Application-Specific Service Technologies for Commodity OSes in Real-Time Environments

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Computer Science

Introduction

- Leverage commodity systems and generic hardware for real-time applications
  - Eliminate cost of proprietary systems & custom hardware
  - Use a common code base for diverse application requirements
    - e.g., use existing device drivers
  - ***BUT****…mismatch exists between the requirements of real-time applications and the service provisions of commodity OSes*

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
    - Do not leverage commodity OSes
    - Do not explicitly consider real-time requirements (bounded dispatch latencies and execution)
  - RTLinux, RTAI etc
    - Do not focus on isolation of service extensions from core kernel

Extending Commodity Systems

- Desktop systems now support QoS-constrained applications
  - e.g., Windows Media Player, RealNetworks Real Player
- Many such systems are monolithic and not easily extended or only support limited extensibility
  - e.g., kernel modules for device drivers in Linux
  - No support for extensions to override system-wide service policies

Objectives

- Aim to **extend** commodity systems to:
  - better meet the service needs of individual applications
  - provide first-class application-specific services
- Service extensions must be `QoS safe':
  - Need CPU-, memory- and I/O-space protection to ensure
    - Service isolation
    - Predictable and efficient service dispatching
    - Bounded execution of services

First-class Services

- Where possible, have same capabilities as kernel services but kernel can still revoke access rights
  - Grant access rights to subset of I/O-, memory-space etc
  - Dispatch latencies close to those of kernel-level interrupt handlers
  - Avoid potentially unbounded scheduling delays
    - Bypass kernel scheduling policies
    - Eliminate process context-switching
      - Eliminate expensive TLB flushes/reloads

First-class Services cont.

- Process, P_i, may register a service that runs even when P_i is not executing
  - Like a fast signal handling mechanism
  - Example usages:
    - Asynchronous I/O
    - Resource monitoring / management
      - e.g., P_i wishes to adjust its CPU usage even when not running perhaps because it wasn't getting enough CPU!

Contributions

- Comparison of kernel- and user-level extension technologies
  - "User-level sandboxing" (ULS) versus our prior SafeX work
  - Show how to achieve low service dispatch latency for app-specific services, while ensuring some degree of CPU-, I/O and memory protection

SafeX – Safe Kernel Extensions

- Extension architecture for general purpose systems
  - Allows applications to customize system behavior
  - Extensions run in context of a kernel "bottom half"
    - Enables low-latency execution in response to events & eliminates heavyweight process scheduling

SafeX Approach

- Supports compile- and run-time safety checks to:
  - Guarantee QoS
    - The QoS contract requirement
  - Enforce timely & bounded execution of extensions
    - The predictability requirement
  - Guarantee an extension does not improve QoS for one application at the cost of another
    - The isolation requirement
  - Guarantee internal state of the system is not jeopardized
    - The integrity requirement

SafeX Features

- Extensions written in Popcorn & compiled into Typed Assembly Language (TAL)
  - TAL adds typing annotations / rules to assembly code
- Memory protection:
  - Prevents forging (casting) pointers to arbitrary addresses
  - Prevents de-allocation of memory until safe
- CPU protection:
  - Requires resource reservation for extensions
  - Aborts extensions exceeding reservations
  - SafeX decrements a counter at each timer interrupt to enforce extension time limits

Synchronization

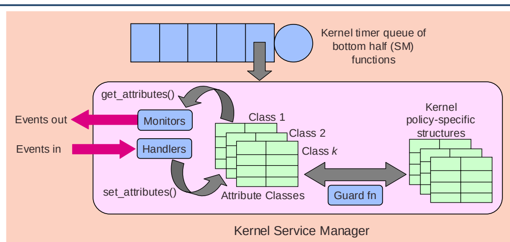
- Extensions cannot mask interrupts
  - Could violate CPU protection since expiration counter cannot decrement
- Problems aborting an extension holding locks
  - e.g., extension runs too long
  - May leave resources inaccessible or in wrong state

  - Extensions access shared resources via SafeX interfaces that ensure mutual exclusion

