Introduction to Real-Time Systems

ECE 397-1

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Homework index

Goals for lecture

- Lab four
- Example scheduling algorithm design problem
  - Will initially focus on static scheduling
- Real-time operating systems
- Comparison of on-line and off-line scheduling code

Lab four

- Talk with Promi SD101
- Sample sound at 3 kHz
- Multihop

Example problem: Static scheduling

- What is an FPGA?
- Why should real-time systems designers care about them?
- Multiprocessor static scheduling
- No preemption
- No overhead for subsequent execution of tasks of same type
- High cost to change task type
- Scheduling algorithm?

Problem: Uniprocessor independent task scheduling

- Problem
    - Independent tasks
    - Each has a period = hard deadline
    - Zero-cost preemption
- How to solve?

Rate monotonic scheduling

Main idea

- 1973, Liu and Layland derived optimal scheduling algorithm(s) for this problem
- Schedule the job with the smallest period (period = deadline) first
- Analyzed worst-case behavior on any task set of size n
- Found utilization bound: $U(n) = n \cdot (2^{1/n} - 1)$
- 0.828 at $n = 2$
- As $n \to \infty$, $U(n) \to \log 2 = 0.693$
- Result: For any problem instance, if a valid schedule is possible, the processor need never spend more than 71% of its time idle

Optimality and utilization for limited case

- Simply periodic: All task periods are integer multiples of all lesser task periods
- In this case, RMS/DMS optimal with utilization 1
- However, this case rare in practice
- Remains feasible, with decreased utilization bound, for in-phase tasks with arbitrary periods

Rate monotonic scheduling

- Constrained problem definition
- Over-allocation often results
- However, in practice utilization of 85%–90% common
  - Lose guarantee
- If phases known, can prove by generating instance

Critical instants

Main idea:

> A job's critical instant a time at which all possible concurrent higher-priority jobs are also simultaneously released

Useful because it implies latest finish time

Proof sketch for RMS utilization bound

- Consider case in which no period exceeds twice the shortest period
- Find a pathological case
  - Utilization of 1 for some duration
  - Any decrease in period/deadline of longest-period task will cause deadline violations
  - Any increase in execution time will cause deadline violations

RMS worst-case utilization

- In-phase
- $\forall_{k \text{ s.t. } 1 \leq k \leq n-1} : e_k = p_{k+1} - p_k$
- $e_n = p_n - 2 \cdot \sum_{k=1}^{n-1} e_k$

Proof sketch for RMS utilization bound

- See if there is a way to increase utilization while meeting all deadlines
- Increase execution time of high-priority task
  - $e_i' = p_{i+1} - p_i + \varepsilon = e_i + \varepsilon$
- Must compensate by decreasing another execution time
- This always results in decreased utilization
  - $e_k' = e_k - \varepsilon$
  - $U' - U = \frac{e_i'}{p_i} + \frac{e_k'}{p_k} - \frac{e_i}{p_i} - \frac{e_k}{p_k} = \frac{\varepsilon}{p_i} - \frac{\varepsilon}{p_k}$
  - Note that $p_i < p_k \rightarrow U' > U$

Proof sketch for RMS utilization bound

- Same true if execution time of high-priority task reduced
- $e_i'' = p_{i+1} - p_i - \varepsilon$
- In this case, must increase other e or leave idle for $2 \cdot \varepsilon$
- $e_k'' = e_k + 2\varepsilon$
- $U'' - U = \frac{2\varepsilon}{p_k} - \frac{\varepsilon}{p_i}$
- Again, $p_k < 2 \rightarrow U'' > U$
- Sum over execution time/period ratios

Proof sketch for RMS utilization bound

- Get utilization as a function of adjacent task ratios
- Substitute execution times into $\sum_{k=1}^{n} \frac{e_k}{p_k}$
- Find minimum
- Extend to cases in which $p_n > 2 \cdot p_k$

Notes on RMS

- Other abbreviations exist (RMA)
- DMS better than or equal RMA when deadline $\neq$ period
- Why not use slack-based?
- What happens if resources are under-allocated and a deadline is missed?

Essential features of RTOSs

- Provides real-time scheduling algorithms or primatives
- Bounded execution time for OS services
  - Usually implies preemptive kernel
  - E.g., linux can spend milliseconds handling interrupts, especially disk access

Threads

- Threads vs. processes: Shared vs. unshared resources
- OS impact: Windows vs. Linux
- Hardware impact: MMU

Threads vs. processes

- Threads: Low context switch overhead
- Threads: Sometimes the only real option, depending on hardware
- Processes: Safer, when hardware provides support
- Processes: Can have better performance when IPC limited

Software implementation of schedulers

- TinyOS
- Light-weight threading executive
- μC/OS-II
- Linux
- Static list scheduler

TinyOS

- Most behavior event-driven
- High rate → Livelock
- Research schedulers exist

BD threads

- Brian Dean: Microcontroller hacker
- Simple priority-based thread scheduling executive
- Tiny footprint (fine for AVR)
- Low overhead
- No MMU requirements

μC/OS-II

- Similar to BD threads
- More flexible
- Bigger footprint

Old linux scheduler

- Single run queue
- $\mathcal{O}\left(n\right)$ scheduling operation
- Allows dynamic goodness function

$\mathcal{O}(1)$ scheduler in Linux 2.6

- Written by Ingo Molnar
- Splits run queue into two queues prioritized by goodness
- Requires static goodness function
  - No reliance on running process
- Compatible with preemptible kernel

Real-time linux

- Run linux as process under real-time executive
- Complicated programming model
- RTAI (Real-Time Application Interface) attempts to simplify
  - Colleagues still have problems at $>$ 18 kHz control period

Real-time operating systems

- Embedded vs. real-time
- Dynamic memory allocation
- Schedulers: General-purpose vs. real-time
- Timers and clocks: Relationship with HW

Summary

- Static scheduling
- Example of utilization bound proof
- Introduction to real-time operating systems

Reading assignment

- Read Chapter 12 in J. W. S. Liu, *Real-Time Systems*. Prentice-Hall, Englewood Cliffs, NJ, 2000
- Read K. Ghosh, B. Mukherjee, and K. Schwan, "A survey of real-time operating systems," tech. rep., College of Computing, Georgia Institute of Technology, Feb. 1994

Goals for lecture

- Lab four?
- Lab six
- Simulation of real-time operating systems
- Impact of modern architectural features

Lab four

- Please email or hand in the write-up for lab assignment four
- Problems? See me.
    - Will need everything from lab four working for lab six

Lab six

- Develop priority-based cooperative scheduler for TinyOS that keeps track of the percentage of idle time.
- Develop a tree routing algorithm for the sensor network.
- Send noise, light, and temperature data to a PPC, via the network root.
- Have motes respond to *send audio samples* and *buzz* commands.
- Play back or display this data on PPCs to verify the that the system functions.

Outline

- Introduction
- Role of real-time OS in embedded system
- Related work and contributions
- Examples of energy optimization
- Simulation infrastructure
- Results
- Conclusions

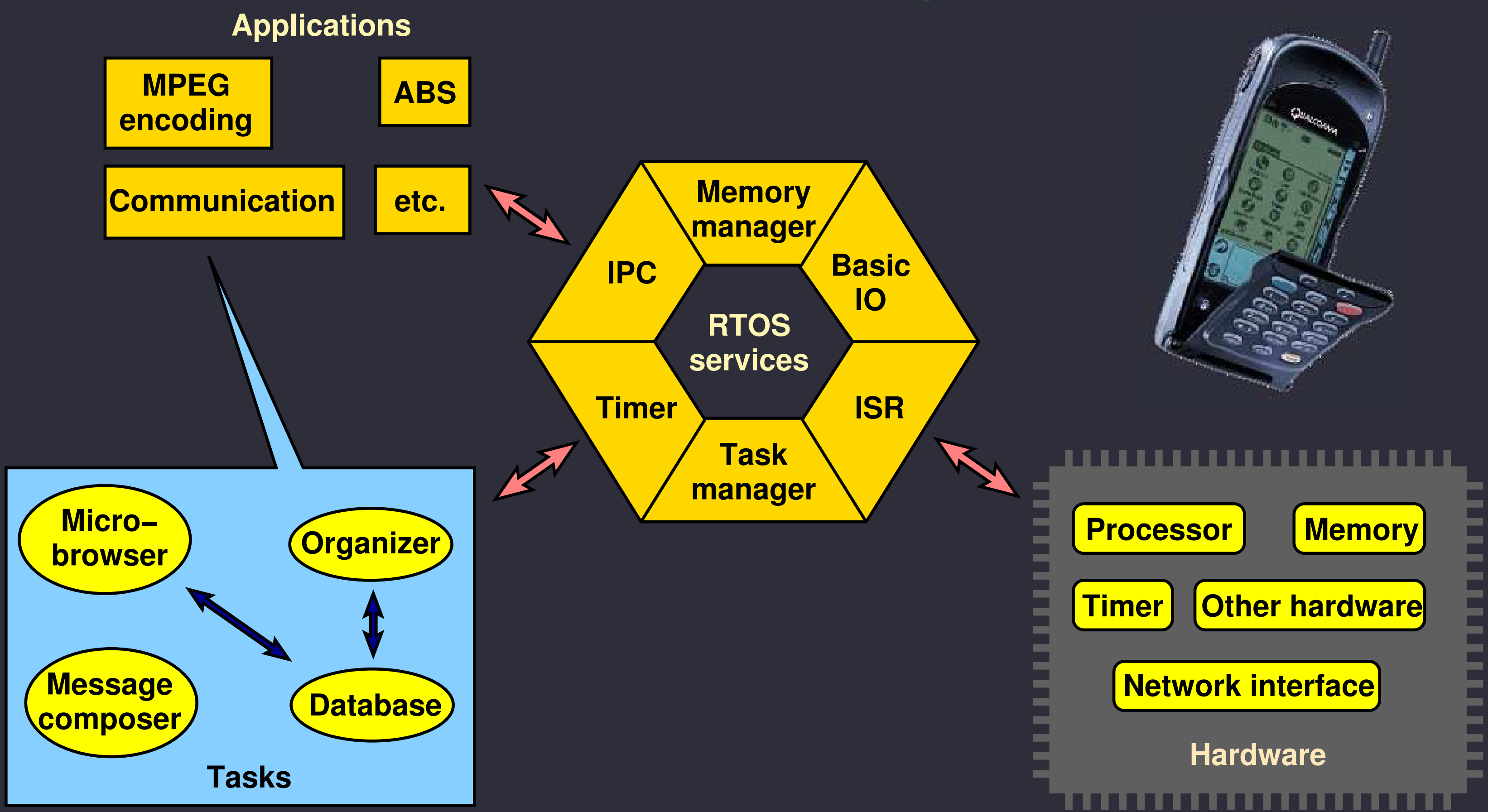
Introduction

- 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.

