Cooperative I/O
A Novel I/O Semantics for Energy-Aware Applications

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Outline

- A New I/O Semantics
- Power Management of Hard Disks
- Cooperative I/O
- Implementation
- Measurements
- Conclusion

Cooperative I/O: Principle of Operation

- "Traditional" OS power management policies:
  - ◆ times of disk operations issued by user applications are unknown and cannot be influenced
- Cooperative I/O: more flexible timing of disk operations
  - ➜ *deferrable* and *abortable* I/O requests
  - ➜ new system calls (in addition to the original interface)

```
read_coop(int fd, void *buf, size_t count,
          int time-out, int abort);
write_coop(int fd, void *buf, size_t count,
           int time-out, int abort);
open_coop(const char *pathname, int flags,
          int time-out, int abort);
```

  - ➜ the OS can decide when to serve these requests

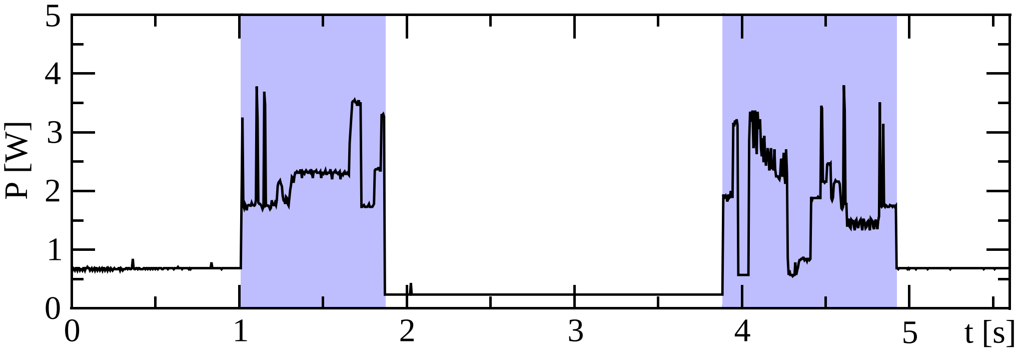
Device States of Hard Disks

- Hard disks support several modes with low power consumption
- Drawback of low-power modes: access delays
- Modes of operation of an IBM Travelstar:

Mode	Properties	Power consumption	Access delay
Active	read and write operations	2.1–4.7 W	—
Idle	entered after I/O operation	1.85 W	—
Low-Power Idle	heads on parking ramp	0.7 W	300 ms
Standby	spindle motor off	0.25 W	1.0–9.5 s
Sleep	(almost) all electronics off	0.1 W	3.0–9.5 s

Mode Transitions

- Mode transitions consume time and energy:
  - parking and positioning of heads
  - spindle motor activation and slow down



- Definition of the *break-even time:*

energy consumption in standby mode
+ transition to standby mode and back = energy consumption in idle mode

Travelstar: break-even time = 8.7 s

Mode Transitions (2)

- No energy savings in standby mode if idle period is too short (< break-even time)
- The OS does not know whether a mode transition will save energy
- Traditional approach of “spin-down policies”:
  - keep track of disk operations
  - try to predict the time of future I/O operations according to the access pattern