SafeX Service Managers

- Encapsulations of resource management subsystems
- Have policies for providing service of a specific type
  - e.g., a CPU service manager has policies for CPU scheduling and synchronization
- Run as bottom-half handlers (in Linux)
  - Invoked periodically or in response to events within system
- Invoke monitor and handler extensions
  - Can execute asynchronously to application processes
  - Apps may influence resource allocations even when not running

Kernel Service Managers



- Monitors & handlers operate on attribute classes
  - name-value pairs (e.g. process priority – value)
- Service extensions with valid access rights can modify attributes

Attribute Classes & Guards

- Attribute classes store name-value pairs for various app-specific service attributes
  - e.g., priority-value for CPU scheduling

  - Access to these classes is granted to the extensions of processes that acquire permission from the class creators
- Guard functions are generated by SafeX
  - Responsible for mapping values in attribute classes to kernel data structures
  - Can enforce range and QoS guarantee checks

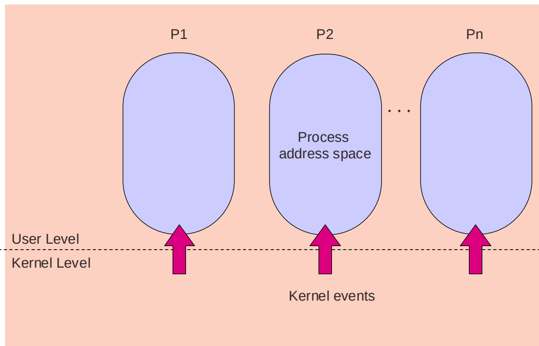
SafeX Interfaces

- SafeX provides get_/set_attribute () interfaces
  - Extensions use these interfaces to update service attributes
  - Extensions are not allowed to directly access kernel data structures
- Interfaces can only be used by extensions having necessary capabilities
  - Capabilities are type-safe (unforgeable) pointers
- Interfaces limit global affects of extensions
  - Balance application control over resources with system stability

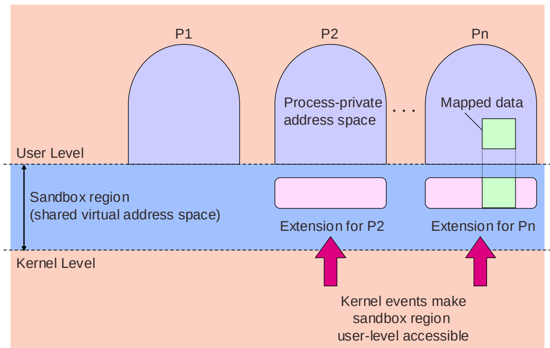
User-Level Sandboxing (ULS)

- Provide “safe” environment for service extensions
- Separate kernel from app-specific code
- Use only page-level hardware protection
  - Can use type-safe languages e.g., Cyclone for memory safety of extensions, SFI etc., or require authorization by trusted source
- Approach does not require (but may benefit from) special hardware protection features
  - Segmentation
  - Tagged TLBs

Traditional View of Processes



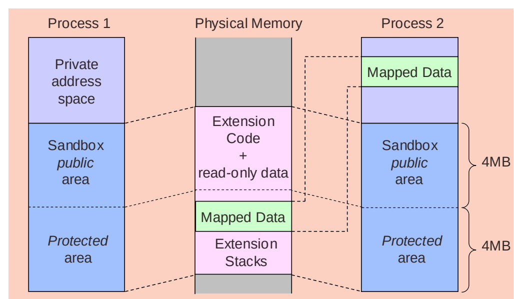
Sandbox Region Shared by Processes



ULS Implementation

- Modify address spaces of all processes to contain one or more shared pages of virtual addresses
  - Shared pages used for sandbox
    - Normally inaccessible at user-level
    - Kernel upcalls toggle sandbox page protection bits & perform TLB invalidate on corresponding page(s)
- Current x86 approach
  - 2x4MB superpages (one data, one code)
  - Modified libc to support mmap, brk, shmget etc
  - ELF loader to map code & data into sandbox
  - Supports sandboxed threads that can block on syscalls

Virtual-to-Physical Memory Mapping



ULS Implementation (2)

