Study Project

Packet Capturing Using the Linux Netfilter Framework

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1. Introduction
Packet sniffers (also known as network analyzers) are software tools (usually) or hardware devices designed to log traffic passing over a network. As data streams travel back and forth over the network, a sniffer captures packets and eventually analyzes the contents. The following document covers functions and data structures from kernel 2.6.14 used to design a kernel sniffer. They also apply to any 2.6 kernel with slightly differences.

1.1 Motivation
The goal of the project is to build a kernel module as a sniffer using the Linux netfilter framework and to compare the capturing rates between the module and an existing capturing library (libpcap). The implementation of a sniffer as a kernel module allows increasing of the capturing rates, because it saves expensive copy operations from/to kernelspace in normal userlevel implementations and also reduces the number of context switches between kernel- and userspace. During the development of the kernel module different problems have occurred, because of the fact that a typical userspace application is moved to the kernelspace. The project deals not only with the networking of the kernel but also with other subsystems such as the memory management or the filesystem management which makes it interesting, exciting and sophisticated.

1.2 Structure of this Paper
The next chapter (2) covers some basic terms that are not directly related to the project but are useful to understand the differences between the two approaches (NAPI/non-NAPI) to receive data used by the network device drivers. Chapter 3 introduces some data structures used by the kernel to represent for example a network device or a packet. Chapter 4 deals with the packet path through the kernel and with the resulting differences between the two approaches. Chapter 5 describes the Linux netfilter framework and its design. The next chapter (6) begins with an overview of the Virtual File System (VFS); how file operations are working inside the kernel and after that follows a description of the capturing mechanism of the kernel module. The last chapter (7) summarizes the data structures and the functions mentioned in the paper.
2. Background

This chapter introduces two basic approaches used by network device drivers: interrupt or interrupt-polled driven. Under certain conditions each method has advantages and disadvantages. The second one however has been developed later to avoid the receive livelock problem [ERLIK]. At last an overview of the TCP/IP kernel stack is presented.

2.1 Interrupts

Here the device driver instructs the device to generate a hardware interrupt when specific event occurs and the kernel, interrupted from its other activities, invokes an interrupt handler registered by the driver to take care of the device's need [ULNI]. When the event is a reception of a frame, the interrupt handler will queue the packet and will notify the kernel about it. With increasing traffic rates the amount of time, spent in interrupt handling, also increases and can compromise the system's stability. This technique is used by the most device drivers and represents the best option under low traffic loads.

2.2 Receive Livelock

The processing of an incoming packet through the kernel is split in two parts: first of all the driver saves an incoming packet into input queue accessible by the kernel and then the kernel processes the frame to an appropriate network layer. The code, that accepts a packet is executed in interrupt context and can preempt the processing part due to its higher priority. Under high network load [ULNI] the device generates an interrupt for every single packet which will lead to a system collapse, because the interrupt code will always preempt the processing code. At some point the input queue will be full, because the entire CPU time is spent in interrupt handling and the processing code, that is supposed to dequeue and process the frames from the queue, can not be executed. New frames cannot be queued since there is no available space and old packets cannot be processed, because there is no CPU time available for them. This condition is called receive-livelock.

2.3 Device Polling

"Device polling" refers to a technique for handling devices which does not rely on generated interrupts when they need attention, but on constantly checking a device whether it has anything to say [ULNI]. The disadvantage of this method is, that it can spend a lot of CPU time in checking for potential events and if the device can use interrupts it is recommended to avoid this method. Still, there are cases, where polling is the better choice. The main advantage of polling is in saving a bit of CPU cycles by reducing the number of context switches needed for interrupt handling.

2.4 Processing Multiple Frames During an Interrupt (NAPI)

To avoid the receive-livelock condition a new approach has been developed by Jamal Hadi Salim, Robert Olsson and Alexey Kuznetsov [BS], that reduces the number of interrupts generated by the system. The method is known as “new-API” or NAPI and uses the advantages of the polite behavior, where the interrupt – based handling of network devices is replaced with a mixed interrupt-polling mode. The device driver interrupts the CPU upon reception of the “first” packet, then the interrupt handler adds the device to a poll list and informs the kernel for the frame reception [ULNI]. The driver disables further interrupts for
incoming frames and all devices in the poll list are polled until certain number of packets is processed (to ensure fairness among devices). At last the driver re-enables receive interrupts. Under normal network load there are no differences between NAPI and non – NAPI device drivers, but a performance boost is achieved under heavy load.

2.5 Overview of the TCP/IP Kernel Stack

The Linux kernel supports many different network architectures and each of them describes how a specific network works. The architecture defines a set of layers and programs from each layer that communicate to one another by using a shared set of rules. For this project however the network architecture of interest is the IPv4 protocol stack and only related routines will be described. Figure 1 shows the different network layers and the correspondent protocols for each of them. At the bottom stands the link layer, that ensures the packet delivery from one network node to another and might provide methods to detect and possibly correct errors occurred during transmission. The device driver operates in this level and proceeds incoming /outgoing packets to/from the kernel and communicates directly with the network device. The next one is the network layer, responsible for end-to-end packet delivery and provides functions for network routing, fragmentation/defragmentation and error control. The transport layer provides transparent transfer of data between hosts and it is usually responsible for end-to-end error recovery and flow control and ensures complete data transfer.

The application layer at the top supports applications and end-user processes and everything at this layer is application-specific. The kernel sniffer works “somewhere at the top” of the link layer (protocol handlers) and inside the network layer (IPv4 netfilter hooks) that is why this paper describes the packet input traversal in these 2 layers.
3. Main Data Structures and Functions
This chapter will discuss main data structures and functions that are going to help to understand how device drivers work and how packet handling is implemented within the kernel.

3.1 Linux Socket Buffer
The socket buffer `sk_buff` is the structure used to address and manage a packet during its entire processing in the Linux kernel. A socket buffer consists of two parts: packet data, which stores the actual data of a packet that has been received or is about to be transmitted. And management data, in which the kernel maintains implementation specific data such as timers, pointers, counters etc. It is defined in `include/linux/skbuff.h` and from one kernel version to another there are slightly differences in some fields. Figure 2 shows some of the fields of `sk_buff` structure.