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Cooperative I/O

- *Deferrable* and *abortable* I/O requests

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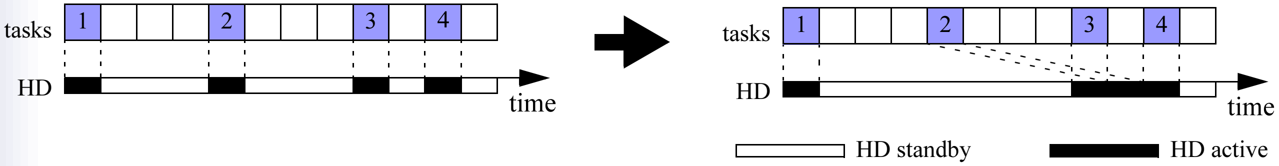
```

- Hard disk in active or idle mode:
  - ◆ deferrable operations are executed immediately
- Hard disk in standby mode:
  - ◆ operations are deferred until hard disk is activated by another process
  - ◆ *or* until user-defined time-out is reached
  - ◆ then: force activation of hard disk or cancel the operation

Cooperative I/O (2)

- Disk operations are clustered/grouped together



- generate long periods of inactivity
- fewer mode transitions
- hard disk can be kept longer in standby mode

- Examples:
  - audio-/video player
  - web browser
  - background processes
  - auto-save

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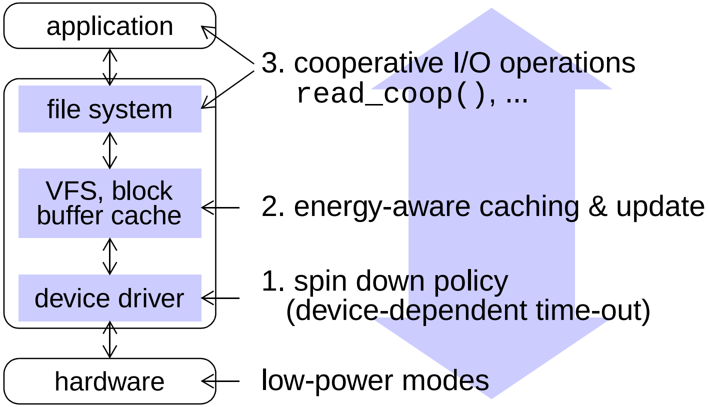
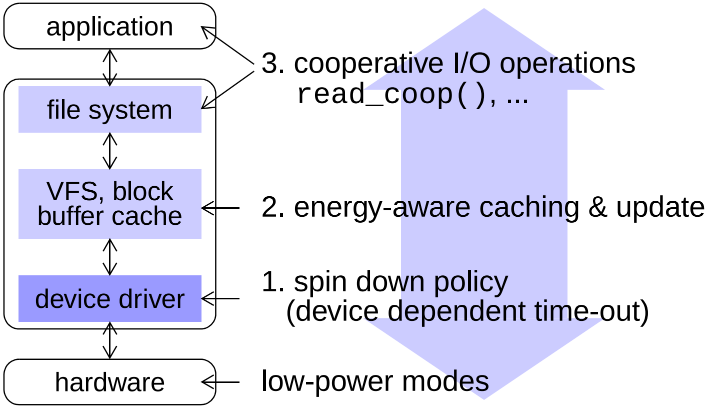
Implementation

- Integration of all layers—from the hardware to the application



- Implementation
  - ◆ Linux Kernel 2.4.19
  - ◆ modifications to the IDE device driver, VFS (block buffer cache and update mechanism) and ext2 file system

Implementation (2)



3. cooperative I/O operations
   `read_coop()`, ...

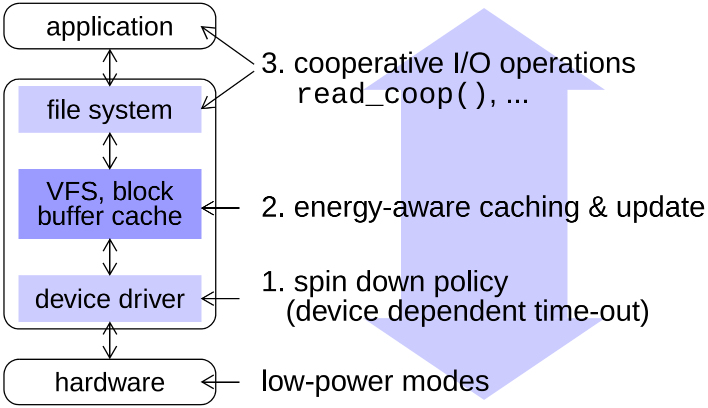
2. energy-aware caching & update

1. spin down policy
   (device dependent time-out)

low-power modes