Introduction

- Real Time Operating Systems important part of embedded systems
  - Abstraction of HW
  - Resource management
  - Meet real-time constraints
- Used in several low-power embedded systems
- Need for RTOS power analysis
  - Significant power consumption
  - Impacts application software power
  - Re-used across several applications

Role of RTOS in embedded system



Applications

MPEG encoding

ABS

Communication

etc.

Micro–browser

Organizer

Message composer

Database

Tasks

Memory manager

IPC

Basic IO

RTOS services

Timer

ISR

Task manager

Processor

Memory

Timer

Other hardware

Network interface

Hardware

Related work and contributions

- **Instruction level power analysis**

  V. Tiwari, S. Malik, A. Wolfe, and T.C. Lee, Int. Conf. VLSI Design, 1996

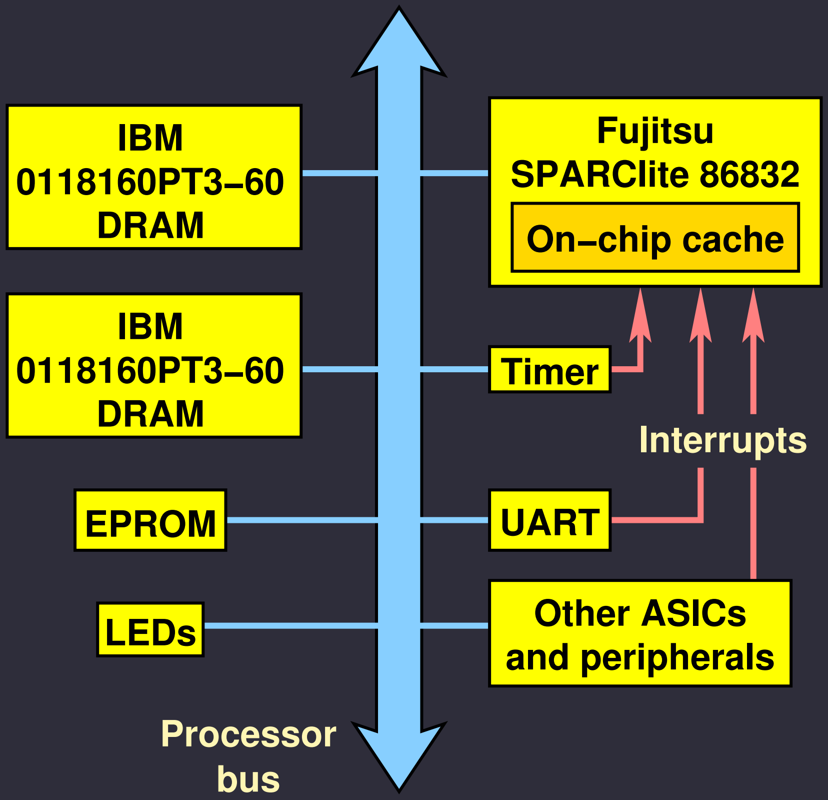
- **System-level power simulation**

  Y. Li and J. Henkel, Design Automation Conf., 1998

- **MicroC/OS-II**: J.J. Labrosse, R & D Books, Lawrence, KS, 1998

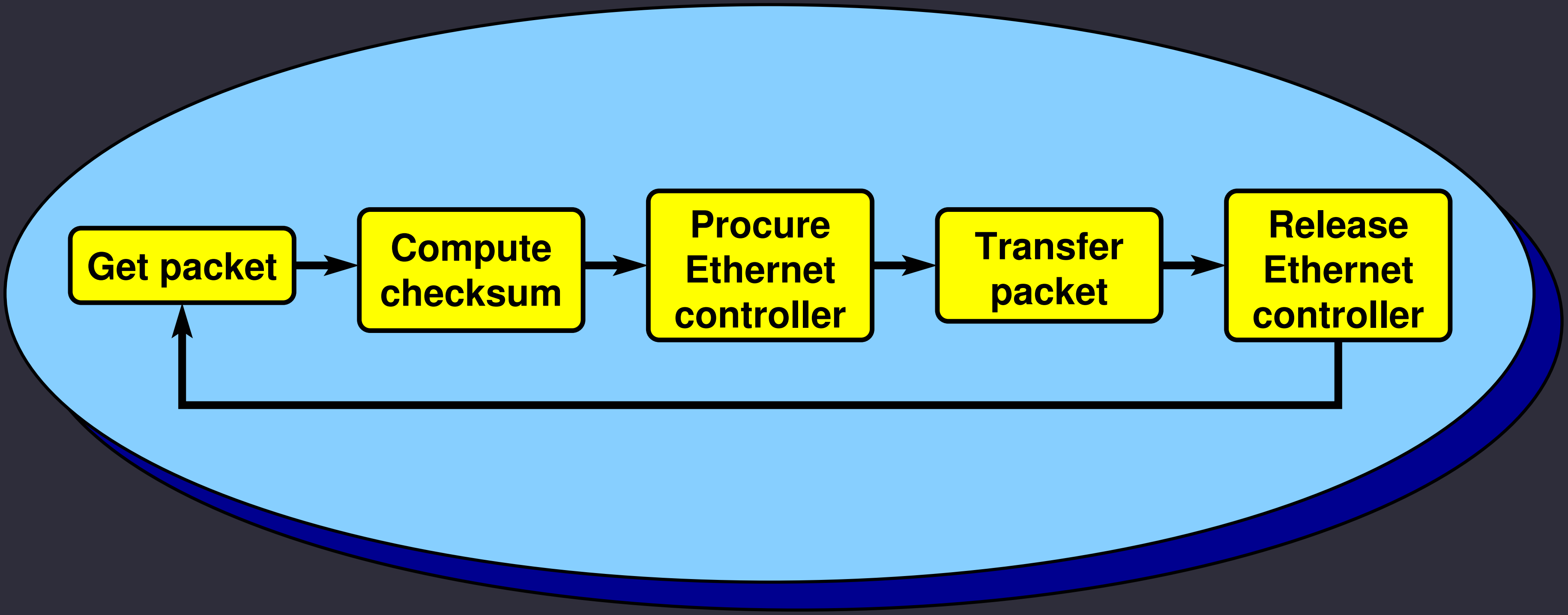
- **Our work**
  - First step towards detailed power analysis of RTOS
  - Applications: low-power RTOS, energy-efficient software architecture, incorporate RTOS effects in system design

