RTEMS-SMP Improvement for LEON multi-core

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- TO: M. Verhoef / T. Tsiodras

RTEMS SMP - Ready for Launch

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Overview

Topics of this Presentation

- What is RTEMS?
- Overall RTEMS features
- Some RTEMS SMP details

What is RTEMS?

Real-Time Operating System for Multiprocessor Systems (RTEMS)

- Operating system
- Multi-threaded
- Single address-space
- No kernel-space/user-space separation
- Real-time
- Permissive open source license (GPLv2 with linking exception, no obligations for application code)

RTEMS History

- 1988 RTEMS development started by On-Line Applications Research Corporation (OAR)
  - Classic real-time operating system
  - $O(1)$ priority scheduler
  - Non-transitive priority inheritance
  - Priority ceiling
- 2008 EDISOFT tailors RTEMS 4.8.0 now used in over 20 missions, qualified to DAL-B
- 2009 Astrium uses of tailored RTEMS 4.6.1 for space applications
- 2014 Start of Symmetric Multiprocessing (SMP) support development
  - Sponsored by ESA with two parallel projects Gaisler/Airbus/OAR and SpaceBel/EB/UoP
  - Other RTEMS users
- 2017 State-the-Art SMP support available as a result of this project (RTEMS 4.12)
  - System initialization via constructors
  - Scalable timer/timer support
  - Giant lock removal
  - OMIP implementation

RTEMS Features - SMP Platforms

SMP Platforms

- SPARC
  - GR712RC
  - GR740
- PowerPC
  - QorIQ (e.g. P1020, P2020, T2080, T4240, etc.)
- ARMv7-A
  - Altera Cyclone V
  - Xilinx Zynq
  - Raspberry Pi 2
- Other (ARMv8, RISC-V, x86) - just ask for support

RTEMS Features - APIs

APIs

- Classic
- POSIX (pthreads)
- C11 threads
- C++11 threads
- Newlib and GCC internal
- Futex (synchronization via user-space atomic operations combined with futex system calls)

A broad range of standard software runs on RTEMS

RTEMS Features - Programming Languages/Compiler

Programming Languages

- C/C++/OpenMP (RTEMS Source Builder, RSB)
- Ada (RSB, –with-ada)
- Google Go
- Fortran (RSB, –with-fortran)
- Erlang
- Python and MicroPython

Available Compiler

- GCC (default, best supported and recommended)
- LLVM/clang (works, but currently not available via RSB)
- Other (not out of the box)

RTEMS Features - Devices

Devices

- Termios (serial interfaces)
- I2C (Linux user-space API compatible)
- SPI (Linux user-space API compatible)
- Network stacks (legacy, libbsd, lwIP)
- USB stack (libbsd)
- SD/MMC card stack (libbsd)
- Framebuffer (Linux user-space API compatible, Qt)

libbsd

- Port of FreeBSD user-space and kernel-space components to RTEMS
- Easy access to FreeBSD software for RTEMS
- Support to stay in synchronization with FreeBSD

RTEMS Features - Basic Infrastructure

Basic Infrastructure

- C11/C++11 thread-local storage
- Lock-free timestamps (FreeBSD timecounters)
- Scalable timer and timeout support
- Link-time configuration (RTEMS is a library)
- System initialization via constructors (linker sets, similar to global C++ constructors)

RTEMS Features - Schedulers and Locking Protocols

Clustered Scheduling

- Independent scheduler instances for processor subsets (cache topology)
- Flexible link-time configuration
- Fixed-priority scheduler
- Job-level fixed-priority scheduler (EDF)

Locking Protocols for Mutual Exclusion

- Transitive priority inheritance
- $O(m)$ Independence-Preserving Protocol (OMIP)
- Priority ceiling
- Multiprocessor Resource-Sharing Protocol (MrsP)

What is new?

Symmetric Multiprocessing (SMP) Support for RTEMS

SMP machines consist of a set of processors (players) attached to a common memory (field).

The operating system provides means to ensure fair play.

Why use SMP?

