Designing Systems for Dependability and Predictability

Richard West

Boston University

Boston, MA

richwest@cs.bu.edu

Introduction: Existing OSes

- Today's world of operating systems:
  - Desktop
    - e.g., MS Vista, Mac OS X, Linux
  - Server
    - e.g., Solaris, Linux
  - Embedded (Real-time, mobile etc)
    - e.g., VxWorks, QNX, VRTX, Symbian, PalmOS…

  - Revisiting an old idea: Virtualization
    - VM kernels and monitors
      - e.g., VMware ESX Server, Xen

Virtualization – What's the Big Deal?

- Virtualization is BIG!
  - Revisiting an idea from 1960s (e.g., IBM s/360)
  - New chips from Intel (VT/Vanderpool), AMD (Pacifica) and others for CPU virtualization
  - Good for server consolidation, disaster recovery, prototyping / sandboxing...
  - BUT…
    - The VM kernel is the new OS
    - Is it really different from other OS kernels?
      - e.g., micro-kernels

So Not Much New Then…

- What's missing with today's OSes?

(1) Semantic gap

- between application needs and service provisions of the system

(2) Time management

- time is not a first-class resource

(3) Static system structure

- Are you a "micro-kernel" guy or a member of the church of monoliths?

Focus on Embedded Systems

- Currently numerous proprietary systems for RT/embedded computing
  - e.g., QNX, PSOS, LynxOS, VxWorks, VRTX
  - Many diverse hardware platforms
    - ARM, x86, PowerPC, Hitachi SH, etc

  - Focus on small footprints, fast context-switching, static priority/preemptive scheduling, priority inheritance/synchronization, limited / no VM, off-line profiling tools for WCET analysis

COTS / Open-Source Systems

- COTS hardware and open-source systems emerging
  - Eliminate costs of proprietary systems and custom hardware
  - e.g., Linux use in embedded/RT settings

- BUT…
  - Problems as mentioned earlier:
    - Semantic gap
    - Time management
    - Static structure

Bridging the `Semantic Gap’

- There is a `semantic gap’ between the needs of applications and services provided by the system

- Implementing functionality directly in application processes
  - **Pros:** service/resource isolation (e.g., memory protection)
  - **Cons:**
    - Does not guarantee necessary responsiveness
    - Must leverage system abstractions in complex ways
    - Heavyweight scheduling, context-switching and IPC overheads

Bridging the `Semantic Gap' Cont.

- Other approaches:
  - Special systems designed for extensibility
    - e.g., SPIN, VINO, Exo-/μ-kernels (Aegis / L4), Palladium
    - Semantics of new services restricted by those upon which they are built
      - e.g., IPC costs $\rightarrow$ no timeliness / predictability guarantees on service invocation
  - Single-address space approaches
    - Do not focus on isolation of service extensions from core kernel (e.g., RTLinux, RTAI) or predictability (e.g., Singularity)

Time Management

- Inherent unpredictability in existing systems
  - Arbitrary orderings of accesses to shared resources requires synchronization
    - Possibly unbounded blocking delays
    - Basic primitives provided by system but may be incorrectly used by programs!
      - Deadlocks & races may still occur
  - Interrupts, paging activity, unaccounted time in system services (scheduling / dispatching / IPC)
  - Crosstalk b/w different threads due to resource sharing (e.g., cache, TLB impacts)

Time Management (cont.)

- Time is not a first-class resource
  - APIs don’t allow specification of time bounds on service requests (e.g., read / write I/O requests)
    - Not even implicit specification based on urgency / importance of a task
  - Scheduling / resource mgmt policies are not explicitly temporal

Static System Structure

- Monolithic systems (e.g., Linux) are inflexible to changes in structure and services they support
  - Do support kernel modules (mostly for device drivers), but…
  - Not easily customizable with app-specific services
  - No support for extensions to override system-wide service policies

- While micro-kernels support extensibility, the organization of system services is statically-defined
  - system designer typically determines which services are available and how they are isolated
    - Is this organization suitable for all applications?

Static System Structure (cont.)

- Resource contention and changes in availability affect predictability of service requests

  - IPC costs, scheduling / dispatching / context-switching / TLB flushing, cache usage patterns, etc
    - affect time to complete service requests

- A static organization of services cannot adapt to dynamic variations in resource usage and service invocation patterns

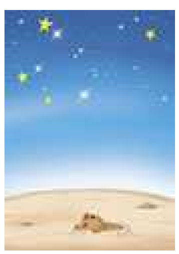
Example: App-Specific System Structure

Data acquisition

Communication

Motor / sensor control

Robot Exploration



Planet surface

Earth

Service Characteristics

- Different timing requirements / criticalities in terms of late or missed processing
  - e.g., can miss some data (image) acquisition but sensor & motor control operations are more critical

- Safety / dependability trade-offs
  - Scheduling functionality isolated from services to collect, process & communicate data
  - Communication functionality must be maintained in case of need for remote reboot or changes to mission objectives
  - Data gathering service not so safety critical
    - e.g., direct access to a buffer (and overruns) not catastrophic, as long as base services remain functional

- Design systems around flexibility in system structure

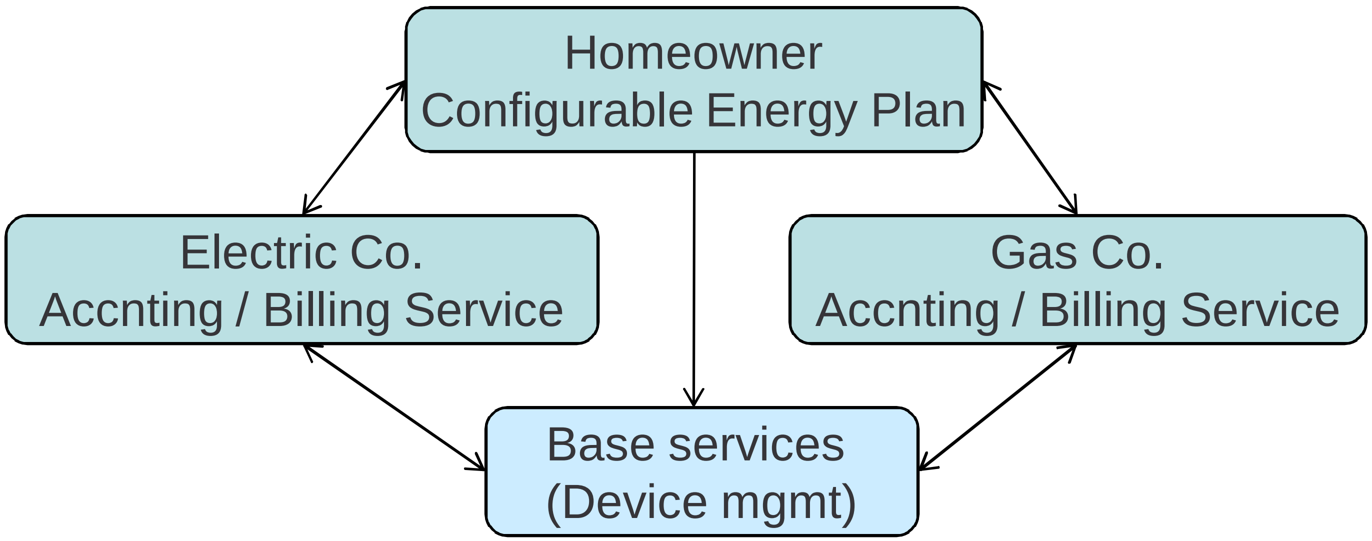
Example: Intelligent Home Network

- www.epa.gov/ne/pr/2004/jan/040110.html
  - Study suggested that by replacing 5 most used light-bulbs w/ energy efficient bulbs in every US household could reduce electricity usage by 800 billion KWh per year
    - Equivalent to $60/yr per homeowner or output from 21 power plants per year
    - Would reduce one trillion pounds of greenhouse gases that cause global warming

- Allow homeowners to control various appliances according to desired energy plan

Example: Intelligent Home (cont.)

- Homeowner service may query service providers billing service BUT should not be able to change a billing policy
- Gas and Electric Co. may share billing / appliance monitoring services if part of the same parent company
- Appliance control & usage accounting needs to be predictable $\rightarrow$ avoid customer mis-charges for appliance usage



Case Studies

(1) Improving time management (predictability) in existing systems

- e.g., Process-aware interrupt scheduling and accounting in Linux

(2) Mutable Protection Domains (MPDs)

- Dynamically reorganize system component services to meet safety (isolation) and predictability (resource) requirements

(1) Improving Time Management (Predictability) in Existing Systems

Process-Aware Interrupt Scheduling & Accounting

Commodity OSes for Real-Time

- Many variants based on systems such as Linux:
  - Linux/RK, QLinux, RED-Linux, RTAI, KURT Linux, and RT Linux
  - e.g., RTLinux Free provides predictable execution of kernel-level real-time tasks
    - Bounds are enforced on interrupt processing overheads by deferring non-RT tasks when RT tasks require service
    - NOTE: Many commodity systems suffer unpredictability (unbounded delays) due to interrupt-disabling, e.g., in critical sections of poorly-written device drivers

The Problem of Interrupts

- Asynchronous events e.g., from hardware completing I/O requests and timer interrupts…
  - Affect process/thread scheduling decisions
  - Typically invoke interrupt handlers at priorities above those of processes/threads
    - i.e., interrupt scheduling disparate from process/thread scheduling
- Time spent handling interrupts impacts the timeliness of RT tasks and their ability to meet deadlines
- Overhead of handling an interrupt is charged to the process that is running when the interrupt occurs
  - Not necessarily the process associated (if any) with the interrupt

Goals

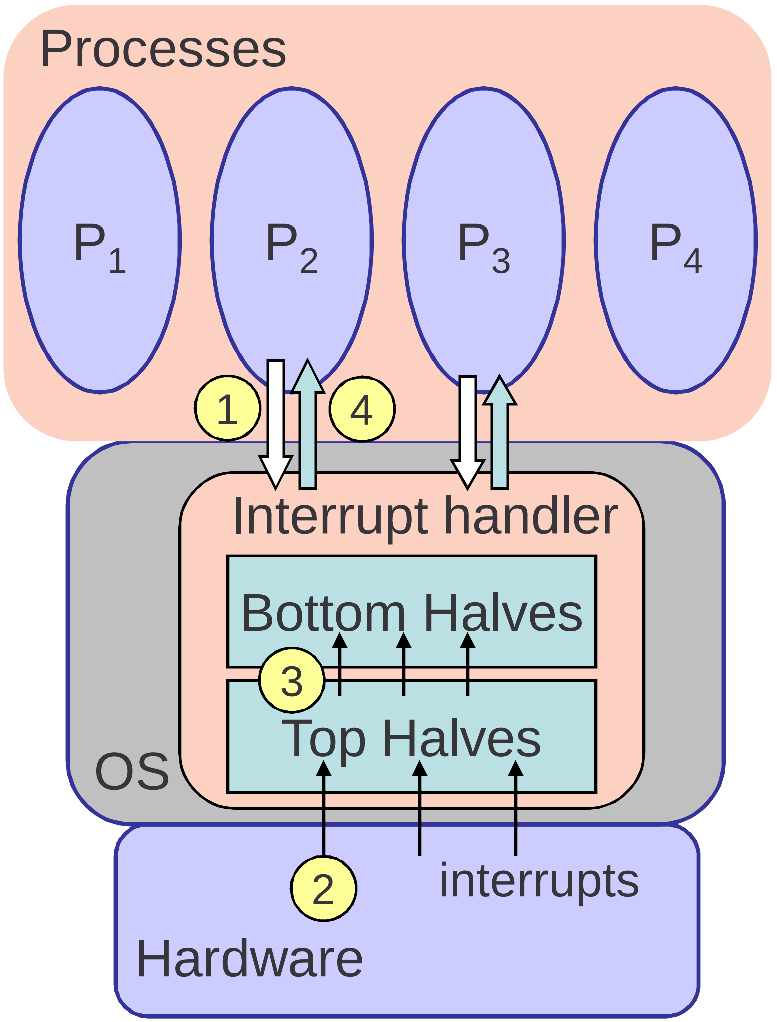
- How to properly account for interrupt processing and correctly charge CPU time overheads to correct process, where possible
- How to schedule deferrable interrupt handling so that predictable task execution is guaranteed

