacity of the data busses (PCI and FSB);
  - By the ability of the **CPUs** and of the **OS** to handle **packet processing** and **interrupt rates** raised by the network interface cards in due time.
- **Data throughput** & **CPU load** measures reported:
  - **NIC** mounted on the **PCI-E bus** of **commodity PCs** as transmitters and receivers.



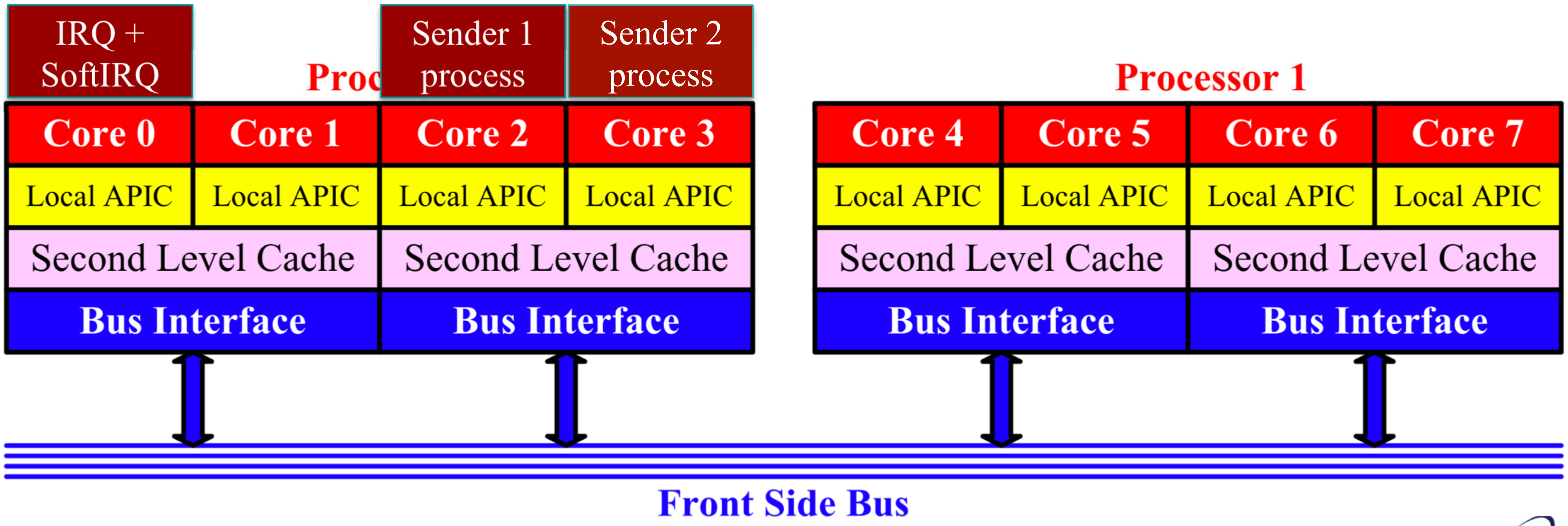
CPU Affinity Settings

10-GbE Receiver		
Core	**L2 Cache**	**Task**
0	0	(IRQ + softIRQ) from Ethernet NIC
1		Receiver process



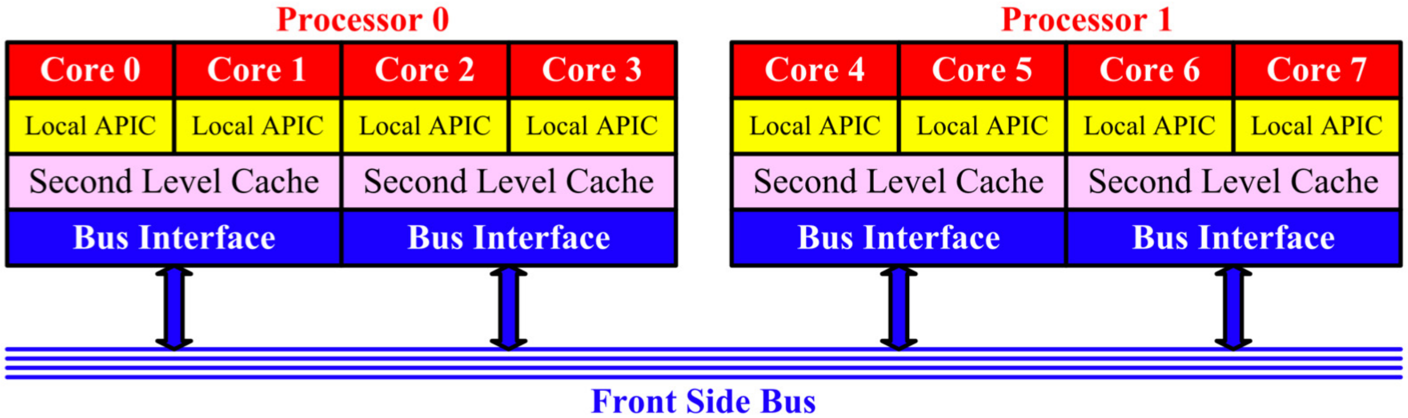
CPU Affinity Settings (II)

10-GbE Sender		
Core	**L2 Cache**	**Task**
0	0	(IRQ + softIRQ) from Ethernet NIC
1		
2	1	Sender process
3		Second sender process [2 sender tests]



Test Platform

Motherboard	IBM X3650
Processor type	Intel Xeon E5335
Procesors x cores x clock (GHz)	2 x 4 x 2.00
L2 cache (MiB)	8
L2 speed (GHz)	2.00
FSB speed (MHz)	1333
Chipset	Intel 5000P
RAM	4 GiB
NIC	Myricom 10G-PCIE-8A-S
NIC DMA Speed (Gbit/s) ro / wo /rw	10.44 / 14.54 / 19.07



Settings

net.core.rmem_max (B)	16777216
net.core.wmem_max (B)	16777216
net.ipv4.tcp_rmem (B)	4096 / 87380 / 16777216
net.ipv4.tcp_wmem (B)	4096 / 65536 / 16777216
net.core.netdev_max_backlog	250000
Interrupt Coalescence (μ s)	25
PCI-E speed (Gbit/s)	2.5
PCI-E width	x8
Write Combining	enabled
Interrupt Type	MSI

UDP Data Transfer

- **User Datagram Protocol**:
  - **Connectionless**, **unreliable** messages (**datagrams**) of a fixed **maximum length of 64 KiB**.
  - What does UDP do:
    - **Simple interface to IP** protocol (fragmentation, routing, etc.);
    - **Demultiplexing** multiple processes using the **ports**.
  - What does **not** UDP do:
    - Retransmission upon receipt of a bad packet;
    - Flow control;
    - Error control;
    - Congestion control.

bits	0 - 15	16 - 31
0	Source Port	Destination Port
32	Length	Checksum
64	Data	

Why UDP?

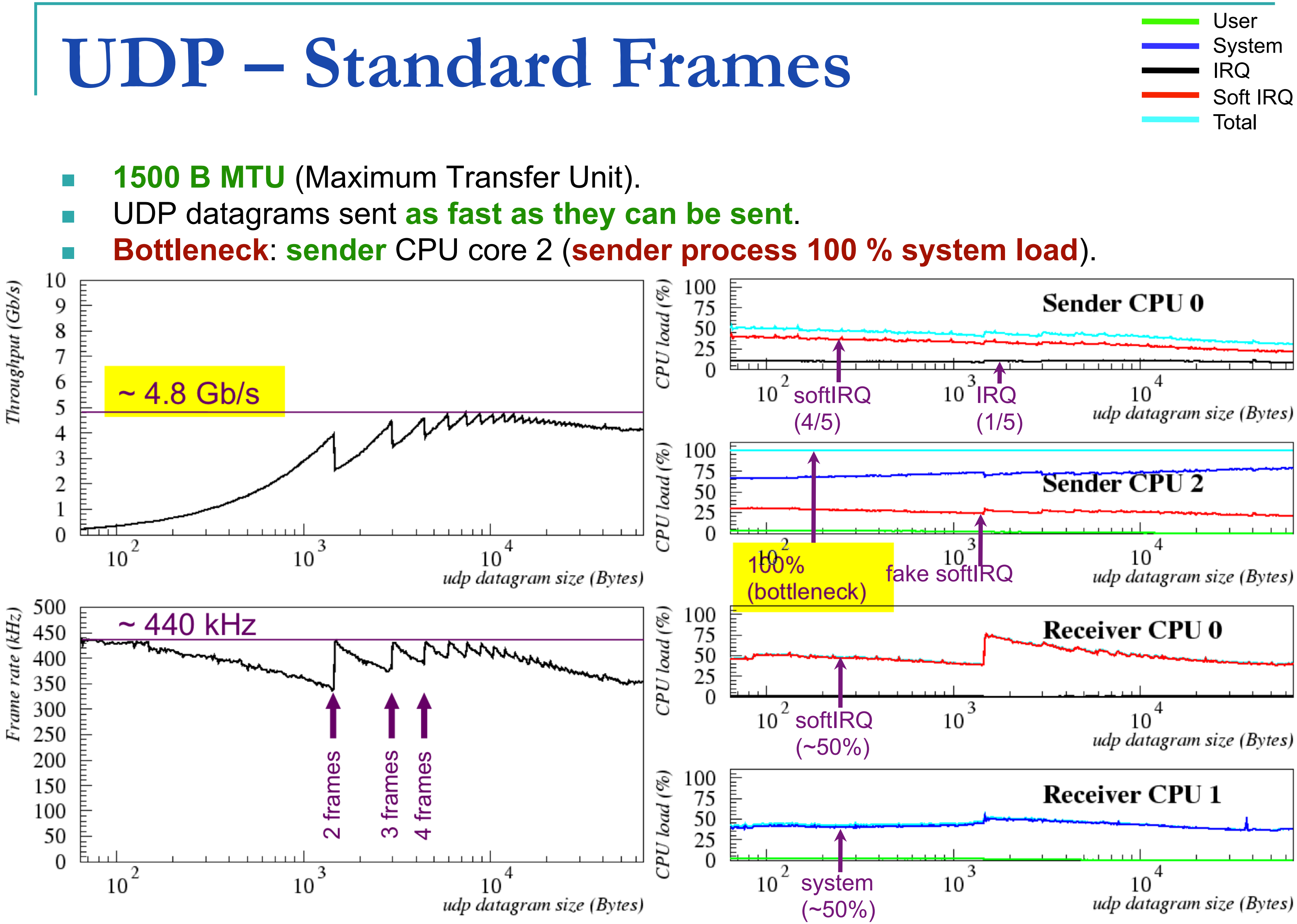
- TCP is optimized for **accurate** delivery rather than for **timely** delivery:
  - **Relatively long delays** (in the order of **seconds**) while waiting for **out-of-order** messages or **retransmissions** of lost messages.
- TCP not particularly suitable for **real-time applications**:
  - In time-sensitive applications, **dropping** packets is sometimes **preferable** to **waiting** for **delayed** or **retransmitted** packets.
  - UDP/RTP (Real-time Transport Protocol) preferred:
    - e.g. Voice over IP.