Simulated embedded system



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

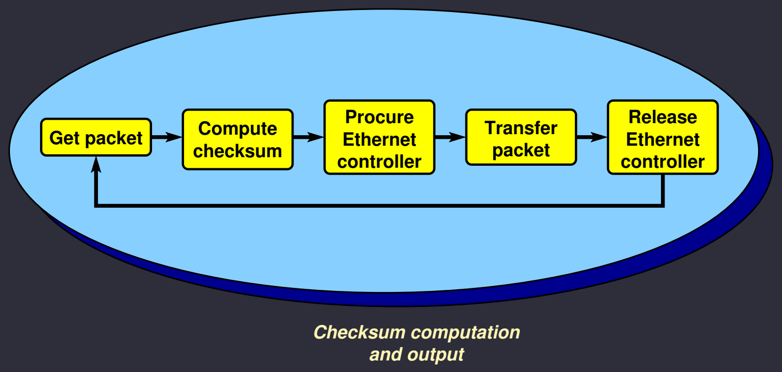
Single task network interface



Checksum computation and output

Procuring Ethernet controller has high energy cost

TCP example



Get packet

Compute checksum

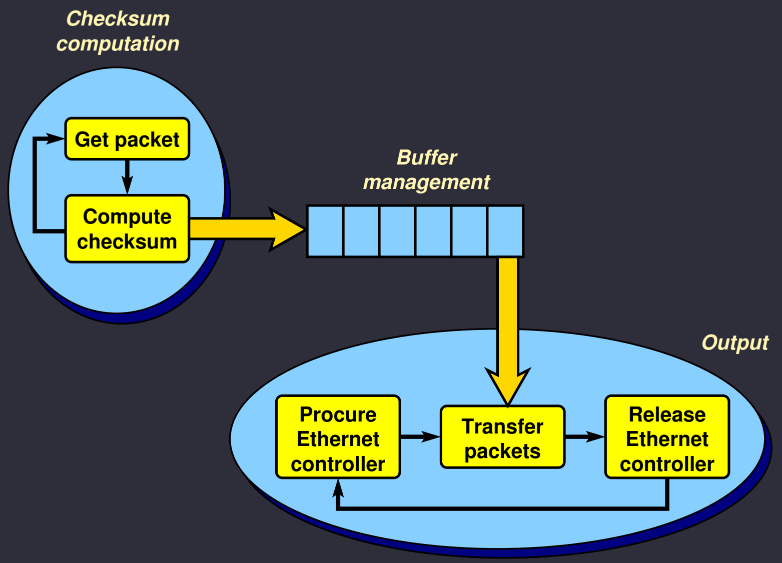
Procure Ethernet controller

Transfer packet

Release Ethernet controller

Checksum computation and output

Straight-forward implementation



Checksum computation

Get packet

Compute checksum

Buffer management

Output

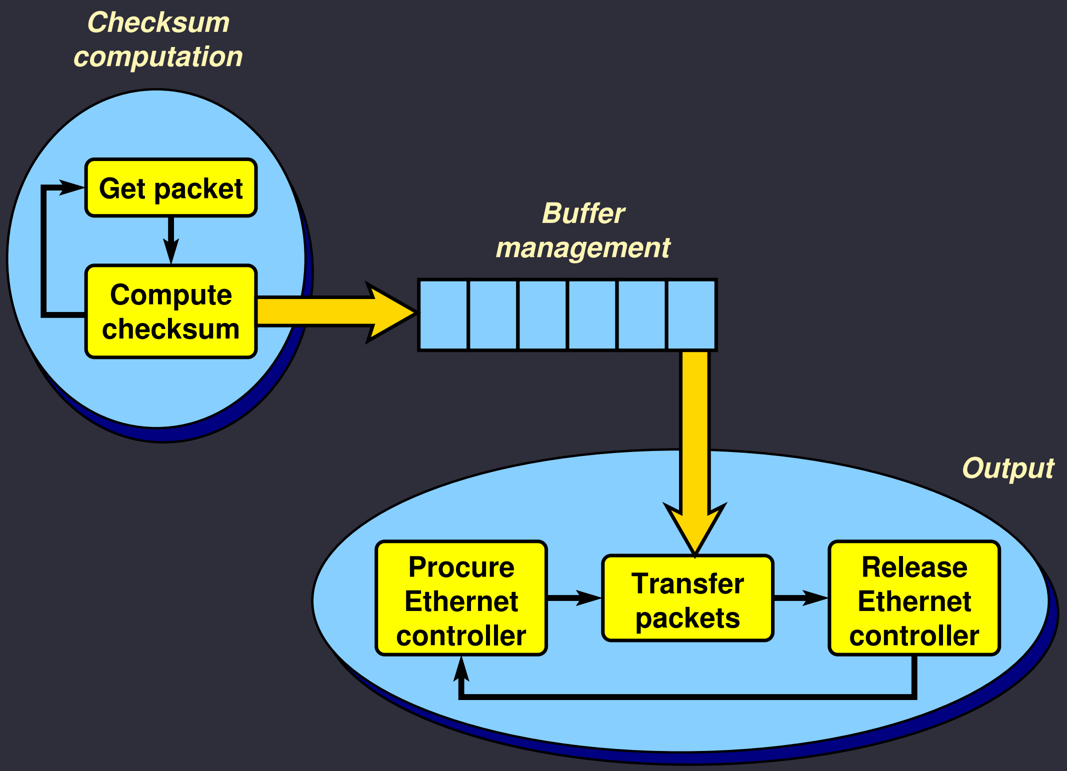
Procure Ethernet controller

Transfer packets

Release Ethernet controller

Multi-task implementation

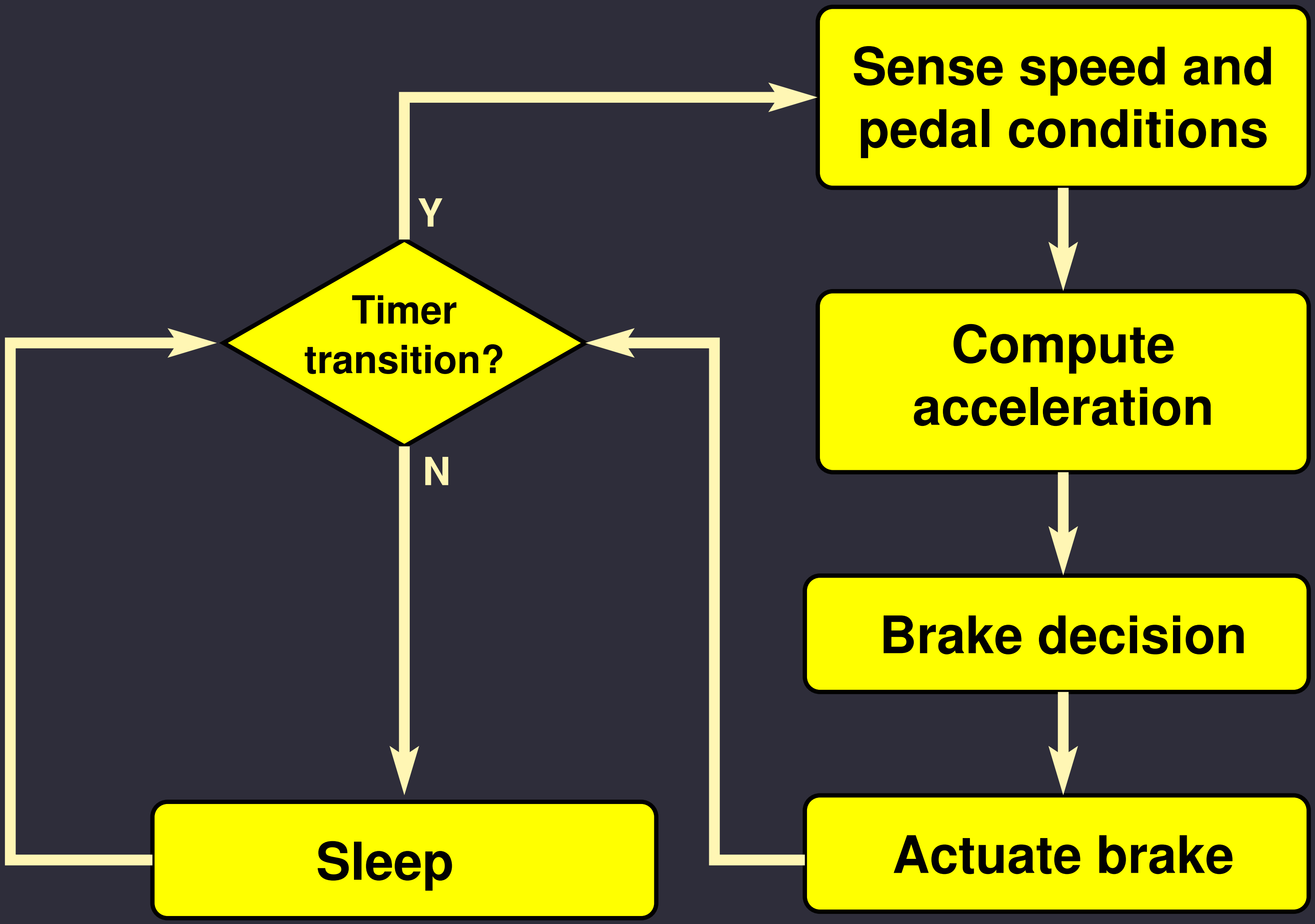
Multi-tasking network interface



RTOS power analysis used for process re-organization to reduce energy

21% reduction in energy consumption. Similar power consumption.

ABS example



Sense speed and pedal conditions

Compute acceleration

Brake decision

Actuate brake

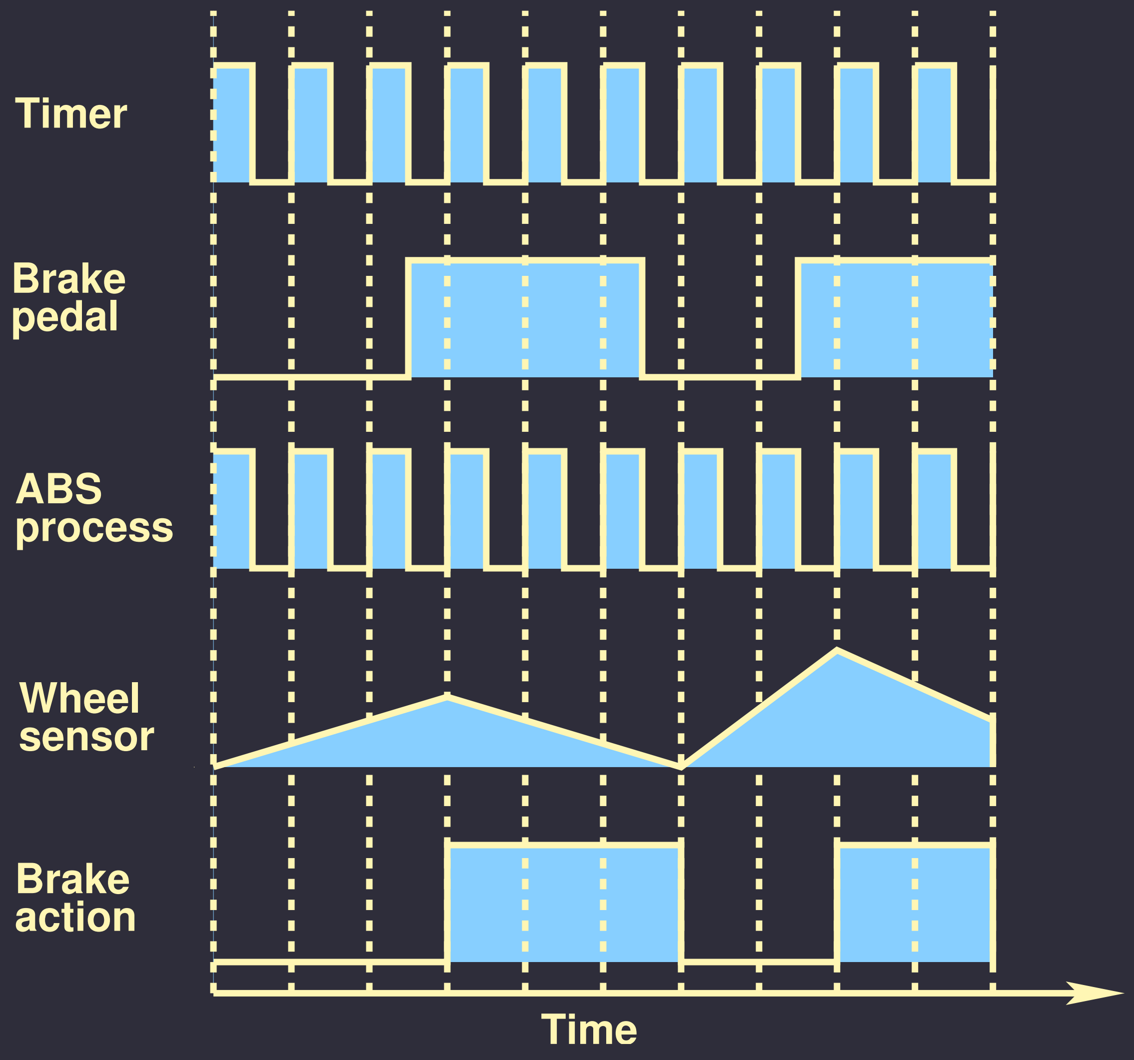
Timer transition?