Interrupt Handling

- Interrupt service routines are often split into “top” and “bottom” halves
  - Idea is to avoid lengthy periods of time in “interrupt context”
  - Top half executed at time of interrupt but bottom half may be deferred (e.g., to a schedulable thread)

Process-Independent Interrupt Service

- Traditional approach:
  - (1) I/O service request via kernel
  - (2) OS sends request to device via driver code;
  - Hardware device responds w/ an interrupt, handled by a "top half"
  - (3) Deferrable "bottom half" completes service for prior interrupt and wakes waiting process(es) – Usually runs w/ interrupts enabled
  - (4) A woken process can then be scheduled to resume after blocking I/O request



Example: Linux

- Avoid undue impact of interrupt handling on CPU time for a running process

  - Execute a finite # of pending deferrable fns after top half execution (in “interrupt context”)
    - Linux deferrable fns: softirqs and tasklets (bottom halves now deprecated)
    - Iterate through softirq handling a fixed number of times to avoid undue delay to processes but good responsiveness for interrupts (e.g., via network)

  - Defer subsequent bottom halves to threads
    - Awaken “ksoftirqd_CPUn” kernel thread

Linux Problems

- A real-time or high-priority blocked process waiting on I/O may be unduly delayed by a deferred bottom half
  - Mismatch between bottom half priority and process
- Interrupt handling takes place in context of an arbitrary process
  - May lead to incorrect CPU time accounting
- Why not schedule bottom halves in accordance with priorities of processes affected by their execution?
- For fairness and predictability: charge CPU time of interrupt handling to affected process(es), where possible

Process-Aware Interrupt Handling

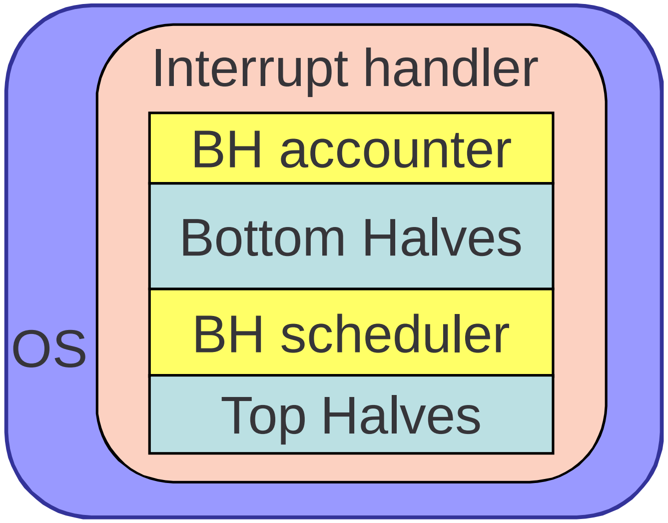
- Not all interrupts associated with specific processes
  - e.g., timer interrupt to update system clock tick, IPIs…
  - Not necessarily a problem if we can account for such costs in execution time of tasks e.g., during scheduling

- I/O requests via syscalls (e.g., read/write) associate a process with a device that may generate an interrupt
  - For this class of interrupts we assign process priorities to bottom half (deferrable) interrupt handling

  - Allow top halves to run with immediate effect but consider dependency between bottom halves and processes

Bottom Half Scheduling / Accounting

- Modify Linux kernel to include interrupt accounting
  - TSC measurements on bottom halves
  - Determine target process for interrupt processing and update system time accordingly
- BH/interrupt scheduler immediately between *do_irq()* and *do_softirq()*
  - Predict target process associated with interrupt and set BH priority accordingly



Interrupt Accounting Algorithm

- Measure the average execution time of a bottom half (BH) across multiple BH executions
  - On x86 use rdtsc since time granularity typically < 1 clock tick
- Measure total interrupts processed and # processed for each process in 1 clock tick
- Adjust system CPU time for processes due to mischarged interrupt costs

- For simplicity, focus on interrupts for one device type (e.g., NIC) but idea applies to all I/O devices

System CPU Time Compensation (1/2)

- **N(t)** - integer # interrupts whose total BH execution time = 1 clock tick (or *jiffy*)
  - Actually use an Exponentially-Weighted Moving Avg for N(t), N'(t)
  - $N'(t) = (1-\gamma)N'(t-1) + \gamma N(t) \mid 0 < \gamma < 1$

- **m(t)** - # interrupts processed in last clock tick
- **x_k(t)** - # unaccounted interrupts for process **P_k**

- Let $P_i(t)$ be active at time t
  - $m(t) - x_i(t)$ (if +ve) is # interrupts overcharged to P_i

System CPU Time Compensation (2/2)

- At each clock tick (do_timer) update accounting info as follows:

$x_i(t) = x_i(t) – m(t);$ // current # under-charged if +ve

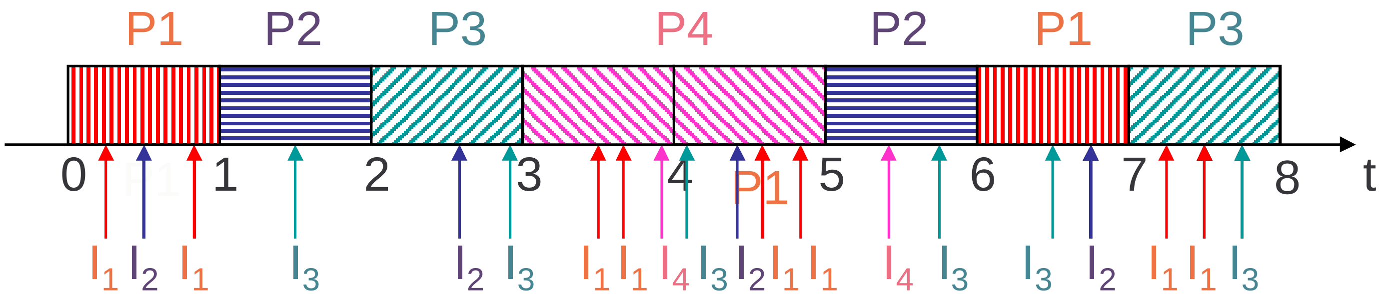
sign = sign of ($x_i(t)$);

while (abs($x_i(t)$) >= N(t)) // update integer # of jiffies

- system_time(P_i) += 1*sign;
- timeslice(P_i) -= 1*sign;
- $x_i(t) = x_i(t) – N(t);$

m(t) = 0;

Example: System CPU Time Compensation



$x_1(1)$: -3 + 2 = -1, $x_2(2)$: -1 + 1= 0,

$x_3(3)$: -2 + 2 = 0, $x_4(4)$: -3 + 1 =-2,

$x_4(5)$: -2 + -4+ 0= -6, $x_2(6)$: 0 + -2 + 2 = 0,

$x_1(7)$: -1 + -2+ 4= 1, $x_3(8)$: 0 + -3 + 4 = 1,

Interrupt Scheduling Algorithm

- (1) Find candidates associated with interrupt on device, D
  - In top half can determine D
  - A blocked process waiting on D may be associated with the interrupt
  - We require I/O requests to register process ID and priorities with corresponding device
- (2) Predicting process associated with interrupt on D
  - At end of top half select highest priority ($\rho_{max(D)}$) from processes waiting on D
  - Use a heap structure for waiting processes
- (3) Compare priority of BH with running process
  - If ($\rho_{max(D)} = \rho_{BH}$) > $\rho_{current}$ run BH else process

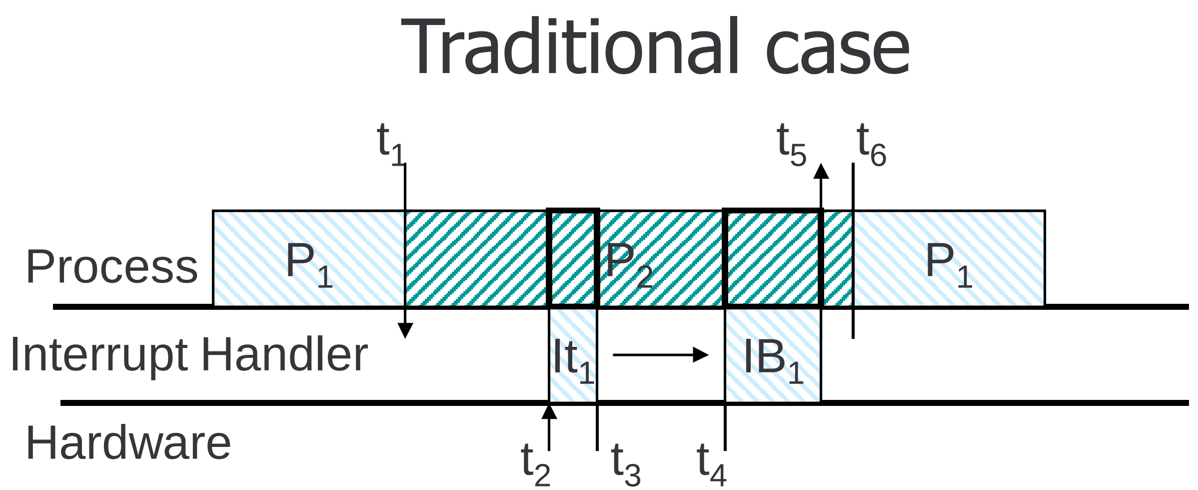
Interrupt Scheduling Observations

- No need for ksoftirqd_CPUn
  - Run interrupt scheduler at time of process scheduling
  - If pending BH highest prio run in context of current process, else do switch to highest prio process

- Setting prio of BH (ρ_{BH}) to highest process prio ($\rho_{max(D)}$) for device D
  - Rationale: no worse than current approach of always preferring BH (at least for finite occurrences) over process
    - Simple priority scheme can provide better predictability for more important processes