- Fast Upcalls
  - Leverage SYSEXIT/SYSENTER on x86
    - Support traditional IRET approach also
- Kernel Events
  - Generic interface supports delivery of events to specific extensions
  - Each extension has its own stack & thread struct
    - Extensions share credentials (including fds) with creator
  - Events can be queued ala POSIX.4 signals

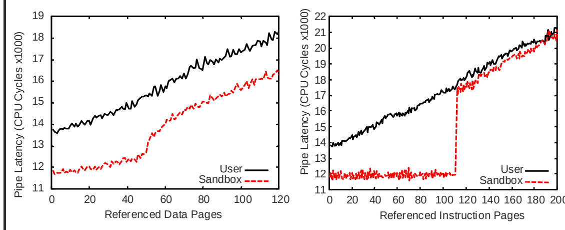
Experimental Evaluation

- (a) Inter-Protection Domain Communication
  - Look at overheads of IPC between thread pairs
    - Exchange 4-byte messages
    - Vary the working set of one thread to assess costs
    - 1.4GHz P4, patched Linux 2.4.9 kernel
- (b) Adaptive CPU service management
  - Aim: to meet the needs of CPU-bound RT tasks under changing resource demands from a `disturbance' process
  - Compare ULS and SafeX to process-based approaches
  - 550 Mhz Pentium III, 256MB RAM, patched 2.4.20 Linux

Data and Instruction TLB Misses

- Inter-protection domain communication costs
- Costs of 4-byte messages between two threads using pipes
- Vary working set of one process-private thread while other is in sandbox

Pipe Latency



- Pipe latency remains lower for RPC with sandboxed thread
  - Even when data TLB miss rates are similar
- NOTE: d-TLB sizes simulated by thread reading 4 bytes of data from addresses spaced 4160 bytes apart. i-TLB sizes simulated using relative jumps to instructions 4160 bytes apart.

System Service Extensions

- Can we implement system services in the sandbox?
- Here, we show performance of a CPU service manager (CPU SM)
  - Attempt to maintain CPU shares amongst real-time processes on target in presence of background disturbance
  - Use a MMPP disturbance w/ avg inter-burst times of 10s and avg burst lengths of 3 seconds

Kernel Service Management

- A service manager monitors CPU utilization and adapts process timeslices
  - Timeslices adjusted by PID function of target & actual CPU usage
  - Monitoring performed every 10mS
- Kernel monitoring functions invoked via timer queue

User-Level Management

- A periodic RT process acts as a CPU service manager
  - Reads /proc/pid/stat
  - Adapts service via kill() syscalls
    - Using SIGSTOP & SIGCONT signals

Experimental Setup

- 3 CPU-bound processes, P1, P2 & P3
  - P1 – target CPU = 40mS every period = 400mS
  - P2 – target CPU = 100mS every 500mS
  - P3 – target CPU = 60mS every 200mS
- An MMPP disturbance (CPU "hog")
  - 10 sec exponential inter-burst gap & 3 sec geometric burst lengths

Experimental Setup cont.

- Each app process has initial RT priority = 80 x (target / period)
  - target & period denote target CPU time in a given period
- User-level service manager & disturbance start at RT priority = 96
- Kernel daemons run at RT priority = 97
- Utilization points recorded over 1 sec intervals

Monitors and Handlers

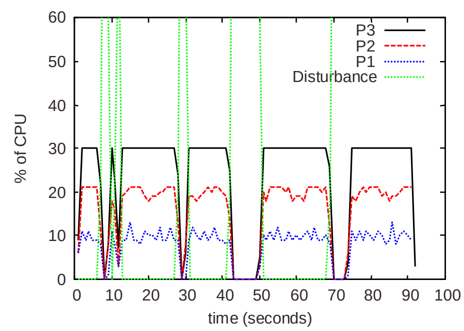
```
void monitor () {
  actual_cpu = get_attribute (“actual_cpu”);
  target_cpu = get_attribute (“target_cpu”);
  raise_event (“Error”, target_cpu - actual_cpu);
}

void handler () {
  e[n] = ev.value; // nth sampled error

  /* Update timeslice adjustment by PID fn of error */
  u[n] = (Kp+Kd+Ki).e[n] - Kd.e[n-1] + u[n-1];

  set_attribute (“timeslice-adjustment”, u[n]);
}
```