Y

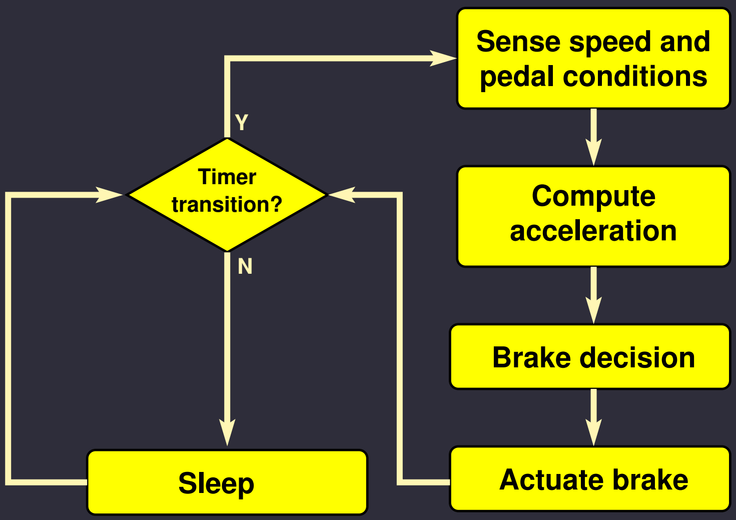
N

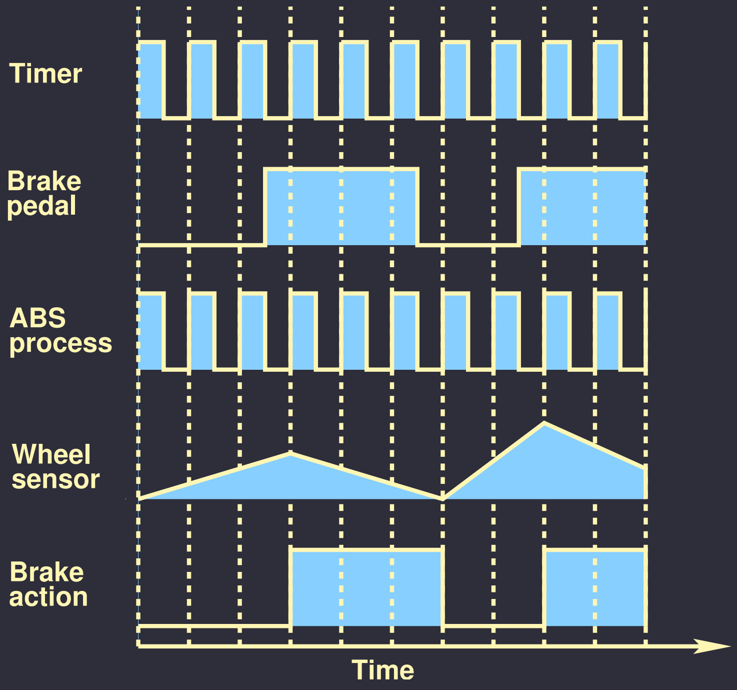
Sleep

ABS example timing

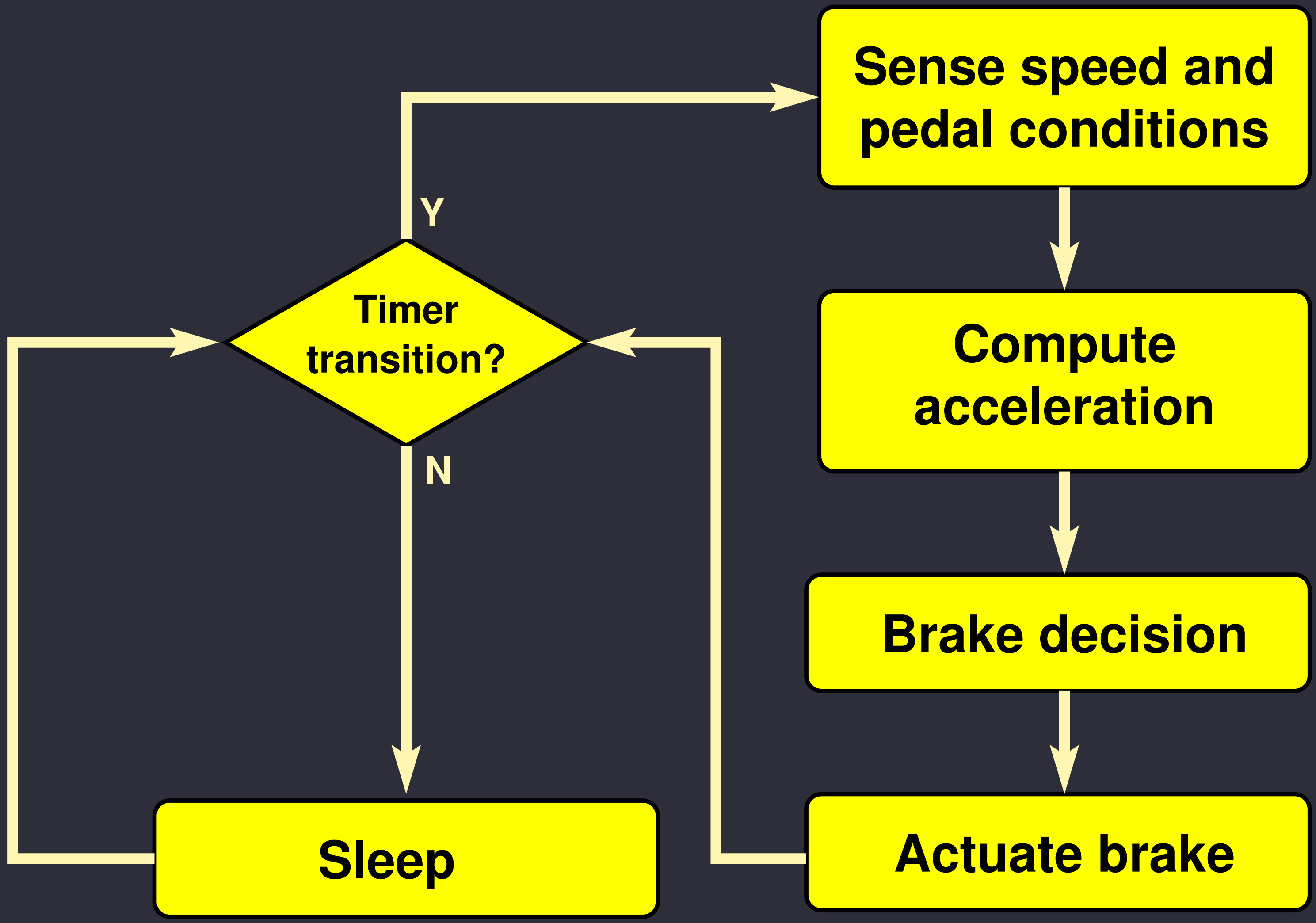


Straight-forward ABS implementation

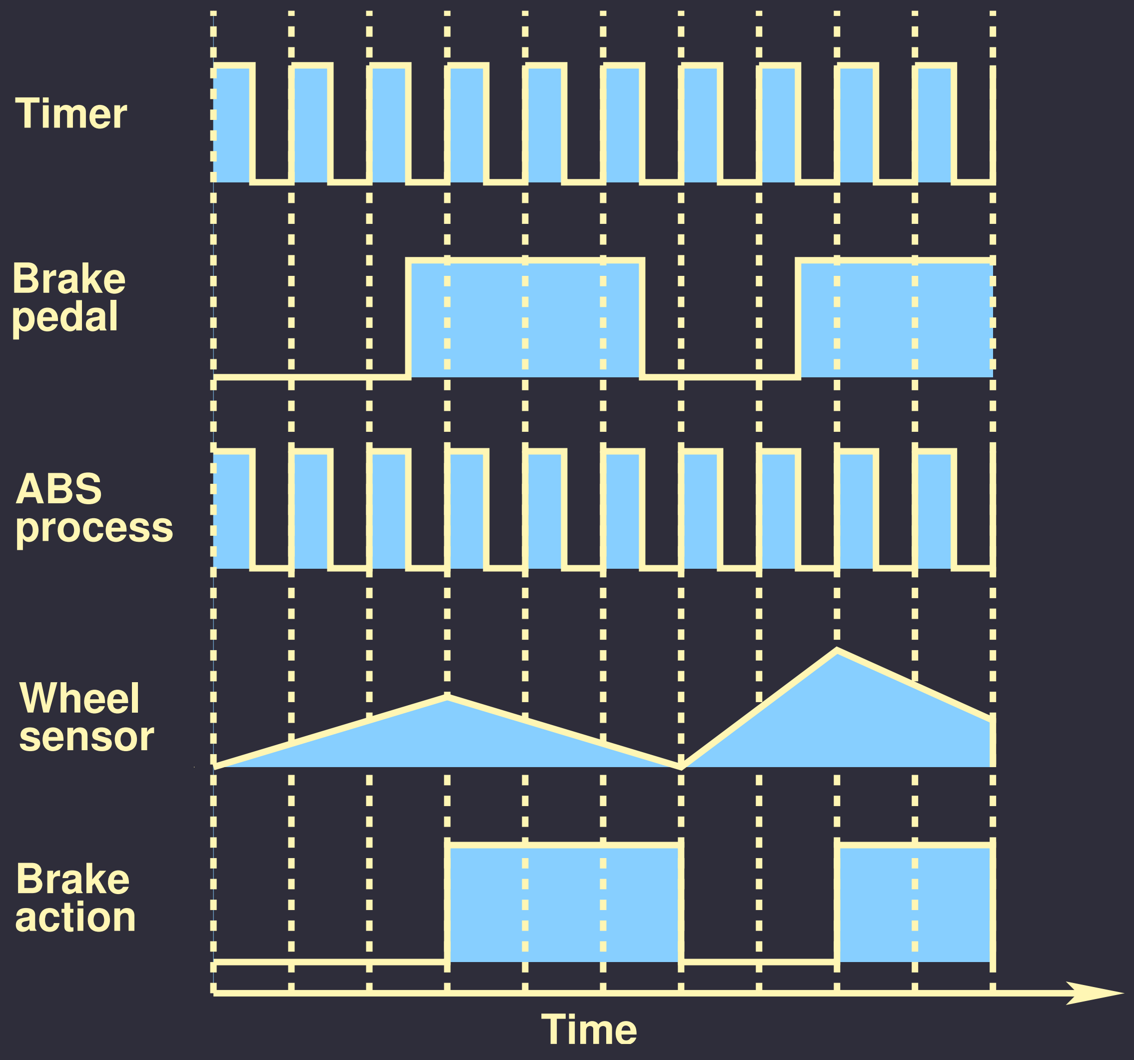




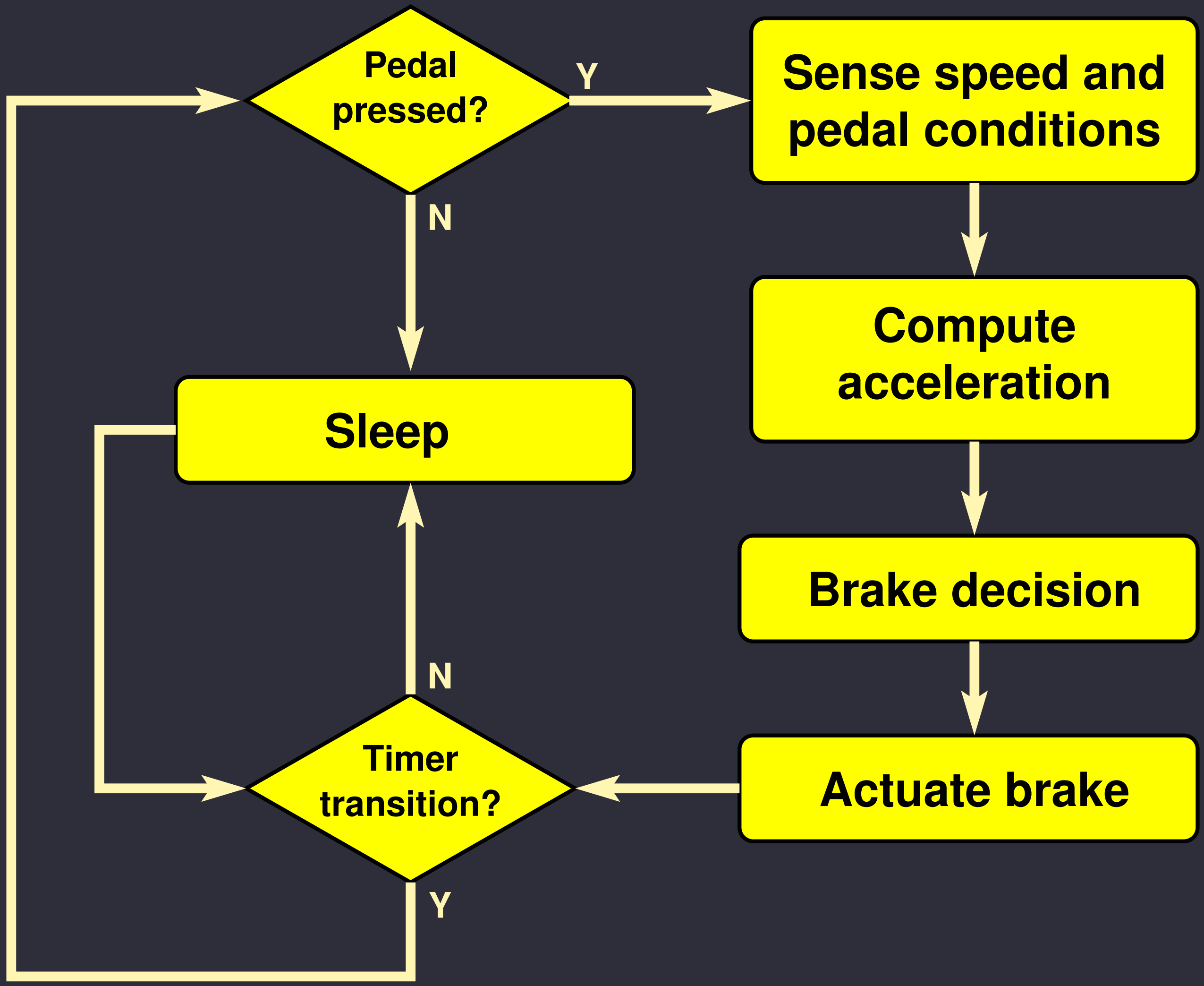