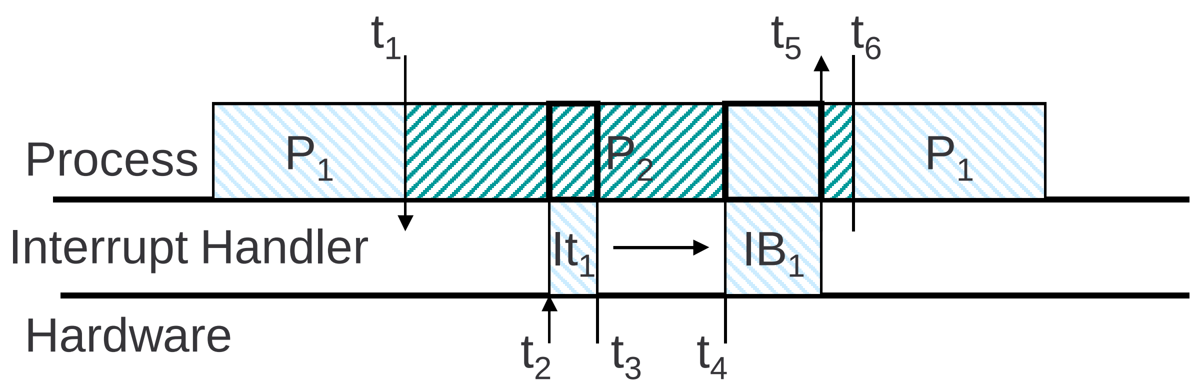
Example: Interrupt Scheduling (1/3)

- t_1: P_1 issues I/O request and blocks, allowing P_2 to run
- t_2: top half interrupt processing for P_1 in P_2's context
- t_3: top half completes
- t_4-t_5: bottom half runs
- t_6: P_1 wakes up and runs



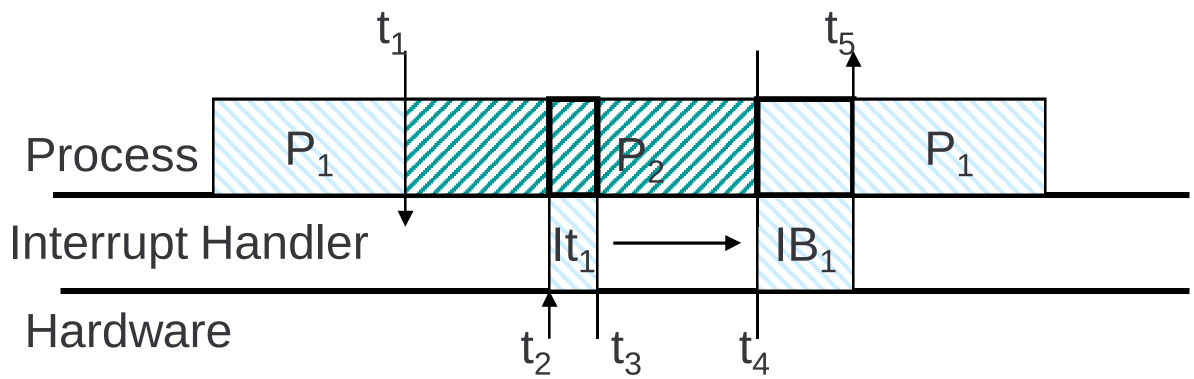
Example: Interrupt Scheduling (2/3)

- Previous case: top and bottom half processing charged to P_2
- Our approach: correctly charge bottom half processing to P_1



Example: Interrupt Scheduling (3/3)

- If P_2 is higher priority than P_1, let P_2 finish and defer the BH for P_1



System Implementation

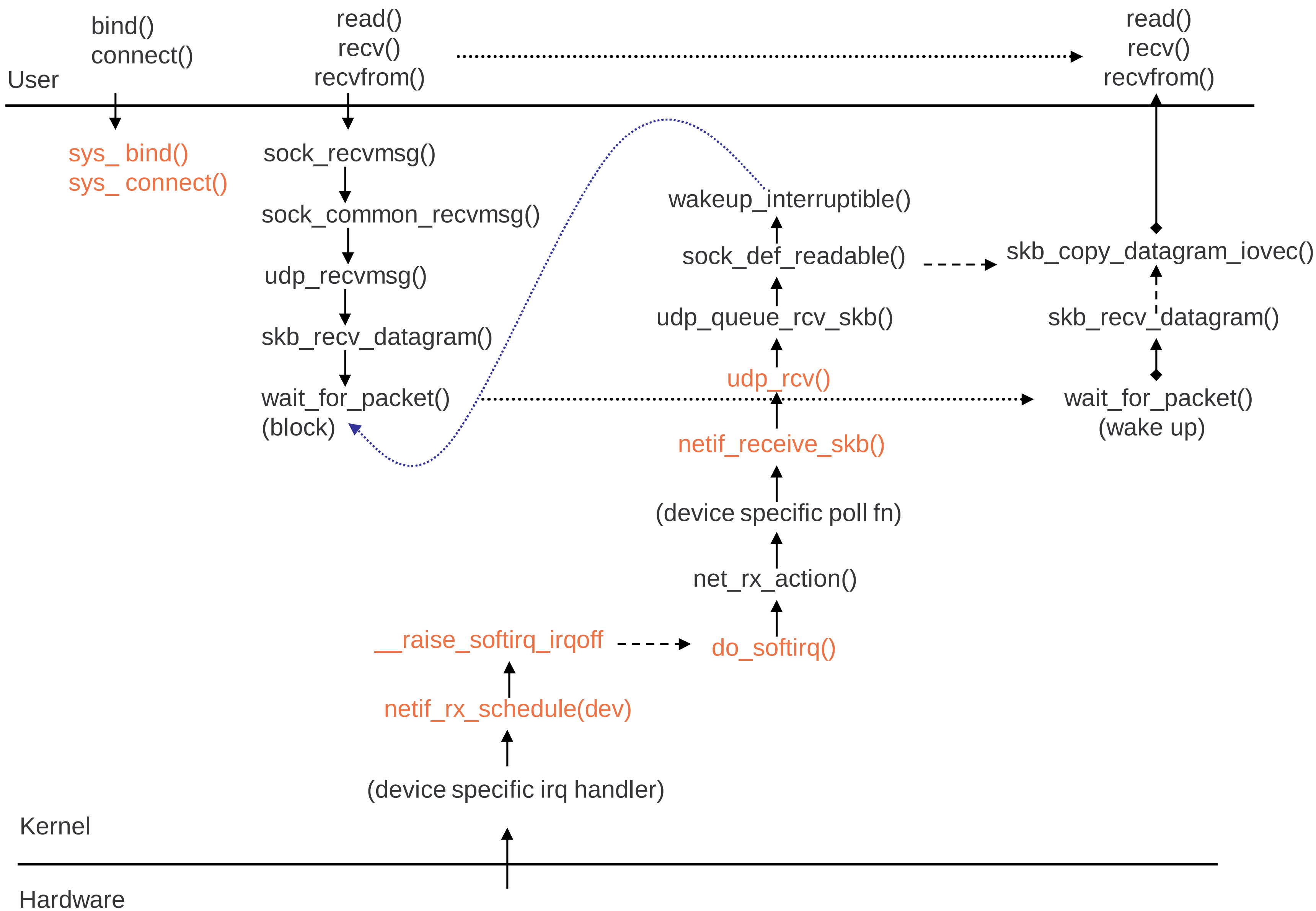
- Implemented scheduling & accounting framework on top of existing Linux bottom half (specifically, softirq) mechanism

- Focus on network packet reception (NET_RX_SOFTIRQ)
- Read TSC for each net_rx_action call as part of softirq
- Determine # pkts received in one clock tick
- udp_rcv() identifies proper socket/process for arriving pkt(s)

- Modify account_system_time() to compensate processes

- Interrupt scheduling code implemented in do_softirq()
  - Before call to softirq handler (e.g., net_rx_action())

Linux Control Path for UDP Packet Reception



Experiments

- UDP server receives pkts on designated port
  - CPU-bound process also active on server to observe effect of interrupt handling due to pkt processing
- UDP client sends pkts to server at adjustable rates

- Machines have 2.4GHz Pentium IV uniprocessors and 1.2GB RAM each
- Gigabit Ethernet connectivity
- Linux 2.6.14 with 100Hz timer resolution

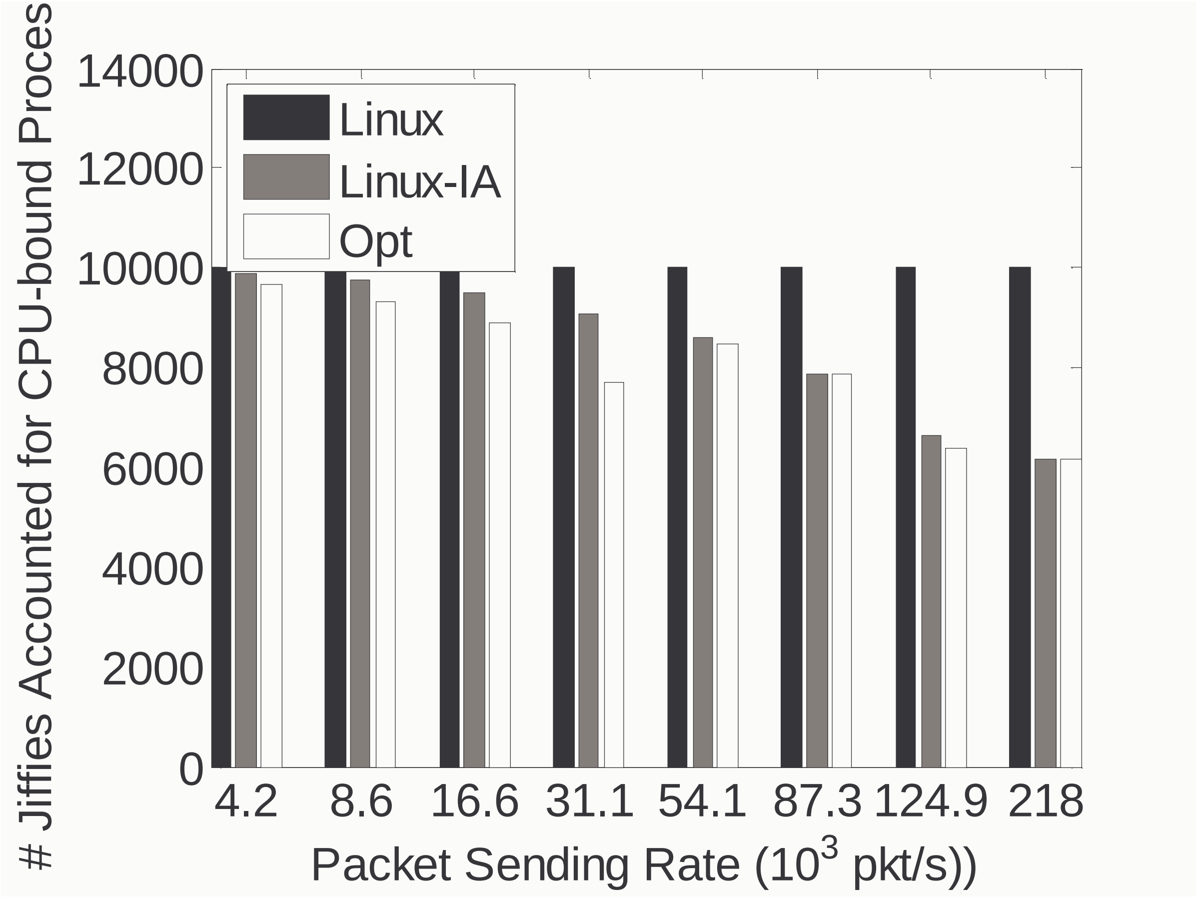
- Compare base 2.6.14 kernel w/ our patched kernel running accounting (Linux-IA) and scheduling (Linux-ISA) code

