A roaring journey through sk_buff and net_device

From Userspace through the Networking Subsystem into the Driver – and back again

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Preface

- Requirements:
  - Low latency
  - High througput
  - Low CPU and memory utilization
  - Fair behavior against other protocols and components
- Driver specific code is based on `e1000` adapter (exceptions are marked)
- No e1000 feature show today (sorry – that presentation was held last time ;-)

```
/* The code following below sending ACKs in SYN-RECV and TIME-WAIT states
   outside socket context is ugly, certainly. What can I do?  */
```

NIC Initialization

- Initialization: `pci_register_driver()` → `e1000_probe()`
- `request_irq()` → registers IRQ handler
- `e1000_open()` (called when if is made active)
  1. Allocate transmit descriptors `e1000_setup_all_tx_resources()`
  2. Allocate receive descriptors `e1000_setup_all_rx_resources()`
  3. Power up `e1000_power_up_phy()`
  4. Tell firmware that we are the NIC is now open `e1000_get_hw_control()`
  5. Allocate interrupt `e1000_request_irq()`
  6. `e1000_configure_rx()`
- BTW: `SA_SAMPLE_RANDOM`

Virtual vs. Real Devices

- Each network device is represented by a instance of `net_device` structure
- Virtual Devices:
  - Build on top of a real (or virtual) device
  - Bonding, VLAN (802.1Q), IPIP, GRE, ...
  - Similar handling like real devices (register device et cetera)
- Real Devices:
  - RTL 8139/8169/8168/8101 `;-)`
- Mappings $n : m$

Frame Arrival – Hippie Revival

- Interrupt Handler: `e1000_intr()` → `__netif_rx_schedule()`
- Iterrupt handler branch to arival workmode
- Get RX ring address (and current offset) (`e1000_clean_rx_irq_PS()`)
- Get frame size and status from DMA buffer (`E1000_WRITE_REG`, `le32_to_cpu()` and friends)
- Receive Checksum Offload `e1000_rx_checksum()`
- Allocate new buffer: `dev_alloc_skb()` (non-NAPI)
- `skb_copy_to_linear_data`
- Get protocol: `eth_type_trans()` and update statistics
- `net/core/dev.c:netif_rx()` → save data in CPU input queue (Limit: `net.core.netdev_max_backlog`) and `netif_rx_schedule()`
- NAPI: `netif_rx_schedule()` and `netif_rx_schedule_prep()` directly

Frame Transmission

- `hard_start_xmit()`: driver/hardware specific network stack → Hardware entry point
- `hard_start_xmit()` → `NETIF_F_LLTX` (Duplicate Transmission Locking)
- `e1000_xmit_frame`
  1. `tx_ring = adapter->tx_ring;`
  2. Sanity checks (`skb->len <= 0`, adapter workarounds and friends)
  3. Count frags: `count += TXD_USE_COUNT(len, max_txd_pwr);` (thousends of errata)

4. Flush `e1000_tx_queue()`

```
static void e1000_tx_queue(struct e1000_adapter *adapter,
        struct e1000_tx_ring *tx_ring, int tx_flags, int count)
{
        [...]
        while (count--) {
                buffer_info = &tx_ring->buffer_info[i];
                tx_desc = E1000_TX_DESC(*tx_ring, i);
                tx_desc->buffer_addr = cpu_to_le64(buffer_info->dma);
                tx_desc->lower.data = cpu_to_le32(txd_lower | buffer_info->length);
                tx_desc->upper.data = cpu_to_le32(txd_upper);
                if (unlikely(++i == tx_ring->count)) i = 0;
        }
        [...]
        writel(i, adapter->hw.hw_addr + tx_ring->tdt);
        [...]
}
```

Queuing Disciplines

- Each NIC has a assigned queuing discipline
- The egress queue is handled by tc
- L2 Congestion Management: **Ingress Path:** throtteling? → UDP? TCP? No (ECN? Maybe!)

