Embedded Systems: An Application-Centered Approach

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Introduction

- Real-Time Operating Systems are often used in embedded systems
- They simplify use of hardware, ease management of multiple tasks, and adhere to real-time constraints
- Power is important in many embedded systems with RTOSs
- RTOSs can consume significant amount of power
- They are re-used in many embedded systems
- They impact power consumed by application software
- RTOS power effects influence system-level design

Real-time operating systems (RTOS)

- Interaction between HW and SW
  - Rapid response to interrupts
  - HW interface abstraction
- Interaction between different tasks
  - Communication
  - Synchronization
- Multitasking
  - Ideally fully preemptive
  - Priority-based scheduling
  - Fast context switching
  - Support for real-time clock

General-purpose OS stress

- Good average-case behavior
- Providing many services
- Support for a large number of hardware devices

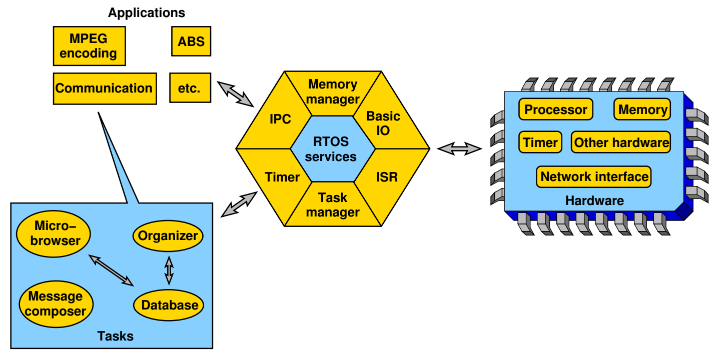
RTOSs stress

- Predictable service execution times
- Predictable scheduling
- Good worst-case behavior
- Low memory usage
- Speed
- Simplicity

Predictability

- General-purpose computer architecture focuses on average-case
  - Caches
  - Prefetching
  - Speculative execution
- Real-time embedded systems need predictability
  - Disabling or locking caches is common
  - Careful evaluation of worst-case is essential
  - Specialized or static memory management common

RTOS overview



RTOS power consumption

- Used in several low-power embedded systems
- Need for RTOS power analysis
  - Significant power consumption
  - Impacts application software power
  - Re-used across several applications

RTOS and real-time references

- K. Ramamritham and J. Stankovic. Scheduling algorithms and operating systems support for real-time systems.
  Proc. IEEE, 82(1):55–67, January 1994
- Giorgio C. Buttazzo. *Hard Real-Time Computing Systems.*
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Prior work

- Vivek Tiwari, Sharad Malik, and Andrew Wolfe. Compilation techniques for low energy: An overview.
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Embedded OS power references I

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  In *Proc. Int. Wkshp. on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, pages 96–103, August 2000.
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Embedded OS power references II

- A Shye, B Scholbrock, and G Memik. Into the wild: studing real user activity patterns to guide power optimizations for mobile architectures.
  In *Proc. Int. Symp. on Microarchitecture*, pages 168–178, 2009.
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Embedded OS power references III

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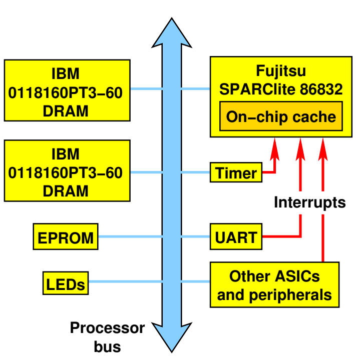
RTOS power references

- K. Baynes, C. Collins, E. Fiterman, B. Ganesh, P. Kohout, C. Smit, T. Zhang, and B. Jacob. The performance and energy consumption of three embedded real-time operating systems.
  In *Proc. Int. Conf. Compilers, Architecture & Synthesis for Embedded Systems*, pages 203–210, November 2001
- T.-K. Tan, A. Raghunathan, and Niraj K. Jha. EMSIM: An energy simulation framework for an embedded operating system.
  In *Proc. Int. Symp. Circuits & Systems*, pages 464–467, May 2002