Why UDP in DAQ Chain?

- **High link occupancy** is **desirable**:
  - To maximize the physical event rate.
- The **data flow** is **driven** by **accelerator/detector** rates (**time-sensitive** application):
  - Independent on the PC which process data.
- Mechanisms which **slow down** data transmission are **not** appreciated:
  - E.g. in TCP: **slow start**, **congestion avoidance**, **flow control**.
- Mechanisms for **reliability** (retransmission) can be **useless** due to **latency limits**.
- **Retransmission** requires **additional bandwidth**, which is **stolen from the event bandwidth**:
  - If the **available bandwidth** is **limited**, retransmission will probably trigger a throttling system which discards physical events in any case.

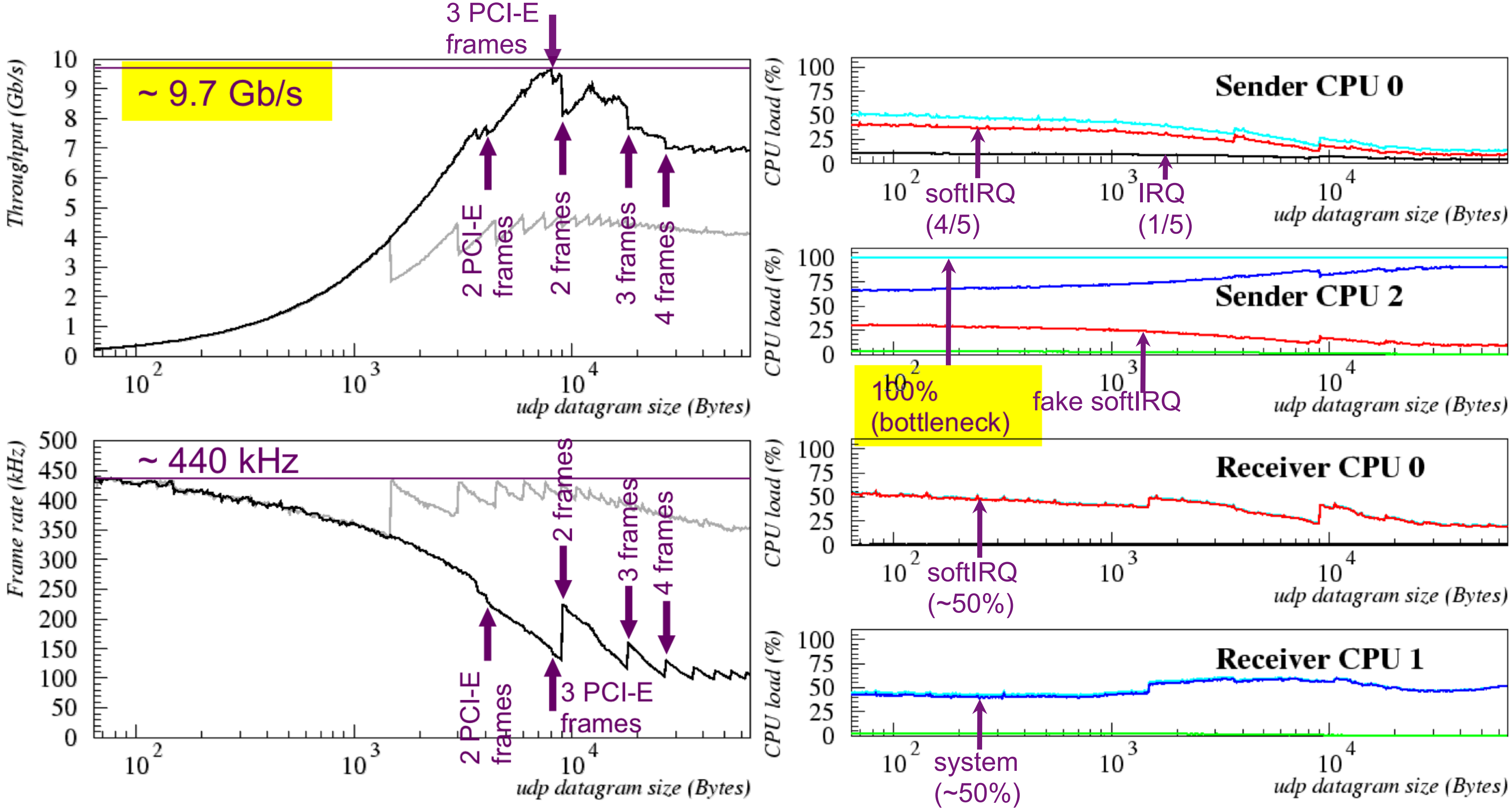
UDP – Standard Frames

- **1500 B MTU** (Maximum Transfer Unit).
- UDP datagrams sent **as fast as they can be sent**.
- **Bottleneck**: **sender** CPU core 2 (**sender process 100 % system load**).



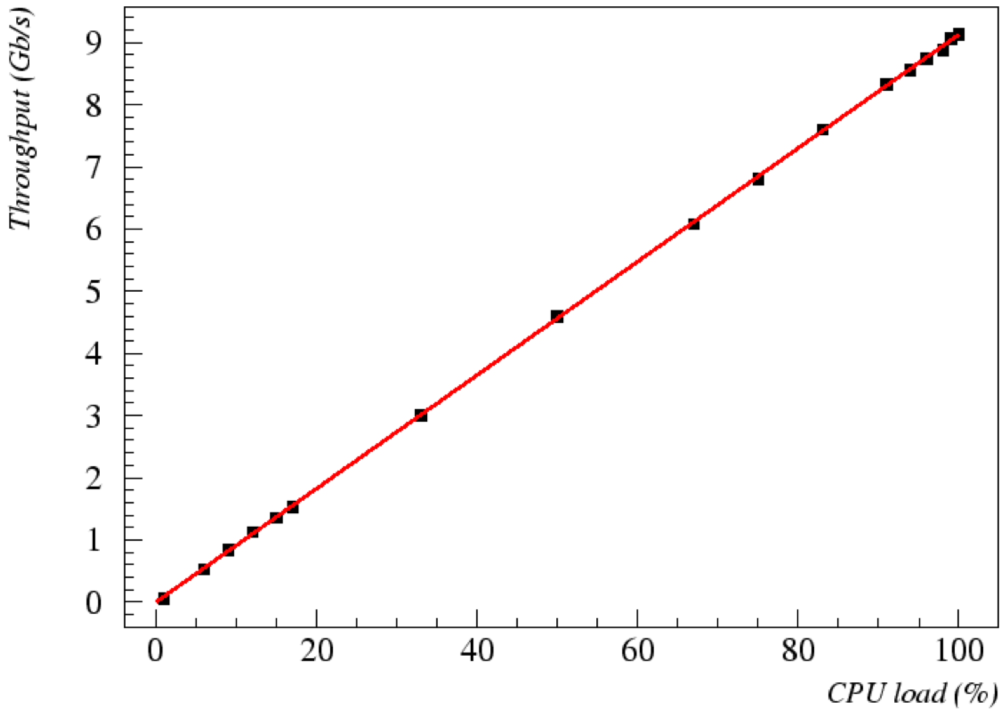
UDP – Jumbo Frames

- 9000 B MTU.
- Sensible **enhancement** with respect to 1500 MTU.



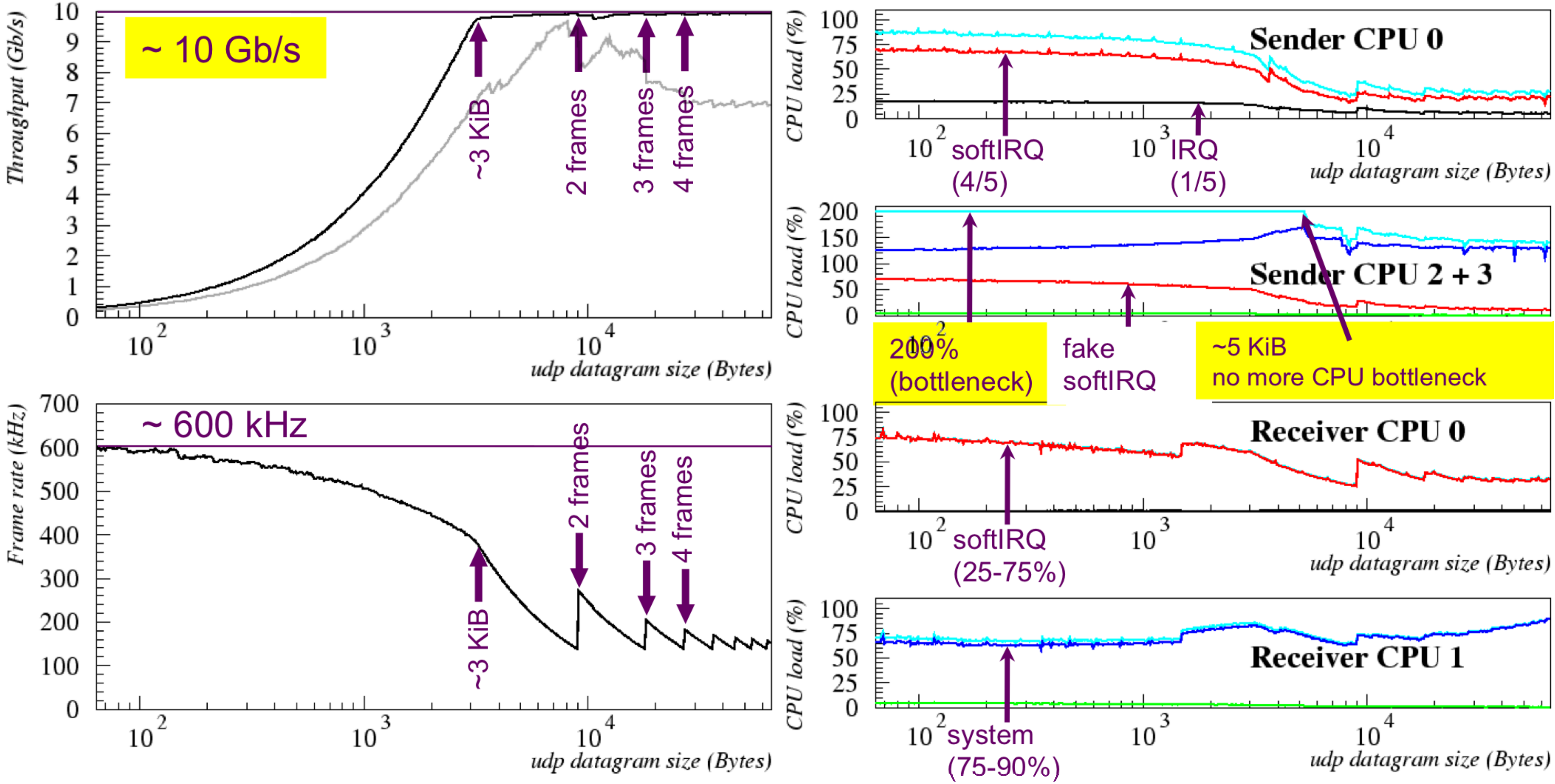
UDP – Jumbo Frames (II)

- Additional dummy **ps**, **bound** to the **same core** of the **tx ps** (CPU 2), **wasting CPU resources**.
- CPU available for tx process **trimmed** using relative **priority**.
- The **perfect linearity** confirms that the **system CPU load @ sender side** was actually **the main bottleneck**.
- **2 GHz ➔ 3 GHz CPU** (same architecture):
  - Potential increase of 50% in the maximum throughput:
    - Provided that bottlenecks of other kinds do not show up before such increase is reached.



