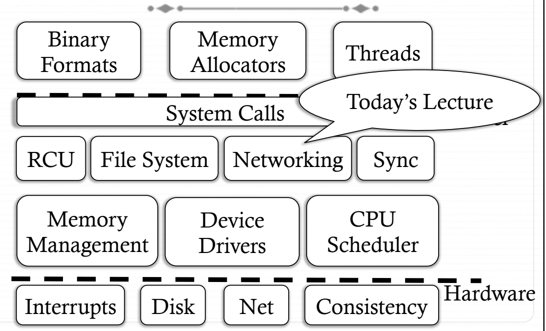
Networking

Don Porter → Vyas Sekar
CSE 506

Logical Diagram



Networking (2 parts)

- Goals:
  - Review networking basics
  - Discuss APIs
  - Trace how a packet gets from the network device to the application (and back)
  - Understand Receive livelock and NAPI

4 to 7 layer diagram

(from Understanding Linux Network Internals)

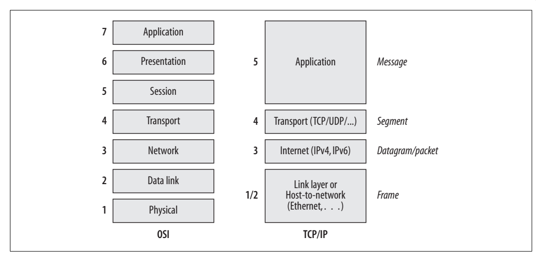


Figure 13-1. OSI and TCP/IP models

Nomenclature

- Frame: hardware
- Packet: IP
- Segment: TCP/UDP
- Message: Application

TCP/IP Reality

- The OSI model is great for undergrad courses
- TCP/IP (or UDP) is what the majority of programs use
  - Some random things (like networked disks) just use ethernet + some custom protocols

Ethernet (or 802.2 or 802.3)

- All slight variations on a theme (3 different standards)
- Simple packet layout:
  - Header: Type, source MAC address, destination MAC address, length, (and a few other fields)
  - Data block (payload)
  - Checksum
- Higher-level protocols "nested" inside payload
- "Unreliable" – no guarantee a packet will be delivered

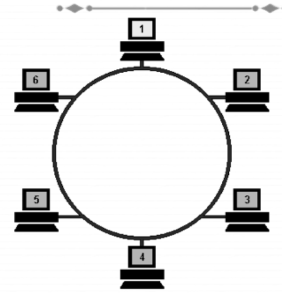
Ethernet History

- Originally designed for a shared wire (e.g., coax cable)
- Each device listens to all traffic
  - Hardware filters out traffic intended for other hosts
    - I.e., different destination MAC address
  - Can be put in "promiscuous" mode, and record everything (called a network sniffer)
- Sending: Device hardware automatically detects if another device is sending at same time
  - Random back-off and retry

Early competition

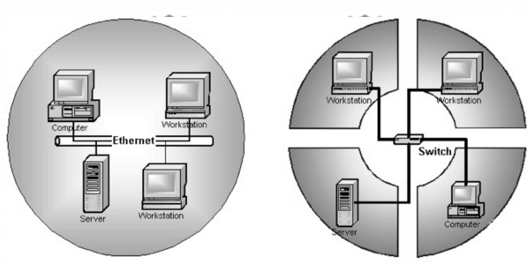
- Token-ring network: Devices passed a "token" around
  - Device with the token could send; all others listened
  - Like the "talking stick" in a kindergarten class
- Send latencies increased proportionally to the number of hosts on the network
  - Even if they weren't sending anything (still have to pass the token)
- Ethernet has better latency under low contention and better throughput under high

Token ring



Source: http://www.datacottage.com/nch/troperation.htm

Shared vs Switched



Shared Ethernet: : 1 collision domain for multiple nodes. The possibility of collisions. Non-deterministic

Switched Full Duplex Ethernet: 1 collision domain per node. Use of switch. No possibility of collisions. Deterministic.