![Fields of the sk_buff structure](image)

```c
struct sk_buff *next
struct sk_buff *prev

struct sock *sk
```

These fields are used to link the data structure in a double circular linked lists. There are generic `sk_buff` routines for adding packets to the front and to the end of these lists and for removing them.

```c
struct sock *sk
```

This is a pointer to a sock data structure of a socket that owns the buffer. This pointer is needed when data is either locally generated or being received by a local process, because socket-related informations are used by transport layer protocols such as TCP and UDP and by user applications. When a buffer has to be forwarded this pointer is NULL.
struct skb_timeval tstamp
This field represents the time stamp of a packet that has been received and it is initialized during the reception. By default however this value is set to 0.0 to decrease the processing time of a single frame. Activation/deactivation of the time stamp is done by invoking the functions net_enable_timestamp/net_disable_timestamp, defined in net/core/dev.c.

struct net_device *dev
This field represents a network device receiving or transmitting this buffer. More detailed information about its type will be introduced later.

union {...} h
union {...} nh
union {...} mac
These are pointers to protocol headers for each network layer, h describes transport layer protocols (TCP, UDP), nh is the network layer protocol set and the mac field is for the link layer protocols. Each of these unions contain the *raw member that is used by the initialization of protocol and it can be used to access the protocol header instead the protocol specific pointer. Please refer to Figure 3.

struct dst_entry *dst
This member is used by the routing subsystem that is not covered in this document. For more details refer to the kernel source code or read O'Reilly's “Understanding Linux Network Internals” [ULNI].

__u8 pkt_type
This is the packet class based on the destination address: multicast, broadcast etc. The possible values are defined in include/linux/if_packet.h.

__be16 protocol
This is an unsigned short value that describes a network layer protocol. Because each protocol has its own function handler for processing incoming frames, the device driver informs the network layer what handler to use. The protocol specific values are defined in include/linux/if_ether.h.

atomic_t users
Reference counter or the number of entities using this socket buffer. It is used to avoid freeing the sk_buff structure when someone is still using it.

unsigned char *head, *data, *tail, *end
The head and end pointers point to the total location that can be used for packet data. The data and tail pointers point to currently valid packet data. The space between head and data is the so called headroom, and the space between tail and end is known as tailroom. The headroom and the tailroom allow a protocol to add protocol data in front of or after the currently valid packet data. The interaction with the actual packet data is depicted in Figure 3.
One of the problems having many network layers is the passing of a packet data from one layer to another, because each protocol needs to add protocol data by the transmission and to remove the data by reception. This make passing data buffers between the protocols difficult as each layer needs to find where its particular protocol headers and tails are. One solution is to copy buffers at each layer but that would be inefficient. Instead, Linux uses the sk_buff structure to pass data between the protocol layers and the network device drivers.

While the head and end pointers are fixed, when the packet is allocated, the data and tail pointers are moved forward or backward when the packet is passed from one layer to another. Before passing a packet to another layer, the current layer initializes its own pointers and to prepare the packet for further procession moves the data pointer to the beginning of the next layer. Figures 3.a and 3.b [ULNI] show how the data pointer is moved, when a packet is passed from link layer to network layer and from network layer to link layer.
3.2 Linux Network Device

Besides the socket buffer used to represent packets the core of the networking is the network device itself. In the Linux kernel every network device either a real one or a virtual one is represented through network device structure or net_device and it is defined in include/linux/netdevice.h (see Figure 4).

```
net_device

+-------------------+----------------------------------+
| name              | Name of the device               |
| mem_end           | End address of the shared memory |
| mem_start         | Beginning of the shared memory   |
| base_addr         | Beginning of the I/O memory      |
| irq               | Interrupt number                 |
| state             | State of the device              |
| next              | Pointer to the next device       |
| init              | Function pointer used to initialize the device |
| ...               |                                  |
| flags             | Interface flags                  |
| ...               |                                  |
| mtu               | The maximum transfer unit        |
| hard_header_len   | The size of the device header in octets |
| promiscuity       | Counter for promiscuous mode     |
| ...               |                                  |
| poll_list         | Used to link the structure in a list of devices that are in polling mode |
| ...               |                                  |
| open              | Function pointer used to enable the device |
| stop              | Function pointer used to disable the device |
| hard_start_xmit   | Function pointer used to transmit a packet |
| poll              | Function pointer used to poll the device |
| hard_header       | Function pointer used to build the hardware-header |
```

Figure 4: Fields of the net_device structure

char name[IFNAMSIZ]
This field stores the name of the network device and its size is up to 16 characters (IFNAMSIZ=16).

unsigned long mem_end
unsigned long mem_start
This fields describe the end and the beginning of the shared memory used by the device to communicate with the kernel.

unsigned long base_addr
This field stores the beginning address of the I/O memory mapped to the device's memory.

unsigned int irq
This field is the interrupt number used by the device. It can be shared among several devices.

unsigned long state
A set of flags used to represent the current state of the device.
unsigned short flags
Some bits in the flags field describe capabilities of the network device
(IFF_MULTICAST) and others represent its status (IFF_UP: device is running,
IFF_DOWN: device is stopped, IFF_PROMISC: device is in promiscuous mode).
The different flags are defined in include/linux/if.h.

unsigned int mtu
MTU is the abbreviation for Maximum Transfer Unit and it represents the maximum size of
frames in bytes that the device can handle.

unsigned short hard_header_len
This value is the size of the device header in octets, for example the Ethernet header is
14 bytes long.

int promiscuity
This value is a counter that indicates whether a device is in promiscuous mode or not. The
reason [ULNI] to be a counter rather than a simple flag is because several interested parties
may ask for promiscuous mode. When the device enters in this mode the value is incremented
by 1 and when leaves decreased by 1. The device is so long in promiscuous mode until the
counter reaches 0.

struct list_head poll_list
As mentioned before the NAPI approach avoids the receive-livelock condition with reducing
the number of generated interrupts by polling the device. As the name suggests this member
is used to link the data structure in a global linked list of devices in polling mode.

int (*init)(struct net_device *dev)
int (*open)(struct net_device *dev)
int (*stop)(struct net_device *dev)
int (*hard_start_xmit) (struct sk_buff *skb,
                          struct net_device *dev)
int (*poll) (struct net_device *dev, int *quota)
int (*hard_header) (struct sk_buff *skb,
                          struct net_device *dev,
                          unsigned short type,
                          void *daddr, void *saddr,
                          unsigned len)

To be more generic the net_device structure contains also a set of function pointers that
are device specific and implemented in the device driver. The first interesting member is the
init function called once by the initialization of the network interface. The open and stop
methods open or stop a device, for example ifconfig eth0 up/down will
activate/deactivate the eth0 device by calling the open/stop function. The function pointer
hard_start_xmit initiates the transmission of the socket buffer. The method poll is
provided for NAPI device drivers to proceed packets with disabled interrupts and the
hard_header function builds the hardware header form source and destination addresses.
3.3 Linux Socket Buffer Queue
The kernel maintains sk_bufts structures in double linked lists, but its organization is more complicated than that of traditional linked lists. Each list is accessed by socket buffer head structure or sk_buff_head. It is defined in include/linux/skbuff.h and contains the members shown in Figure 5.

```
struct sk_buff_head
{
    struct sk_buff *next;
    struct sk_buff *prev;
    _u32 qlen;
    spinlock_t lock;
};
```

Figure 5: sk_buff_head interaction with sk_buff

The next and prev fields are sk_buff pointers that are the boundaries of lists.

```
_next u32 qlen
qlen is unsigned integer value and represents the number of elements in the list.

spinlock_t lock
This is synchronization primitive used to avoid race conditions among shared data and ensures in this case consistent list handling.
For more details see [UtLK] chapter 5 “Kernel Synchronization”.
```
3.4 Managing ingress/egress traffic

The next data structure is used to manage ingress/egress traffic and it is called `softnet_data`. As Figure 6 shows the structure includes both fields for reception and for transmission.