Periodically triggered ABS



Periodically triggered ABS timing



Selectively triggered ABS



Pedal pressed?

Y

N

Sense speed and pedal conditions

Compute acceleration

Brake decision

Actuate brake

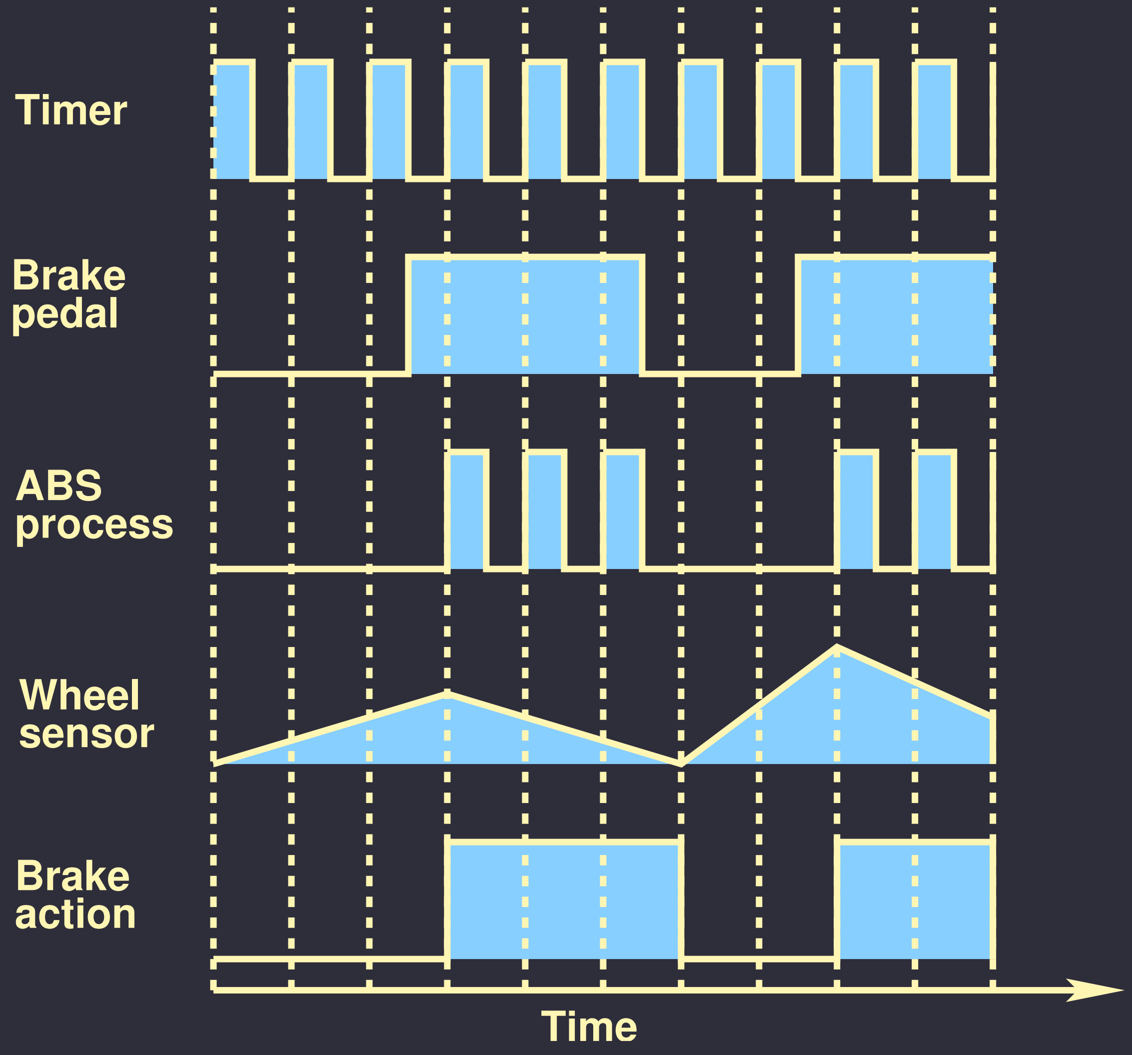
Sleep

Timer transition?

