EECS 571 “Principles of Real-Time Embedded Systems”

Lecture Note #10:

EMERALDS: A Small-Memory Real-Time Microkernel

ACM SOSP’99 paper by Zuberi *et al.*

Outline

- Motivation
- Overview of EMERALDS
- Minimizing Code Size
- Minimizing Execution Overheads
- Conclusions

Why Small memories, slow processors?

- Small-memory embedded systems used everywhere!
  - automobiles
  - home appliances
  - telecommunication devices, PDAs,…
  - factory automation and avionics
- Massive volumes (10K-10M units per annum)

➡ Saving even a few dollars per unit is important:
  - cheap, low-end processors (Motorola 68K, Hitachi SH-2)
  - max. 32-64 KB SRAM, often on-chip
  - low-cost networks, e.g., Controller Area Network (CAN)

RTOS for Small-Memory Embedded Systems

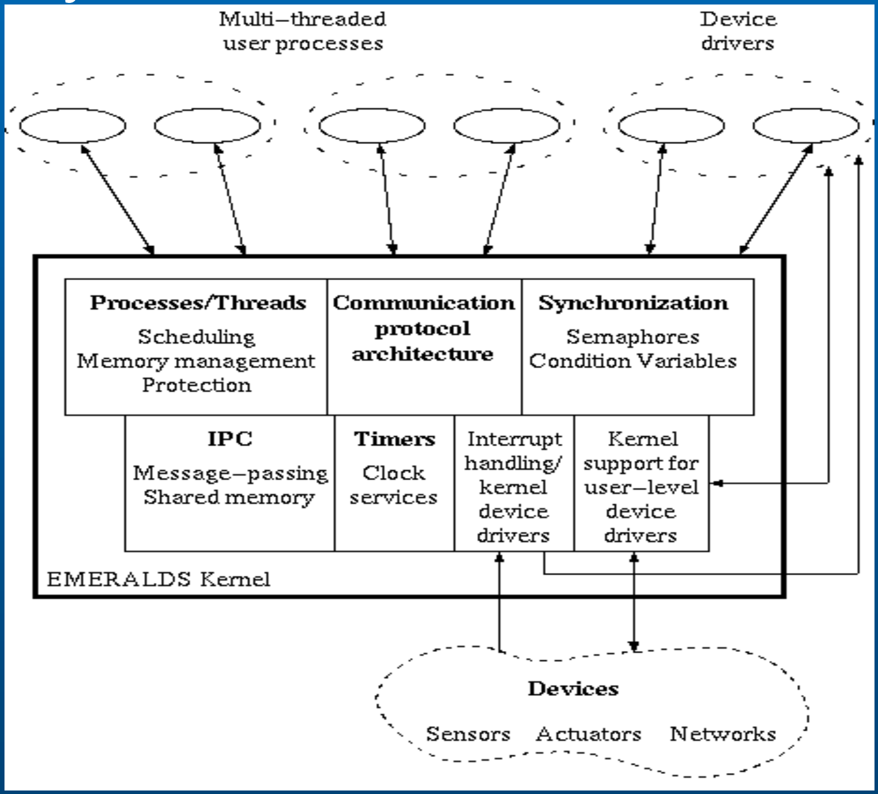
- Despite restrictions, must perform increasingly complex functions
- *General-purpose* RTOSs (VxWorks, pSOS, QNX) too large or inefficient
- Some vendors provide smaller RTOSs (pSOS Select, RTXC, Nucleus) by carefully *handcrafting* code to get efficiency

RTOS Requirements for Small-Memory Embedded Systems

- Code size ~ 20 kB
- Must provide all basic OS services: process management, IPC, task synchronization, scheduling, I/O
- All aspects must be *re-engineered* to suit small-memory embedded systems:
  - API
  - IPC, synchronization, and other OS mechanisms
  - Task scheduling
  - Networking

EMERALDS Architecture

- Extensible Microkernel for Embedded ReAL-time Distributed Systems



Minimizing Kernel Size

- Location of resources known
  - allocation of threads on nodes
  - compile-time allocation of mailboxes => no naming services
- Memory-resident applications:
  - no disks or file systems
- Simple messages
  - e.g., sensor readings, actuator commands
  - often can directly interact with network device driver