Contributions

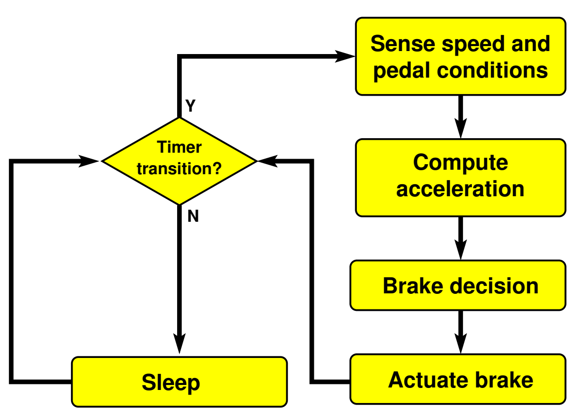
- First detailed power analysis of RTOS
  - Proof of concept later used by others
- Applications
  - Low-power RTOS
  - Energy-efficient software architecture
  - Incorporate RTOS effects in system design

Simulated embedded system

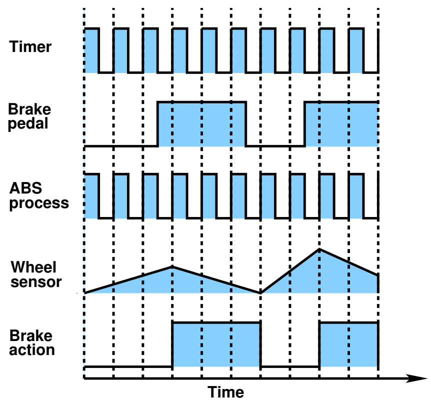


- Easy to add new devices
- Cycle-accurate model
- Fujitsu board support library used in model
- μC/OS-II RTOS used

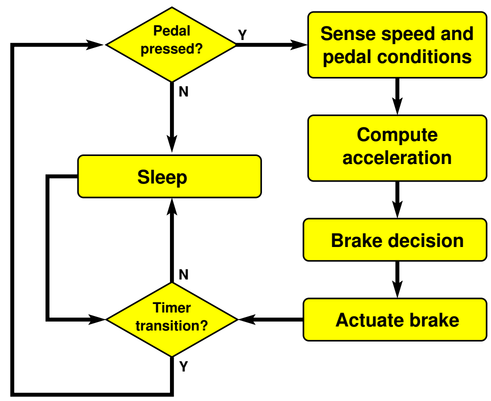
Periodically triggered ABS



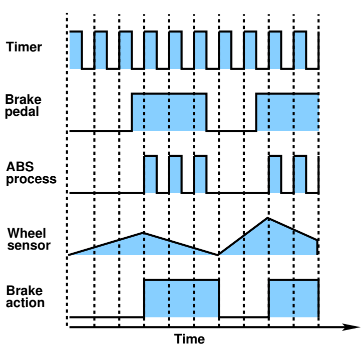
Periodically triggered ABS timing



Selectively triggered ABS

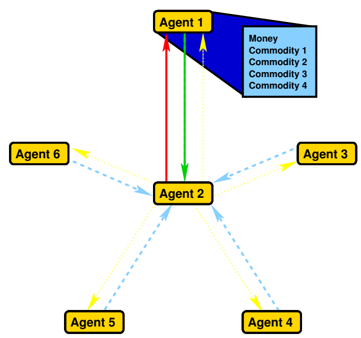


Selectively triggered ABS timing



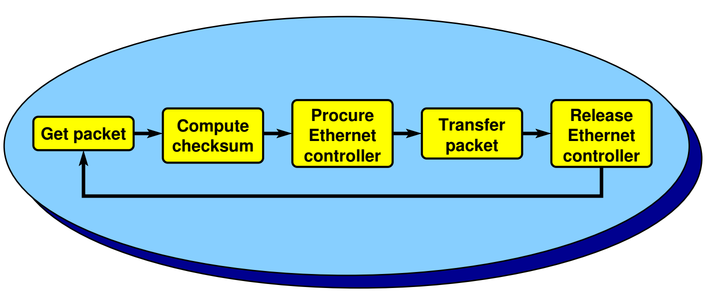
63% reduction in energy and power consumption