Solve same problem faster - Amdahl's law

$$Speedup(n) = \frac{1}{(1-p) + \frac{p}{n}}$$

Solve larger problem in the same time - Gustafsons's law

$$Speedup(n) = 1 - p + np$$

Special case: Space and Time Partitioning (TSP)

No reason for SMP

Simplify application development – you use SMP since you must

RTEMS SMP Details

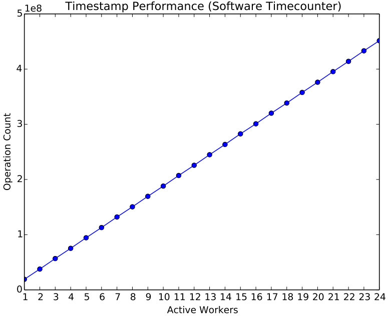
Topics

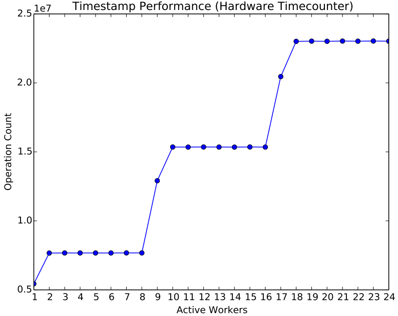
- Timestamps
- Timer/Timeout Support
- System Initialization
- Clustered Scheduling
- Locking Protocols

Plot Data: Testsuite Results

All plots are generated (Python Matplotlib) from data obtained by standard RTEMS testsuite resuls (XML).

Lock-Free Timestamps






```
void worker(void)
{
  while (true) {
    timestamp();
  }
}
```

- Timestamps for uptime and wall clock time
- Port of FreeBSD Timecounters
- Time synchronization via NTP and PPS possible
- Timestamp performance obtained by *SPTIMECOUNTER 2* test program
- Example platform QorIQ T4240 running at 1.5*GHz*
- With software timecounter approximately 79 processor cycles per timestamp

Timer/Timeout Support

Timer

Perform an action at a certain time in the future. Timer usually expire.

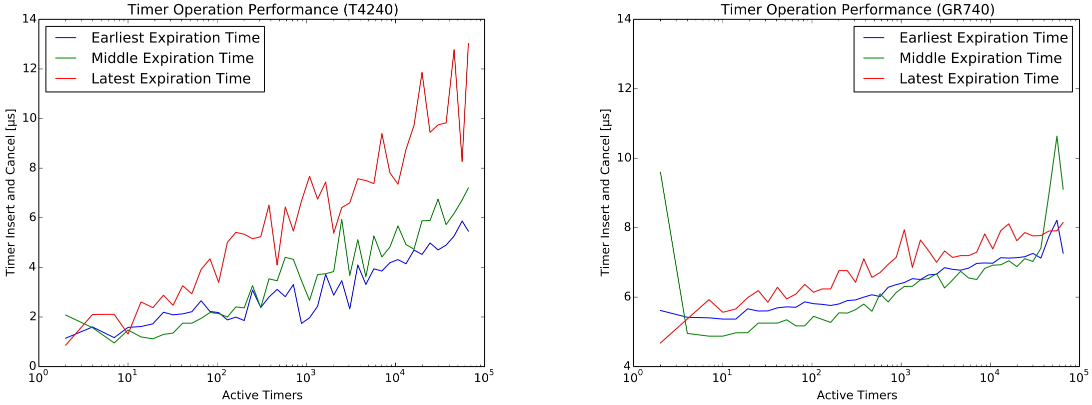
Timeouts

Set time limits to actions. Timeouts hopefully expire rarely.

Timer/Timeout Implementations

- Priority queues (expiration time as key), e.g. red-black tree
  - $O(log(n))$ insert and cancel operations (n active timer count)
  - $O(m \cdot log(n))$ expire operation (m count of timer to expire)
  - Used by RTEMS
- Timer wheel (hash table)
  - $O(1)$ insert and cancel operations
  - Unpredictable expiration operation runtime
  - Used by network stack

Timer Support - Scalable with Active Timer Count



- Timer implementation based on red-black trees
- Timer performance obtained by *TMTIMER 1* test program
- Example platform QorIQ T4240 running at 1.5*GHz* (left)
- Example platform GR740 running at 250*MHz* (right)

Timer Support - Scalable with Processor Count

Per-Processor Timer Maintenance

- Each processor has its own data set to maintain timers
- Thread operation timeouts use current processor
- Timer use dedicated processor set during timer creation

System Initialization via Constructors (1)

Standard System Initialization without Constructors

```
void system_init(void)
{
  init_subsystem_a();
  init_subsystem_b();
  init_subsystem_c();
  init_subsystem_d();
  init_subsystem_e();
}
```

Disadvantage

In case a subsystem is not required by the application, it is still initialized

System Initialization via Constructors (2)

System Initialization via Constructors

```
void system_init(void)
{
  constructor *c = constructor_begin;

  while (c != constructor_end) {
    (*c->init)();
    ++c;
  }
}
```

Subsystem X

```
void subsystem_x_init(void)
{
  /* Some init stuff */
}

REGISTER_CONSTRUCTOR(subsystem_x_init, ORDER_X);
```

Advantage

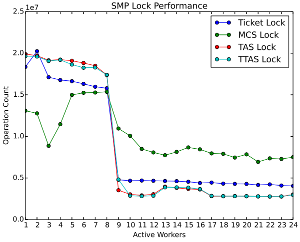
Only subsystems used by the application are initialized and present in the executable

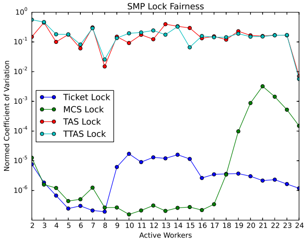
Disadvantage

Requires linker and object file format support

Used by major software systems, e.g. C++, Linux, FreeBSD, etc.