Protocol Support

ETH_P_IP	net/ipv4/ip_input.c:ip_rcv()
ETH_P_ARP	net/ipv4/arp.c:arp_rcv()
ETH_P_IPV6	net/ipv6/ip6_input.c:ipv6_rcv()

Software IRQ

- To delay work (IRQ handler isn't the right place)
- Backlog queue per CPU
- CPU IRQ affinity
- After system call or IRQ handler returns
- Optimized for SMP/CMP systems
- `NET_RX_SOFTIRQ`
- `4 ?        S<     0:00 [ksoftirqd/0]`

NIC Data Mode: poll vs. interrupt

- Interrupt based:
  - NIC informs the driver if new data is available
  - Interrupt: new data, transmission failures and DMA transfer completed (`e1000_clean_tx_irq()`)
  - Queues the frame for further processing
- Polling based:
  - Driver check the device constantly if new data is available
  - Pure polling is rare!
- Currently: NAPI (“interrupt-polled-driven”, “site:jauu.net filetype:pdf napi”)

Network Driver Principles

- Each device driver register themselves (`register_netdevice()`; linked list of network devices)
- `include/linux/netdevice.h:struct net_device:`
  - `unsigned long mem_end, mem_start, base_addr, irq;`
  - `unsigned long state;`
  - `unsigned long features;`
    - `NETIF_F_SG, NETIF_F_HW_CSUM, NETIF_F_HIGHDMA,,...`
  - `int (*poll) (struct net_device *dev, int *quota);`
  - `struct Qdisc *qdisc;`
  - `int (*hard_start_xmit) (struct sk_buff *skb, struct net_device *dev);`

View From Userspace

- Socket Descriptor (`int fd`)
- can perform I/O on socket descriptor depending on socket state
- Various syscalls to create sockets/change state, etc
  - `socket()`, `listen()`, `connect()`, etc.
- Kernel keeps track of socket state
- *real* communication (the protocol itself) handled by kernel
- Kernel maps each process' descriptor to a structure

How to tell if descriptor is a socket?

- `current->files`: open file table structure
- contains list of `struct file`
- `if (file->f_op == &socket_file_ops) return file->private_data;`
- `f_op/socket_file_ops`: `struct file_operations`
  - function pointers for `read`, `write`, `ioctl`, `mmap`, `open`, ... hence the name: all deal with file operations
  - `socket_file_ops` is the `file_operations` structure for sockets
  - if `file->f_op` is something other than the socket fops, this is not a socket ;)
- `->private_data` points to a `socket` structure

socket structure

- Represents a Socket
- identifies:
  - socket type (`SOCK_STREAM`, etc).
  - socket state (`SS_CONNECTED`, etc).
- contains pointers to various other structures, incl. `proto_ops` and `struct sock`
- also contains wait queue/wakelist, etc.

sock structure

- Network layer representation of sockets
- large structure (≈ 60 members)
- contains protocol id, packets send/receive queue heads, listen backlog, timers, peercred, ...
- also has some callbacks:

```
void       (*sk_state_change)(struct sock *sk);
void       (*sk_data_ready)(struct sock *sk, int bytes);
void       (*sk_write_space)(struct sock *sk);
void       (*sk_error_report)(struct sock *sk);
int        (*sk_backlog_rcv)(struct sock *sk,
                              struct sk_buff *skb);
void       (*sk_destruct)(struct sock *sk);
```

struct proto_ops

- Recap:
  - `fd` $\longrightarrow$ `struct file`
  - `struct file` has `f_ops` (== `socket_file_ops` in case of sockets)
  - `struct file` also has a pointer to private data (which points to socket structure)
  - socket structure has `struct sock` (see previous slide). Also has `proto_ops`.
- `struct proto_ops` contains the (family dependent) implementation of socket functions: `bind`, `connect`, `setsockopt`, ...
- Example (simplified):

```
asmlinkage long sys_listen(int fd, int backlog) {
        struct socket *sock;

        sock = sockfd_lookup_light(fd, &err, &fput_needed);
        return sock->ops->listen(sock, backlog);
}
```

struct proto

- `struct proto`: socket layer → transport layer interface. Example:

```
struct proto tcp_prot = {
        .name                   = "TCP",
        .owner                  = THIS_MODULE,
        .close                  = tcp_close,
        .connect                = tcp_v4_connect,
[..]
```