N

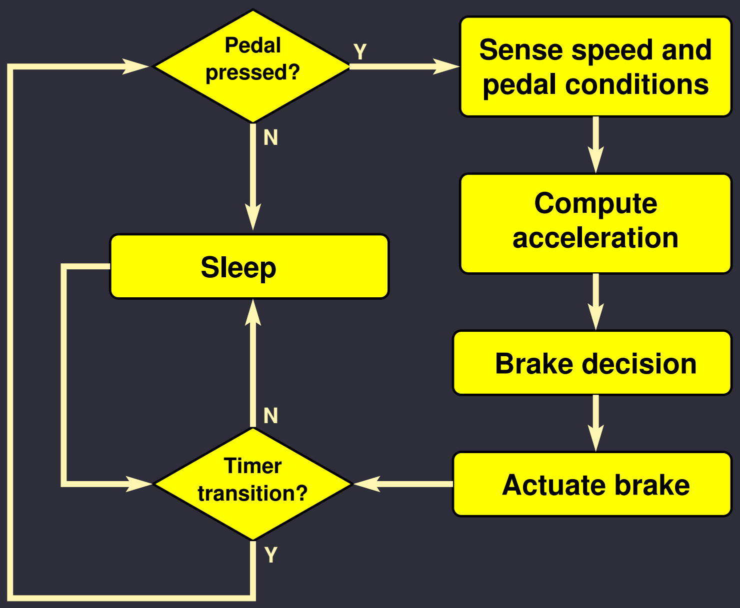
Y

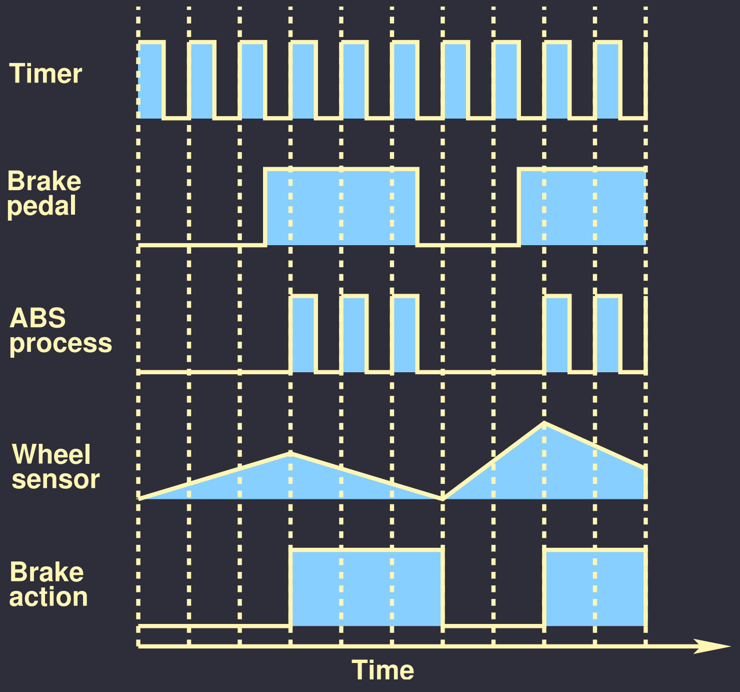
Selectively triggered ABS timing



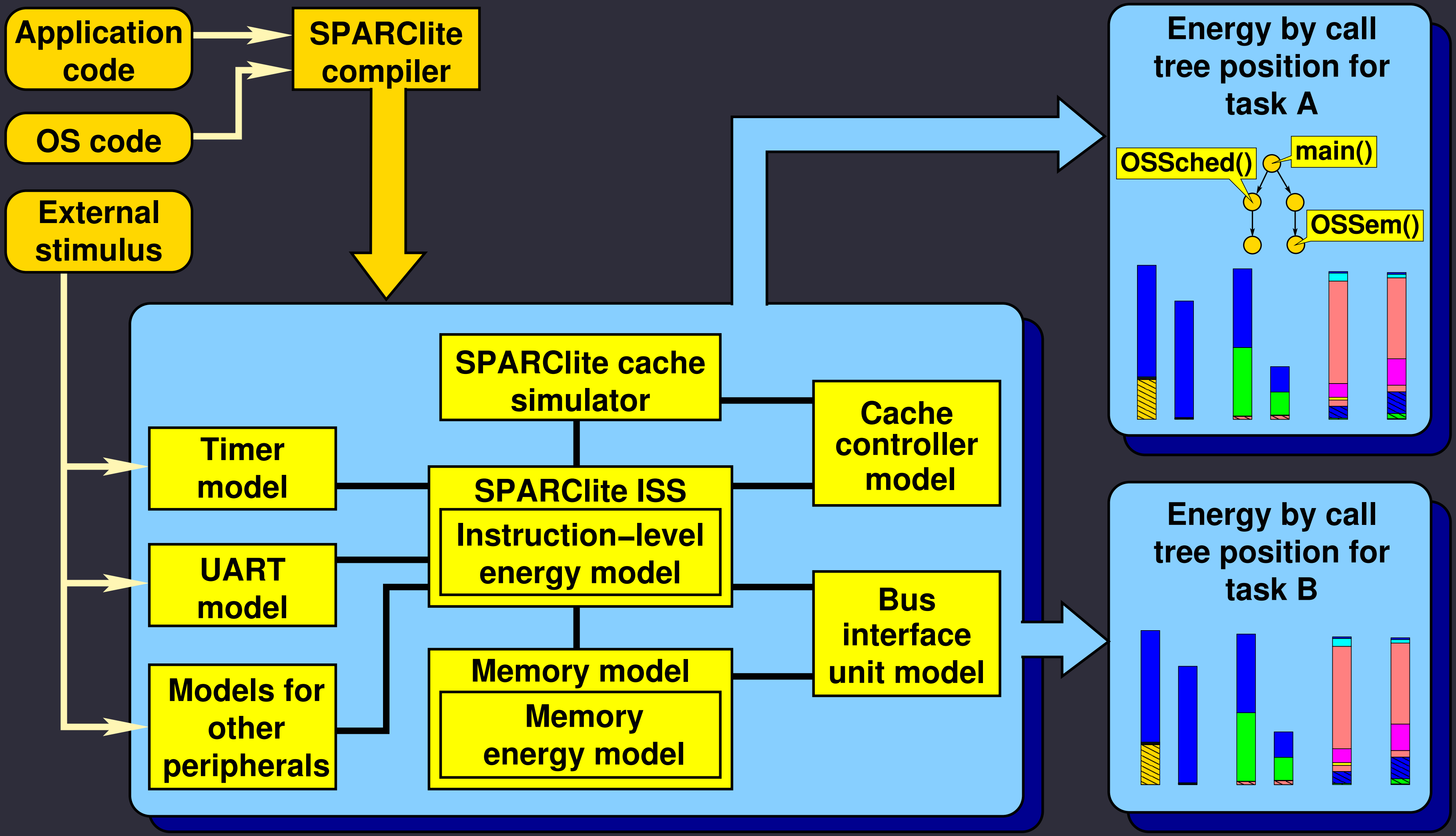
63% reduction in energy and power consumption