Source: http://www.industrialethernetu.com/courses/401_3.htm

Switched networks

- Modern ethernets are switched
- What is a hub vs. a switch?
  - Both are a box that links multiple computers together
  - Hubs broadcast to all plugged-in computers (let computers filter traffic)
  - Switches track who is plugged in, only send to expected recipient
    - Makes sniffing harder ☹

Internet Protocol (IP)

- 2 flavors: Version 4 and 6
  - Version 4 widely used in practice---today's focus
- Provides a network-wide unique device address (IP address)
- This layer is responsible for routing data across multiple ethernet networks on the internet
  - Ethernet packet specifies its payload is IP
  - At each router, payload is copied into a new point-to-point ethernet frame and sent along

Transmission Control Protocol (TCP)

- Higher-level protocol that layers end-to-end reliability, transparent to applications
  - Lots of packet acknowledgement messages, sequence numbers, automatic retry, etc.
  - Pretty complicated
- Applications on a host are assigned a ***port*** number
  - A simple integer from 0-64k
  - Multiplexes many applications on one device
  - Ports below 1k reserved for privileged applications

User Datagram Protocol (UDP)

- The simple alternative to TCP
  - None of the frills (no reliability guarantees)
- Same port abstraction (1-64k)
  - But different ports
  - I.e., TCP port 22 isn't the same port as UDP port 22

Some well-known ports

- 80 – http
- 22 – ssh
- 53 – DNS
- 25 – SMTP

Example

(from Understanding Linux Network Internals)

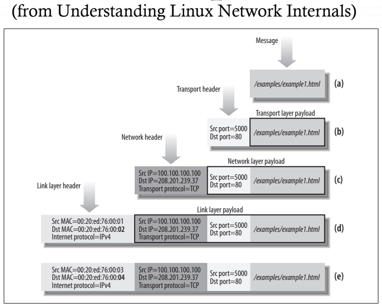


Figure 13-4. Headers compiled by layers: (a…d) on Host X as we travel down the stack; (e) on Router RT1

Networking APIs

- Programmers rarely create ethernet frames
- Most applications use the **socket** abstraction
  - Stream of messages or bytes between two applications
  - Applications still specify: protocol (TCP vs. UDP), remote host address
    - Whether reads should return a stream of bytes or distinct messages
- While many low-level details are abstracted, programmers must understand basics of low-level protocols

Sockets, cont.

- One application is the **server**, or **listens** on a pre-determined port for new connections
- The **client connects** to the server to create a message channel
- The server **accepts** the connection, and they begin exchanging messages

Creation APIs

- int socket(domain, type, protocol) – create a file handle representing the communication endpoint
  - Domain is usually AF_INET (IP4), many other choices
  - Type can be STREAM, DGRAM, RAW
  - Protocol – usually 0
- int bind(fd, addr, addrlen) – bind this socket to a specific port, specified by addr
  - Can be INADDR_ANY (don't care what port)

Server APIs

- int listen(fd, backlog) – Indicate you want incoming connections
  - Backlog is how many pending connections to buffer until dropped
- int accept(fd, addr, len, flags) – Blocks until you get a connection, returns where from in addr
  - Return value is a new file descriptor for child
  - If you don't like it, just close the new fd

Client APIs

- Both client and server create endpoints using socket()
  - Server uses bind, listen, accept
  - Client uses connect(fd, addr, addrlen) to connect to server
- Once a connection is established:
  - Both use send/recv
  - Pretty self-explanatory calls

Client/server toy example

- Quick demo ..
- Client/server code from

  http://www.linuxhowtos.org/C_C++/socket.htm

Linux implementation

- Sockets implemented in the kernel
  - So are TCP, UDP and IP
- Benefits:
  - Application doesn't need to be scheduled for TCP ACKs, retransmit, etc.
  - Kernel trusted with correct delivery of packets
- A single system call (i386):
  - sys_socketcall(call, args)
    - Has a sub-table of calls, like bind, connect, etc.