UDP – Jumbo Frames – 2 Senders

- **Doubled availability** of **CPU cycles** to the **sender** PC.
- **10GbE** fully **saturated.**
- **Receiver** (playing **against 2 senders**) **not yet saturated**.



TCP Data Transfer

- **Transmission Control Protocol**:
  - Provides a **reliable** end-to-end **byte stream** over an unreliable network.
  - Designed to **dynamically adapt** to properties of the internetwork and to be **robust** in the face of many kinds of failures.
- TCP **breaks** outgoing data **streams** into pieces (**segments**) which usually **fit** in a single network **frame** and which are sent as **separate IP datagrams**.

TCP Header

Bit offset	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	Source port																Destination port															
32	Sequence number																															
64	Acknowledgment number																															
96	Data offset				Reserved				CWR	ECE	URG	ACK	PSH	RST	SYN	FIN	Window Size															
128	Checksum																Urgent pointer															
160	Options (if Data Offset > 5)																															
...	...																															

TCP Data Transfer (II)

- TCP key feature:
  - **Ordered data transfer**:
    - The destination host rearranges segments according to **sequence number**.
  - **Retransmission of lost packets**:
    - Any cumulative stream **not acknowledged** will be retransmitted.
  - **Discarding duplicate packets**.
  - **Error-free data transfer**:
    - Checksum.
  - **Flow control** (sliding windows):
    - **Limits the rate** a sender transfers data to guarantee reliable delivery;
    - The receiver specifies in the receive **window** field the amount of additional received data (in bytes) that it is willing to buffer for the connection;
    - When the receiving host's buffer fills, the next acknowledgement contains a 0 in the window size, to stop transfer and allow the data in the buffer to be processed.
  - **Congestion avoidance**:
    - Avoid congestion collapse.

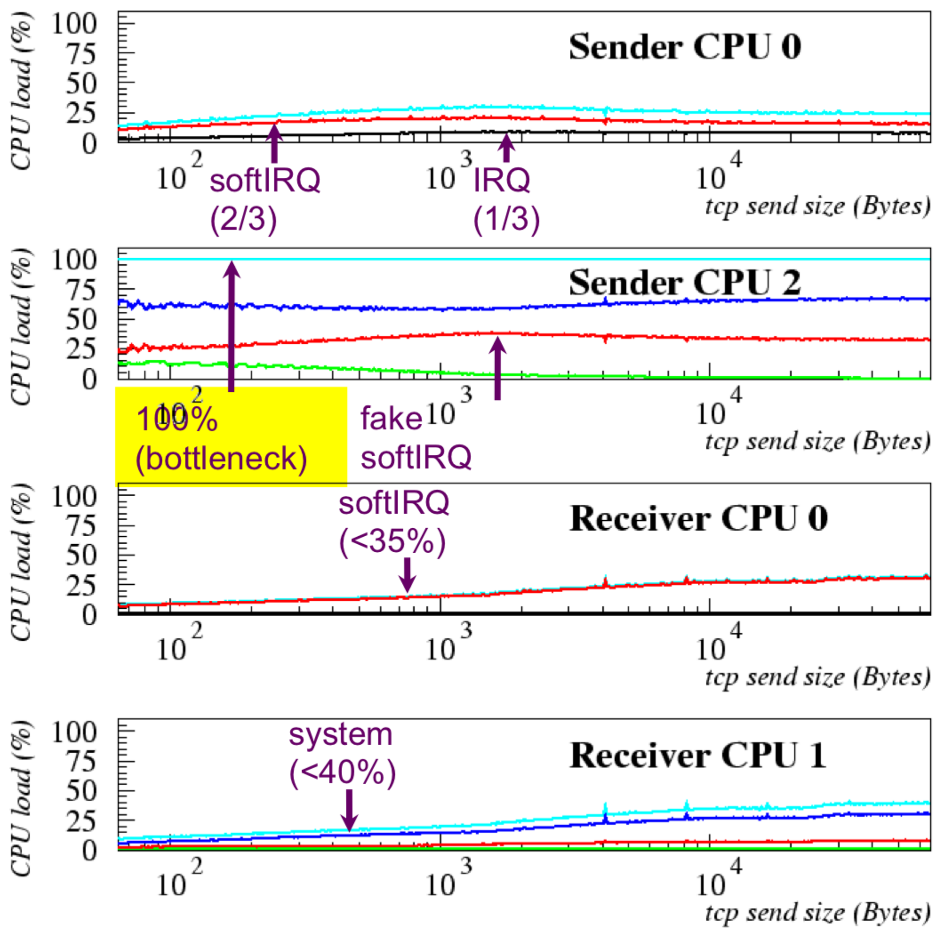
TCP Data Transfer (III)

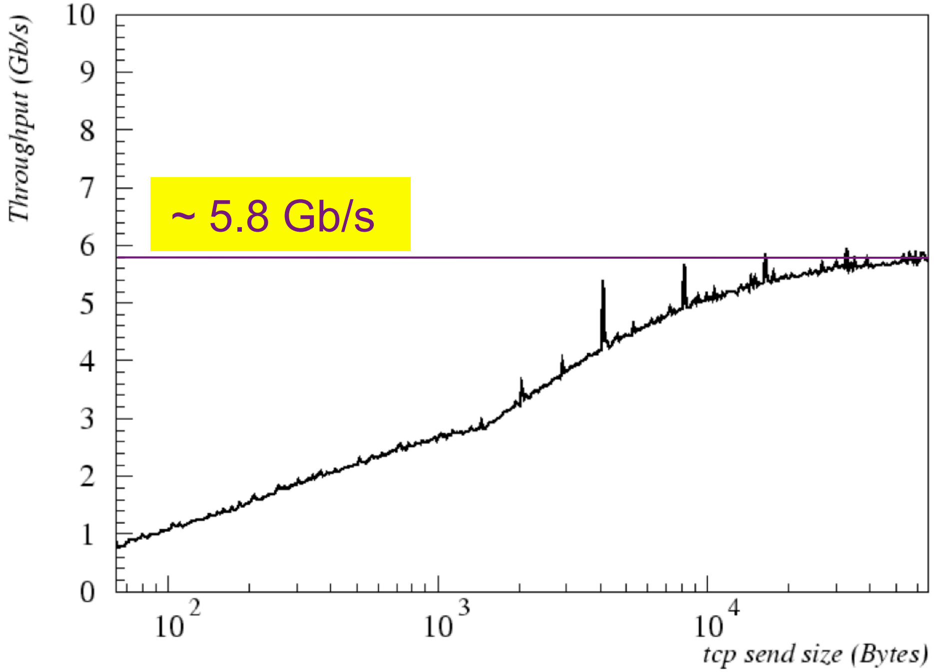
- TCP provides many **additional control mechanisms**:
  - **Selective acknowledgments**;
    - Allows the receiver to acknowledge discontiguous blocks of packets that were received correctly.
  - **Nagle's algorithm**:
    - To cope with the small packet problem.
  - **Clark's solution**:
    - To cope with the silly window sindrome.
  - **Slow-start**, **congestion avoidance**, **fast retransmit**, and **fast recovery**:
    - Which cooperate to congestion control.
  - **Retransmission timeout**:
    - **Karn's algorithm**, **TCP timestamps**, **Jacobson's algorithm** for evaluating round-trip time.

TCP – Standard Frames

User
System
IRQ
Soft IRQ
Total

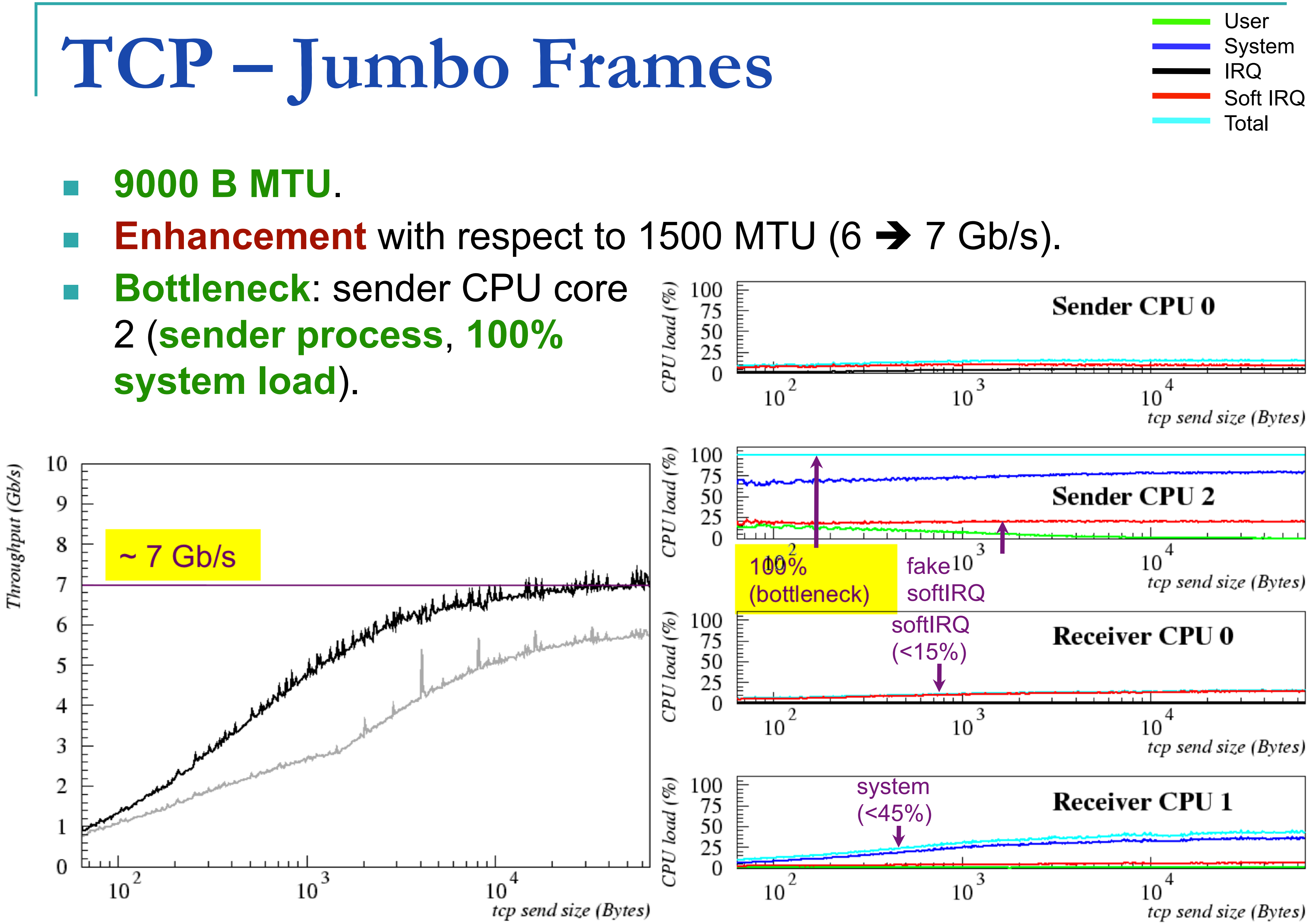
- **1500 B MTU** (Maximum Transfer Unit).
- TCP segments sent **as fast as they can be sent**.
- **Bottleneck**: sender CPU core 2 (**sender process**, **100% system load**).