- `struct inet_protosw`: transport → network interface. Example:

```
static struct inet_protosw inetsw_array[] = {
        {
                .type =       SOCK_STREAM,
                .protocol =   IPPROTO_TCP,
[..]
```

AF_INET internals

```
net/ipv4/af_inet.c:
const struct proto_ops inet_stream_ops = {
        .family            = PF_INET,
[..]
}
const struct proto_ops inet_dgram_ops = {
        .family            = PF_INET,
[..]
```

Linux `AF_INET` implementation holds valid `proto_ops` inside an array. Assignment to sock structure depends on `socket(2)` arguments

```
static struct inet_protosw inetsw_array[] = {
        {
                .type =       SOCK_STREAM, .protocol = IPPROTO_TCP,
                .prot =       &tcp_prot, .ops = &inet_stream_ops,
[..]
```

Socket creation

Userspace does: `socket(AF_INET, SOCK_STREAM, IPPROTO_TCP)`

- kernel allocates a new inode/socket. BTW: `grep sockfs /proc/filesystems`
- kernel sets `sock->type` as specified by User
- checks if family (=`AF_INET` in our case) is known (`net_proto_family[family] != NULL`)
- calls `net_proto_family[family]->create`
  - `create` function must be implemented by all address families
  - address families register themselves at the socket layer at initialization
  - in our case `create` will be `inet_create()`
- `inet_create()` searches `inet_protosw inetsw_array[]` for the requested type/protocol pair

Socket creation (2)

- sets `sock->ops` and other values as specified in `inetsw_array`.
- allocates new `struct sock` (`sk`), records `struct proto` as specified in `inetsw_array` (in our case `&tcp_prot`)
- finally calls `sk->sk_prot->init()` (i.e. `tcp_v4_init_sock`, set in `&tcp_prot`)
  - sets TCP specific stuff: ssthresh, mss_cache, `tcp_init_congestion_ops`, etc.

From write to the wire...