Accounting Accuracy

- CPU-bound process set to real-time priority 50 in SCHED_FIFO class
  - Repeatedly runs for 100 secs & then sleeps 10 secs
- UDP server process non-real-time
- UDP client sends 512 byte pkts to server at constant rate

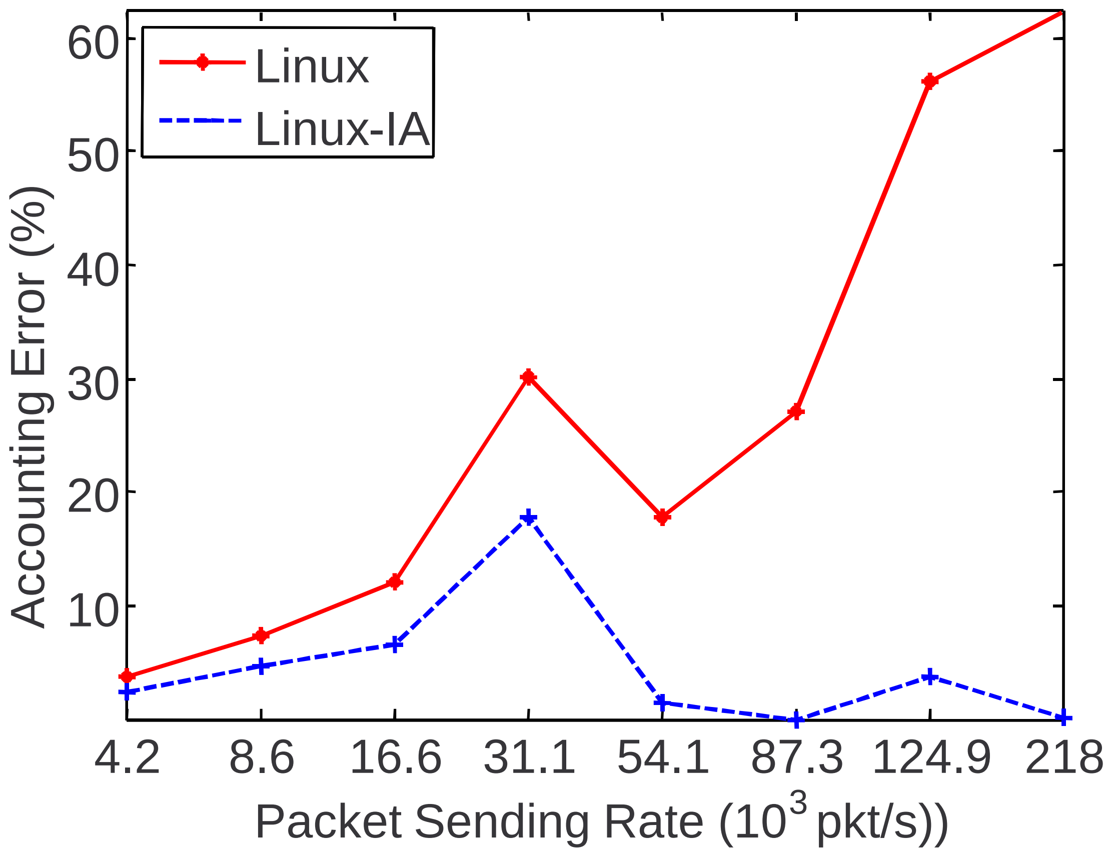
- Read /proc/pid/stat to measure user/system time

Accounting Accuracy Results



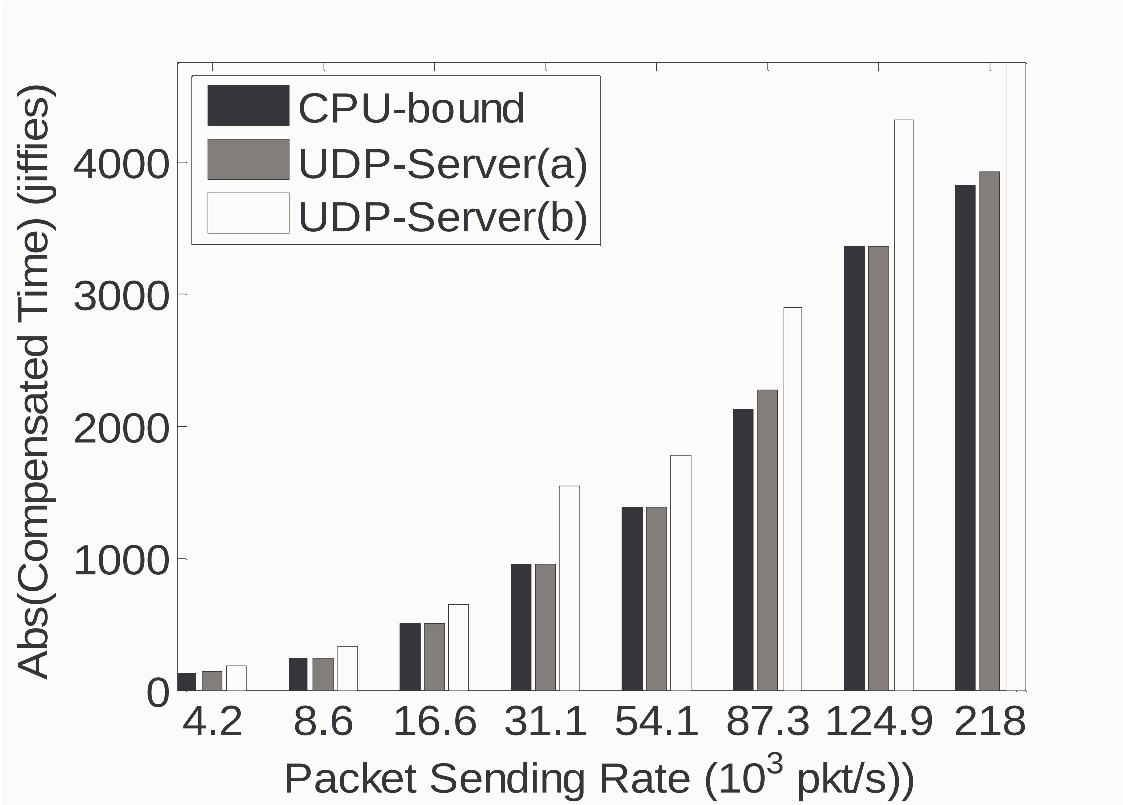
- Optimal case (Opt) is total user/system-level CPU time that should be charged to CPU-bound process discounting unrelated interrupt processing
- Linux-IA close to optimal but original Linux miss-charges all interrupt processing

Ratio of Accounting Error to Optimal



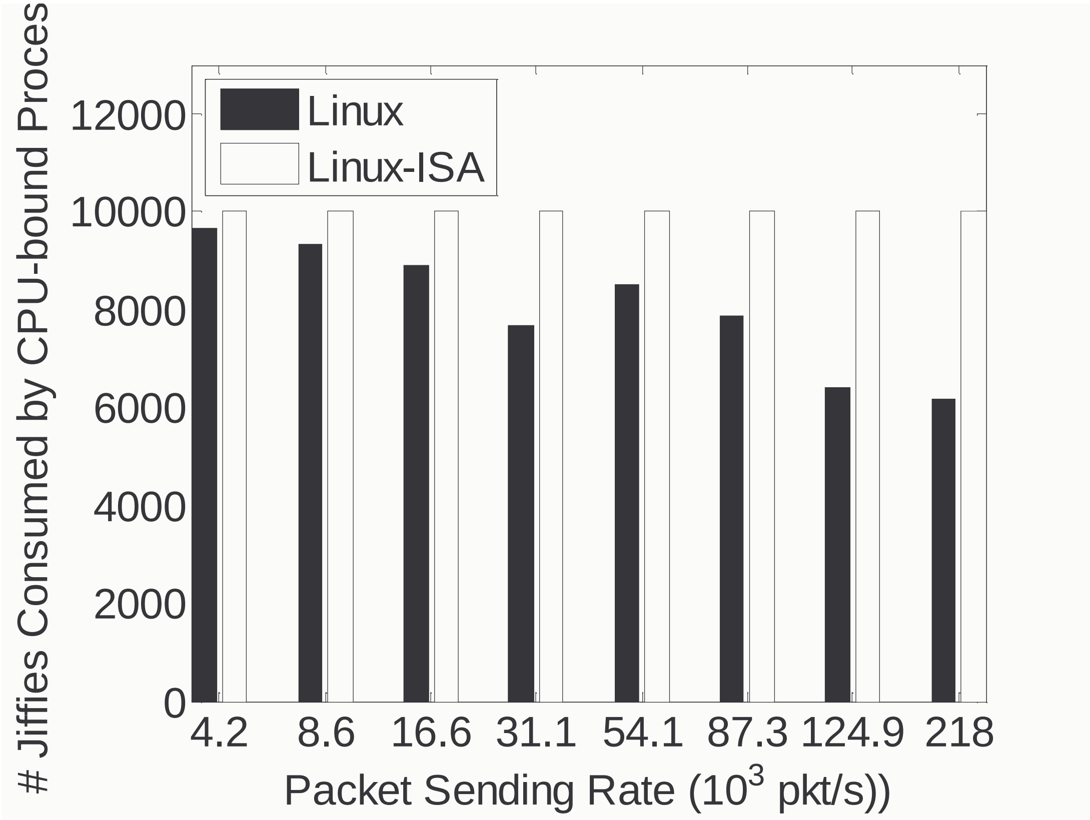
- Error as high as 60% in Linux
- Less than 20% and more often less than 5% using Linux-IA

Absolute Compensated Time



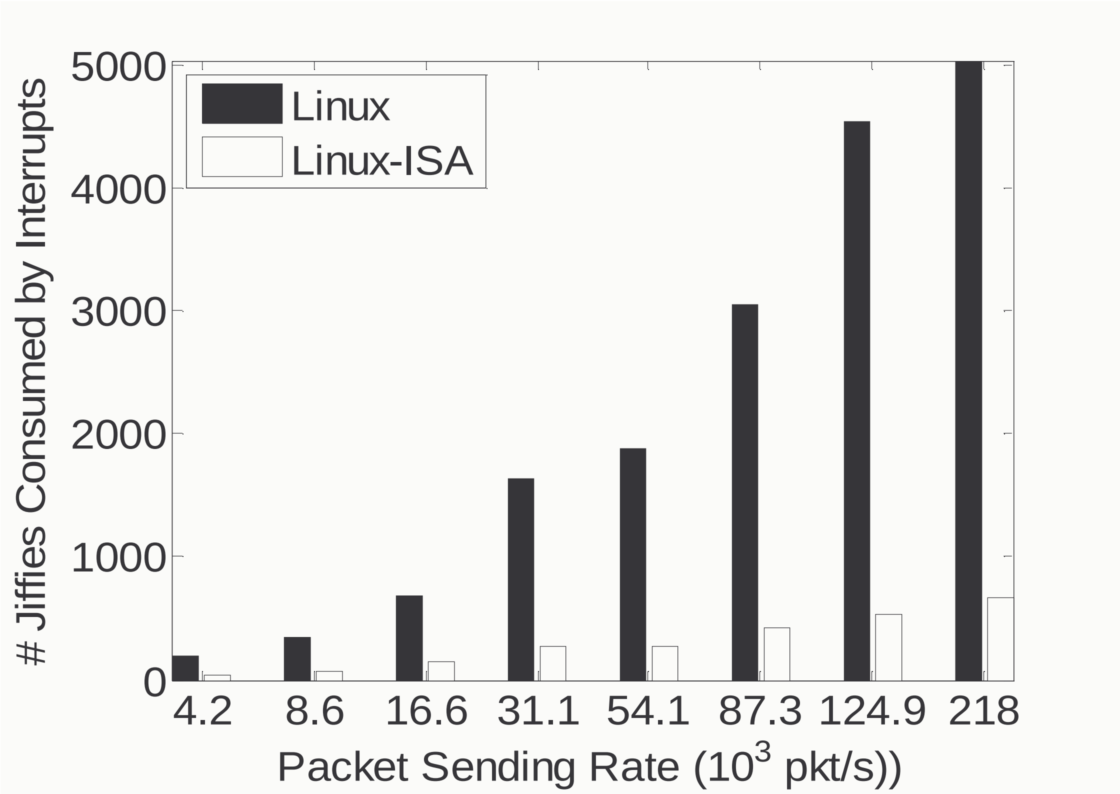
- UDP-Server(a) – charged time for interrupts over 100s of each 110s period of CPU bound process
- UDP-Server(b) – charged time over full 110s period
- CPU-bound – system service time deducted from CPU-bound process