TCP – Jumbo Frames

- **9000 B MTU**.
- **Enhancement** with respect to 1500 MTU (6 → 7 Gb/s).
- **Bottleneck**: sender CPU core 2 (**sender process**, **100% system load**).



Nagle's Algorithm

- Nagle's algorithm **active by default** when using **TCP-streamed transfers**.
- Introduced in the TCP/IP stack (RFC 896) in order to solve the so called **small packet problem**.
  - An application repeatedly emits data in **small chunks**, frequently only 1 byte in size. Since TCP packets have a 40 byte header (20 bytes for TCP, 20 bytes for IPv4), this results in a 41 byte packet for 1 byte of useful information, a **huge overhead**.
  - This situation often occurs in **`telnet` sessions**, where most key-presses generate a single byte of data which is transmitted immediately.
    - Worse, over slow links, many such packets can be in transit at the same time, potentially leading to **congestion collapse**.
- The **Nagle's algorithm** automatically **concatenates** a number of small data packets in order to **increase the efficiency** of a network application system, i.e. **reducing the number of physical packets** that must be sent.

Nagle’s Algorithm (II)

- When there are **few bytes to send**, but **not a full packet’s worth**, and there are **some unacknowledged data in flight**:
  - Then the Nagle’s algorithm **waits**, **keeping data buffered**, until:
    - Either **the application provides more data**:
      - Enough to make **another full-sized TCP segment** or **half of the TCP window size**;
    - Or **the other end acknowledges all the outstanding data**, so that there are **no** longer any **data in flight**.

Linux Settings on Nagle's Algorithm

- The Linux operating system provides two options to **disable** the Nagle's algorithm in **two opposite ways**, which can be set by means of the **`setsockopt()`** system call:
- **`TCP_NODELAY`**
  - The OS always **send segments as soon as possible**:
    - Even if there is only a small amount of data.
  - The **behavior** of **TCP** transfers is expected to **match more closely** that of **UDP** ones:
    - Since **no** small packet **aggregation** at the sender side is performed.
- **`TCP_CORK`**
  - The OS **does not send out partial frames at all** until the application provides more data:
    - Even if the other end acknowledges all the outstanding data.
  - Only full frames can be sent out:
    - If an application does not fill the last frame of a transmission, the system will delay sending the last packet forever.

Linux Settings on Nagle's Algorithm (II)

cork.c (~/Documents/didattica/ESC09) - VIM1

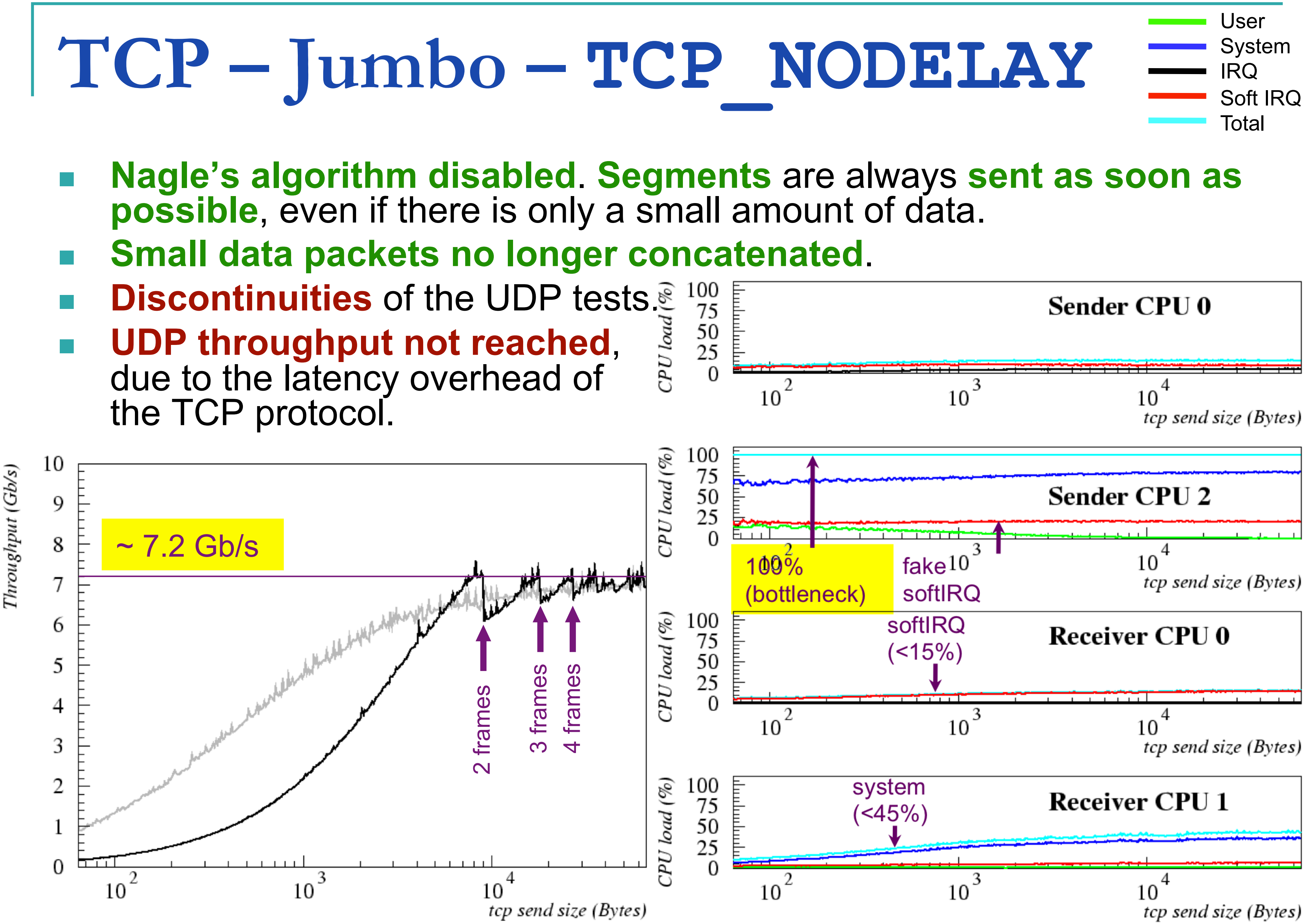
```c
#include <sys/socket.h>
int main()
{
  int mySock;
  int opt=1;
  ......................................
  mySock = socket(AF_INET,SOCK_STREAM,0);
  ret_code = setsockopt(mySock, IPPROTO_TCP, TCP_CORK, (char*)&opt, sizeof(opt));
  ......................................
}
```

nodelay.c (~/Documents/didattica/ESC09) - VIM

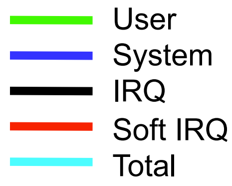
```c
#include <sys/socket.h>
int main()
{
  int mySock;
  int opt=1;
  ......................................
  mySock = socket(AF_INET,SOCK_STREAM,0);
  ret_code = setsockopt(mySock, IPPROTO_TCP, TCP_NODELAY, (char*)&opt, sizeof(opt));
  ......................................
}
```

TCP – Jumbo – TCP_NODELAY

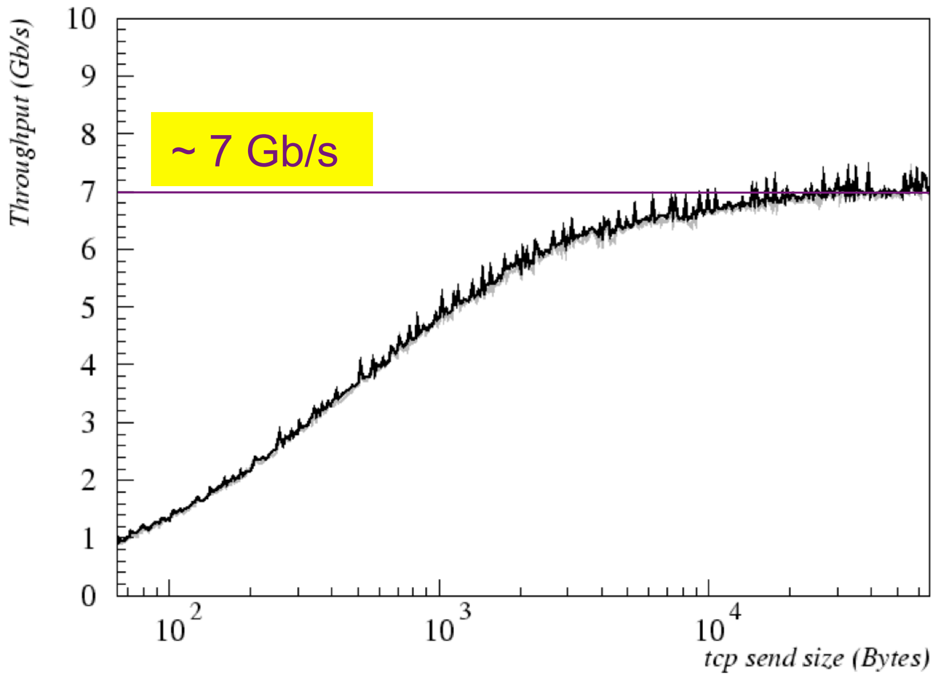
- **Nagle's algorithm disabled**. **Segments** are always **sent as soon as possible**, even if there is only a small amount of data.
- **Small data packets no longer concatenated**.
- **Discontinuities** of the UDP tests.
- **UDP throughput not reached**, due to the latency overhead of the TCP protocol.