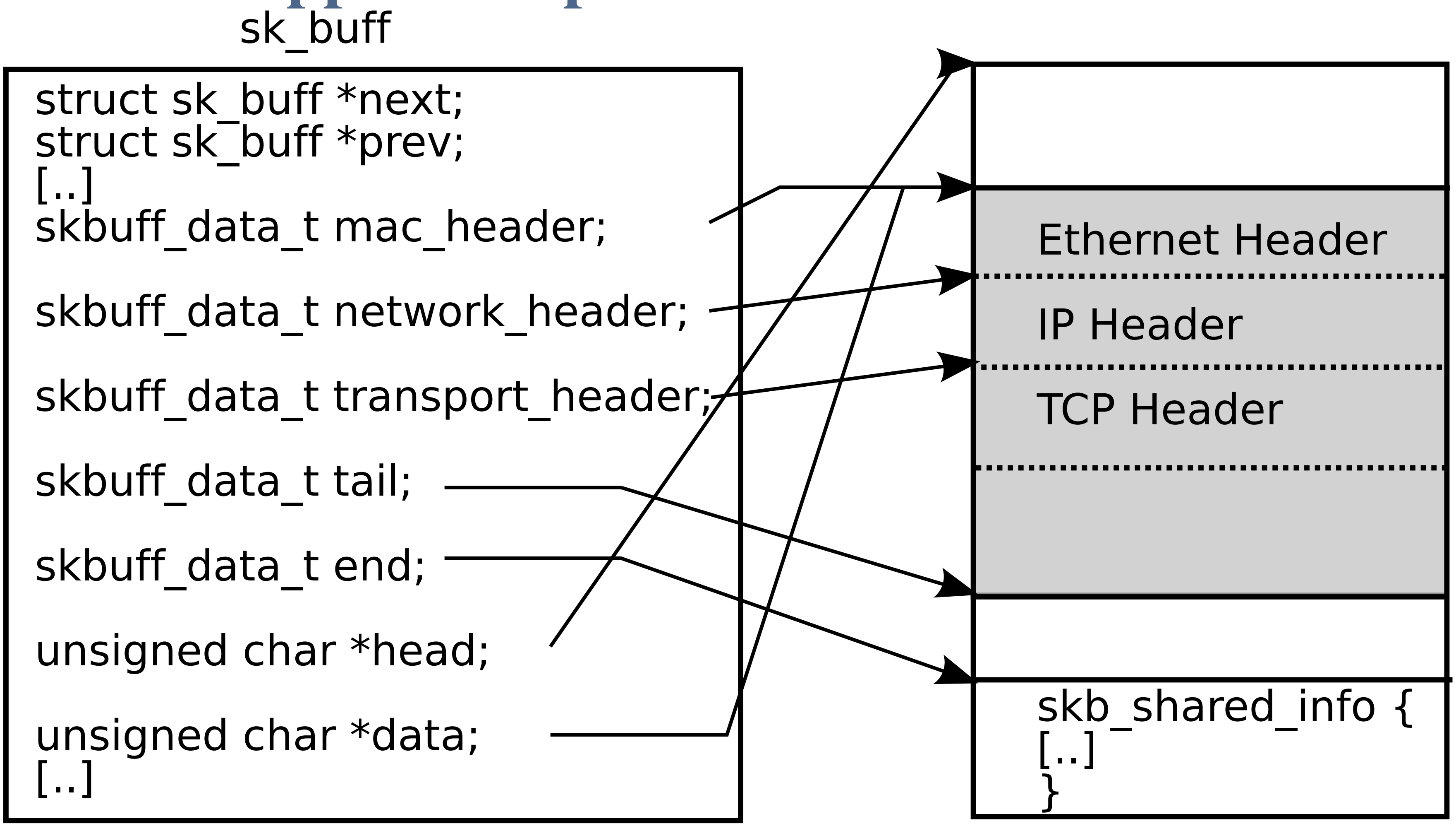
Lets have a look what happens when data ist written to a socket via `write`.

- kernel looks up the corresponding `struct file`.
- we end up inside `vfs_write()`, which calls `file->f_op->aio_write()`. (i.e. `socket_file_ops`)
- eventually we end up in `sock_sendmsg()`, which then calls `sock->ops->sendmsg` (i.e. `inet_protosw`'s entry for `SOCK_STREAM/IPPROTO_TCP`: `inet_stream_ops`)
  - now we are at the TCP level (`sock->ops->sendmsg` is `tcp_sendmsg`).
  - will look at TCP state (connecting, being shut down, . . .)
  - fetches a skb from write queue
  - if no skb: allocate new one, or: `sk_stream_wait_memory()`

skbuffs

- struct skbuff: The most important data structure in the Linux networking subsystem.
- every packet received/sent is handled using the skbuff structure
- problems to solve:
  - Memory accounting.
  - Queueing of packets.
  - parsing of layer 2/3/4 protocol information.
  - insertion of additional headers at the beginning of packet, etc.