![Fields of the softnet_data structure](image)

```c
struct net_device *output_queue
This is a list of devices that have something to transmit.

struct sk_buff_head input_pkt_queue
The `input_pkt_queue` member is a socket buffer queue, where incoming frames are stored before being processed by the driver. This queue is used only by non-NAPI device drivers and NAPI drivers are using their own queues.

struct list_head poll_list
Both NAPI and non-NAPI device drivers are inserted in this list when they have frames waiting to be processed. The `net_device` structure as mentioned before contains also a field `poll_list` but it is used to link the data structure in this list.

struct sk_buff *completion_queue
`completion_queue` is a list of socket buffers that have been successfully transmitted and can be released.

struct net_device backlog_dev
This field is used by non-NAPI device drivers and it represents a virtual device that has scheduled the `net_rx_action` software interrupt.

The `softnet_data` structure is defined per CPU so that no locking of the structure is needed among the different CPUs while processing the frames [ULNI].
```
3.5 Protocol Handler

When a packet has been received by the device driver it must be delivered to an appropriate network layer protocol (IPv4, ARP, IPv6) according to its protocol type. For each network layer protocol there is a protocol handler that proceeds the frames into its protocol stack. This is the `packet_type` structure (take a look at Figure 7) defined in `linux/include/netdevice.h`.

<table>
<thead>
<tr>
<th>Member</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>The protocol code</td>
</tr>
<tr>
<td>dev</td>
<td>Pointer to the device for which the protocol is enabled</td>
</tr>
<tr>
<td>func</td>
<td>Function pointer to the protocol handler</td>
</tr>
<tr>
<td>af_packet_priv</td>
<td>Pointer to the sock data structure</td>
</tr>
<tr>
<td>list</td>
<td>Used to link the data structure</td>
</tr>
</tbody>
</table>

Figure 7: Fields of the `packet_type` structure

- **__be16 type**
  This is an unsigned short value that represents the protocol code and the possible values are defined in `include/linux/if_ether.h`.

```c
struct net_device *dev
```

This is the network device for which the protocol is enabled [ULNI]. By setting this field to NULL means that the protocol is enabled for all devices. This parameter would allow to have different handlers for the different devices or one handler for a specific device.

```c
int (*func) (struct sk_buff *, struct net_device *,
             struct packet_type *, struct net_device *)
```

The `func` member is the function handler that processes each frame into the network protocol stack. With invoking this handler a packet leaves the link layer and enters into the network layer. Table 1 shows some protocols and their correspondent function handlers.

```c
void *af_packet_priv
```

The field is used by PF_PACKET sockets to deliver incoming frames to the right socket.

```c
struct list_head list
```

This member is used to link the data structure in a linked list.

Each protocol registers itself by adding a `packet_type` data structure into either the `ptype_all` list or into the `ptype_base` hash table both defined in `net/core/dev.c`. The list `ptype_all` contains handlers for protocol sniffers while `ptype_base` hash table is hashed by protocol identifier and is used to decide which network layer protocol should receive the incoming packet.

When the fields of the `packet_type` data structure are initialized it can be inserted in the `ptype_all` list or in `ptype_base` hash table with `dev_add_pack` function defined in `net/core/dev.c`. This function checks the `packet_type`'s member `type` and decides if the structure must be linked in the list or in the hash table. Deletion of an entry from the list or from the hash table is done with `dev_remove_pack` function (wrapper to `__dev_remove_pack` function) also defined in `net/core/dev.c`.

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Table 1: Some protocols and their function handlers

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Protocol code</th>
<th>Function handler</th>
<th>File</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETH_P_IP</td>
<td>0x0800</td>
<td>ip_rcv</td>
<td>net/ipv4/ip_input.c</td>
</tr>
<tr>
<td>ETH_P_ARP</td>
<td>0x0806</td>
<td>arp_rcv</td>
<td>net/ipv4/arp.c</td>
</tr>
<tr>
<td>ETH_P_IPV6</td>
<td>0x86DD</td>
<td>ipv6_rcv</td>
<td>net/ipv6/ip6_input.c</td>
</tr>
<tr>
<td>ETH_P_IPX</td>
<td>0x8137</td>
<td>ipx_rcv</td>
<td>net/ipx/af_ipx.c</td>
</tr>
<tr>
<td>ETH_P_ALL</td>
<td>0x0003</td>
<td>packet_rcv</td>
<td>net/packet/af_packet.c</td>
</tr>
<tr>
<td>ETH_P_RARP</td>
<td>0x8035</td>
<td>ic_rarp_recv</td>
<td>net/ipv4/ipconfig.c</td>
</tr>
</tbody>
</table>
4. NAPI/Non-NAPI Frame Reception
As mentioned before there are two modes for packet reception that may be implemented by
the device driver: interrupt (non-NAPI) or interrupt-poll driven (NAPI). Let us start with
non-NAPI frame reception. To become a more detailed and clear picture of the frame
reception let see the initialization of the data structures discussed above that happens during
the booting process in the net_dev_init (1) function.