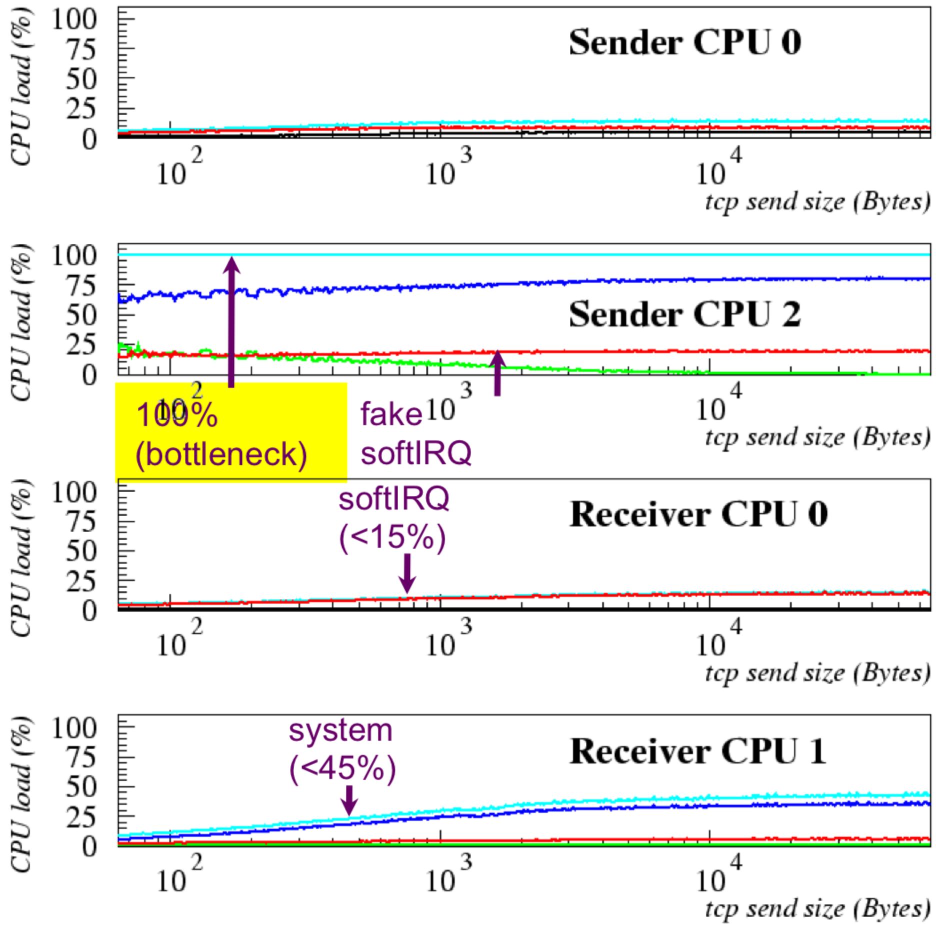


TCP – Jumbo – TCP_CORK



- **Nagle's algorithm disabled**. OS **does not send out partial frames at all** until the application provides more data, even if the other end acknowledges all the outstanding data.
- **No relevant differences**.





TCP – Zero Copy

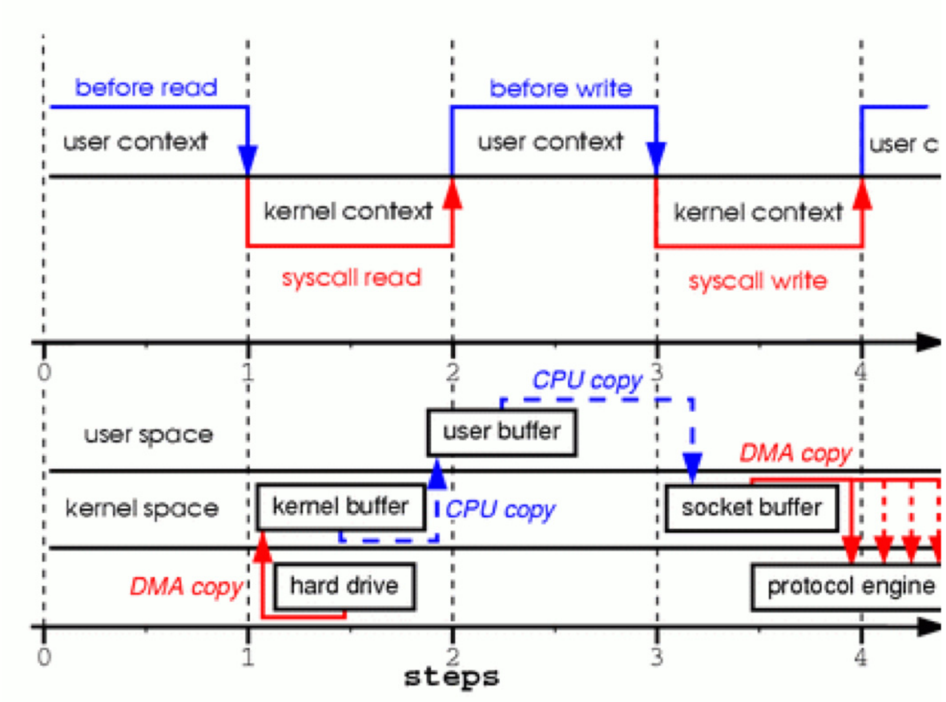
- The `send()` system call is used to send data stored in a **buffer** in the **user space** to the network through a TCP socket.
  - This requires the copy of the data from the user space to the kernel space on transmission.
- The `sendfile()` system call allows to send data read from a **file descriptor** to the network through a TCP socket.
  - Since both the **network** and the **file** are **accessible** from **kernel mode**, any time-expensive copy from user space to kernel space can be avoided.

TCP – Zero Copy (II)

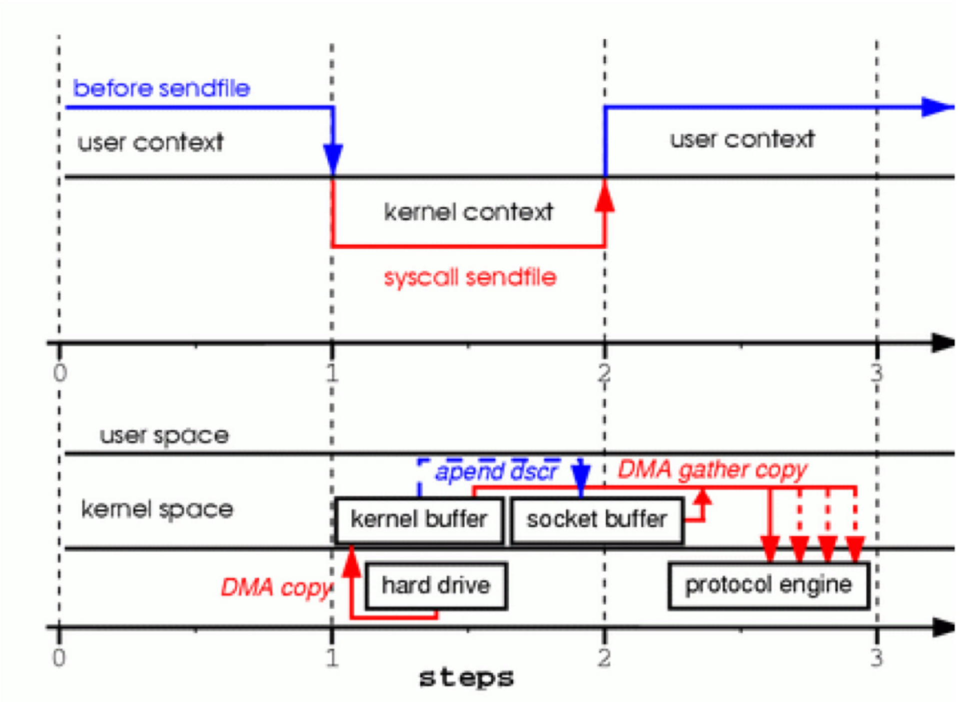
- `#include <sys/sendfile.h>`
- `ssize_t sendfile(int out_fd, int in_fd, off_t *offset, size_t count);`

- `out_fd`: file descriptor of the output socket;
- `in_fd`: file descriptor of the open file;
- `offset`: start position in file;
- `count`: number of Bytes to be copied.

read()+send()

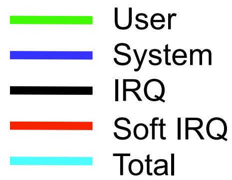


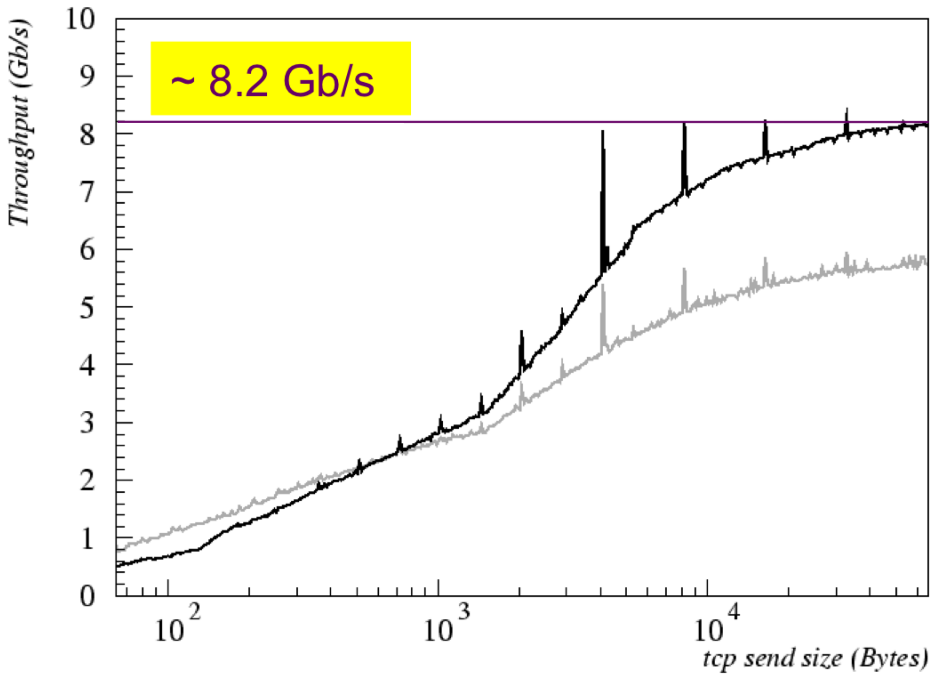
sendfile()