Guard Functions

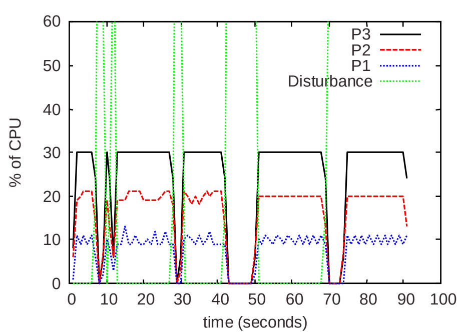
```
// Check the QoS safe updates to a process’ timeslice

guard (attribute, value):
  if (attribute == “timeslice-adjustment”)
    if (CPU utilization is QoS safe)
        timeslice = max (0, target_cpu + value);
    else block process;
```

- CPU utilization is deemed QoS safe if:
  Avg utilization over 2*period <= target utilization

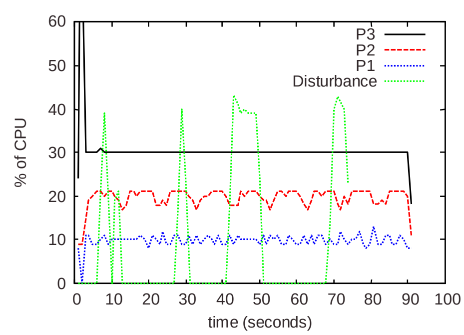
CPU SM: User-level Process



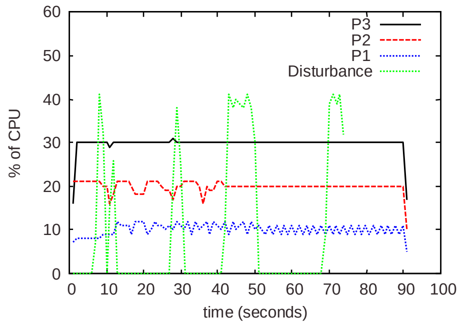
CPU SM: Sandbox Thread



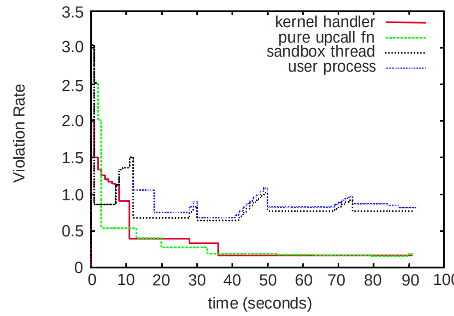
CPU SM: Pure Upcall



CPU SM: Kernel



Deadline Violation Rates



SafeX Benchmarks

- User-level:
  - Signal dispatch = 1.5µS
  - Context-switch between SM and app process = 2.99µS
  - Reading /proc/pid/stat = 53.87µS
  - Monitors and handlers (for 3 processes) = 190µS
- Kernel-level:
  - Executing monitors and handlers (for 3 processes) = 20µS

ULS Benchmarks

Operation	Cost in CPU Cycles
Upcall including TLB flush / reload	11000
TLB flush and reload *includes call to OpenSandbox()	8500
Raw upcall	2500
Signal delivery (current process)	6000
Signal delivery (different process)	46000

Conclusions

- SafeX and ULS both capable of supporting app-specific service invocation without process scheduling / context-switching overheads
  - Avoid TLB flush/reload costs
  - Lower-latency, more predictable service dispatching
  - Both provide finer-grained service management than process-based approaches
    - No scheduling of processes for service management
    - Not dependent on scheduling policies and timeslice granularities
  - ULS has advantage of isolating services outside core kernel

Future Work

- Real-time upcall mechanism for deferrable services
- Better interrupt accounting and "bottom half" scheduling
- Support for complex virtual services
- Comparison with RTAI, RTLinux and similar approaches