Reducing Kernel Execution Overhead

- Task Scheduling: EDF/RM can ``consume'' 10-15% of CPU
- Task Synchronization: semaphore operations incur context switch overheads
- Intertask Communication: often exchange 1000's of short messages, especially if OO is used

Real-Time Scheduling

- Problems with cyclic time-slice schedulers
  - Poor aperiodic response time
  - Long schedules
- Problems with common priority-driven schedulers
  - EDF: High run-time overheads
  - RM: High schedulability overheads

Scheduler Overheads

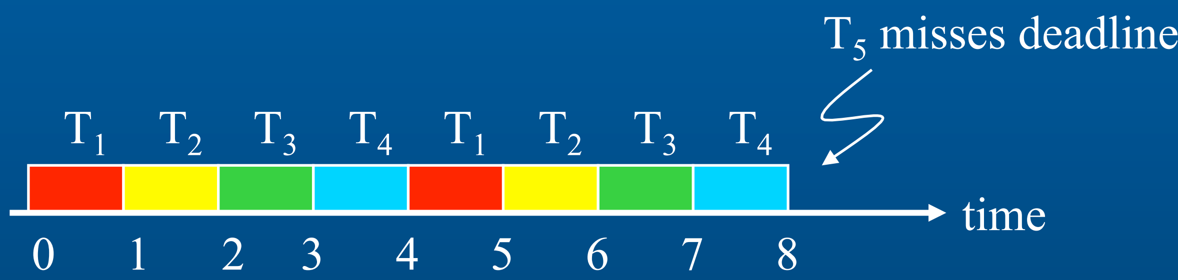
- *Run-time* Overheads: Execution time of scheduler
  - RM: static priorities, low run-time overheads
  - EDF: high run-time overheads
- *Schedulability* Overhead: $1 - U^*$
  - U^* is ideal utilization attainable, assuming no run-time overheads
  - EDF: $U^* = 1$ (no schedulability overhead)
  - RM: $U^* > 0.69$ with avg. 0.88
- Total Overhead: Sum of these overheads
  - Combined static/dynamic (CSD) scheduler finds a balance between RM and EDF

Schedulability Overhead Illustration

- Example of RM schedulability issue

Task	1	2	3	4	5	6	7	8	9	10
P (ms)	4	5	6	7	8	20	30	50	100	130
c (ms)	1	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5

- *U* = 0.88; EDF schedulable, but not under RM



Combined Static and Dynamic Scheduling

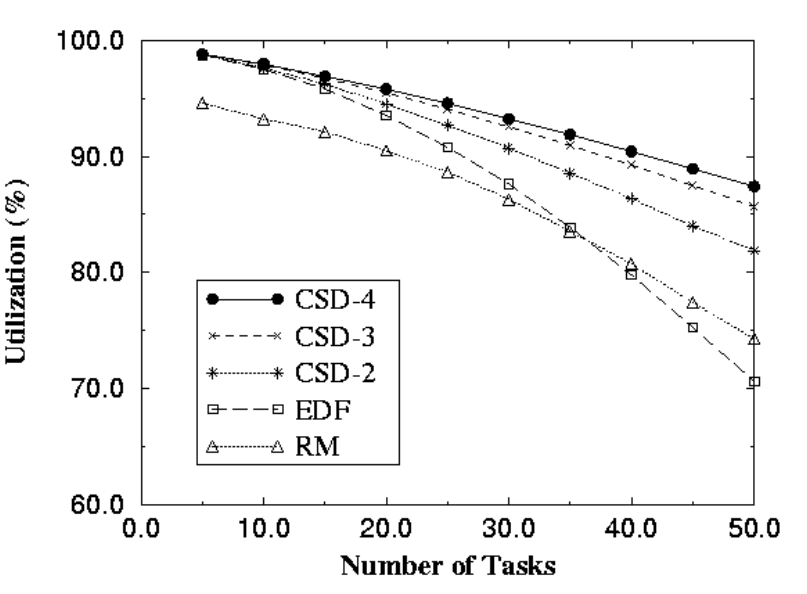
- CSD maintains two task queues:
  - Dynamic Priority (DP) scheduled by EDF
  - Fixed Priority (FP) scheduled by RM
- Given workload $\{T_i : i = 1,2,...,n\}$ sorted by RM-priority
  - Let r be smallest index such that T_{r+1} - T_n are RM-schedulable
  - T_1 - T_r are in DP queue
  - T_{r+1} - T_n are in FP queue
  - DP is given priority over FP queue