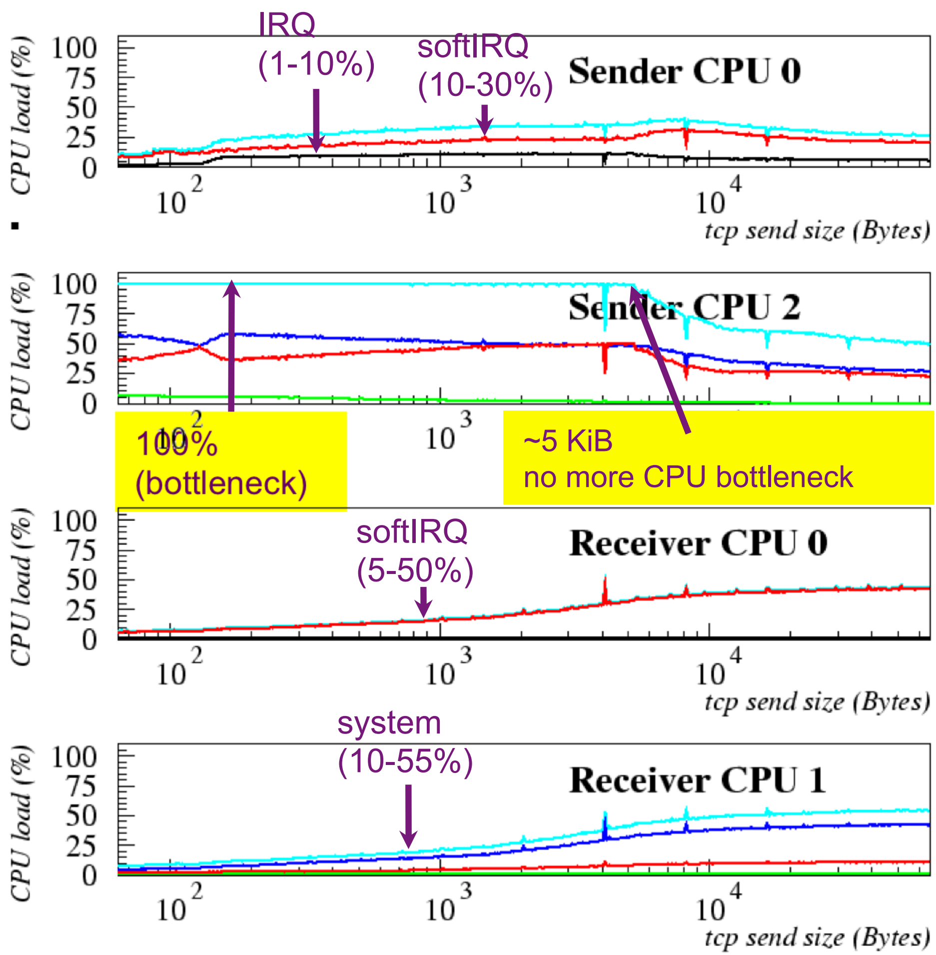


TCP – Standard – Zero Copy

- **1500 B** MTU.
- **Significant increase in throughput**
  - with respect to `send()`.

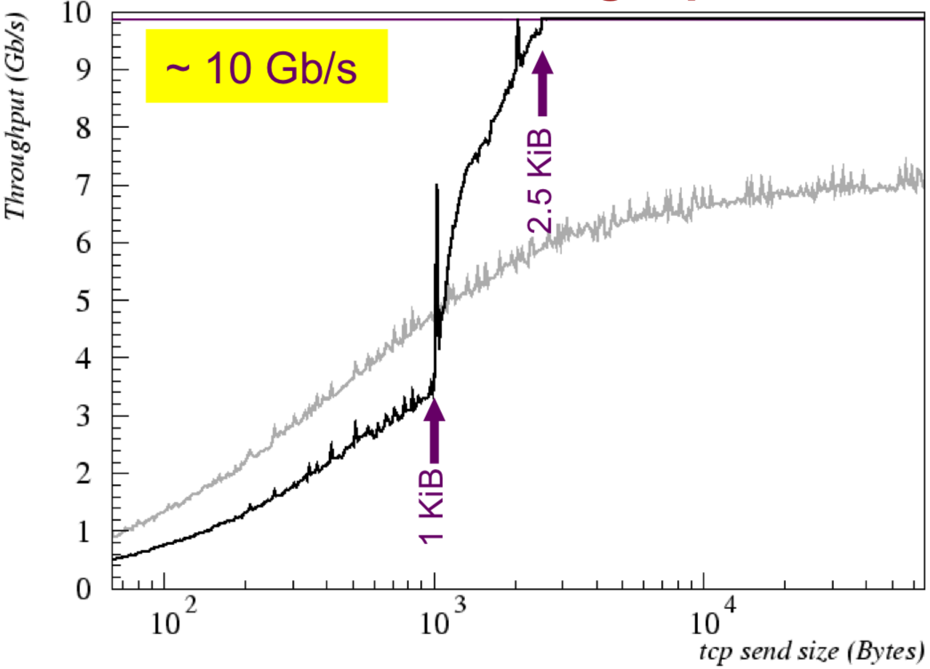


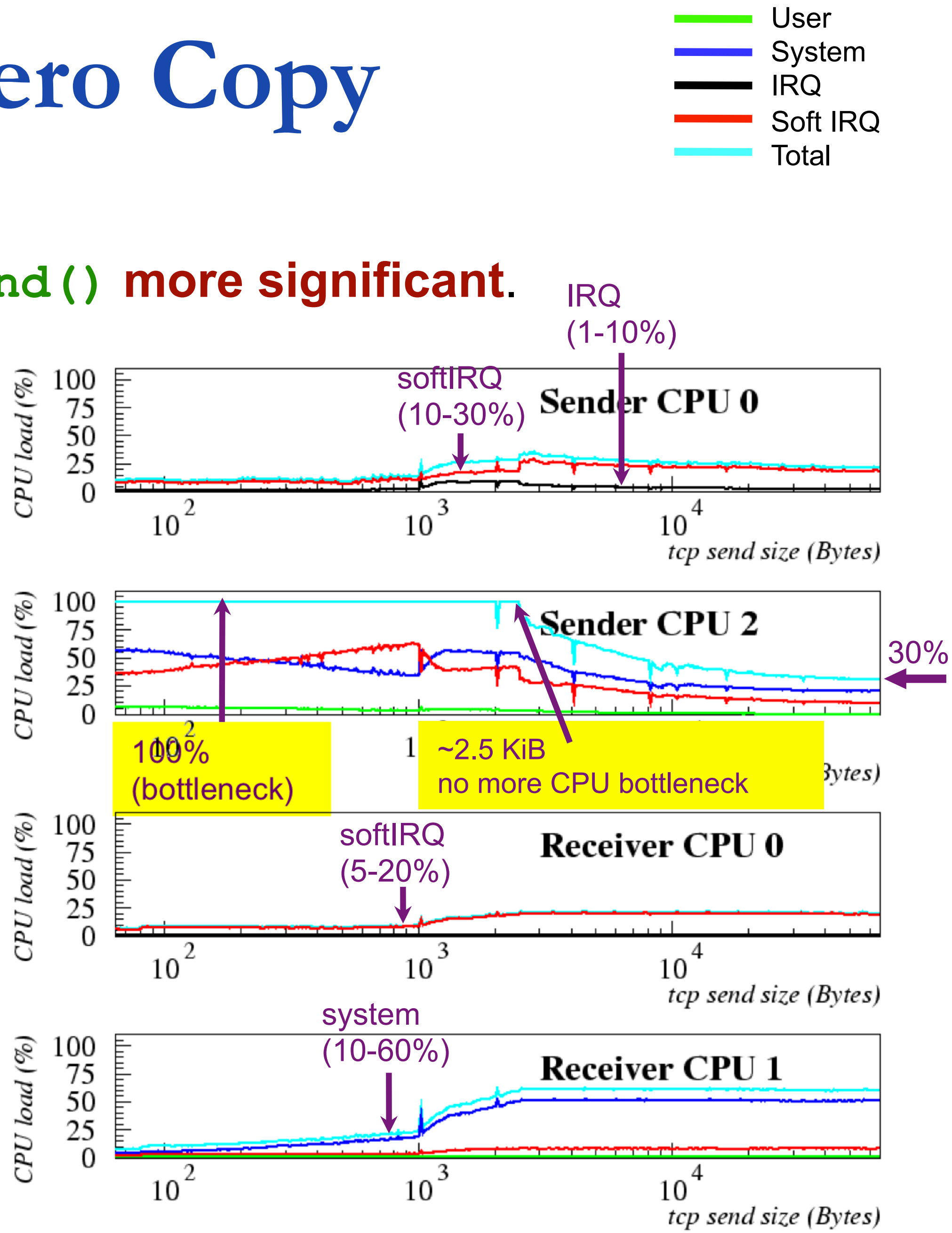




TCP – Jumbo – Zero Copy

- `sendfile()` system call.
- **Improvement** with respect to `send()` **more significant**.
- For send size > 2.5 KiB:
  - Throughput = 10 Gbit/s
  - Sender CPU 2 load < 100%:
    - down to 30%.
- **Only test able to saturate 10-GbE with a single ps**.





TCP Hardware Offload

- Modern network adapters usually implement various kinds of **hardware offload functionalities**:
  - The **kernel can delegate** heavy parts of its tasks **to the adapter**.
  - This is one of the most effective means available to improve the performance and reduce the CPU utilization.