Low-Level Synchronization - SMP Locks



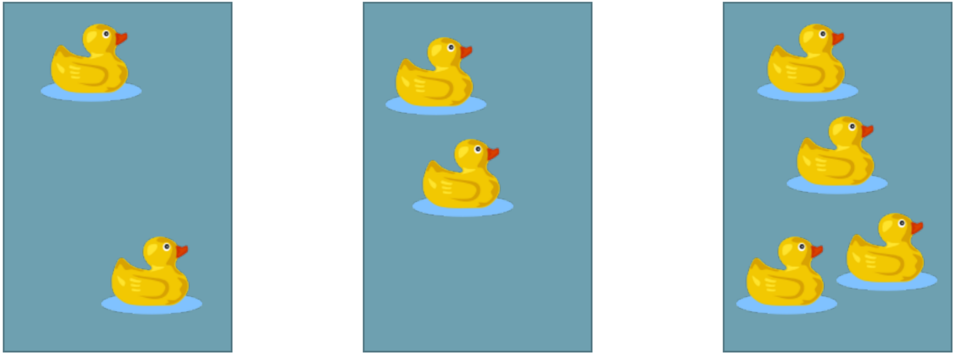


- Several options exist for low-level synchronization in SMP systems
- Test-and-set (TAS)
- Test and test-and-set locks (TTAS)
- Ticket locks
- Mellor-Crummey Scott (MCS) locks
- SMP lock performance obtained by *SMPLOCK 1* test program
- Example platform QorIQ T4240 running at 1.5GHz

Basic Requirement: FIFO Fairness

Ticket lock was selected as standard SMP lock for RTEMS SMP

Clustered Scheduling (1)



Clustered Scheduling

Independent scheduler instances for pair-wise disjoint processor subsets

Clustered Scheduling (2)

Advantages

- Keep worst-case execution time (WCET) under control: SMP lock FIFO fairness ⇒ WCET increases linear with processor count
- Scheduler instances based on cache topology to minimize thread migration overhead (important for priority based schedulers)
- Optimal choice of scheduler algorithms
- Easy implementation compared to schedulers with local run queues and load balancing

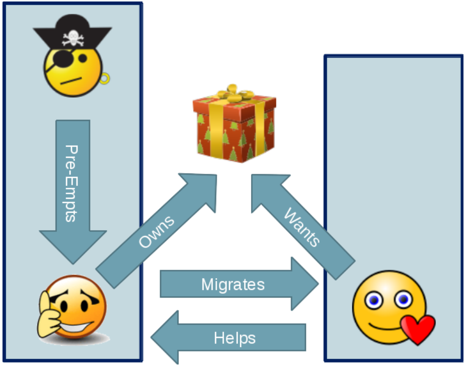
Disadvantage

Thread assignment to scheduler instance is a system design decision (bin-packing problem)

Warning

Priority values of different scheduler instances are not comparable

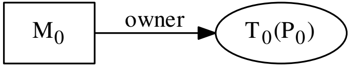
Locking Protocols for Mutual Exclusion (1)



Clustered Scheduling

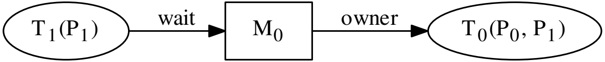
Temporary thread migration is required to minimize latency

Locking Protocols for Mutual Exclusion (2)



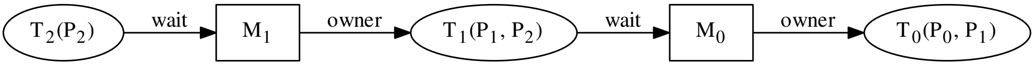
Mutex M_0 with owner thread T_0 (thread priority P_0)

Locking Protocols for Mutual Exclusion (2)



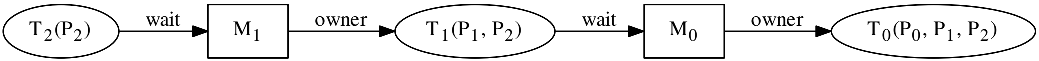
Mutex M_0 with owner thread T_0 and priority inheritance due to waiting thread T_1