1. Transition to standby mode if hard disk is idle
   - simple, efficient and proven algorithm:
     Device-Dependent Time-out [Lu, Micheli 2001 (Stanford)]
   - spin down if:
     current time - time of last access > break-even time

Implementation (3)



2. Energy-aware caching & update

➜goal: clustering of disk operations

◆ update writes all “dirty” blocks to disk, independent of their age

◆ updates are attached to other disk accesses

◆ If device driver decides to switch to standby mode, force update before the mode transition

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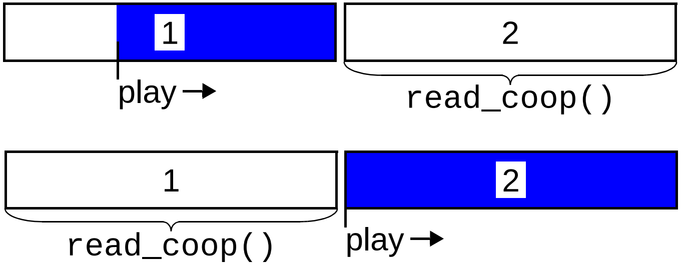
Measurements

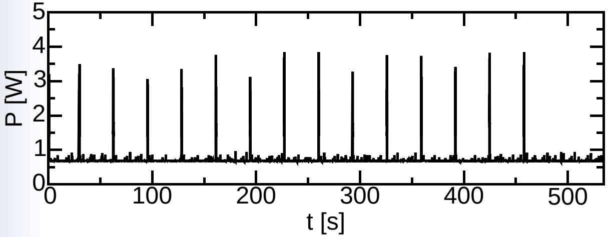
- DAQ system
  - measurement of voltage drop at defined resistors in the 5V supply line of the hard disk
  - resolution: 256 steps; 20000 samples per second
- MP3 player AMP using deferrable `read_coop()` requests
- Player with two read buffers
  - audio data is read from one buffer
  - thread fills other buffer with deferrable read calls.
  - modifications: ~ 150 lines



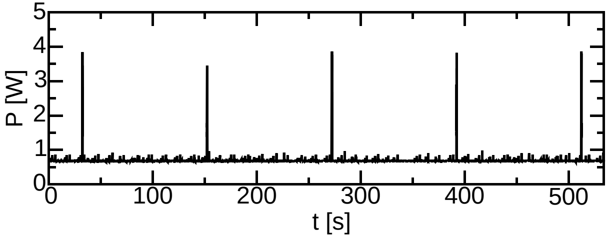
- Mail reader stores new mails in file on hard disk using `write()`

MP3-Player + Mail-Reader

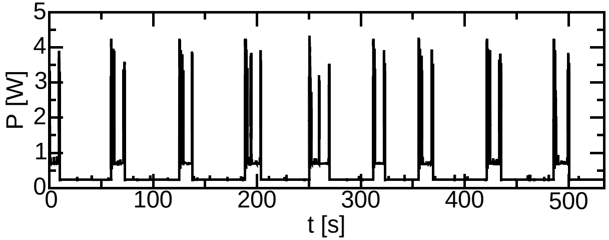
- Write requests of mail reader and read requests of AMP are grouped together



unmodified AMP using `read()` (373 J)



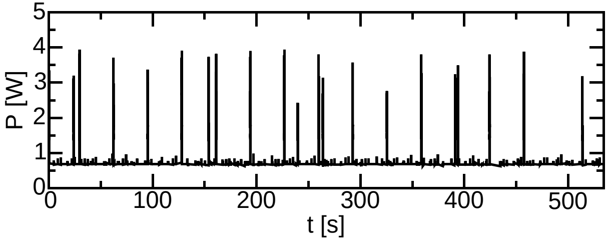