Setting the Hardware Offload

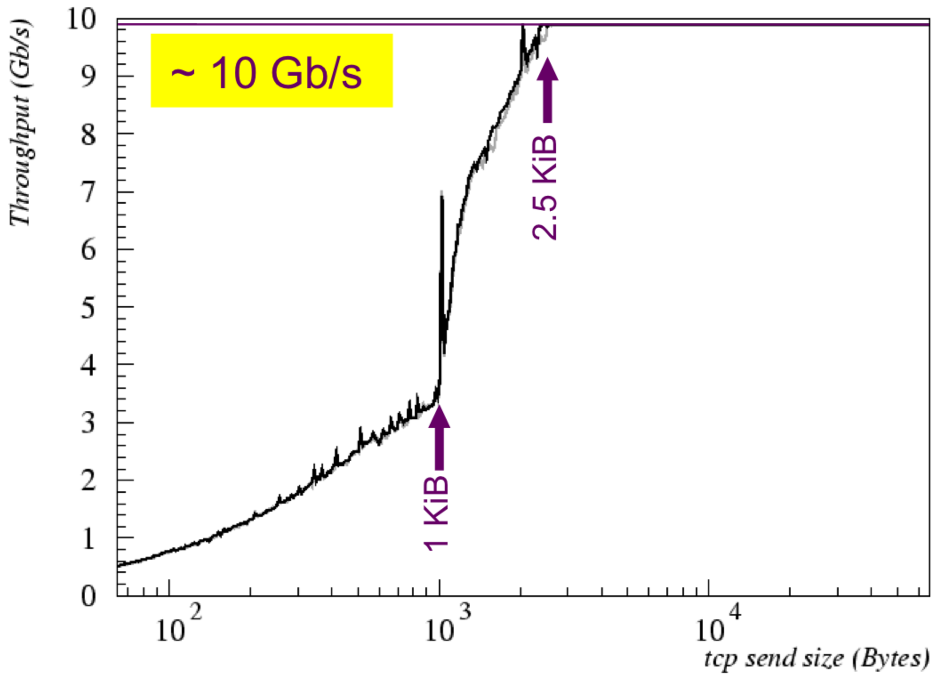
- Print offload functionalities:
  - `ethtool -k ethX`
- Set offload functionalities:
- `ethtool -K ethX [rx on|off] [tx on|off] [sg on|off] [tso on|off] [ufo on|off] [gso on|off] [gro on|off] [lro on|off]`
  - `rx`: receiving checksumming;
  - `tx`: transmitting checksumming;
  - `sg`: scatter-gather I/O;
  - `tso`: TCP segmentation offload;
  - `ufo`: UDP fragmentation offload;
  - `gso`: generic segmentation offload;
  - `gro`: generic receive offload;
  - `lro`: large receive offload.

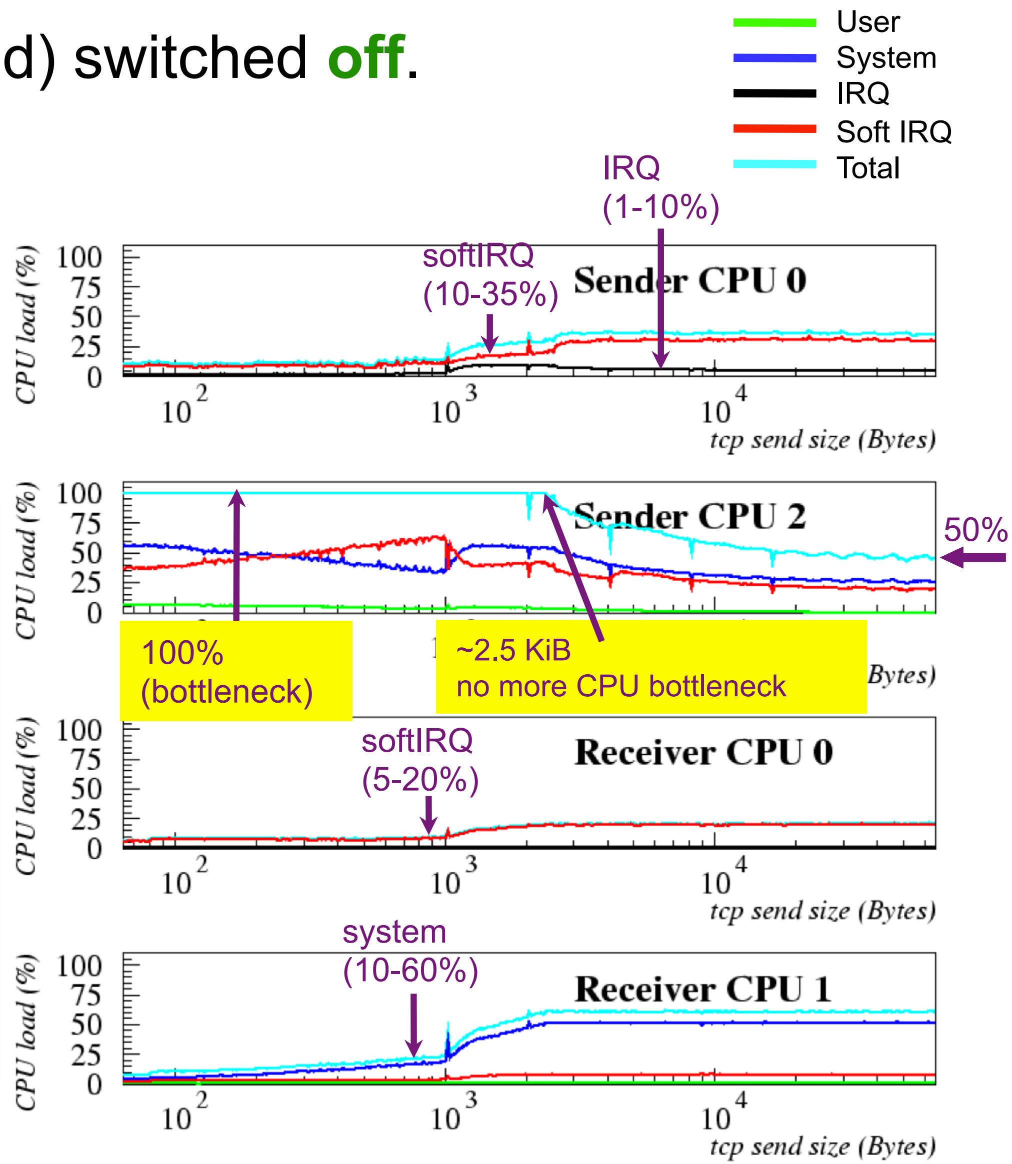
TCP Segmentation Offload (TSO)

- When a **data packet larger than the MTU** is sent by the kernel to the network adapter, the data must first be **sub-divided into MTU-sized packets** (**segmentation**).
- With **old adapters**, this task was commonly performed at the **kernel level**, by the **TCP layer** of the TCP/IP stack.
- In contrast, when **TSO is supported** and active, the host **CPU is offloaded** from such a segmentation task, and it can **pass** segments **larger than one MTU** (**up to 64 KiB**) **to the NIC** in a single transmit request.

TCP – Jumbo – Zero Copy – No TSO

- **TSO** (TCP Segmentation Offload) switched **off**.
- **No differences in throughput**:
  - 10-GbE link already **saturated** (size > 2.5 KiB).
- **CPU load reduced** by TSO (size > 2.5 KiB).



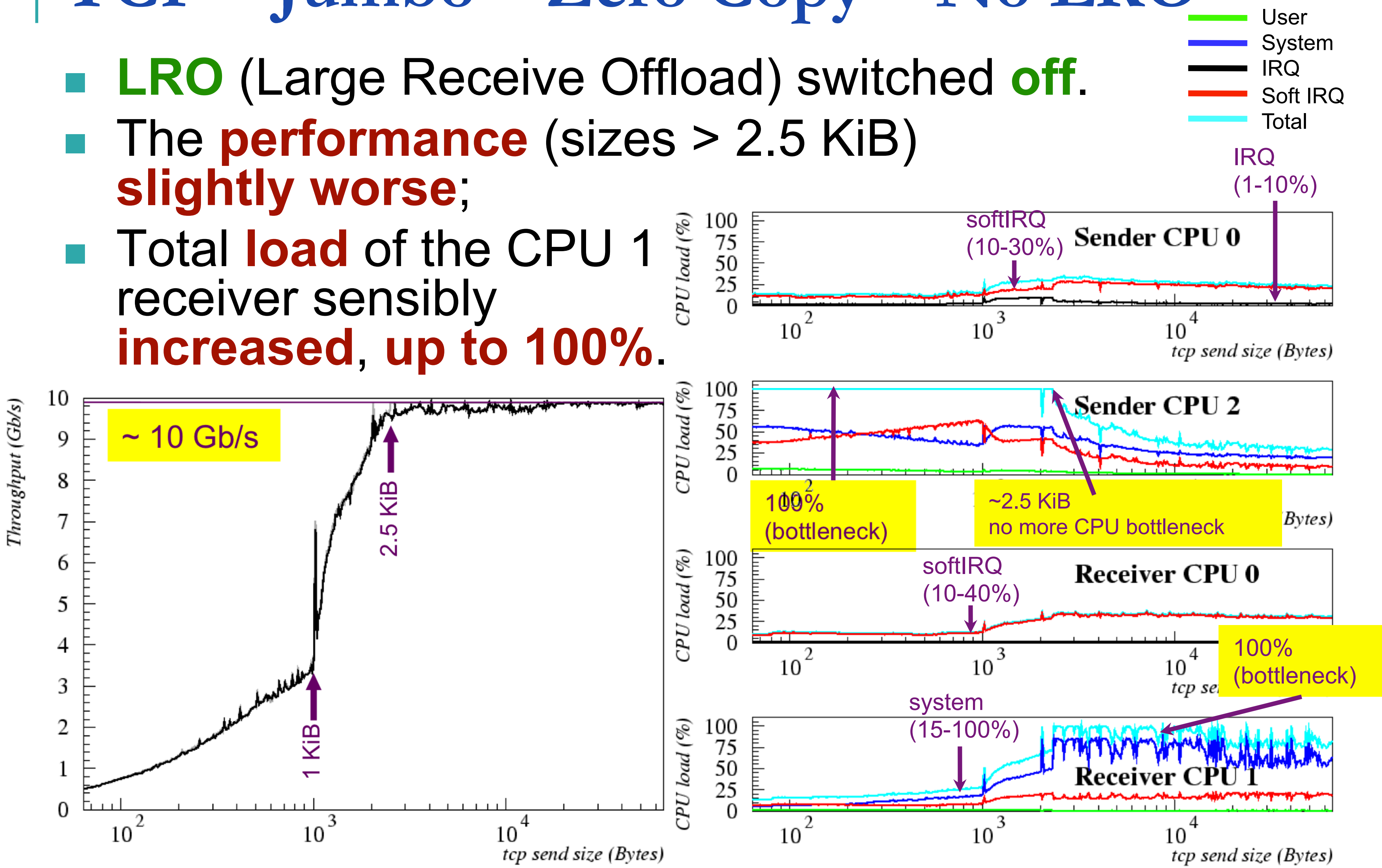


Large Receive Offload (LRO)

- Assists the **receiving host** in **processing incoming TCP packets**:
  - By **aggregating** them at the **NIC level** into fewer larger packets;
  - It may **reduce** considerably the number of physical packets actually processed by the kernel;
  - Hence offloading it in a significant way.

TCP – Jumbo – Zero Copy – No LRO

- **LRO** (Large Receive Offload) switched **off**.
- The **performance** (sizes > 2.5 KiB) **slightly worse**;
- Total **load** of the CPU 1 receiver sensibly **increased**, **up to 100%**.