Power-optimized ABS example

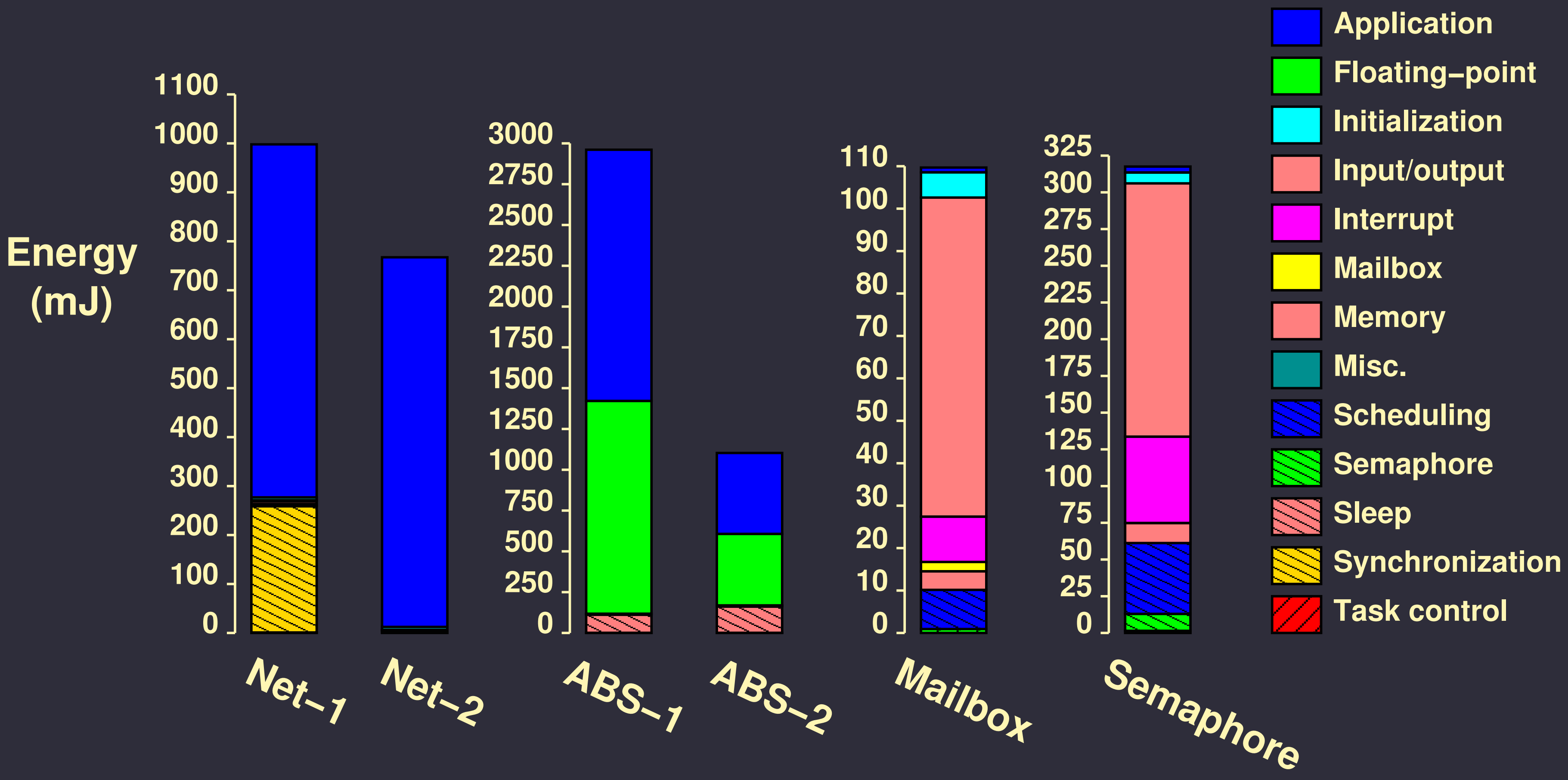




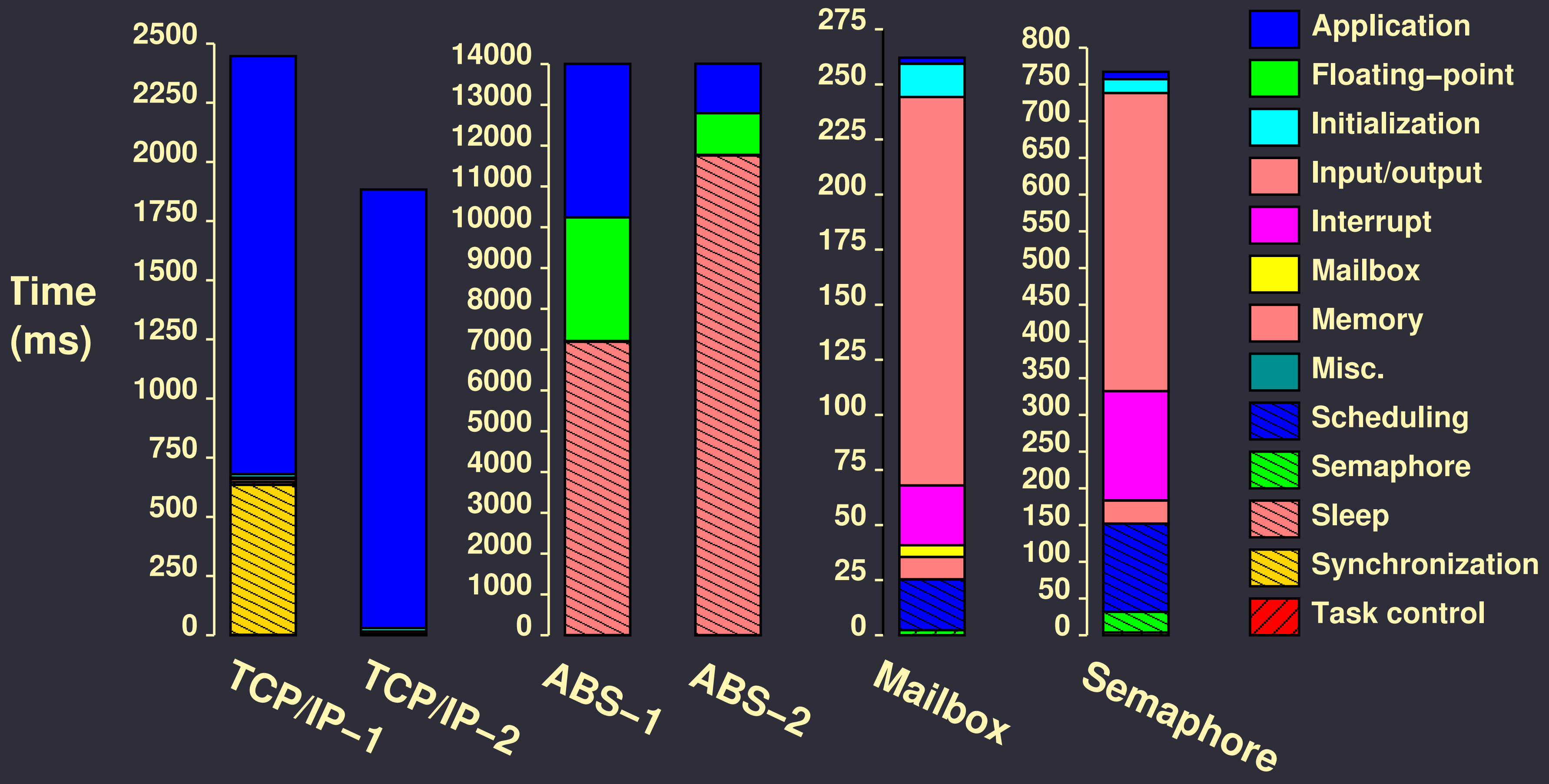
Infrastructure



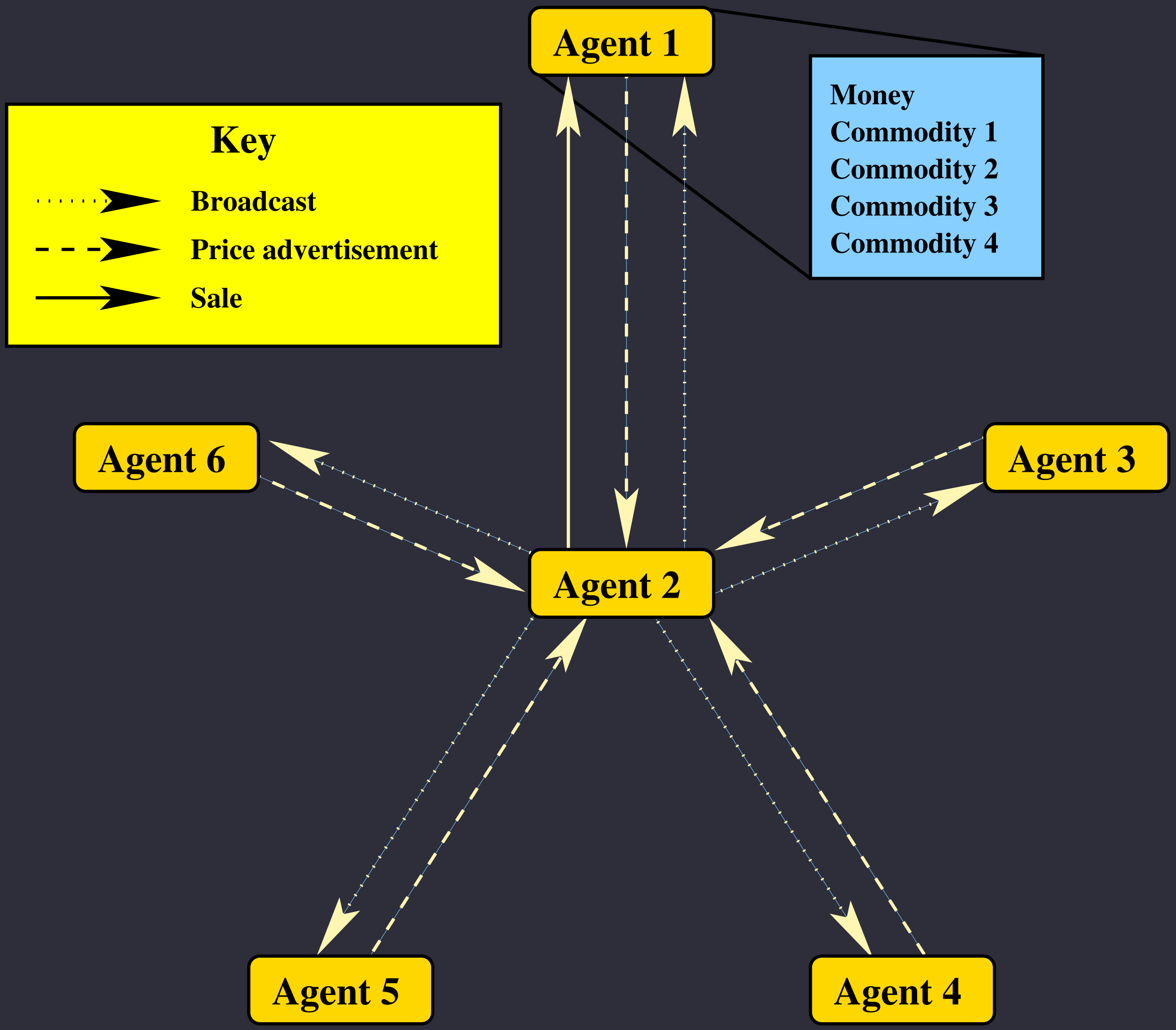
Experimental results



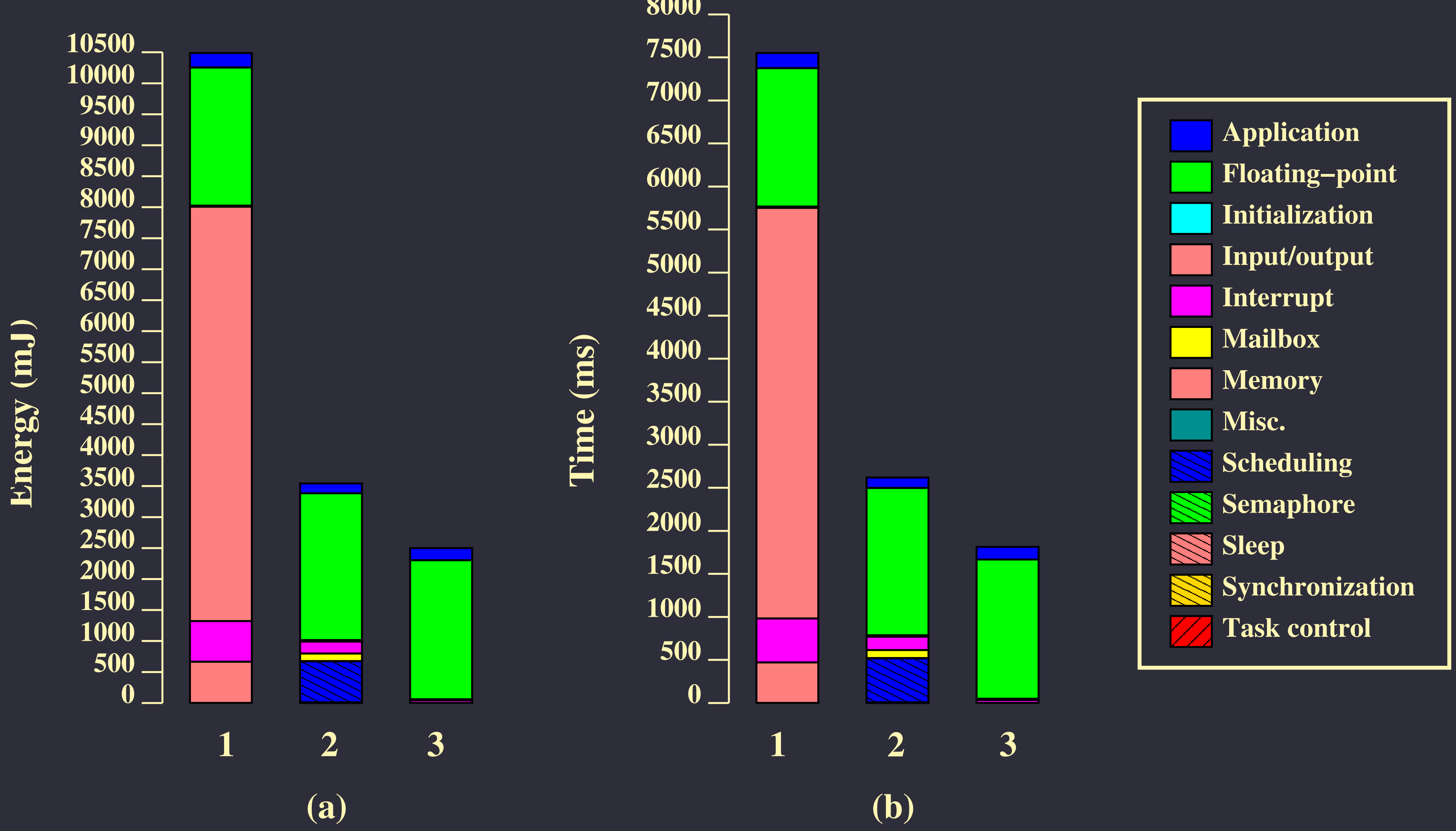
Experimental results – time



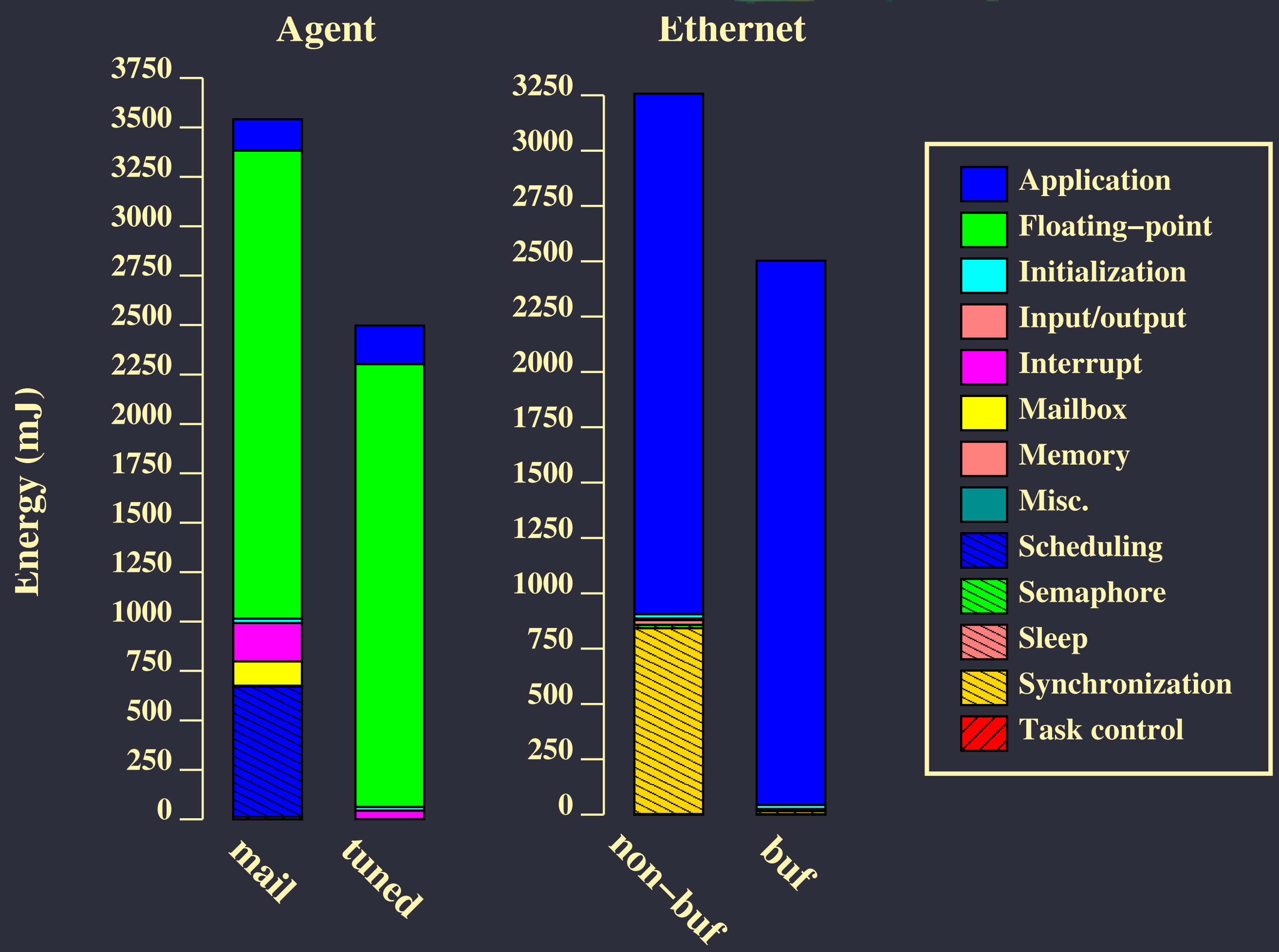
Agent example



Experimental results



Experimental results



(a) (b)

Optimization effects

TCP example:

- 20.5% energy reduction
- 0.2% power reduction
- RTOS directly accounted for 1% of system energy

ABS example:

- 63% energy reduction
- 63% power reduction
- RTOS directly accounted for 50% of system energy

Mailbox example: RTOS directly accounted for 99% of system energy

Semaphore example: RTOS directly accounted for 98.7% of system energy

Partial semaphore hierarchical results

		Function	Energy/invocation (uJ)	Energy (%)	Time (mS)	Calls
realstart 6.41 mJ total 2.02 %	init_tvecs		0.41	0.00	0.00	1
	init_timer 5.51 mJ total 1.74 %	liteled	1.31	0.00	0.00	1
	startup 0.90 mJ total 0.28 %	do_main	887.44	0.28	2.18	1
		save_data	1.56	0.00	0.00	1
		init_data	1.31	0.00	0.00	1
		init_bss	0.88	0.00	0.00	1
		cache_on	2.72	0.00	0.01	1
Task1 155.18 mJ total 48.88 %	win_unf_trap		1.90	1.20	9.73	1999
	_OSDisableInt		0.29	0.09	0.78	1000
	_OSEnableInt		0.32	0.10	0.89	1000
	sparcsim_terminate		0.75	0.00	0.00	1