4.1 net_dev_init
The net_dev_init (1) function defined in net/core/dev.c initializes the
ptype_all list, the ptype_base hash table and the per-CPU defined softnet_data
structures.

```c
static int __init net_dev_init(void)
{
    ...
    1. The ptype_all list is initialized.
    List or hash table related functions are defined in include/linux/list.h.
    INIT_LIST_HEAD(&ptype_all);

    2. The sixteen lists in the ptype_base hash table are initialized.
    for (i = 0; i < 16; i++)
        INIT_LIST_HEAD(&ptype_base[i]);

    3. Initializes the softnet_data structures for each CPU.
    for (i = 0; i < NR_CPUS; i++) {
        struct softnet_data *queue;

        3.1 Defines for CPU i this softnet_data.
        queue = &per_cpu(softnet_data, i);

        3.2 Initializes the input queue for received packets input_pkt_queue
        by invoking the skb_queue_head_init function defined in include/linux/skbuff.h.
        skb_queue_head_init(&queue->input_pkt_queue);

        3.3 The queue for transmitted buffers is NULL because no packets have been transmitted yet.
        queue->completion Queue = NULL;

        3.4 Initializes the poll list where devices in polling mode will be inserted.
        INIT_LIST_HEAD(&queue->poll_list);

        3.5 Initializes the poll method for the virtual device backlog_dev with
        the process_backlog function defined in net/core/dev.c.
        queue->backlog_dev.poll = process_backlog;

    }

    ...

    4. Initializes the software interrupt handlers for transmission and reception of frames
    with net_tx_action/net_rx_action both defined in net/core/dev.c.
    open_softirq(NET_TX_SOFTIRQ, net_tx_action, NULL);
    open_softirq(NET_RX_SOFTIRQ, net_rx_action, NULL);

    out:
    ...
}
```

1. net_dev_init function
The confusing part in `net_dev_init` function is may be 3.5 - the initialization of the poll method for the virtual device `backlog_dev` that is used only by non-NAPI drivers. You would ask why non-NAPI drivers are providing poll method or the `process_backlog` function? The new approach requires kernel changes which are going to result in old driver incompatibilities and the kernel will support only the new ones. To avoid this problem both NAPI and non-NAPI drivers must provide the poll method for packet processing, but non-NAPI haven't polite behavior. Therefore the `backlog_dev` virtual device is defined to provide the `process_backlog` function as poll method and to process the packets from the input queue of the current CPU `input_pkt_queue`.

### 4.2 `netif_rx`

After the per-CPU `softnet_data`'s, the list `ptype_all` and the hash table `ptype_base` are initialized. We can start how device drivers are notifying the kernel for frame reception. In non-NAPI device drivers the code below is more or less similar and represents a generic interrupt handler (2). When a network device receives a frame the driver allocates `sk_buff` structure, stores the incoming packet in it. And to ensure that the packet is delivered to the appropriate network layer handler the protocol field of the `sk_buff` is set. For Ethernet devices this is done by invoking the `eth_type_trans` function defined in `net/ethernet/eth.c`. The important part is however the call of the `netif_rx` function defined in `net/core/dev.c` that saves incoming frames into the input queue for the current CPU `input_pkt_queue`.

```c
static irqreturn_t netdevice_interrupt(int irq, void *dev_id, struct pt_regs *regs)
{
1. Allocate sk_buff structure for the incoming packet.
   skb = dev_alloc_skb(...);
   ...
   if(skb!=NULL) {
   ...
2. Assign the receiving device to the sk_buff.
   skb->dev = dev;
   ...
3. Initialize the protocol field so that the packet is to be passed to an appropriate network layer protocol.
   skb->protocol = eth_type_trans(skb,dev);
   ...
4. Invoke netif_rx function.
   netif_rx(skb);
   ...
}
}
```

2. Generic non-NAPI interrupt handler

More information about Linux network device drivers can be found in [LDD] chapter 17 “Network Drivers”. 

```c
static irqreturn_t netdevice_interrupt(int irq, void *dev_id, struct pt_regs *regs)
{
1. Allocate sk_buff structure for the incoming packet.
   skb = dev_alloc_skb(...);
   ...
   if(skb!=NULL) {
   ...
2. Assign the receiving device to the sk_buff.
   skb->dev = dev;
   ...
3. Initialize the protocol field so that the packet is to be passed to an appropriate network layer protocol.
   skb->protocol = eth_type_trans(skb,dev);
   ...
4. Invoke netif_rx function.
   netif_rx(skb);
   ...
}
```

2. Generic non-NAPI interrupt handler

More information about Linux network device drivers can be found in [LDD] chapter 17 “Network Drivers”.

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Now let us take a closer look in the netif_rx (3) function. It uses the incoming frame as argument and performs the following:

```c
int netif_rx(struct sk_buff *skb)
{
    struct softnet_data *queue;
    ...
1. If the device driver has not already time stamped the packet, it is done here.
    if (!skb->tstamp.off_sec)
        net_timestamp(skb);
    ...
2. Get the softnet_data structure for current CPU where the packet will be queued.
    queue = &__get_cpu_var(softnet_data);
    ...
3. The queue size is limited, so check if there is available space in the queue.
    It can be modified with sysctl -w net.core.netdev_max_backlog=300
    if (queue->input_pkt_queue.qlen <= netdev_max_backlog) {
        ...
        enqueue:
            4. Insert the packet into the softnet_data queue input_pkt_queue.
                __skb_queue_tail(&queue->input_pkt_queue, skb);
                ...
      5. Schedule software interrupt to process the packets. After that the kernel takes
         care for the packets and dequeues them from the queue.
        netif_rx_schedule(&queue->backlog_dev);
        ...
    }
    ...
}
```

3. netif_rx function

With the last step the kernel is notified for the received frame and this is done by invoking the netif_rx_schedule function defined in include/linux/netdevice.h. The function takes the device that receives the frame as an argument and it is a wrapper that checks if the device is running and that the software interrupt is not already scheduled. The “real job” is done by __netif_rx_schedule (4) also defined in include/linux/netdevice.h. It performs in general two things. First, the device for which the function is called is linked into the softnet_data’s poll_list. In the non-NAPI case this is the softnet_data’s virtual device backlog_dev. Second, the software interrupt is scheduled.

```c
static inline void __netif_rx_schedule(struct net_device *dev)
{
    ...
1. Link the device into a list of devices in polling mode for the current CPU.
   This list is the softnet_data member poll_list.
   list_add_tail(&dev->poll_list,
                &__get_cpu_var(softnet_data).poll_list);
    ...
2. Schedule the softirq for reception.
    __raise_softirq_irqoff(NET_RX_SOFTIRQ);
}
```

4. __netif_rx_schedule function
Now all structures of interest are initialized, the packet is inserted into the input_pkt_queue and the virtual device backlog_dev is linked into the poll_list of the current CPU. After the second step in the __netif_rx_schedule function the device driver isn’t anymore responsible for the packet and the kernel takes control over it. The __raise_softirq_irqoff function causes the execution of software interrupt handler and as previously shown in the net_dev_init routine the net_rx_action function has been installed as a handler for the softirq NET_RX_SOFTIRQ.