Bottom Half Scheduling Effects



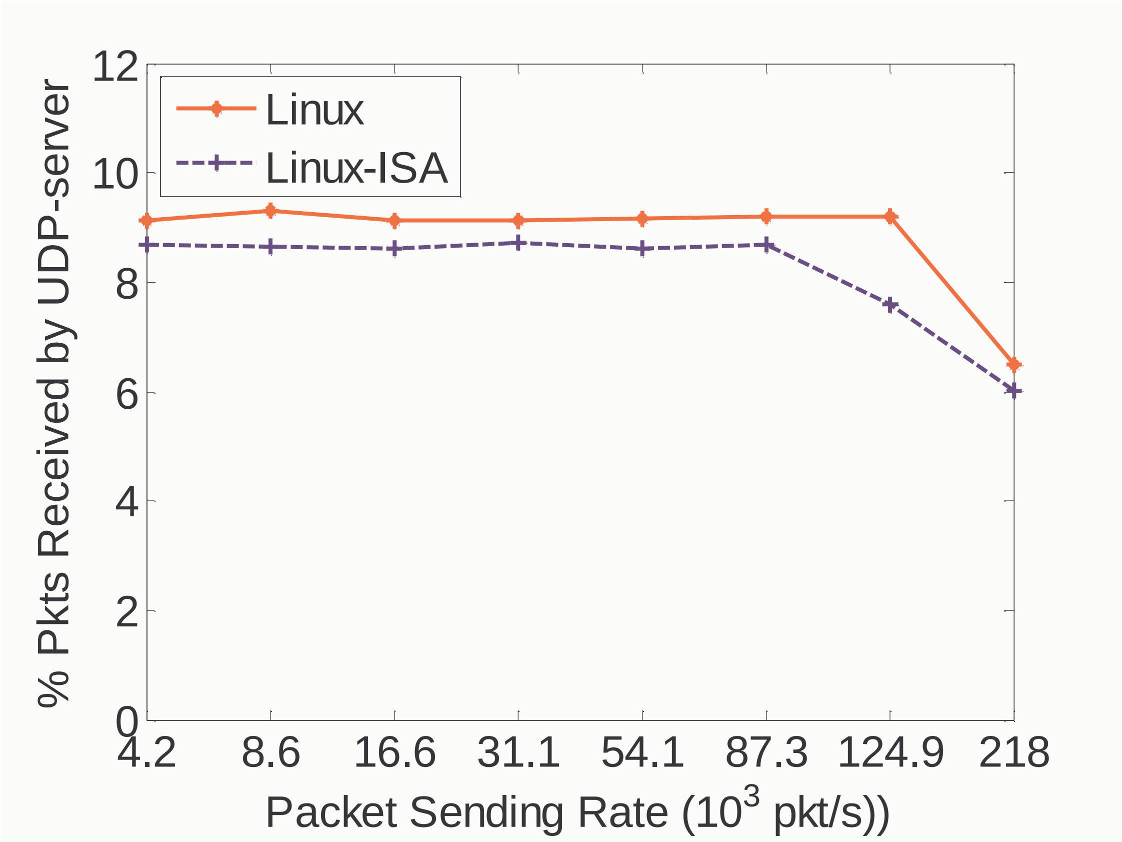
- Linux – CPU-bound process affected by interrupts
- Linux-ISA – defer bottom-half interrupt processing until (higher priority) real-time CPU-bound process sleeps

Time Consumed by Interrupts (every 110s)



- Time consumed by CPU-server every 110s handling interrupts
- Linux-ISA – bottom half handling deferred to interval [100-110s]
- Linux – bottom half processing not deferred

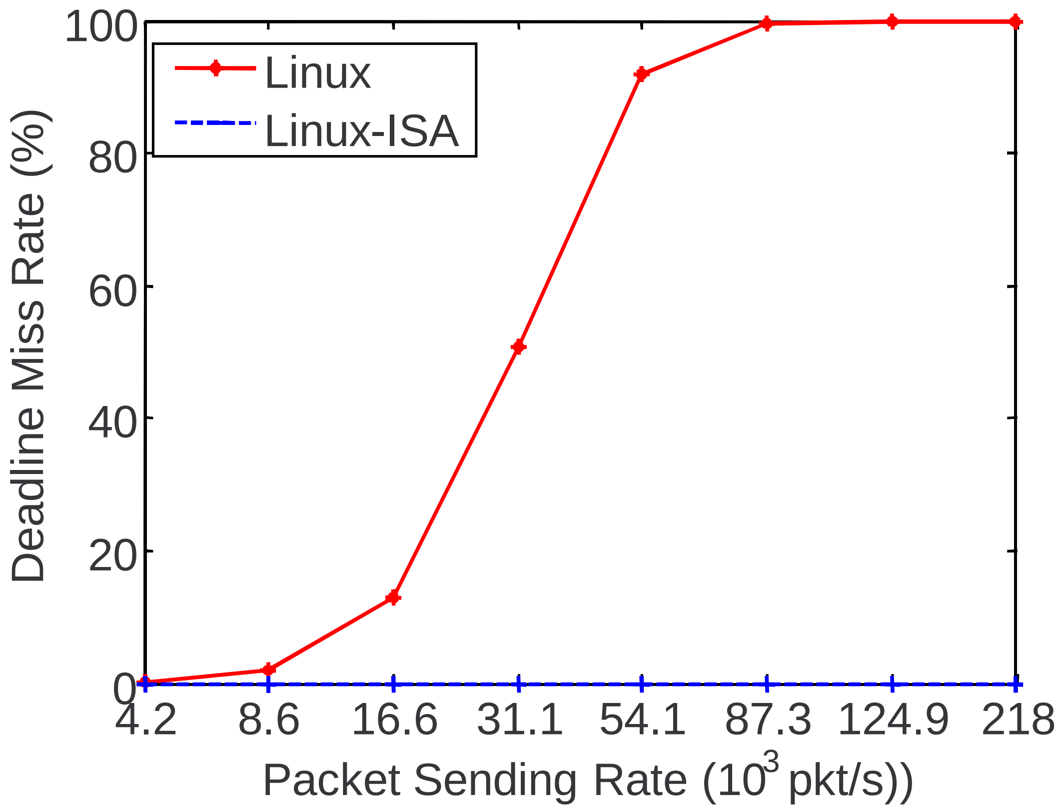
UDP-Server Packet Reception Rate



Bursty Packet Transmission Experiments

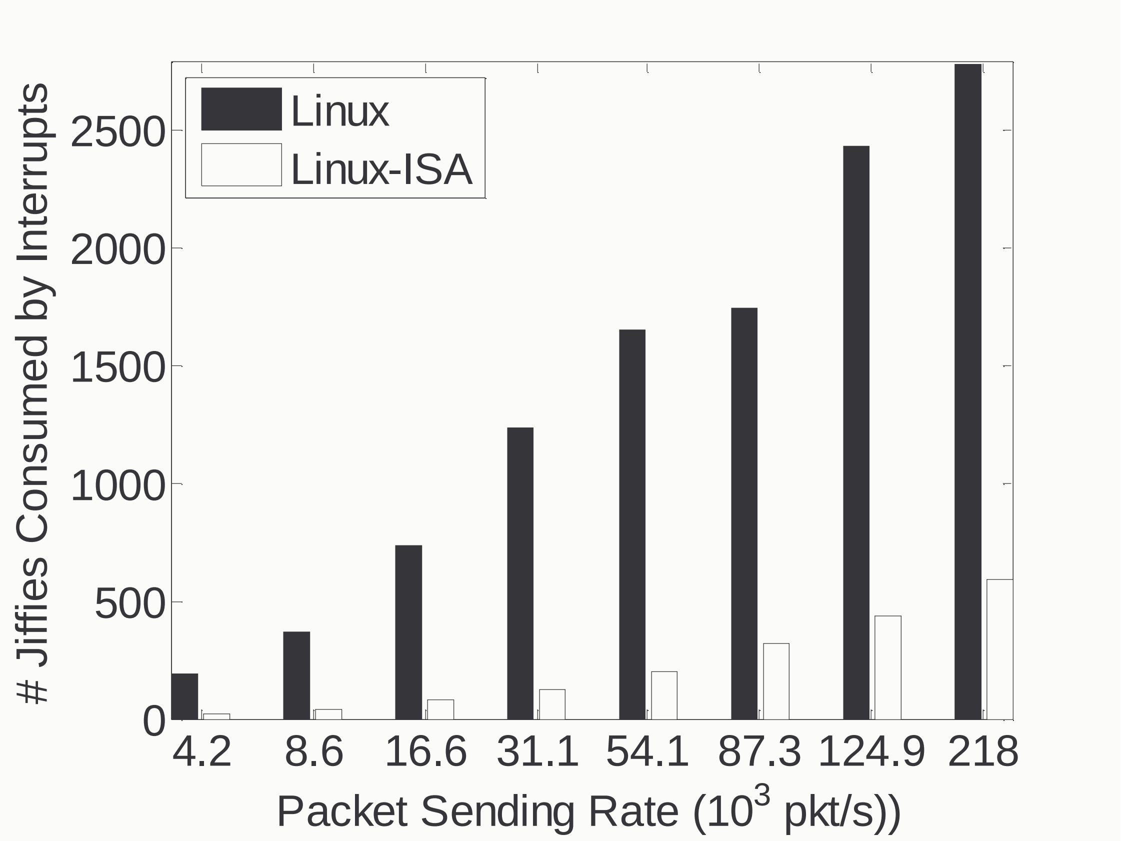
- UDP-client sends bursts of pkts w/ avg geometric sizes of 5000 pkts
  - Different avg exponential burst inter-arrival times
- CPU-bound process is periodic w/ C=0.95s and T=1.0s
  - Runs for 100s as before
- Deadline at end of each 1s period

