Adaptive and Reflective Middleware and OS Services for Mobile Applications

Managing Power in Dynamic Distributed Environments through cross-layer adaptation

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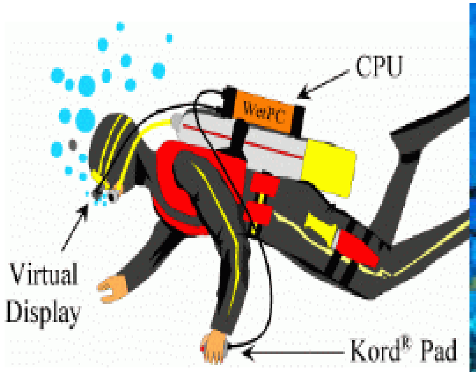
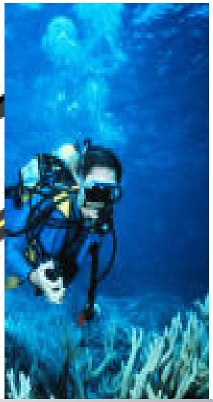
MESL . UCSD . EDU

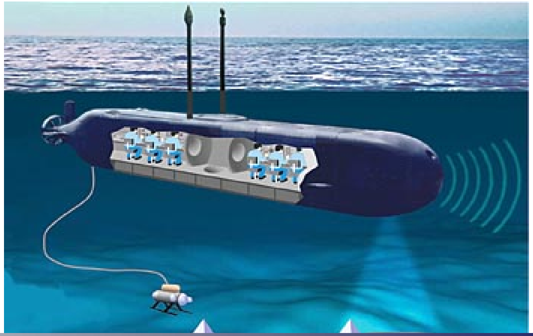
The Real Culprits

- Meta-Data and Its Use in Component Compositions
  - BALBOA Project
    - Sudipta Kundu, Frederic Doucet, Ingolf Krueger
    - Hiren Patel, Gaurav Singh, Sandeep Shukla, Virginia Tech.
- Awareness For Energy, Location
  - Energy awareness:
    - Zhen Ma, Yuvraj Agrawal, Zhong Yi Jin
    - Jihong Kim, SNU
    - Nalini Venkatasubramaniam, Nikil Dutt, Alex Nicolau, UC Irvine
  - Location awareness
    - SPATIAL PROGRAMMING
      - Ryo Sugihara, R. K. Shyamasundar, IRL & TIFR, India
    - DYNAMIC RESOURCE DISCOVERY
      - Jeffrey Namkung , Chalermek Intanagonwiwat, Amin Vahdat

RADIOS ARE EVERYWHERE…







…AND SO IS THE NEED FOR POWER

Low Power Has Been A Design Focus

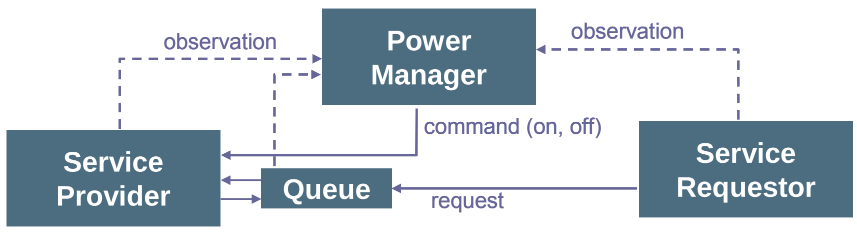
- Speed power efficiency has indeed gone up
  - 10x / 2.5 years for μPs and DSPs in 1990s
    - between 100 mW/MIP to 1 mW/MIP since 1990
  - IC processes have provided 10x / 8 years since 1965
  - rest from power conscious IC design in recent years
- Another 20X is possible.

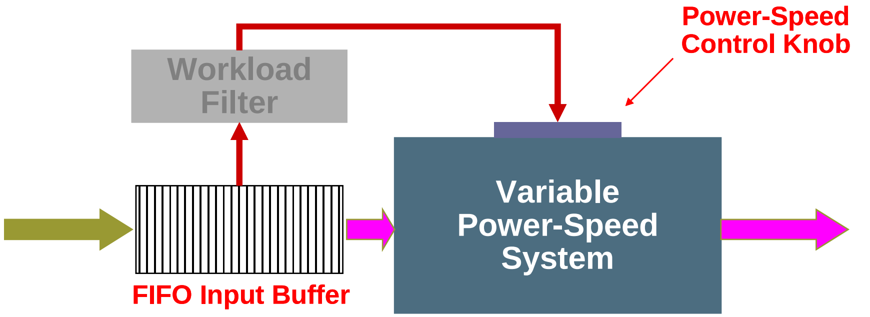
Processor	MHz	Year	SPECint-95	Watts
P54VRT (Mobile)	150	1996	4.6	3.8
P55VRT (Mobile MMX)	233	1997	7.1	3.9
PowerPC 603e	300	1997	7.4	3.5
PowerPC 604e	350	1997	14.6	8
PowerPC 740 (G3)	300	1998	12.2	3.4
PowerPC 750 (G3)	300	1998	14	3.4
Mobile Celeron	333	1999	13.1	8.6