skbuff mapped to a packet



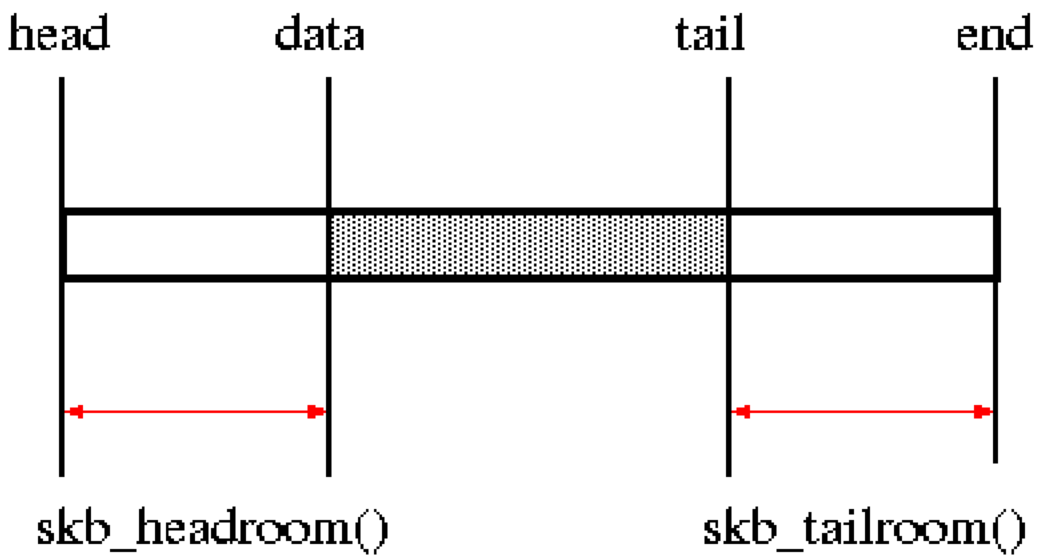
`next/prev`: List management (think ’receive/send queue this skb is on’)

`sk_buff_data_t`: pointer or offset (`unsigned int`, 64 bit platforms)

struct sk_buff

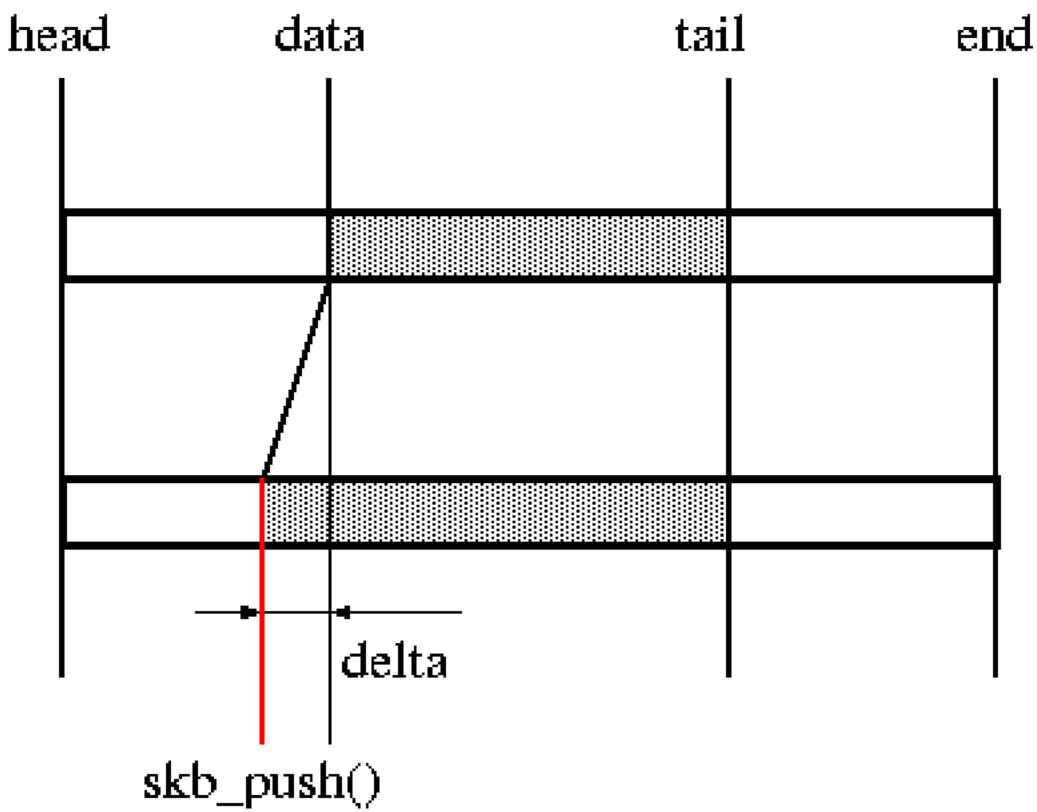
- `struct sk_buff { [..]`
  - `struct sock *sk;`: An skb is mapped to a socket, e.g. for memory accounting
  - `ktime_t tstamp;`: skb-timestamping (packet sniffer, `TCP_CONG_RTT_STAMP`, . . .): `net_timestamp()`, i.e. normally unused
  - `struct net_device *dev;`: interface skb arrived on/leaves by
  - `struct dst_entry *dst;`: Destination cache/routing. Keeps track of pmtu and other properties; also deals with route (e.g. link down).
    - Destination cache/routing. Keeps track of pmtu and other properties; also deals with route (e.g. link down).
      Has `struct dst_ops` which are implemented by each (network) protocol
  - `char cb[48]`: e.g. TCP control block (sequence number, flag, SACK, . . .)
  - keeps track of total length, data length, `cloned` etc.
  - optional pointers for `_NF_CONTRACK`, bridge, traffic shaping, . . .