CSD Overhead

- CSD has near zero schedulability overhead
  - Most EDF schedulable task sets can work under CSD
- Run-time overheads lower than EDF
  - *r*-long vs. *n*-long DP queue
  - FP tasks incur only RM-like overhead
- Reducing CSD overhead further
  - split DP queue into multiple queues
  - shorter queues for dynamic scheduling
  - need careful allocation, since schedulability overhead incurred between DP queues

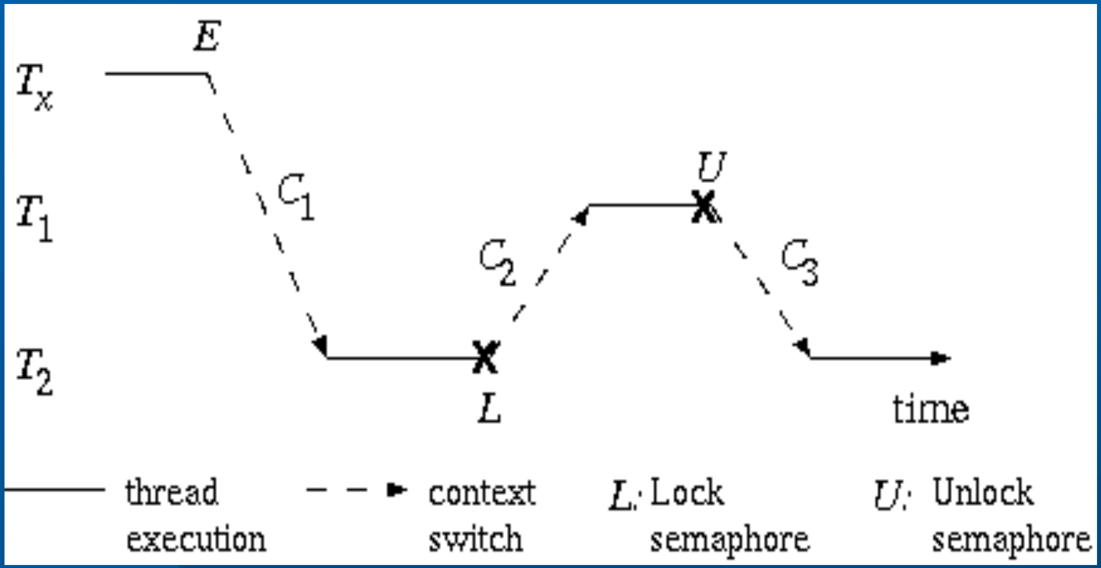
CSD Performance

- Comparison of CSD-*x*, EDF, and RM
  - 20-40% lower overhead than EDF for 20-30 tasks
  - CSD-*x* improves performance, but diminishing returns



Efficient Semaphores

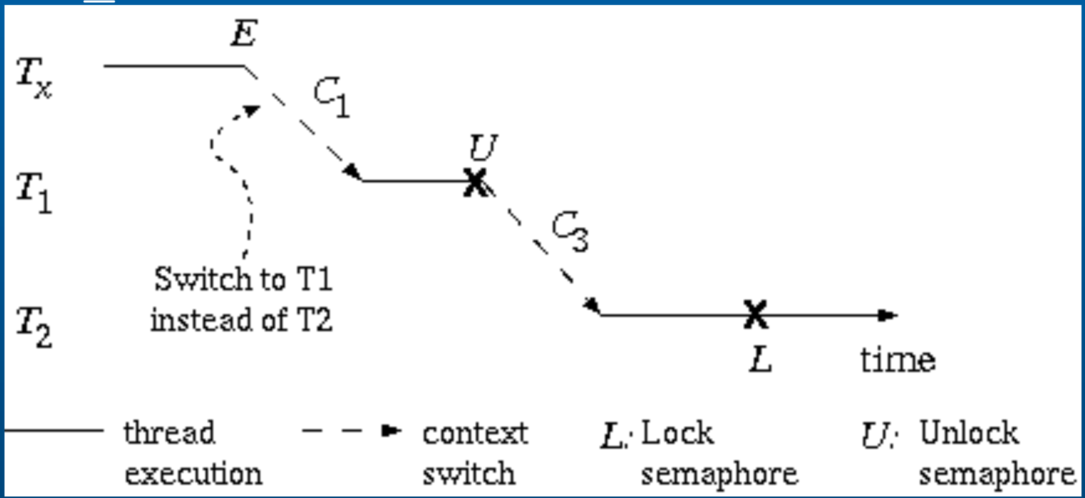
- Concurrency control among tasks
- May cause a large number of context switches
- Typical scenario: Tx>T2 > T1 and T1 is holding lock