mail reader using `write()` (164 J)



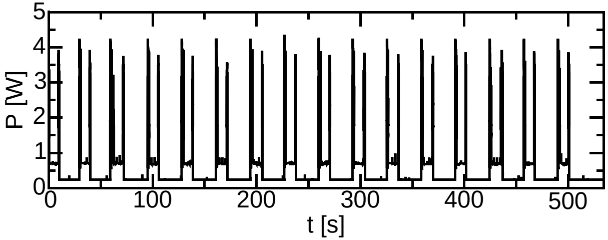
Cooperative-I/O kernel,
AMP using `read_coop()` + mail reader (227 J)

MP3-Player + Mail-Reader

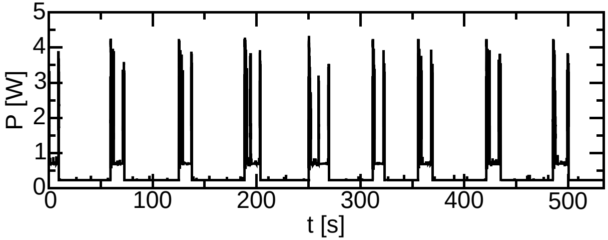
- Linux kernel w/o power management (373 J):



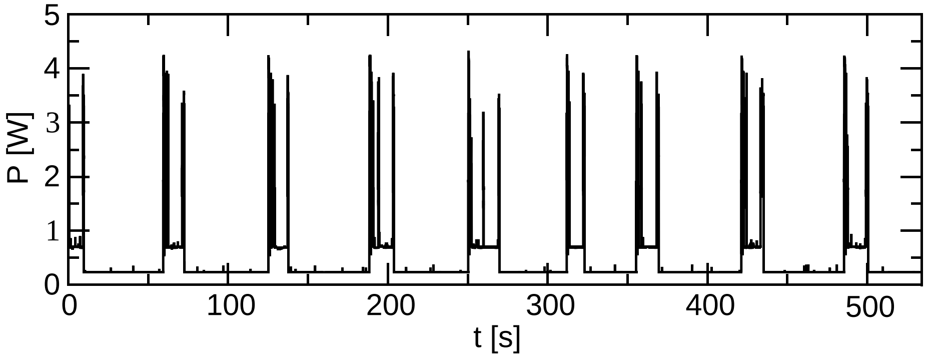
- Cooperative-I/O kernel, AMP using `read()` (265 J):



- Cooperative-I/O kernel, AMP using `read_coop()` (210 J):



MP3-Player + Mail-Reader (2)



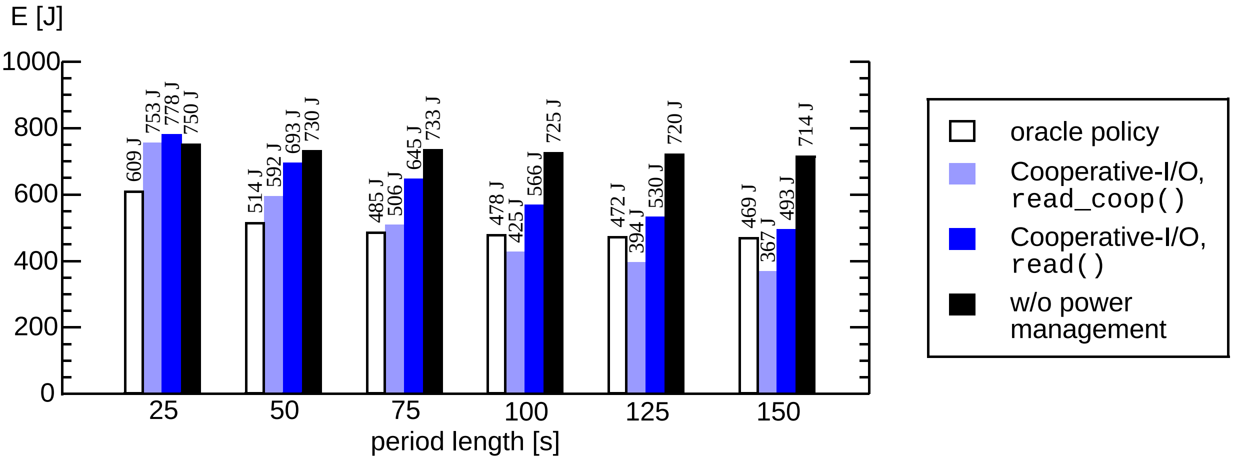
Cooperative-I/O, AMP using `read_coop()` (210 J)

- Two `read_coop()` requests to fill the two read buffers
- If device is in standby mode:
  - ◆ first request is deferred until active buffer is empty
  - ◆ force spin-up to serve request; device is in idle mode
  - ➜ `read_coop()` request for second buffer is executed immediately
  - ➜ effectively two read operations are grouped together
- Write requests are attached to read operations of AMP

Synthetic Tests

- Five processes wake up periodically and issue cooperative read or write requests after random wait times
- Comparison of four policies:
  - ■ Linux kernel without power management
  - 🟦 Cooperative-I/O kernel, test programs use `read()` or `write()`
  - 🟪 Cooperative-I/O kernel, use `read_coop()` or `write_coop()`
  - □ Oracle
- "Oracle" spin-down policy
  - ◆ knows timing of future disk operations (traces!)