Source: ISI/USC, DARPA PACC Program

There are basically two ways to save power…(true for pretty much everything on-chip)

- Shutdown through choice of right system & device states
  - Multiple sleep states
  - Also known as Dynamic Power Management (DPM)
- Slowdown through choice of right system & device states
  - Multiple active states
  - Also known as Dynamic Voltage/Frequency Scaling (DVS)
- DPM + DVS
  - Choice between amount of slowdown and shutdown





"System Design" for Low Power

- Energy efficiency (has to) cut across all system layers
  - circuit, logic, software, protocols, algorithms, user interface, power supply...
  - Computation versus Communication; Node versus network
- Trade-off between energy consumption & QoS
  - optimize energy metric while meeting "quality" constraint

And thus began our love affair with ‘awareness’

- Knowing an application’s intent one can do a lot of power saving tricks at all levels: architecture, compiler, OS, middleware
- Conversely, if the awareness for power/energy is seeped into all these levels, one can reduce power significantly
- Together they can create a new contract in the computing system!
- Since power is important in radios, things with radios move (or they monitor things that move), location awareness is even more phenomenal for power reduction.

Outline:

Bringing energy awareness in application, OS and Middleware

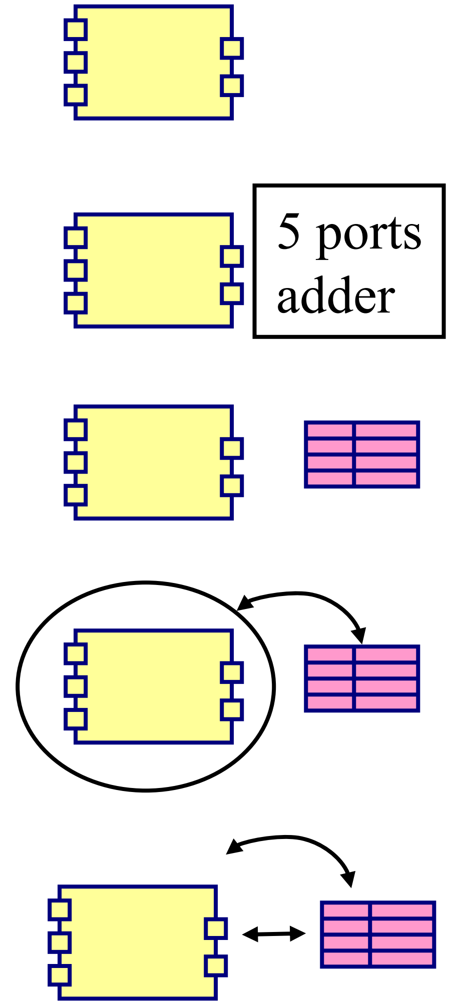
- A Application
- B OS
- C Middleware

What does is mean to be ‘aware’?

- That the application and the services know about energy, power
  - File system, memory management, process scheduling
  - Make each of them energy aware
- How does one make software to be “aware”?
  - Use “reflectivity” in software to build adaptive software
  - Ability to reason about and act upon itself (OS, MW)