Locking Protocols for Mutual Exclusion (2)



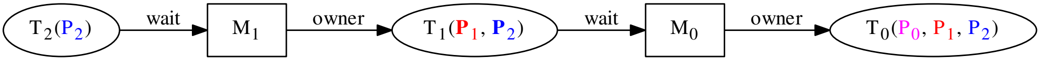
Non-transitive priority inheritance: thread priority P_2 is not propagated to thread T_0

Locking Protocols for Mutual Exclusion (2)



Transitive priority inheritance: thread priority P_2 is propagated to thread T_0 via thread T_1

Locking Protocols for Mutual Exclusion (2)



Transitive priority inheritance and clustered scheduling with three scheduler instances magenta, red and blue

Thread T_0 has access to all three scheduler instances while owning mutex M_0

Implementation Challenge: Fine Grained Locking

Synchonization objects, threads and schedulers have dedicated SMP locks.

Locking Protocols for Mutual Exclusion (3)

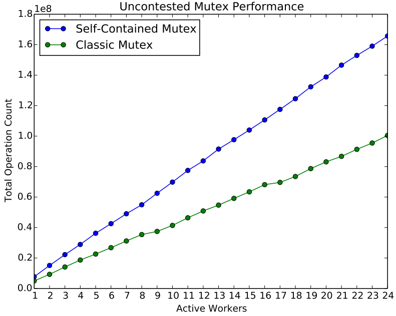
$O(m)$ Independence-Preserving Protocol (OMIP)

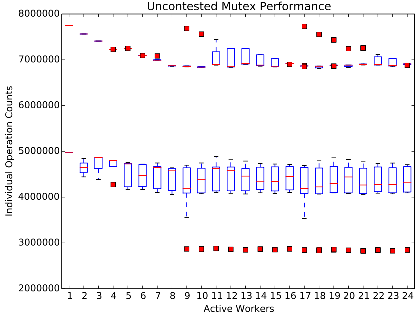
- Generalization of transitive priority inheritance to clustered scheduling
- Suitable for general purpose libraries

Multiprocessor Resource-Sharing Protocol (MrsP)

- Generalization of priority ceiling to clustered scheduling
- User must specify ceiling priorities per scheduler instance
- Protocol design had schedulability analysis in mind

Fine Grained Locking





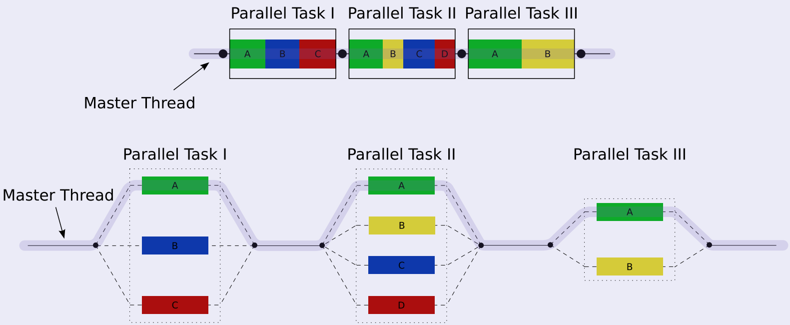

```
void worker(void)
{
  mutex mtx;

  while (true) {
    mtx.acquire();
    mtx.release();
  }
}
```

- Each synchronization object (mutex, message queue, counting semaphore, etc.) has its own SMP lock
- Very important for average case performance
- Mutex performance obtained by *TMFINE 1* test program
- Example platform QorIQ T4240 running at 1.5*GHz*
- Classic API objects are subject to false cache line sharing

OpenMP

- Compiler supported parallelization using a fork-join model



- OpenMP 4.5 support via GCC provided libgomp
- Highly optimized RTEMS configuration of libgomp
- Uses barrier implementation of Linux based on futex system call

Embedded Multicore Building Blocks (EMB^2)/MTAPI

EMB^2

- Set of C/C++ libraries providing:
  - Task management
  - Dataflow
  - Algorithms
  - Containers
- Initially designed for embedded systems
- 2-clause BSD license
- Developed and used by Siemens
- Fully supported by RTEMS

Multicore Task Management API (MTAPI)

- Open source reference implementation contained in the EMB^2
- Custom implementation available from Gaisler

Status and Future Work

Status

- RTEMS SMP is the result of test driven development (RTEMS testsuite contains more than 600 test programs)
- RTEMS 4.12 release is planned for Q2-Q3 2017
- RTEMS SMP is available on the GR712RC and GR740
- Used on Altera Cyclone V, Xilinx Zynq and QorIQ T4240 in production systems

Next Step

Space qualification according to ECSS standards (potential GSTP G617-254SW, maybe available in 2019).

Questions?