Plumbing

- Each message is put in a sk_buff structure
- Between socket/application and device, the sk_buff is passed through a stack of protocol handlers
  - These handlers update internal bookkeeping, wrap payload in their headers, etc.
- At the bottom is the device itself, which sends/receives the packets

sk_buff

(from Understanding Linux Networking Internals)

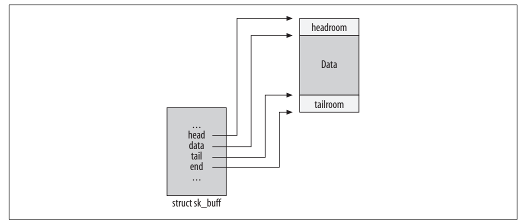


Figure 2-2. head/end versus data/tail pointers

Efficient packet processing

- Moving pointers is more efficient than removing headers
- Appending headers is more efficient than re-copy

Networking Part Two

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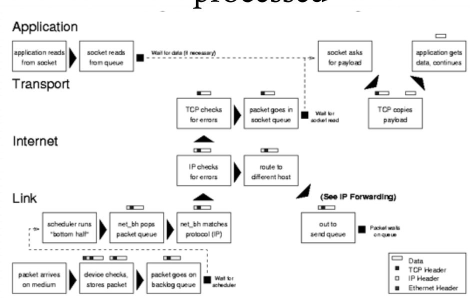
Recap from last class

- Layering
- L2, L3, L4 basics
- Packet walkthrough

Walk through how a rcvd packet is processed



Source = http://www.cs.unh.edu/cnrg/people/gherrin/linux-net.html#tth_sEc6.2

Interrupt handler

- "Top half" responsible to:
  - Allocate a buffer (sk_buff)
  - Copy received data into the buffer
  - Initialize a few fields
  - Call "bottom half" handler
- In some cases, sk_buff can be pre-allocated, and network card can copy data in (DMA) before firing the interrupt
  - Lab 6 will follow this design

Quick review

- Why top and bottom halves?
  - To minimize time in an interrupt handler with other interrupts disabled
  - Gives kernel more scheduling flexibility
  - Simplifies service routines (defer complicated operations to a more general processing context)

Digression: Softirqs

- A hardware IRQ is the hardware interrupt line
  - Also used for hardware "top half"
- Soft IRQ is the associated software "interrupt" handler
  - Or, "bottom half"
- How are these implemented in Linux?
  - Two canonical ways: Softirq and Tasklet
  - More general than just networking

Softirqs

- Kernel's view: per-CPU work lists
  - Tuples of <function, data>
- At the right time, call function(data)
  - Right time: Return from exceptions/interrupts/sys. calls
  - Also, each CPU has a kernel thread ksoftirqd_CPU# that processes pending requests
  - ksoftirqd is nice +19. What does that mean?
    - Lowest priority – only called when nothing else to do

Softirqs, cont.

- Device programmer's view:
  - Only one instance of a softirq function will run on a CPU at a time
    - Doesn't need to be reentrant
      - **reentrant** if it can be interrupted in the middle of its execution and then safely called again ("re-entered") before its previous invocations complete execution
    - If interrupted, won't be called again by interrupt handler
      - Subsequent calls enqueued!
  - One instance can run on each CPU concurrently, though
    - Must use locks

Tasklets

- For the faint of heart (and faint of locking prowess)
- Constrained to only run one at a time on any CPU
  - Useful for poorly synchronized device drivers
    - Say those that assume a single CPU in the 90's
  - Downside: If your driver uses tasklets, and you have multiple devices of the same type---the bottom halves of different devices execute serially

Softirq priorities

- Actually, there are 6 queues per CPU; processed in priority order:
  - HI_SOFTIRQ (high/first)
  - TIMER
  - NET TX
  - NET RX
  - SCSI
  - TASKLET (low/last)

Observation 1

- Devices can decide whether their bottom half is higher or lower priority than network traffic (HI or TASKLET)
  - Example: Video capture device may want to run its bottom half at HI, to ensure quality of service
  - Example: Printer may not care

Observation 2

- Transmit traffic prioritized above receive. Why?
  - The ability to send packets may stem the tide of incoming packets
    - Obviously eliminates retransmit requests based on timeout
    - Can also send "back-off" messages

Receive bottom half

- For each pending sk_buff:
  - Pass a copy to any taps (sniffers)
  - Do any MAC-layer processing, like bridging
  - Pass a copy to the appropriate protocol handler (e.g., IP)
    - Recur on protocol handler until you get to a port
      - Perform some handling transparently (filtering, ACK, retry)
    - If good, deliver to associated socket
    - If bad, drop

Socket delivery

- Once the bottom half/protocol handler moves a payload into a socket:
  - Check and see if the task is blocked on input for this socket
  - If so, wake it up
- Read/recv system calls copy data into application