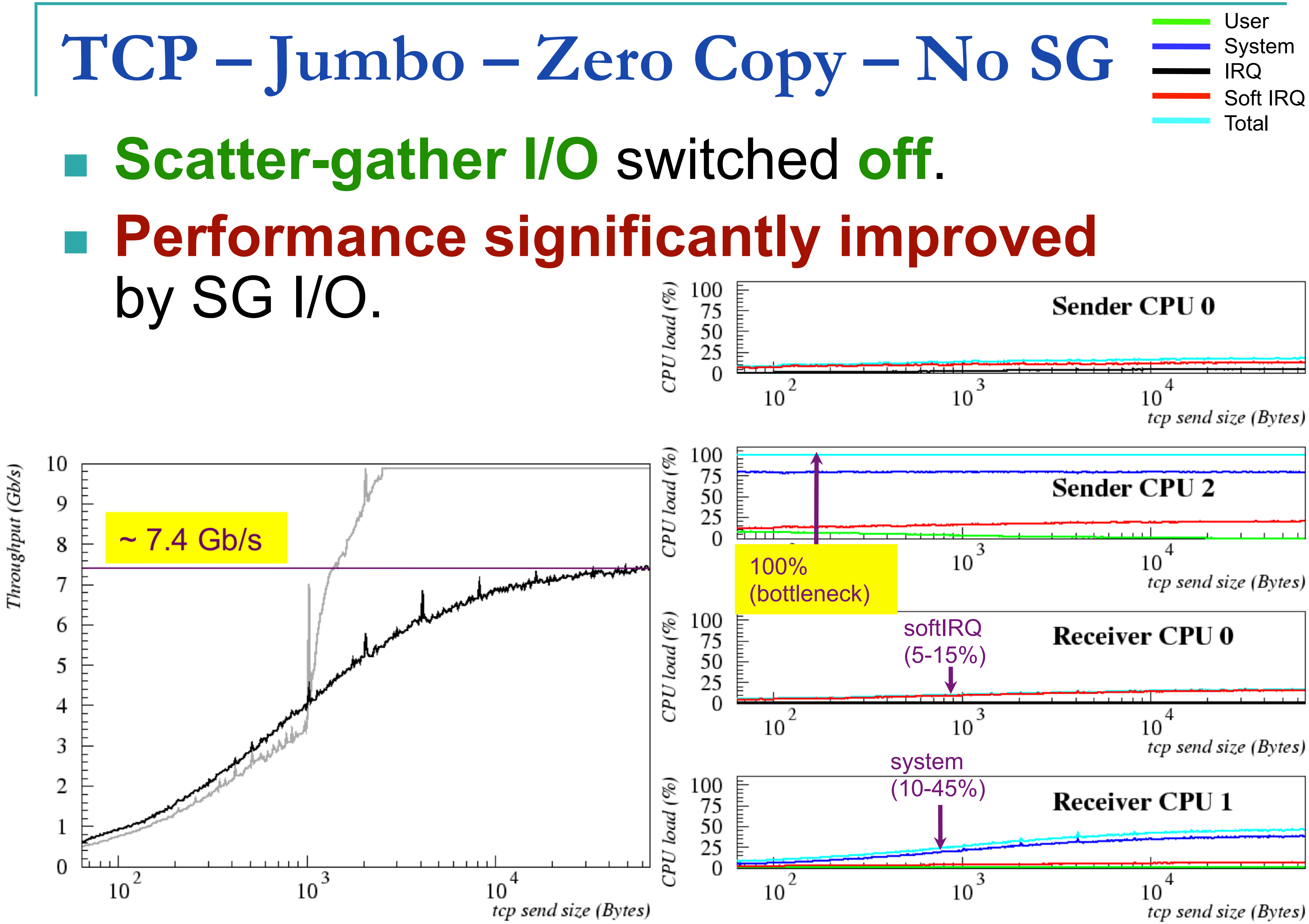


Scatter-Gather I/O (SG)

- The process of **creating a segment** ready to be transmitted through the network, starting **from the transmission requests** coming from the TCP layer, in general requires **data buffering**:
  - In order to assemble **packets** of **optimal size**, to evaluate **checksums** and to add the TCP, IP and Ethernet **headers**.
- This procedure can require a fair amount of **data copying** into a new buffer:
  - To make the **final linear packet**, stored in **contiguous memory locations**.
- However, if the NIC that has to transmit the packet can perform **SG I/O**, the **packet does not need to be assembled into a single linear chunk**:
  - Since the NIC is able to **retrieve through DMA** the **fragments** stored in **non-contiguous memory locations**.
  - This hardware optimization **offloads the kernel** from such a **linearization duty**, hence improving performance.

TCP – Jumbo – Zero Copy – No SG

- **Scatter-gather I/O** switched **off**.
- **Performance significantly improved** by SG I/O.

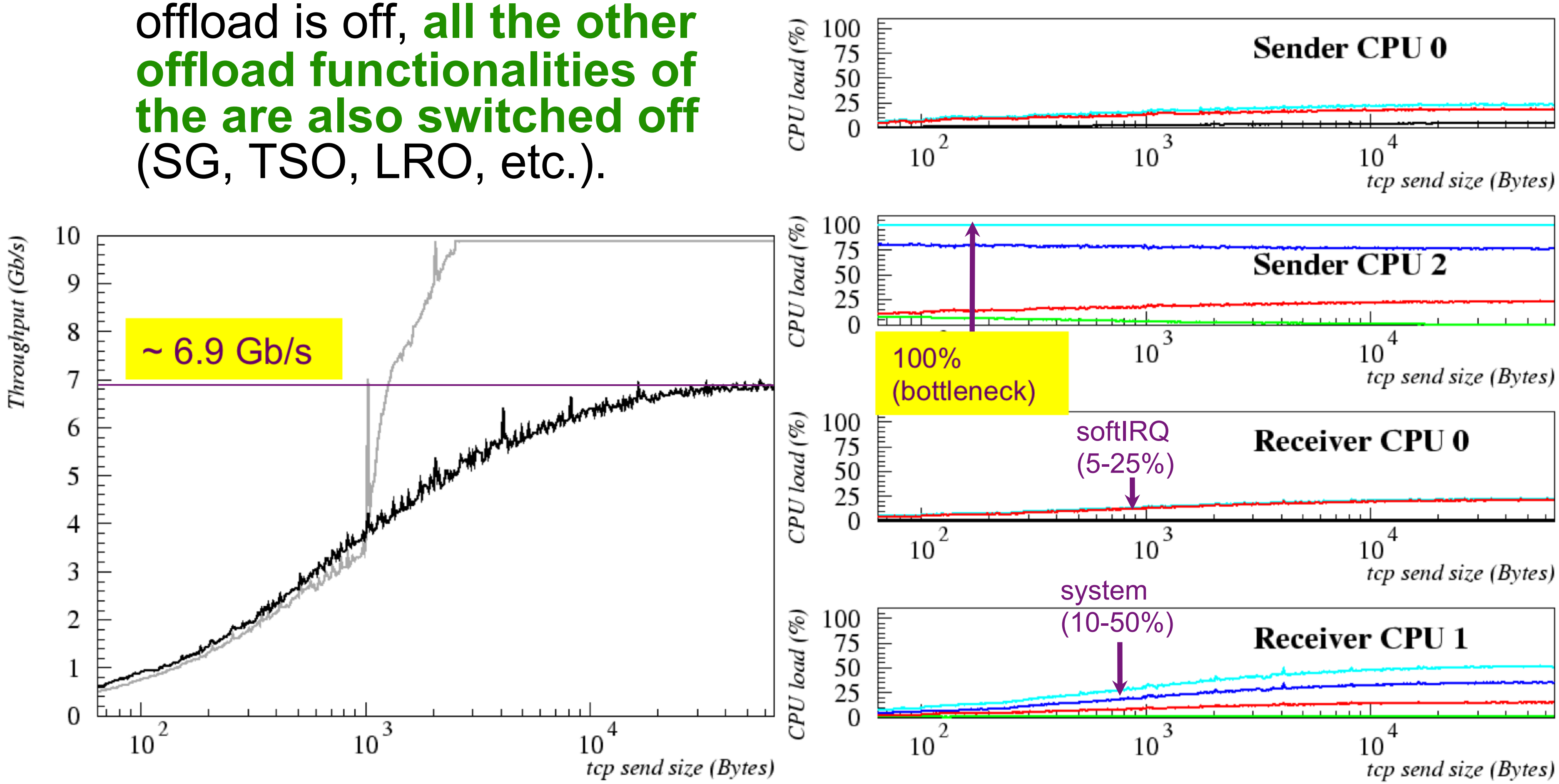


Checksum Offload (CO)

- IP/TCP/UDP **checksum** is performed to make sure that the packet is correctly transferred:
  - by **comparing**, at the receiver side, the value of the checksum field in the **packet header** (set by the sender) with the **value calculated** by the receiver from the packet payload.
- The task of evaluating the TCP checksum can be **offloaded to the NIC** thanks to the so-called Checksum Offload.

TCP – Jumbo – Zero Copy – No CO

- **Checksum offload** switched **off**.
- **Performance is significantly improved**.
- However, when the checksum offload is off, **all the other offload functionalities of the are also switched off** (SG, TSO, LRO, etc.).



Summary

- Main **bottleneck**:
  - **CPU** utilization at the **sender** side:
    - **System load** of the **transmitter process**.
- **Optimization**:
  - CPU **workload** can be **distributed** among **2 CPU** cores by **separating** the sender/receiver **process** from the IRQ/SoftIRQ **handlers**.
  - **Jumbo** frames in fact **mandatory** for 10-GbE.
  - In **TCP transmission**:
    - Improvement can be obtained by **zero-copy** (`sendfile()`);
    - **Scatter-Gather** functionality sensibly improves the performance;
    - The **TSO** functionality helps the sender CPU.
    - The **LRO** functionality helps the receiver CPU.
- **Performances**: review of data transfer via 10-GbE links at full speed:
  - Using either the **UDP** or the **TCP** protocol;
  - By varying the **MTU** and the **packet send size**;
  - **2 UDP sender** needed to **saturate** the link:
    - **1 receiver can play against 2 senders**;
  - Using **TCP+zero-copy+offload**, **1 sender is enough** to saturate the link;
  - **Packet size** crucial:
    - Using 10-GbE you could transfer data at 200 Mb/s maximum!

More Details

Inaccuracy in SoftIRQ Accounting

- Inaccuracy in the kernel accounting (2.6.9-78.0.1, SLC 4.7) can lead to a **wrong assignment of jiffy counts to the SoftIRQ partition**.
- The CPU tick is accredited to **SoftIRQ** if the **softirq_count() macro** returns a value **≠0**.
- This **value** is **incremented** by `__local_bh_disable()` function:
  - **Usually** called by the `__do_softirq()` function, i.e. the one which actually executes the **SoftIRQ** code.
- Problem: `__local_bh_disable()` **also called by** `local_bh_disable()`:
  - In turn **called by other functions in the kernel**.
- If a **timer interrupt** employed for accumulating kernel accounting statistics happens when the kernel is executing a function where `local_bh_disable()` has been called, the tick is incorrectly accredited to **SoftIRQ** time, while it **was indeed a synchronous code** and had to be accounted to **System**.