Agent example



- Advertise
- Bid
- Offer
- Transfer results

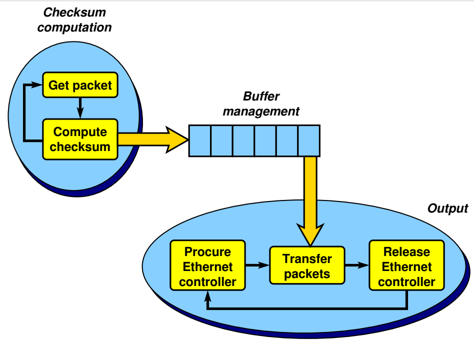
Single task network interface



Checksum computation and output

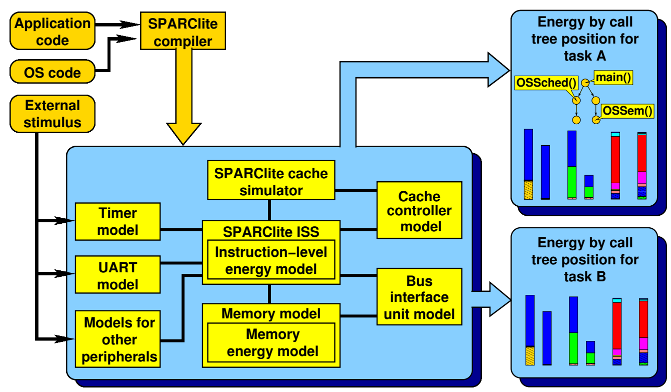
Procuring Ethernet controller has high energy cost

Multi-tasking network interface

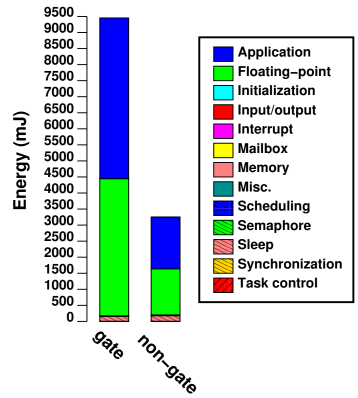


RTOS power analysis suggests process re-organization.
21% reduction in energy consumption. Similar power consumption.

Infrastructure

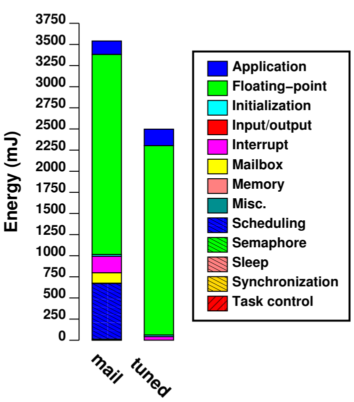


ABS optimization effects



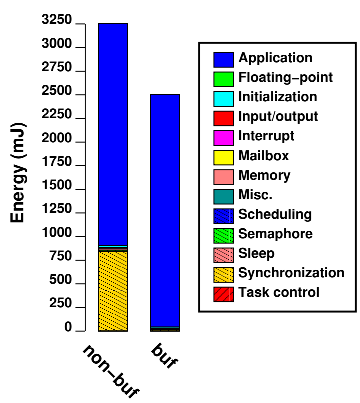
- Redesigned application after using simulator to locate areas where power was wasted
- 63% energy reduction
- 63% power reduction
- RTOS directly accounted for 50% of system energy

Agent optimization effects



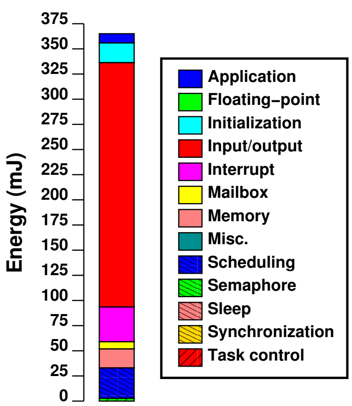
- Mail version used RTOS mailboxes for information transmission
- Tuned version carefully hand-tuned to used shared memory
- Power can be reduced at a cost
  - Increased application software complexity
  - Decreased flexibility

Ethernet optimization effects



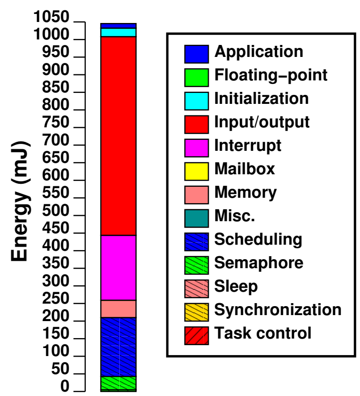
- Determined that synchronization routine cost was high
  - Used RTOS buffering to amortize synchronization costs
- 20.5% energy reduction
- 0.2% power reduction
- RTOS directly accounted for 1% of system energy
  - Energy savings due to improved RTOS use, not reduced RTOS energy