4.3 net_rx_action
As might be expected, its mission is to consume the packets from the input queues. This is done by running over the poll_list on the current CPU and for each device in the list its poll method is called. If poll returns value other than 0 it means that not all packets in the queue were dequeued (to ensure fairness amongst devices) and there are others waiting to be processed. For this reason the net_device structure that called its poll function is removed from the list and then reinserted. As you may be already noticed the poll_list is organized in FIFO-manner so the first inserted device in the list will be also processed first during the execution of the net_rx_action function.

```c
static void net_rx_action(struct softirq_action *h)
{
1. Get the softnet_data for the current CPU.
   struct softnet_data *queue=__get_cpu_var(softnet_data);
   ... ...
2. While the poll_list contains devices it executes its poll method, remove the device from the poll_list and if after that the input queue still contains packets reinsert the device into the poll_list.
   while (!list_empty(&queue->poll_list)) {
      struct net_device *dev;
      ... ...
2.1 Get the device from the poll_list.
      dev = list_entry(queue->poll_list.next, struct net_device, poll_list);
      ... ...
2.2 Call the poll method for this device.
      if (dev->quota <= 0 || dev->poll(dev, &budget)) {
          ... ...
2.3 If poll returns value different from 0 there are packets in the input queue waiting to be processed. So remove the device from the poll_list.
          list_del(&dev->poll_list);
2.4 Reinsert the device into the poll_list.
          list_add_tail(&dev->poll_list, &queue->poll_list);
          ... ...
      } else {
          ... ...
      }
      ... ...
}
```

5. net_rx_action function
4.4 process_backlog

In the net_dev_init (1) function the poll method of the virtual device backlog_dev is initialized with the process_backlog (6) function. It dequeues the frames from the input_pkt_queue, delivers them to an appropriate network layer protocol by calling the netif_receive_skb (7) function and if all packets are processed the backlog_dev is removed from poll_list.

```c
static int process_backlog(struct net_device *backlog_dev,
    int *budget)
{
    ... ...
1. Get the softnet_data for the current CPU.
    struct softnet_data *queue=__get_cpu_var(softnet_data);
    ... ...
    for (;;) {
        struct sk_buff *skb;
        struct net_device *dev;
        ... ...
2. Dequeue a packet from the input_pkt_queue.
        skb=__skb_dequeue(&queue->input_pkt_queue);

3. If the input_pkt_queue is empty the backlog_dev can be removed from the poll_list.
    if (!skb)
        goto job_done;
    ... ...

4. Deliver the packet to an appropriate network layer protocol.
    netif_receive_skb(skb);
    ... ...
    job_done:
    ... ...
5. Remove the backlog_dev from the poll_list.
    list_del(&backlog_dev->poll_list);
    ... ...
    return 0;
}
```

4.5 netif_receive_skb

At this point we are at the end of the link layer and there is only one thing that must be done: to find an appropriate network layer protocol. This responsibility is taken by the netif_receive_skb (7) function. When I introduced the packet handler structure packet_type it was mentioned that ptype_all list and ptype_base hash table contain the registered protocol sniffer and protocol handlers. Both the list and the hash table were initialized in the net_dev_init (1) routine. The idea behind netif_receive_skb (7) is almost trivial: run over the list and the hash table and if an appropriate protocol handler is found invoke its function handler. This is done by a function wrapper deliver_skb defined in net/core/dev.c that first increments the reference counter of the packet and then calls the function handler.
int netif_receive_skb(struct sk_buff *skb) {
1. Initialize the transport layer protocol and the network layer protocol pointers.
   skb->h.raw = skb->nh.raw = skb->data;
1.1 Calculate the MAC size.
   skb->mac_len = skb->nh.raw - skb->mac.raw;
   ....
2. For each entry in the ptype_all list check for registered protocol sniffers.
   list_for_each_entry_rcu(ptype, &ptype_all, list) {
   
   2.1 Protocol handler wants to see all packets (its dev field is 0) or to
      limit the packets to those received on a specific device.
      if (!ptype->dev || ptype->dev == skb->dev) {
   
   2.2 If there is a registered sniffer for all devices or for a certain one call
      its function handler through the deliver_skb.
      if (pt_prev)
         ret = deliver_skb(skb, pt_prev, orig_dev);
         pt_prev = ptype;
      }
   } ...
   
   3. Get the protocol value of the packet. This sk_buff field was initialized by
      the device drivers. In the Ethernet case that was the eth_type_trans function.
      type = skb->protocol;
   4. A Simple hash function finds the correspondent list in the hash table and for each entry
      compares this time not only the packet_type's dev field with the sk_buff's dev field, but
      also the sk_buff's protocol field with the packet_type's protocol field.
      list_for_each_entry_rcu(ptype, &ptype_base[ntohs(type)&15],list)
      {
      if (ptype->type == type &&
         (!ptype->dev || ptype->dev == skb->dev))
         {
         if (pt_prev)
            ret = deliver_skb(skb, pt_prev, orig_dev);
            pt_prev = ptype;
         }
      }
   5. The searching for packet handlers is always one behind in search loop. So on exit from
      the loop invoke the function handler for the last matched protocol.
      if (pt_prev) {
         ret = pt_prev->func(skb, skb->dev, pt_prev, orig_dev);
      } else {
   6. If no protocol was matched the frame is discarded.
      kfree_skb(skb);
      ....
   out: ... ...
   return ret;
}

7. netif_receive_skb function
4.6 NAPI Frame Reception
The differences between non-NAPI and NAPI drivers are that NAPI drivers must provide a poll method while non-NAPI are using the pseudo-polling process_backlog function and in the calling convention for scheduling software interrupt: non-NAPI drivers call netif_rx function while NAPI drivers invoke netif_rx_schedule directly or __netif_rx_schedule in combination with netif_rx_schedule_prep to check if a softirq is already scheduled [ULNI]. However not all devices can operate in NAPI mode, because the device must be able to store several packets on the card itself or in a DMA-ring and should be capable to disable interrupts for receiving packets [LDD]. Besides the device specific stuff in a NAPI device driver, the code below represents primitive interrupt handler and poll method. The interrupt handler is modified so that sk_buff structures for the incoming packets are allocated in the poll method. The interrupts are disabled during the reception of the “first” packet, the device is inserted into the poll_list with netif_rx_schedule and software interrupt is scheduled. Then the processing of the frames is done as by non-NAPI drivers with net_rx_action function that calls the device specific poll method. In general it must dequeue packets from a DMA-ring or a card memory, inserts the incoming data into socket buffers and to be delivered to an appropriate network layer it calls the netif_receive_skb function. The last thing left to be done is to enable the interrupts if the receive buffer is empty.

```c
static irqreturn_t netdevice_interrupt(int irq, void *dev_id, struct pt_regs *regs)
{
    ... ...
    1. Disable further interrupts.
    ... ...
    2. Insert the device into the poll_list for the current CPU.
       netif_rx_schedule(dev);
    ... ...
}
```