unblock T_2
context switch C_1
T_2 calls acquire_sem()
priority inheritance
 (bump-up T_1 to T_2's)
block T_2
context switch C_2
T_1 calls release_sem()
undo T_1 priority
 inheritance
unblock T_2
context switch C_3

Eliminating Context Switch

- For each `acquire_sem(S)` call:
  - pass *S* as an extra parameter to blocking call
  - if *S* unavailable at end of call, stay blocked
  - unblock when *S* is released
  - `acquire_sem(S)` succeeds without blocking



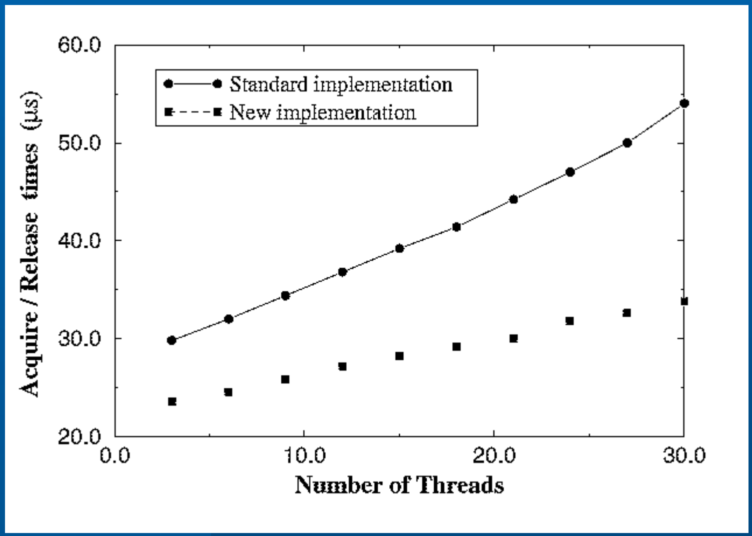
Optimizing Priority Inheritance Steps

- For DP tasks, change one variable, since they are in unsorted queue
- For FP tasks, must remove T_1 from queue and reinsert according to new priority assignment
  - Solution: switch positions of T_1 and T_2
  - Avoids parsing queue
  - Since T_2 is blocked, can be put anywhere as position holder to remember T_1's original position