skb_headroom



- `skb_headroom/_tailroom()`: return number of bytes left at head/tail
- `http://www.skbuff.net/skbbasic.html`

skb_push/_pull



- `skb_push/_pull`: adjusts headroom for tailroom adjustment: `skb_put/_trim`
- `http://www.skbuff.net/skbbasic.html`

Sending a TCP frame

- recap: We are sending data via TCP, `tcp_sendmsg` has picked an skb to use.
- checks `skb_tailroom()`. If nonzero, calls `skb_add_data` which copies data from userspace into skbuff.
- if tailroom exhausted, use fragment list (`skb_shinfo(skb)->nr_frags`)
- if fraglist unusable (pageslots busy, `!(sk->sk_route_caps & NETIF_F_SG)`): push skb and alloc new segment
- eventually calls `tcp_write_xmit`
  - Does MTU probing (`tcp_mtu_probe`), depending on TCP state
  - takes first skb from send queue
  - calls `tcp_transmit_skb(skb, ...)` and advances send_head, i.e. 'packet is sent'.
  - `tcp_transmit_skb`: builds TCP header and hands skb to IP layer (`ip_queue_xmit()`, via `icsk->icsk_af_ops->queue_xmit(skb, ..`)

Sending IP frame

- `ip_queue_xmit()`: make sure packet can be routed (sets `skb->dst`)
- Builds IP header
- Packet is handed to netfilter
- If everything ok: `skb->dst->output(skb);` (`ip_output()`).
  - sets `skb->dev = skb->dst->dev`
  - Packet is handed to netfilter (Postrouting!), calls `ip_finish_output` if ok.
  - finally: `dst->neighbour->output()...`

Almost done... need Layer 2 address

- Our journey through the protocol stack is almost done: `net/ipv4/arp.c`

```
static struct neigh_ops arp_generic_ops = {
        .family =               AF_INET,
[..]
        .output =               neigh_resolve_output,
};
static struct neigh_ops arp_direct_ops = {
        .family =               AF_INET,
        .output =               dev_queue_xmit,
```

`__skb_queue_tail(&neigh->arp_queue, skb)` if `NUD_INCOMPLETE`

dev_queue_xmit

- has to linearize the skb, e.g. if device doesn't support DMA from highmem and at least one page is highmem
- if device `dev->qdisc != NULL`, skb is enqueued now `q->enqueue(skb, q);`
- now a queue run is triggered (unless device is stopped...), eventually calls
- `qdisc_restart()`
  - dequeues skb from the qdisc, acquires per-cpu TX lock
  - `ret = dev->hard_start_xmit`

```
    switch (ret) {
    case NETDEV_TX_OK: /* Driver sent out skb successfully */
[..]
    default: /* Driver returned NETDEV_TX_BUSY - requeue skb */
            ret = dev_requeue_skb(skb, dev, q);
```