8. Generic NAPI interrupt handler
static int netdevice_poll (struct net_device *dev, int *budget)
{
1. Poll the device until the receive buffer (device memory or DMA-ring) contains packets and certain amount of them are processed.
   while (Receive_Buffer_Not_Empty && Processed_Packets < Quota) {
      1.1 Allocate socket buffer.
         skb = dev_alloc_skb (packet_size + 2);
      1.2 Initialize some of the sk_buff fields.
         skb->dev = dev;
         skb->protocol = eth_type_trans(skb, dev);
      1.3 Deliver the packet to an appropriate network layer protocol.
         netif_receive_skb(skb);
         Processed_Packets++;
   }
2. If the receive buffer is empty the interrupts must be enabled.
   if (Receive_Buffer_Empty) {
      2.1 Enable interrupts
      2.2 The net_rx_action function must know that all packets are processed.
         return 0;
   }
2.3 The receive buffer contains still packets. Inform the net_rx_action function to remove and reinsert the device into the poll_list.
   return 1;
}

9. Generic NAPI poll method
5. Linux Netfilter Framework

After calling the `netif_receive_skb` function incoming frames are leaving the link layer if appropriate network protocols are registered for them. However the protocol of interest is IPv4 and the accent will fall on the netfilter hooks in it. This chapter introduces some data structures and functions from the netfilter framework and explains its working mechanism. Linux netfilter is a framework responsible for packet mangling outside the normal Berkley socket interface [NF]. Each protocol defines set of “hooks” (IPv4 defines 5) which are well-defined points in a packet’s traversal of that protocol stack [NF]. At each of this points the protocol calls the netfilter framework to “take care” of the passing packet. Parts of the kernel and kernel modules can register to the different hooks for each protocol and when a packet is passed to the netfilter framework, it checks if anyone has registered for that protocol and hook [NF]. Main features of the framework are:

1. stateless packet filtering
2. statefull packet filtering
3. network address and port translation
4. routing

5.1 nf_hook_ops

The hooks for the different protocols are defined in `include/linux/netfilter_xxx.h` where xxx denotes the protocol and their numbers differs between the protocol stacks: IPv4 defines 5 hooks, ARP – 3, DECnet – 7. The registering to a netfilter hook is done with the `nf_hook_ops` data structure defined in `include/linux/netfilter.h` and its fields are explained in Figure 8.

```
struct list_head list
  • Used to link the data structure

hook
  • Function pointer to the hook-function

owner
  • Module owner

pf
  • Protocol family

hooknum
  • Hook number

priority
  • Priority
```

Figure 8: Fields of the `nf_hook_ops` structure

```
struct list_head list

A function pointer called when a packet is passed to a hook and performs one of the following actions on a packet:

NF_ACCEPT    • will allow a packet to continue the traversal through the protocol stack.
NF_DROP      • will drop the packet
NF_STOLEN    • take control over the packet, don’t continue the traversal
NF_QUEUE     • queue the packet (usually for userspace handling)
NF_REPEAT    • call this hook again.
```

The five values are defined in `include/linux/netfilter.h`.

struct module *owner
Pointer to the kernel module that owns the nf_hook_ops structure.

int pf
The protocol family to that the hook belongs (ARP, IPv4 etc.). Except NF_ARP for ARP defined in include/linux/netfilter_arp.h the possible values are defined in include/linux/socket.h (netfilter hooks are not inserted in every protocol stack).

int hooknum
This represents the different hooks in a protocol stack. For example IPv4 defines 5 hooks defined in include/linux/netfilter_ipv4.h:
NF_IP_PRE_ROUTING
NF_IP_LOCAL_IN
NF_IP_FORWARD
NF_IP_LOCAL_OUT
NF_IP_POST_ROUTING

int priority
This is the priority of a hook entry. Each one is inserted according to its priority so that they are ordered in ascending priority. The values are protocol specific and defined in include/linux/netfilter_xxx.h.

5.2 Netfilter Hooks in IPv4 Protocol Stack
Figure 9 shows the IPv4 hooks. Every packet that enters the protocol stack is passed first to the prerouting hook NF_IP_PRE_ROUTING. Then follows a routing code which decides whether the frame is destined for another interface or a local process. The routing code may drop packets that are unroutable. If the packet is for a local process it enters the NF_IP_LOCAL_IN hook and if it is destined to another interface the NF_IP_FORWARD hook is called. The NF_IP_LOCAL_OUT hook is called for packets created by a local process and at the end every packet leaves the protocol stack through the NF_IP_POST_ROUTING hook [NF].

Figure 9: IPv4 netfilter hooks
5.3 Netfilter Framework in Details
As mentioned before the registered hook entries are stored in two dimensional array called
nf_hooks[NPROTO][NF_MAX_HOOKS] defined in net/netfilter/core.c where
NPROTO is the maximum number of protocols supported from the kernel (at the moment 32)
and NF_MAX_HOOKS is the maximum number of hooks defined in a protocol stack (this is
the DECnet protocol that defines 7 hooks) plus 1. Each element of the table is a list so that
several hooks can register to the same hook but with different priority.
The nf_register_hook (10) function inserts a nf_hook_ops structure into the table
according to its priority (the priority member of the structure) and to remove one there is
the nf_unregister_hook (11) function both defined in net/netfilter/core.c.

```
int nf_register_hook(struct nf_hook_ops *reg)
{
    struct list_head *i;
1. Find the correspondent entry in the table according to the protocol family and
   the hook number. Run over the list until a lower hook object's priority occur.
   list_for_each(i, &nf_hooks[reg->pf][reg->hooknum]) {
       if(reg->priority<((struct nf_hook_ops *)i)->priority)
           break;
   }
2. Insert the nf_hook_ops structure.
   list_add_rcu(&reg->list, i->prev);
   return 0;
}
```

10. nf_register_hook function

```
void nf_unregister_hook(struct nf_hook_ops *reg)
{
1. Remove a hook object from the list.
    list_del_rcu(&reg->list);
    .......
}
```

11. nf_unregister_hook function

Each hook is called by a protocol stack with the NF_HOOK (12) wrapper defined in
include/linux/netfilter.h. It checks if there are registered objects to a hook, calls
the nf_hook_slow function defined in net/netfilter/core.c and if the packet is
accepted from netfilter subsystem the wrapper calls the next protocol routine of the stack.
A general call looks like NF_HOOK (protocol, hook, skb_buffer,
input_device, output_device, next_protocol_call).

```
#define NF_HOOK(pf, hook, skb, indev, outdev, okfn)
({
1. Check list entry from the nf_hooks table and if the packet is accepted.
    if (list_empty(&nf_hooks[pf][hook]) ||
2. Call nf_hook_slow function.
    (__ret=nf_hook_slow(pf,hook, &(skb),
       indev, outdev, okfn, INT_MIN)) == 1)
3. A packet is accepted and can continue its traversal. Invoke the next procol call of the stack.
    __ret = (okfn)(skb);
    __ret;})
```