	OSSemPend 31.18 mJ total 9.82 %	win_unf_trap	2.48	0.78	6.33	999
		_OSDisableInt	0.29	0.18	1.59	1999
		_OSEnableInt	0.29	0.18	1.59	1999
		OSEventTaskWait	3.76	1.18	9.22	999
		OSSched	19.07	6.00	47.97	999
	OSSemPost 2.90 mJ total 0.91 %	_OSDisableInt	0.29	0.09	0.78	1000
		_OSEnableInt	0.29	0.09	0.78	1000
	OSTimeGet 1.43 mJ total 0.45 %	_OSDisableInt	0.27	0.08	0.70	1000
		_OSEnableInt	0.29	0.09	0.78	1000
	CPUInit 0.09 mJ total 0.03 %	BSPInit	1.09	0.00	0.00	1
		exceptionHandler	4.77	0.02	0.17	15
	printf 112.90 mJ total 35.56 %	win_unf_trap	2.05	0.65	5.06	1000
		vfprintf	108.89	34.30	258.53	1000

Energy per invocation for μC/OS-II services

Service	Minimum energy (μJ)	Maximum energy (μJ)
`OSEventTaskRdy`	18.02	20.03
`OSEventTaskWait`	7.98	9.05
`OSEventWaitListInit`	20.43	21.16
`OSInit`	1727.70	1823.26
`OSMboxCreate`	27.51	28.82
`OSMboxPend`	7.07	82.91
`OSMboxPost`	5.82	84.55
`OSMemCreate`	19.40	19.75
`OSMemGet`	6.64	8.22
`OSMemInit`	27.41	27.47
`OSMemPut`	6.38	7.91
`OSQInit`	20.10	20.93
`OSSched`	6.96	52.34
`OSSemCreate`	27.87	29.04
`OSSemPend`	6.54	73.64
etc.	etc.	etc.

Conclusions

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

Impact of modern architectural features

- Memory hierarchy
- Bus protocols ISA vs. PCI
- Pipelining
- Superscalar execution
- SIMD
- VLIW

Summary

- Labs
- Simulation of real-time operating systems
- Impact of modern architectural features