Deadline Miss Rate

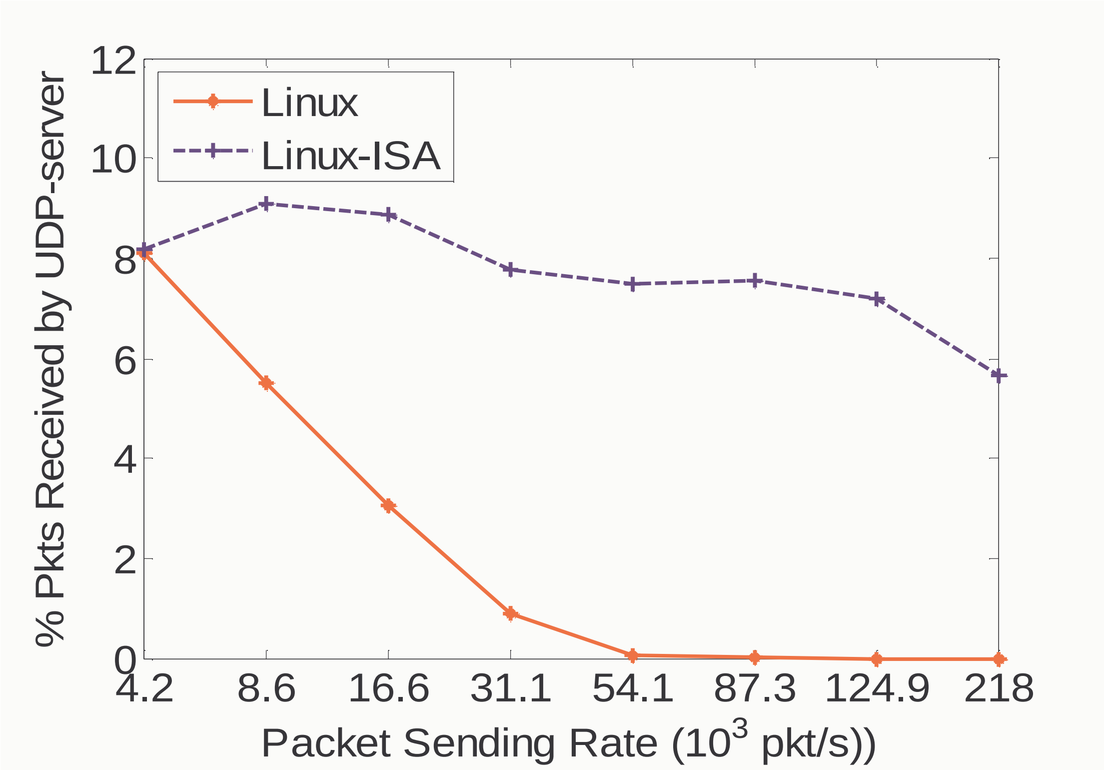


- Linux-ISA – no missed deadlines for CPU-bound process
- Bottom half interrupt handling deferred until CPU-bound process completes each period

Interrupt Overheads (100s interval)



Performance of UDP-server



- CPU-bound process cannot finish executing in 1s period when interrupt overheads are high
  - Always competes for CPU cycles, starving lower priority UDP-server
- Linux-ISA guarantees "slack" time usage for UDP-server

Conclusions and Future Work

- Explore dependency between processes and interrupts
- Focus on bottom half scheduling and accounting
  - Compensate processes for time spent in bottom halves
  - Charge correct processes benefiting from interrupts
- Unify the scheduling of bottom half interrupt handlers w/ processes
  - Improve predictability of real-time tasks while avoiding undue interrupt-handling overheads
  - Consequently, benefit non-real-time tasks also!
- Future? Better predictors of process(es) associated w/ interrupts for scheduling purposes
- Interrupt management on multi-processors/cores

(2) Mutable Protection Domains

Towards a Component-based System for Dependable and Predictable Computing

Complexity of Embedded Systems

- Traditionally simpler software stack
  - limited functionality and complexity
  - focused application domain

- Soon cellphones will have 10s of millions of lines of code
  - downloadable content (with real-time constraints)

- Trend towards increasing complexity of embedded systems

Consequences of Complexity

- Run-time interactions are difficult to predict and can cause faults
  - accessing/modifying memory regions unintentionally
  - corruption to data-structures
  - deadlocks/livelocks
  - race-conditions
  - . . .

- Faults can cause violations in correctness and predictability

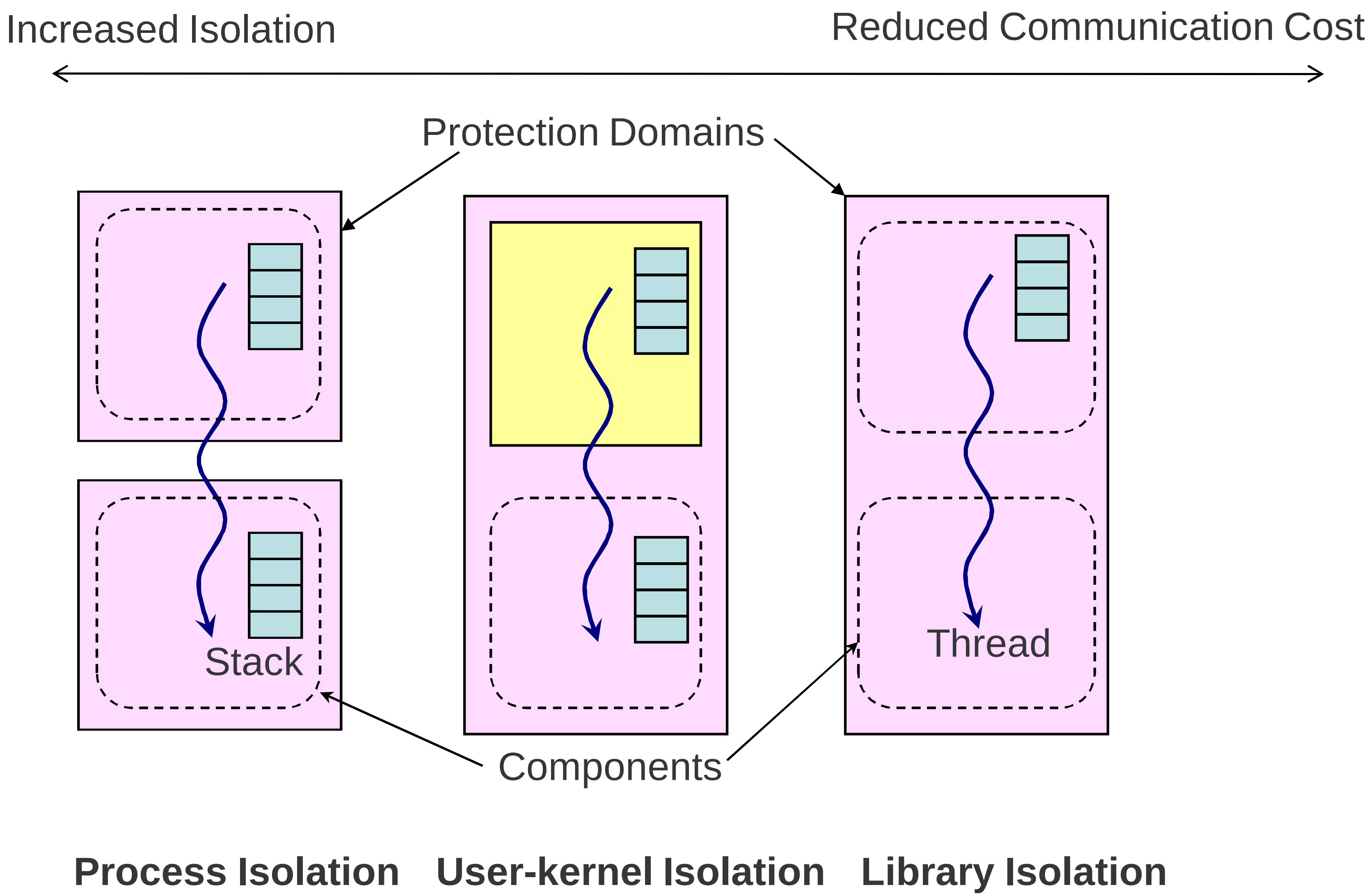
Designing for Dependability & Predictability

- Given increasing complexity, system design must anticipate faults

- Memory fault isolation: limit scope of adverse side-effects of errant software
  - identify and restart smallest possible section of the system
  - recover from faults with minimal impact on system goals
  - employ software/hardware techniques

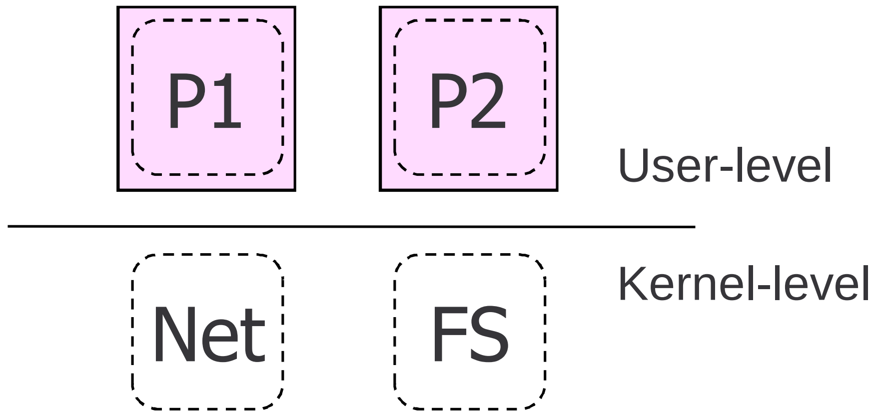
Preserve system reliability and predictability in spite of misbehaving and/or faulty software

Trade-offs in Isolation Granularity



Static HW Fault Isolation Approaches

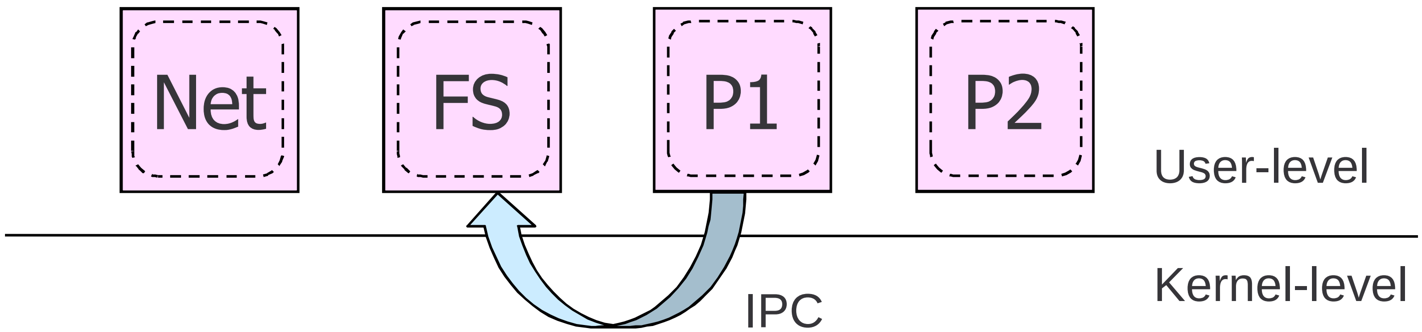
- What is the “best” isolation granularity?



- Monolithic OSs
  - provide minimal isolation to allow process independence
  - large kernel not self-isolated, possibly extensible
- Coarse-grained isolation, **but** low service invocation cost

Static HW Fault Isolation Approaches (II)

- What is the "best" isolation granularity?