12. NF_HOOK wrapper
For better explanation of the netfilter subsystem let see the \texttt{ip_rcv} (13) function where the prerouting \texttt{NF_IP_PRE_ROUTING} hook is placed. First it checks if the packet is destined to the machine so that packets that enter the protocol stack during promiscuous mode are dropped. General checks follow for different kinds of errors such as incorrect size, checksum etc.

```c
int ip_rcv(struct sk_buff *skb, struct net_device *dev, 
    struct packet_type *pt, struct net_device *orig_dev)
{
    1. When the interface is in promiscuous mode drop all the crap 
       that it receives, do not try to analyze it. 
       if (skb->pkt_type == PACKET_OTHERHOST) 
           goto drop; 
       .......
    2. Call the prerouting netfilter hook. 
       return NF_HOOK(PF_INET, NF_IP_PRE_ROUTING, 
                       skb, dev, NULL, ip_rcv_finish); 
    3. By error discard the sk_buff structure. 
       inhdr_error: 
           .......
       drop: 
           kfree_skb(skb); 
    out: 
       .......
}
```

13. \texttt{ip_rcv} function

In the second step a frame enters the netfilter subsystem. In this case the protocol family is IPv4 or \texttt{PF_INET}, the hook is the prerouting \texttt{NF_IP_PRE_ROUTING}, \texttt{skb} is the packet, \texttt{dev} is the device that received the frame and the function \texttt{ip_rcv_finish} is the next protocol call of the stack. The \texttt{nf_hook_slow} (14) gets the correspondent list from the \texttt{nf_hooks} table according the protocol family and the hook. Then it runs over the list and for registered hook objects \texttt{nf_hook_ops} calls their function pointers. The iterating over the list is done with \texttt{nf_iterate} (15) routine also defined in \texttt{net/netfilter/core.c}.
int nf_hook_slow(int pf, unsigned int hook,
    struct sk_buff **pskb, struct net_device *indev,
    struct net_device *outdev,
    int (*okfn)(struct sk_buff *), int hook_thresh)
{

1. Get the correspondent list from the nf_hooks table according to the protocol family and the hook.
   
   elem = &nf_hooks[pf][hook];

next_hook:
2. Start iterating over the list.
   
   verdict = nf_iterate(&nf_hooks[pf][hook], pskb, hook,
        indev, outdev, &elem, okfn, hook_thresh);

3. Check return value.
   
   if (verdict == NF_ACCEPT || verdict == NF_STOP) {
3.1 Packet is accepted and can continue its traversal.
       ret = 1;
       goto unlock;
   } else if (verdict == NF_DROP) {
3.2 Packet is dropped.
       kfree_skb(*pskb);
       ret = -EPERM;
   } else if ........
}
unlock:
   return ret;
}

14. nf_hook_slow function

unsigned int nf_iterate(struct list_head *head,
    struct sk_buff **skb,
    int hook, const struct net_device *indev,
    const struct net_device *outdev,
    struct list_head **i,
    int (*okfn)(struct sk_buff *),
    int hook_thres)
{

    unsigned int verdict;
1. Run over the list.
   
   list_for_each_continue_rcu (*i, head) {
        struct nf_hook_ops *elem = (struct nf_hook_ops *)*i;
2. Call the nf_hook_ops function.
        verdict = elem->hook(hook, skb, indev, outdev, okfn);
3. Check return value.
        if (verdict != NF_ACCEPT) {
......
            if (verdict != NF_REPEAT)
                return verdict;
            (*i) = (*i)->prev;
        }
    }
return NF_ACCEPT;
}

15. nf_iterate function
6. Kernel Sniffer
At this point we know almost everything to create a kernel sniffer except a method to write a captured packet into a file. This chapter deals first with an overview of the Virtual File System (VFS) and then explains the capturing mechanism of the kernel module.

6.1 Accessing File from Kernel Module
Accessing a file from kernelspace is not as trivial as in userspace. File operations are not supposed to be done in kernelspace it is dangerous and can compromise the system stability. However there are several projects that are dealing with files in kernelspace and maybe the best known is the kernel-based web server TUX maintained by Ingó Molnár. The difficulty of accessing files from kernel module is that it can't simply invoke system calls such as `open()` or `write()`, because in that case data is moved from userspace to kernelspace and obviously a kernel module works in kernelspace. The solution of the problem is to use the Virtual Filesystem layer (see Figure 10). Linux supports many different filesystems and to enable the upper levels of the kernel to deal equally with all of these filesystems Linux defines an abstract layer known as Virtual Filesystem or VFS [UtLK]. Each lower level must provide an interface which conforms to VFS.

![Virtual Filesystem Diagram](image)

**Figure 10: Virtual filesystem**

The VFS contains a number of generic object types and methods which can be called on these objects. The basic objects are as follows and their interaction is depicted in Figure 11:

1. file (information about an open file) 
   ```
   include/linux/fs.h
   ```
2. inode (information about a file) 
   ```
   include/linux/fs.h
   ```
3. dentry (information about a directory) 
   ```
   include/linux/dcache.h
   ```
4. superblock (information about a filesystem) 
   ```
   include/linux/fs.h
   ```
For the project the component of interest is the file object that stores information about the interaction between an open file and a process. It is represented through a data structure `struct file` defined in `include/linux/fs.h`. The structure contains also a member `f_op` that is a number of methods for file handling (`struct file_operations` defined in `include/linux/fs.h`) and after a file is opened it can be accessed through this methods. For example when a file is opened it can be written with `file->f_op->write`. To initialize and open a file structure the kernel can not invoke a system call as mentioned above. But following the call chain of the system call `sys_open` defined in `fs/open.c` give us the function that opens a file: `filp_open` defined also in `fs/open.c`. After a file is opened it can be easily manipulated through the methods for file handling in it and it is closed with `filp_close` defined in `fs/open.c`. More information about VFS can be found in [UtLK] chapter 12 “The Virtual Filesystem”.