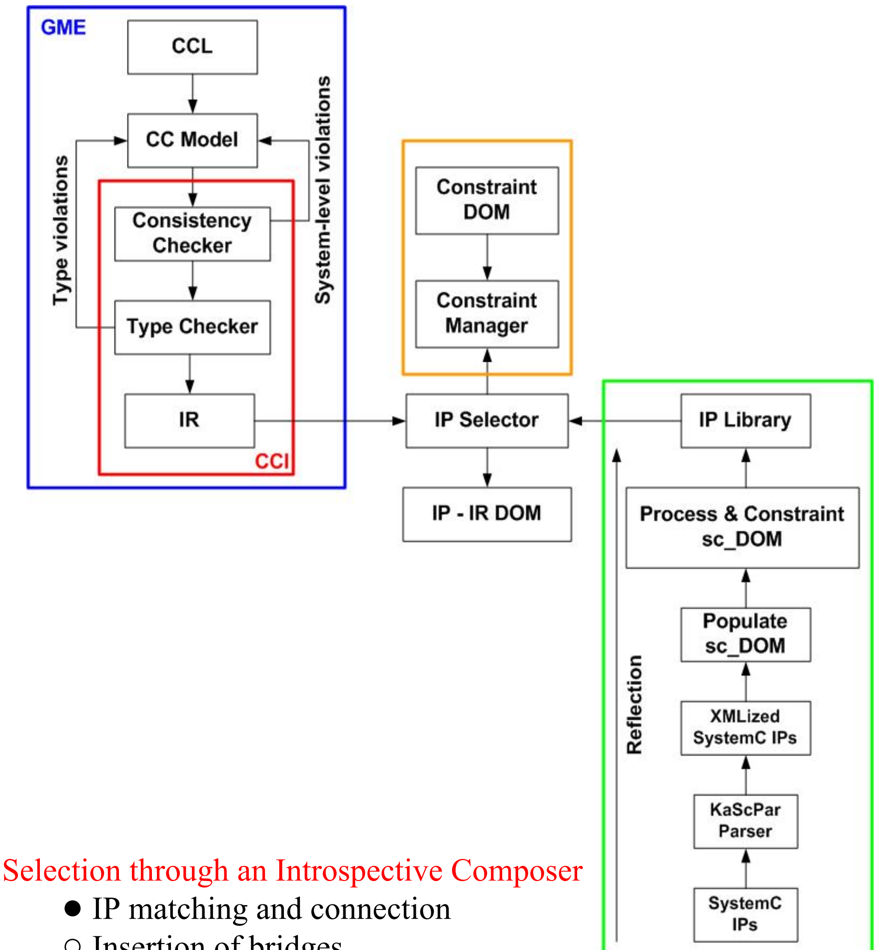
Reflection and Introspection: A HW Guy's Way of Looking At It

- Component:
  - A unit of re-use with an interface and an implementation
- Meta-information:
  - Information about the structure and characteristics of an object
- Reification:
  - A data structure to capture the meta-information about the structure and the properties of the program
- Reflection:
  - An architectural technique to allow a component to provide the meta- information to himself
- Introspection:
  - The capability to query and modify the reified structures by a component itself or by the environment



Building HW Components W/ Meta-data

1. Start with SystemC descriptions of IP blocks
   - Multi-level (RTL, TL) descriptions
2. Capture meta information of these IP into XML
   - Mostly structural information for now.
3. Generate library of 'XMLized' IP blocks
   - Schema to match datatype and protocol type information across IP blocks
   - Create DOM model and constraints for the library
4. Develop methods for IP selection, composition, verification, synthesis
   - Automated methods for IP instantiation, interface generation



IP Selection through an Introspective Composer

- ● IP matching and connection
- ○ Insertion of bridges
- ○ Validation of functionality
- ○ Create an executable specification

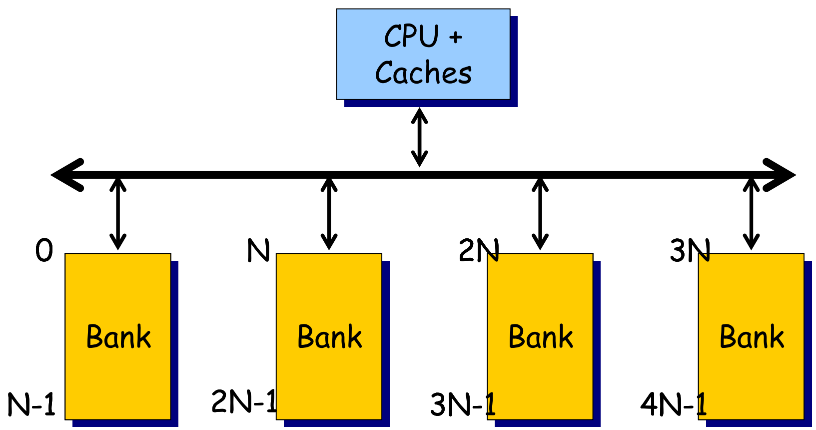
Applying Reflection: performance, energy