- µ-kernels
  - segregate system services out of the kernel, interact w/ Inter-Process Communication (IPC)
  - finer-grained isolation
    - IPC overhead limits isolation granularity
- Finer-grained fault isolation, **but** increased service invocation cost

Mutable Protection Domains (MPD)

Goal: configure system to have finest grained fault isolation while still meeting application deadlines

- Mutable Protection Domains (MPDs)
  - dynamically place protection domains between components in response to
    - communication overheads due to isolation
    - application deadlines being satisfied
- application close to missing deadlines
  - lessen isolation between components
- laxity in application deadlines
  - increase isolation between components

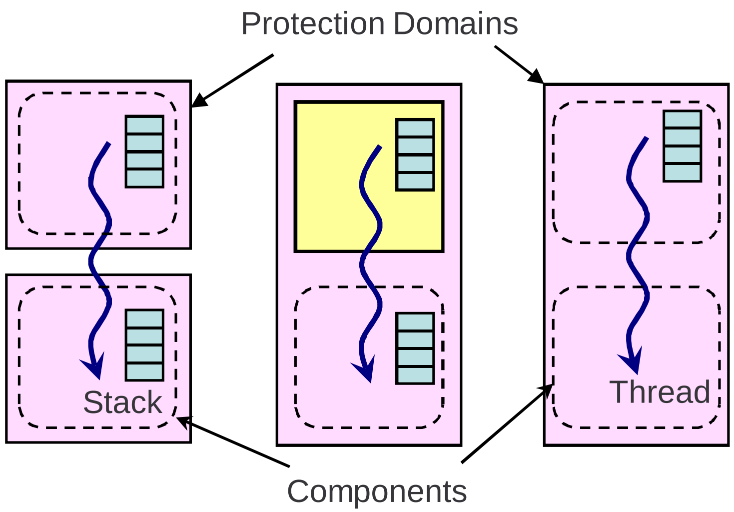
Mutable Protection Domains (MPD) (II)

- Mutable Protection Domains appropriate for soft real-time systems
- Protection domains can be made immutable where appropriate

Setup and Assumptions

- System is a collection of components
- Arranged into a directed acyclic graph (DAG)
  - nodes = components themselves
  - edges = communication between them, indicative of control flow

- Isolation over an edge can be configured to be one of the three isolation levels



Isolation cost and benefit

- Isolation between components causes a performance penalty due to:

  (1) processing cost of a single invocation between those components

  (2) the frequency of invocations between those components

  ⇒ cost of each isolation level/edge

- Isolation levels affect dependability
  - stronger isolation ⇒ higher dependability
- Isolation between specific components more important
  - debugging, testing, unreliable components, . . .

  ⇒ benefit of each isolation levels/edge

Problem Definition

- For a solution set s, where $s_i \in \{1, \ldots, \#\text{ isolation levels}\}$ maximize the dependability of the system . . .
  - i.e., Maximize $\Sigma_{\forall i \in edges}\, benefit_{is_i}$

    while meeting task deadlines:

    $\Sigma_{\forall i \in edges}\, cost_{is_i k} \leq surplus\_resources_k$

    for each task in the system ($\forall k \in tasks$)

Multi-Dimensional, Multiple-Choice Knapsack

- Maximize $\Sigma_{\forall i \in \text{edges}}\ \text{benefit}_{is_i}$

  Subject to: $\Sigma_{\forall i \in \text{edges}}\ \text{cost}_{is_ik} \leq \text{surplus\_resources}_k$

  $\forall k \in$ tasks, $s_i \in \{1, \ldots, \text{max\_isolation\_level}\}$, $\forall i \in$ edges

- This problem is a multi-dimensional, multiple-choice knapsack problem (MMKP)
  - multi-dimensional - multiple resource constraints
  - multiple-choice - configure each edge in one of the isolation levels
- NP-Hard problem: heuristics, pseudo-poly dynamic prog., branch-bound

One-Dimensional Knapsack Problem

- Effective and inexpensive greedy solutions to one-dimensional knapsack problem exist

  - sort isolation levels/edges based on *benefit density*
    - ratio of benefit to cost
  - increase isolation by including isolation levels/edges from head until resources are expended

. . . but we have multiple dimensions of cost

Solutions - Reducing Resource Dimensions

- Compute an *aggregate cost* for each edge
  - single value representing a combination of the costs for all tasks for an edge: $\forall k$, $cost_{isjk} \rightarrow agg\_cost_{isj}$

- some tasks very resource constrained, some aren't
- intelligently weight costs for task k to compute aggregate cost

Solutions - HEU

- (1) compute aggregate cost for each isolation level/edge
- (2) include isolation level/edge with best benefit density in solution configuration
- (3) goto 1 until resources expended

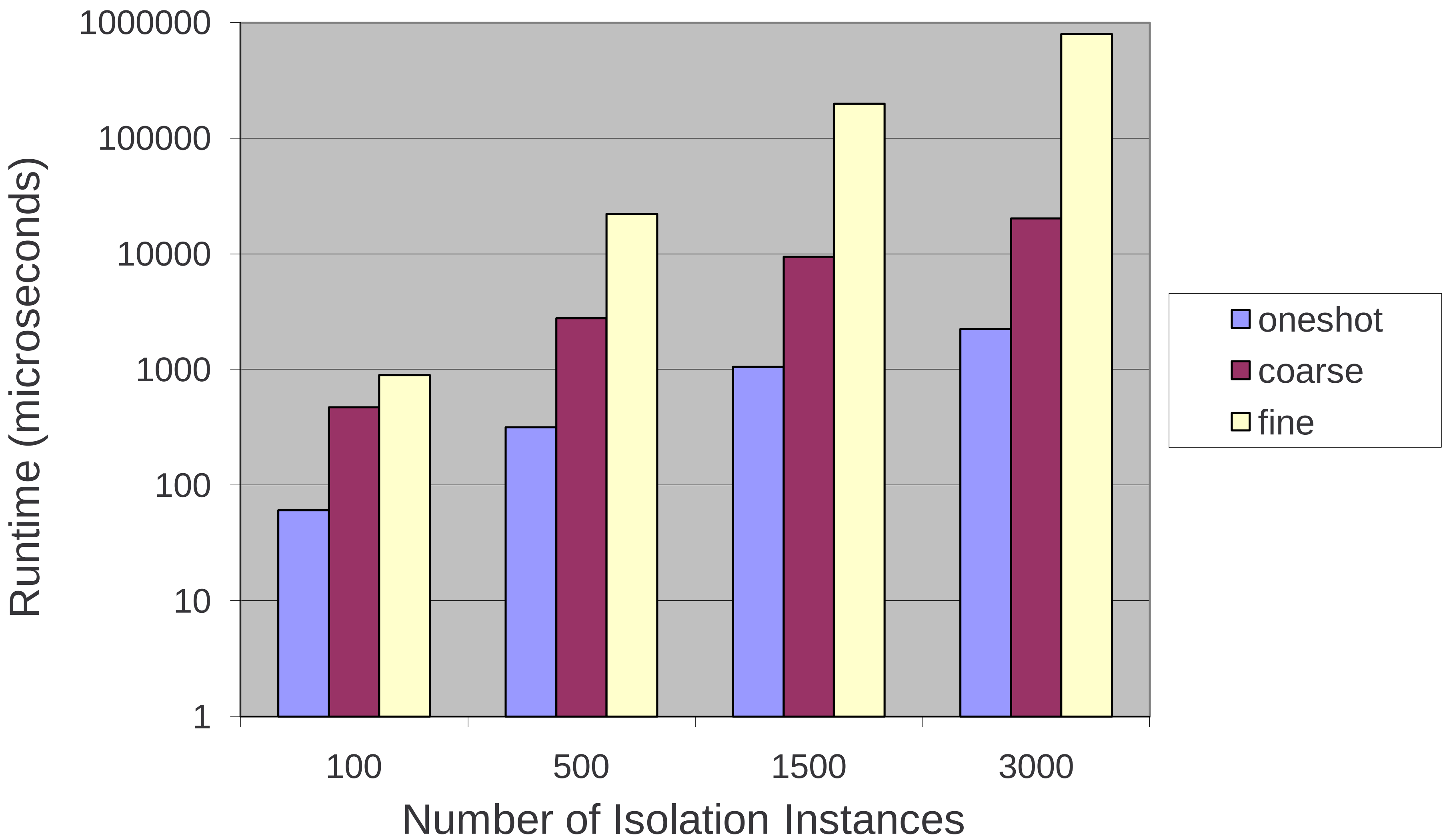
- *Fine-grained* refinement of aggregate cost
  - Re-compute once every time an isolation level/edge is added to the current solution configuration

Solutions - *coarse* and *oneshot* Refinement

- (1) compute aggregate cost for each isolation level/edge
- (2) sort by benefit density
- (3) include isolation level/edge from head
- (4) goto 3, until resources expended
- (5) re-compute aggregate costs based on resource surpluses with solution configuration
- (6) goto 2 N times and return highest benefit configuration

- N > 1: *coarse-grained* refinement
  - Re-compute once per total configuration found
  - Execution time linearly increases with N
- N = 1: *oneshot*
  - Very quick
  - No aggregate cost refinement

Solution Runtimes



System Dynamics

- System is dynamic
  - Changing communication costs over edges as threads alter execution paths between components
  - Changing resource availabilities as threads vary intra-component execution time
  - Per-invocation overheads vary
    - Different cache working sets, invocation argument size, etc, . . .

- System must refine the system isolation configuration as these variables change