Mailbox example



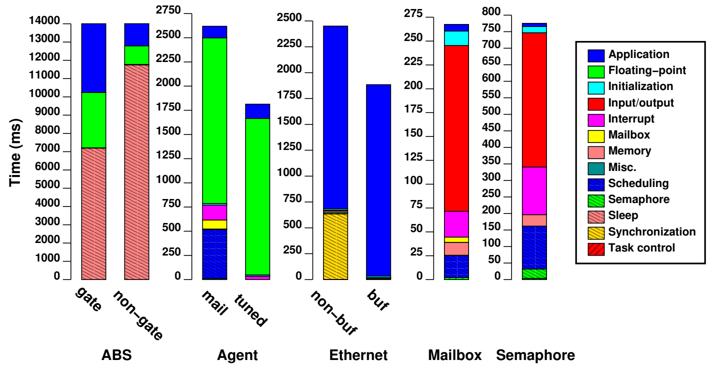
- Rapid mailbox communication between tasks
- RTOS directly accounted for 99% of system energy

Semaphore example



- Semaphores used for task synchronization
- RTOS directly accounted for 98.7% of system energy

Time results



Energy bounds

Service	Minimum energy (µJ)	Maximum energy (µJ)
AgentTask	3.41	4727.88
fptodp	17.46	49.72
BSPInit	3.52	3.52
fstat	16.34	16.34
CPUInit	287.15	287.15
fstat_r	31.26	31.26
GetPsr	0.38	0.55
init_bss	2.86	3.07
GetTbr	0.40	0.53
init_data	4.23	4.37
InitTimer	2.53	2.53
init_timer	18012.10	20347.00
OSCtxSw	46.63	65.65
init_tvecs	1.31	1.31
OSDisableInt	0.84	1.31
...	...	...

Semaphore example hierarchical call tree

		Function	Energy(µJ)/invocation	Energy (%)	Time (ms)	Calls
realstart 25.40 mJ total 2.43 %	init_tvecs		1.31	0.00	0.00	1
	init_timer 18.01 mJ total 1.72 %	liteled	4.26	0.00	0.00	1
	startup 7.39 mJ total 0.71 %	do_main	7363.11	0.70	5.57	1
		save_data	5.08	0.00	0.00	1
		init_data	4.23	0.00	0.00	1
		init_bss	2.86	0.00	0.00	1
		cache_on	8.82	0.00	0.01	1
Task1 508.88 mJ total 48.69 %	win_unf_trap		6.09	1.16	9.43	1999
	OSDisableInt		0.98	0.09	0.82	1000
	OSEnableInt		1.07	0.10	0.92	1000
	OSSemPend 104.59 mJ total 10.01 %	win_unf_trap	6.00	0.57	4.56	999
		OSDisableInt	0.94	0.18	1.56	1999
		OSEnableInt	0.94	0.18	1.56	1999
		OSEventTaskWait	13.07	1.25	9.89	999
		OSSched	66.44	6.35	51.95	999
	OSSemPost 9.82 mJ total 0.94 %	OSDisableInt	0.96	0.09	0.78	1000
		OSEnableInt	0.98	0.09	0.81	1000
	OSTimeGet 4.62 mJ total 0.44 %	OSDisableInt	0.84	0.08	0.66	1000
		OSEnableInt	0.98	0.09	0.81	1000
	CPUInit 0.29 mJ total 0.03 %	BSPInit	3.52	0.00	0.00	1
		exceptionHandler	15.51	0.02	0.17	15
	printf 368.07 mJ total 35.22 %	win_unf_trap	6.18	0.59	4.87	1000
		vfprintf	355.04	33.97	257.55	1000

Example power-efficient change to RTOS

- Small changes can greatly improve RTOS power consumption
- µC/OS-II tracks processor loading by incrementing a counter when idle
- However, this is not a good low-power design decision
- NOPs have lower power than add or increment instructions
- Sleep mode has *much* lower power
- Can disable loading counter and use NOPs or sleep mode

Example power-efficient change to RTOS

- Alternatively, can use timer-based sampling
  - Normally NOP or sleep when idle
  - Wake up on timer ticks
  - Sample highest non-timer ISR task
  - If it's the idle task, increment a counter
  - Can dramatically reduce power consumption without losing functionality

RTOS Conclusions

- Demonstrated that RTOS significantly impacts power
- RTOS power analysis can improve application software design
- Applications
  - Low-power RTOS design
  - Energy-efficient software architecture
  - Consider RTOS effects during system design

Reference

Kaushik Ghosh, Bodhisattwa Mukherjee, and Karsten Schwan. A survey of real-time operating systems.
Technical report, College of Computing, Georgia Institute of Technology, February 1994

What to do by Friday

- Have 30 customer interviews logged.
- State validated hypotheses.
- Update product definition.
- Update design description.
- Select project number.
- Order parts.
- Schedule project review meeting with me.