6.2 Design
First the kernel module should be registered to the netfilter subsystem and especially to the prerouting and postrouting hooks. So packets that enter the IPv4 protocol stack will be passed through the `NF_IP_PRE_ROUTING` hook and those that leave the machine through the `NF_IP_POST_ROUTING` hook. There is only one problem: packets that are not destined to the machine during promiscuous mode will be dropped from `ip_rcv` (13) function when they enters the IPv4 protocol stack(see 6. Linux Netfilter Framework). So how can the module capture those packets? The answer is the `ptype_all` list that contains protocol sniffers. Adding an entry in it ensures that every packet that enters the machine will be passed first to a protocol handler from the list and then eventually to one from the hash table `ptype_base` where the “real” handlers are stored. The protocol handler inserted in `ptype_all` must capture only those packets that are not destined to the machine otherwise packets destined to the machine will be captured twice: first from the protocol handler in `ptype_all` and second from the netfilter hooks. Now the kernel module can monitor each packet that enters or leaves the IPv4 protocol stack. However frames must be saved somewhere before being written into file. For this reason a sniffer usually uses a circular buffer of fixed size to store the captured packets. Nevertheless I chose another approach: to use the same methods as the kernel to maintain packets: fixed size queues. So when a packet is passed through one of these three points it will be enqueued in a socket buffer queue and dequeued after it is being written into a file. Figure 12 makes an overview of the sniffer. First the module creates a file object with `filp_open` function where the captured packets will be saved. When the file is initialized the pcap file header must be written with the `write` method of the file `file->f_op->write`. The next step is to set the device that are to be sniffed in promiscuous mode with `dev_set_promiscuity` and to enable the time stamp for packets with `net_enable_timestamp`. After that the packet capturing can begin and the module registers to the prerouting `NF_IP_PRE_ROUTING` hook, the postrouting `NF_IP_POST_ROUTING` hook with the `nf_register_hook` (10) function and inserts a `packet_type` handler in the `ptype_all` list with the `dev_add_packet` function to capture packets not destined to the machine. The last thing left to be done is to start a kernel thread that will dequeue frames from a socket buffer queue and writes them in to a file with `file->f_op->write`. 

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Packet capturing at high network rates is a challenge due to various hardware limitations. Disk I/O operations are very slow in comparison with other system activities and they are performance killer. A lot of time is spent for writing frames into a file and this causes packets lost, because the amount of data received from the network device is bigger then the disc throughput. Also invoking a write operation for every single packet will additionally increase this time and it will decrease the capturing rate. To reduce the number of write accesses the kernel thread responsible for dequeuing and writing processes multiple packets at once.

The kernel module can take the following arguments:

- **queue_size**: The maximum queue size of the sniffer by default the size is 10000 packets.
- **device_name**: Captures packets on a specific device by default all devices are sniffed.
- **logfile**: File where captured packets are saved by default log.pcap in the module's directory.
- **snaplen**: Snarf snaplen bytes of data from each packet by default snaplen is 96 bytes.

Changing the queue size can slightly improve the capturing performance of the module.

When the kernel sniffer is inserted it creates entry in /proc/ksniff where different statistics of a network device are exported such as received packets, captured packets, errors etc.
### 6.3 Benchmarks

Below are listed some tests and comparisons with tcxdump done on Athlon XP 1800, RAM:256 MB and maximal disk's write speed ~ 34 MB/s.

<table>
<thead>
<tr>
<th>TEST 1: kernel sniffer, snaplen=1500</th>
<th>TEST 1: tcxdump, snaplen=1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packets:2000000 (1496byte,0frags)</td>
<td>Packets:2000000 (1496byte,0frags)</td>
</tr>
<tr>
<td>70800pps 847Mb/sec (847432454bps) errors: 0</td>
<td>70800pps 847Mb/sec (84744015bps) errors: 0</td>
</tr>
<tr>
<td>Captured packets:603874</td>
<td>589831 packets captured</td>
</tr>
<tr>
<td>Received packets:655560</td>
<td>661719 packets received by filter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST 2: kernel sniffer, snaplen=96</th>
<th>TEST 2: tcxdump, snaplen=96</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packets:2000000 (1496byte,0frags)</td>
<td>Packets:2000000 (1496byte,0frags)</td>
</tr>
<tr>
<td>70799pps 847Mb/sec (847331807bps) errors: 0</td>
<td>70808pps 847Mb/sec (847431164bps) errors: 0</td>
</tr>
<tr>
<td>Captured packets:647783</td>
<td>642799 packets captured</td>
</tr>
<tr>
<td>Received packets:647783</td>
<td>645014 packets received by filter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST 3: kernel sniffer, snaplen=1500</th>
<th>TEST 3: tcxdump, snaplen=1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packets:10.000.000 (1496byte,0frags)</td>
<td>Packets:10.000.000 (1496byte,0frags)</td>
</tr>
<tr>
<td>47274pps 565Mb/sec (565784851bps) errors: 0</td>
<td>47088pps 563Mb/sec (563557308bps) errors: 0</td>
</tr>
<tr>
<td>Captured packets:3791329</td>
<td>3643704 packets captured</td>
</tr>
<tr>
<td>Received packets:9844006</td>
<td>9930613 packets received by filter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEST 4: kernel sniffer, snaplen=96</th>
<th>TEST 4: tcxdump, snaplen=96</th>
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<tr>
<td>Packets:10.000.000 (1496byte,0frags)</td>
<td>Packets:10.000.000 (1496byte,0frags)</td>
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<tr>
<td>48294pps 577Mb/sec (577992364bps) errors: 0</td>
<td>48666pps 582Mb/sec (582438142bps) errors: 0</td>
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<tr>
<td>Captured packets:9258105</td>
<td>9582944 packets captured</td>
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<td>Received packets:9813181</td>
<td>9726366 packets received by filter</td>
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# 7. Summary

## Data Structures

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<td>struct sk_buff</td>
<td>Data structure used to represent a packet.</td>
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<td>struct net_device</td>
<td>Represents a network device.</td>
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<td>struct sk_buff_head</td>
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<td>struct softnet_data</td>
<td>Used to manage ingress/egress traffic.</td>
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<td>struct packet_type</td>
<td>Protocol handler.</td>
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## Functions

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<td>net_enable_timestamp</td>
<td>Activate timestamp for sk_buffs.</td>
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<td>net_disable_timestamp</td>
<td>Deactivate timestamp for sk_buffs.</td>
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<tr>
<td>dev_add_pack</td>
<td>Inserts a packet_type data structure in ptype_all list or ptype_base hash table.</td>
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<tr>
<td>dev_remove_pack</td>
<td>Removes a packet_type data structure from ptype_all list or ptype_base hash table.</td>
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<td>net_dev_init</td>
<td>Called at a boot time to initialize the per-CPU softnet_data structures, the protocol sniffer list ptype_all, the protocol hash table ptype_base and software interrupt handlers for reception/transmission.</td>
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<td>open_softirq</td>
<td>Registers a software interrupt handler.</td>
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<td>Used by non-NAPI drivers to queue an incoming frames in input_pkt_queue and schedules a software interrupt with netif_rx_schedule.</td>
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<tr>
<td>netif_rx_schedule</td>
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<td>__raise_softirq_irqoff</td>
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<td>netif_receive_skb</td>
<td>Processes incoming packets to an appropriate network layer.</td>
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<td>Registers a nf_hook_ops object to a netfilter hook.</td>
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<td>nf_unregister_hook</td>
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Bibliography


[LKD] Linux Kernel Documentation. linux/Documentation