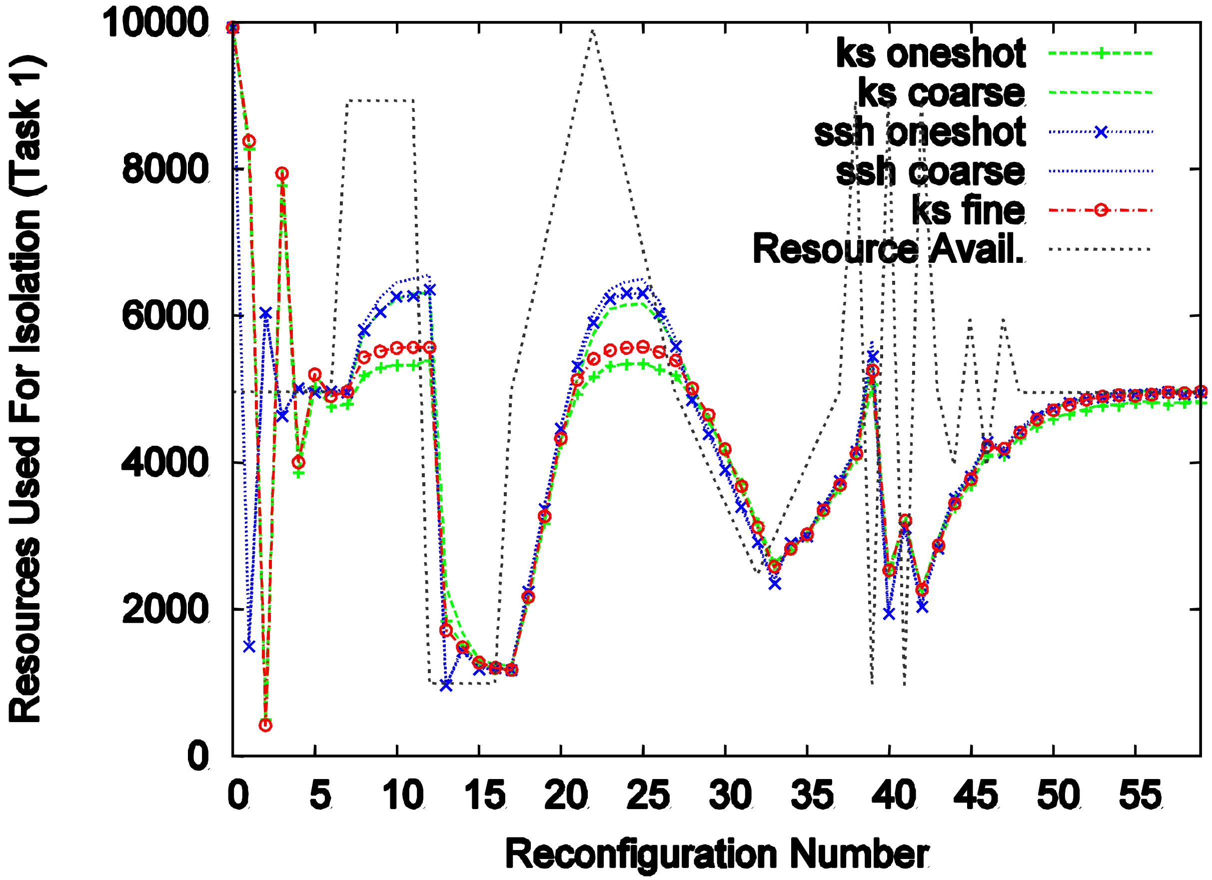
Solutions over time

- System dynamics require re-computation of system configuration
  - (1) disregard current system state, re-compute entirely new system configuration
    - Traditional knapsack (MMKP) approach: *ks*
  - (2) solve for the next system configuration starting from the current system configuration
    - Successive State Heuristic (*ssh*)
      - modifies *coarse* and *oneshot* to start from the current system configuration
      - aim to reduce isolation changes to existing configuration

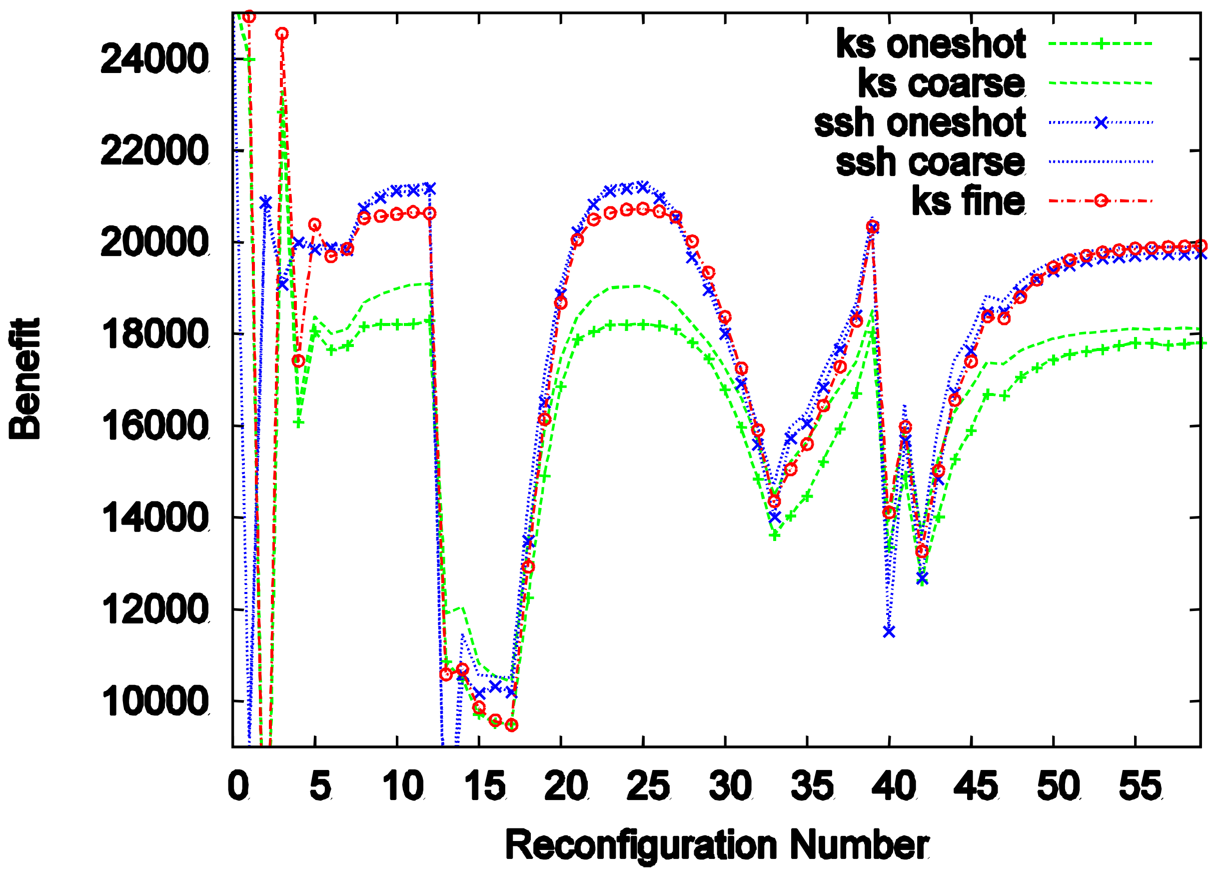
Experimental Simulations

- Simulate a system with
  - widely varying resource surplus for 3 tasks
  - changing communication costs
  - 200 edges, 3 isolation levels
  - Edge benefits uniform & randomly chosen from [0,255] for highest isolation level
    - Linear decrease to 0 for corresponding edge’s lowest isolation level

Resource Usage for Task 1

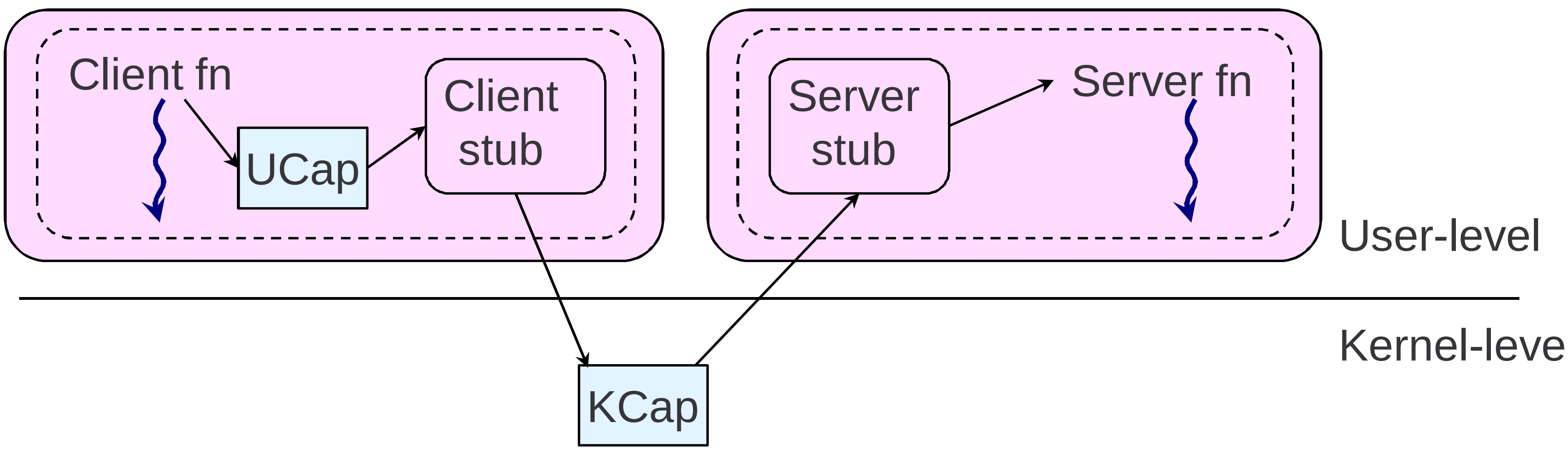


System Isolation-Derived Benefit



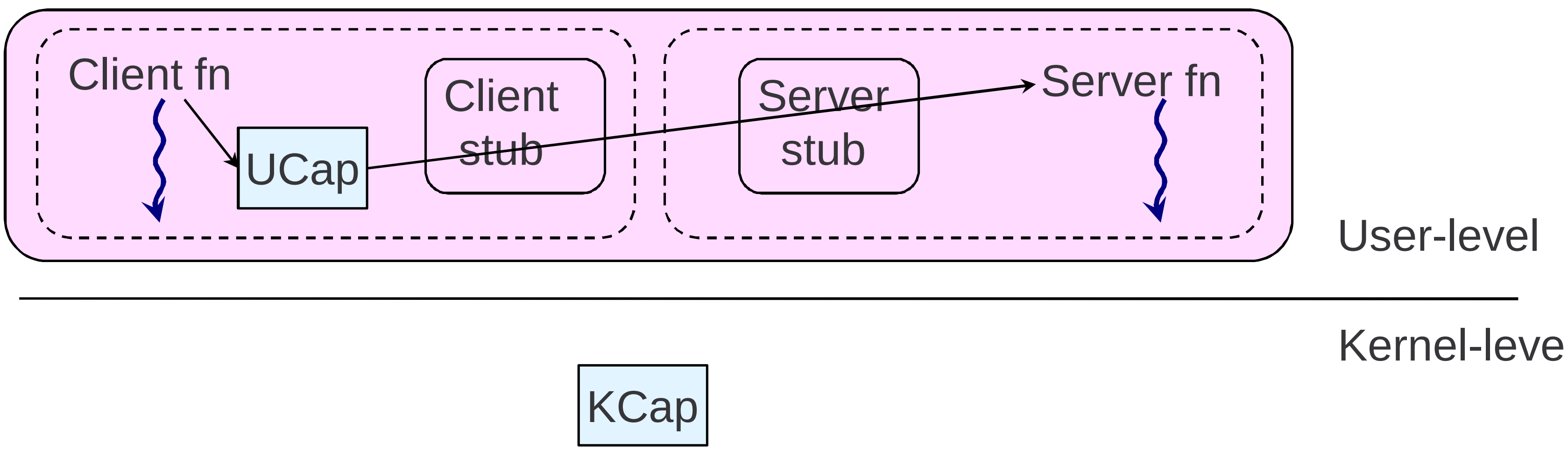
OS Support for MPD

- Composite: component-based OS designed to support MPD



OS Support for MPD (II)

- Composite: component-based OS designed to support MPD



OS Support for MPD (III)

- Switching between the two isolation levels requires changing UCap, KCap, and protection domains

- Prototype running on x86 Pentium IV @ 2.4 Ghz
  - Invocation via kernel - 1510 cycles (0.63 µsecs)
  - Direct invocation - 55 cycles (0.023 µsecs)

Conclusions

- Solution to MMKP based on lightweight successive refinement given dynamic changes in system behavior
  - possibly useful in e.g. QRAM
- Mutable Protection Domains
  - dynamically reconfigure protection domains to maximize fault isolation while meeting application deadlines
  - makes the performance/predictability versus fault isolation tradeoff explicit