Socket sending

- Send/write system calls copy data into socket
  - Allocate sk_buff for data
  - Be sure to leave plenty of head and tail room!
- System call does protocol handling during application's timeslice
  - Note that receive handling done during ksoftirqd timeslice
- Last protocol handler enqueues a softirq to transmit

Transmission

- Softirq can go ahead and invoke low-level driver to do a send
- Interrupt usually signals completion
  - Interrupt handler just frees the sk_buff

Switching gears

- We've seen the path network data takes through the kernel in some detail
- Now, let's talk about how network drivers handle heavy loads

Our cup runneth over

- Suppose an interrupt fires every time a packet comes in
  - This takes N ms to process the interrupt
- What happens when packets arrive at a frequency approaching or exceeding N?
  - You spend all of your time handling interrupts!
- Will the bottom halves for any of these packets get executed?
  - No. They are lower-priority than new packets

Receive livelock

- The condition that the system never makes progress because it spends all of its time starting to process new packets
- Real problem: Hard to prioritize other work over interrupts
- Principle: Better to process one packet to completion than to run just the top half on a million

Receive livelock in practice

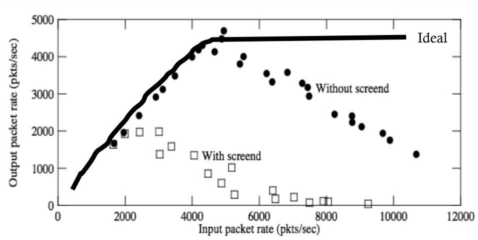


Fig. 2. Forwarding performance of unmodified kernel.

Source: Mogul & Ramakrishnan, ToCS 96

Shedding load

- If you can't process all incoming packets, you must drop some
- Principle: If you are going to drop some packets, better do it early!
- If you quit taking packets off of the network card, the network card will drop packets once its buffers get full

Idea

- Under heavy load, disable the network card's interrupts
- Use polling instead
  - Ask if there is more work once you've done the first batch
- This allows a packet to make it all the way through all of the bottom half processing, the application, and get a response back out
- Ensuring some progress! Yay!

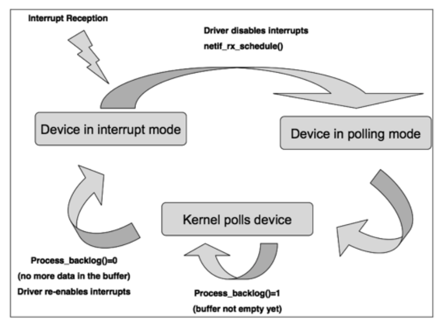
Why not poll all the time?

- If polling is so great, why even bother with interrupts?
- Latency: When incoming traffic is rare, we want high-priority, latency-sensitive applications to get their data ASAP

General insight

- If the expected input rate is low, interrupts are better
- When the expected input rate gets above a certain threshold, polling is better
- Just need to figure out a way to dynamically switch between the two methods…

Pictorially..



Source: *download.intel.com/design/intarch/**PAPERS**/323704.pdf*

Why haven't we seen this before?

- Why don't disks have this problem?
- Inherently rate limited
- If the CPU is bogged down processing previous disk requests, it can't issue more
- An external CPU can generate all sorts of network inputs

Linux NAPI

- Or New API. Seriously.
- Every driver provides a poll() method that does the low-level receive
  - Called in first step of softirq RX function
- Top half just schedules poll() to do the receive as softirq
  - Can disable the interrupt under heavy loads; use timer interrupt to schedule a poll
  - Bonus: Some rare NICs have a timer; can fire an interrupt periodically, only if something to say!

NAPI

- Gives kernel control to throttle network input
- Slow adoption – means some measure of driver rewriting
- Backwards compatibility solution:
  - Old top half still creates sk_buffs and puts them in a queue
  - Queue assigned to a fake "backlog" device
  - Backlog poll device is scheduled by NAPI softirq
  - Interrupts can still be disabled

NAPI Summary

- Too much input is a real problem
- NAPI lets kernel throttle interrupts until current packets processed
- Softirq priorities let some devices run their bottom halves before net TX/RX
  - Net TX handled before RX

General summary

- Networking basics and APIs
- Idea of plumbing from socket to driver
  - Through protocol handlers and softirq poll methods
- NAPI and input throttling