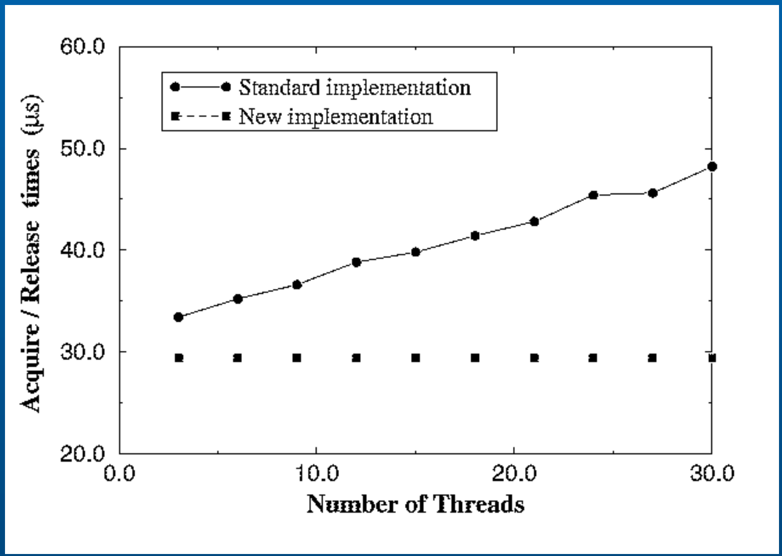
New Semaphore Scheme Performance

- DP tasks - fewer context switches
- FP tasks - optimized PI steps

FP Tasks



DP Tasks



Message Passing

- Tasks in embedded systems may need to exchange 1000's of short messages per second, e.g., OO
- Traditional IPC mechanisms (e.g., mailbox-based IPC) do not work well
  - high overheads
  - no "broadcast" to send to multiple receivers
- For efficiency, application writers forced to use global variables to exchange information
  - unsafe if access to global variables is not regulated

State Messages

- Uses single-writer, multiple-reader paradigm
- Writer-associated state message "mailbox" (SMmailbox)
  - A new message overwrites previous message
  - Reads do not consume messages
  - Reads and writes are non-blocking, synchronization-free
- Read and write operations through user-level macros
  - Much less overhead than traditional mailboxes
  - A tool generates customized macros for each state message

State Messages

- Problem with global variables: a reader may read a half-written message as there is no synchronization
- Solution: *N*-deep circular message buffer for each state message
  - Pointer is updated atomically after write
  - if writer has period 1 ms and reader 5 ms, then *N*=6 suffices
- New Problem: *N* may need to be in the 100's

State Messages in EMERALDS

- Writers and "normal" readers use user-level macros
- Slow readers use atomic read system call
- *N* depends only on faster readers (saves memory)

	State Messages	Mailboxes
send (8 bytes)	2.4 us	16.0 us
receive (8 bytes)	2.0 us	7.6 us
receive_slow (8 bytes)	4.4 us	

Memory Protection

- Needed for fault-tolerance, isolating SW bugs
- Embedded tasks have small memory footprints
  - use only 1 or 2 page tables from lowest level of hierarchy
  - use common upper-level tables to conserve kernel memory
- *Map kernel into all task address spaces*
  - Minimize user-kernel copying as task data and pointers accessible to kernel
  - Reduce system call overheads to a little more than for function calls

EMERALDS-OSEK

- OSEK OS standard consists of
  - API: system call interface
  - Internal OS algorithms: scheduling and semaphores
- OSEK Communication standard (COMM) is based on CAN
- Developed an OSEK-compliant version of EMERALDS for Hitachi SH-2 microprocessor

EMERALDS-OSEK (cont'd)

- Features
  - Optimized context switching for basic and extended tasks
  - Optimized RAM usage
- Developed OSEK-COMM over CAN for EMEMRALDS-OSEK
- Hitachi's application development and evaluation: collision-avoidance and adaptive cruise control systems

Conclusions

- Small, low-cost embedded systems place stringent constraints on OS efficiency and size
- EMERALDS achieves good performance by re-designing basic services for such embedded systems
  - Scheduling overhead reduced 20-40%
  - Semaphore overheads reduced 15-25%
  - Messaging passing overheads 1/4 to 1/5 that of mailboxes
  - complete code ~ 13 kB

Extensions

- Implemented on Motorola 68040
- Ported to 68332, PPC, x86, and strong ARM
- Also investigated networking issues: devicenet, wireless LANs, rt-ethernet, TCP and UDP/IP
- OS-dependent and independent development tools
- Energy-Aware EMERALDS
  - extend to support energy saving hardware (DVS, sprint & halt)
  - Energy-aware storage systems (momory and disks)
  - Energy-aware Quality of Service (EQoS)
  - Applications to info appliances and home networks

Related Publications

- RTAS ‘96 - original EMERALDS
- RTAS ‘97 - semaphore optimizations
- NOSSDAV ‘98 - protocol processing optimizations
- SAE ’99 - EMERALDS-OSEK
- SOSP ‘99 - EMERALDS with re-designed services
- RTSS’00 – Energy-aware CSD
- IEEE-TSE’00 –complete version with schedulability analysis
- SOSP’01- Exploitation of DVS
- ACM TECS (pending) - EQoS
- UNSENIX’03, PACS’04: power-aware memory
- SOSP’05: high-performnace, low-power disk I/O
- USENIX’02 – totally non-blocking IPC

URL: http://kabru.eecs.umich.edu/rtos