  - ◆ transition to standby mode immediately if energy savings are possible
  - ➜ optimal strategy with respect to energy consumption
  - ➜ no influence on times of disk operations!

Synthetic Tests: `read_coop()`

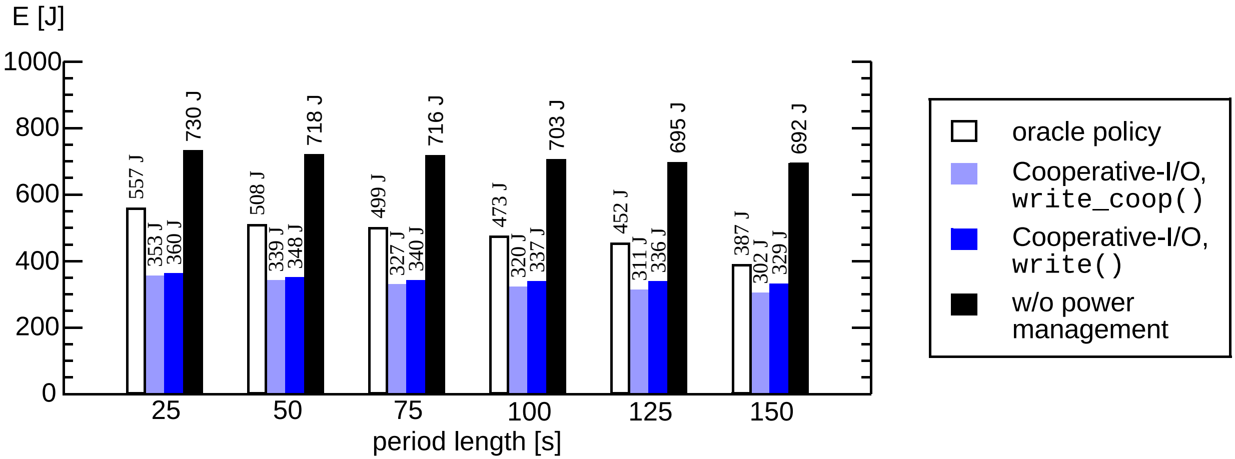


- Higher energy savings than (uncooperative) oracle policy
- Cooperative I/O clusters accesses
  ➜reduction of mode transitions
  ➜more time in standby mode

mode strategy	active + transitions	idle	standby
cooperative	29 s	153 s	868 s
oracle	107 s	132 s	811 s

- Oracle policy does not defer or cluster requests!

Synthetic Tests: `write_coop()`



- `write()` and `write_coop()` requests are already deferred by the update mechanism

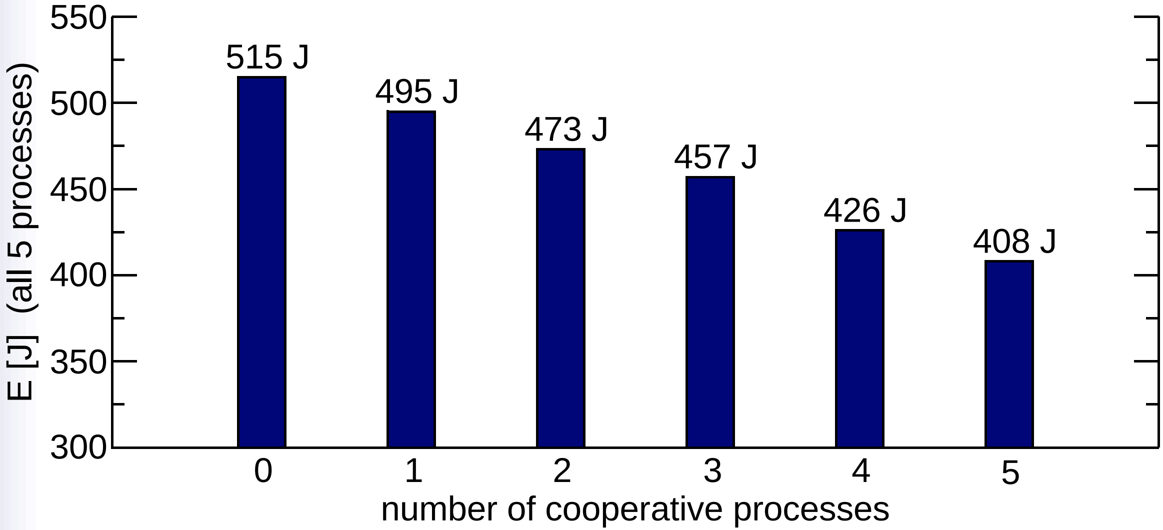
  ➜only little additional savings when using `write_coop()`

- Oracle has no influence on the times of disk operations

  ➜requests are not deferred (synchronous writes)

Varying number of cooperative processes

- 5 processes run in parallel,
  0–5 of them using `read_coop()`, the other `read()`



- The more processes using `read_coop()` instead of `read()`, the higher the energy savings

Conclusion

- Higher energy savings than oracle policy
  ➜higher energy savings than any “traditional” spin-down policy
- Applicable to all types of devices with rotating media
- Starting & stopping the spindle motor causes wear:
  - ◆ common reason for device failures
  - ◆ 50,000–300,000 mode transitions max.