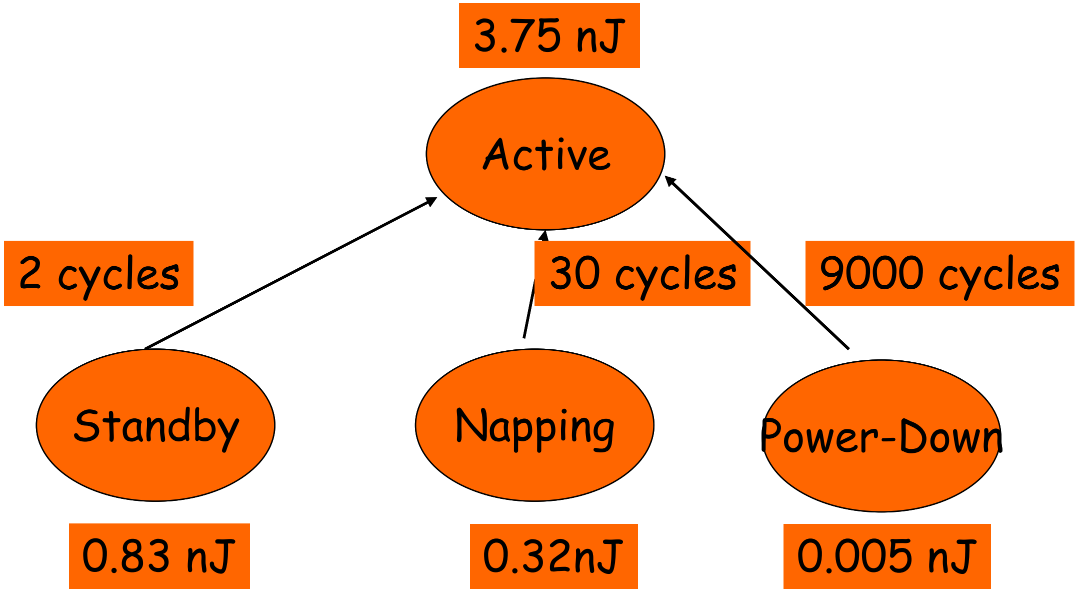
- Use Meta data to represent resource demands, dynamic behavior of the program carrying it.
  - Resources: Memory (R/W, Cache), Processor (IPC)
- Enables energy-performance tuning by exploring resource demand variations throughout programs' execution
  - Example: Profile of application over memory banks
  - Vary frequency of processor based on IPC demand

A

Example: Rambus DRAM (RDRAM)

- High bandwidth (>1.5 GB/sec)
- Each RDRAM module can be activated/deactivated independently
- Read/write can occur only in the active mode
- Three low-power operating modes:
  - Standby, Nap, Power-Down



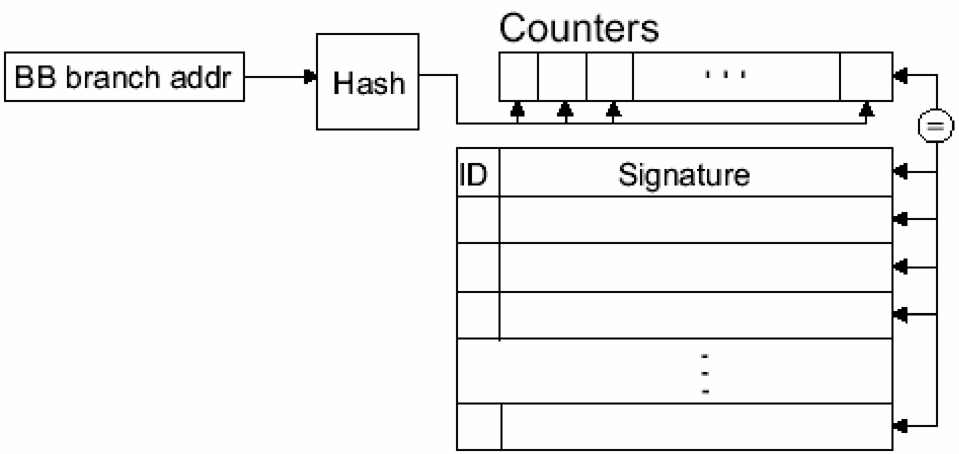


Approach

1. Characterize application offline
   - Divide an application into phases of execution
     - A group of program intervals executing similar code
   - Each phase has similar demand on resources
     - Similar code, similar resource demands (memory, IPC)
2. Annotate source code
   - Phase signatures
3. Enable OS (and hardware) to recognize signature
   - Smart hardware and/or online learning techniques
4. Dynamically tune the power manager
   - As application moves from one phase to another.

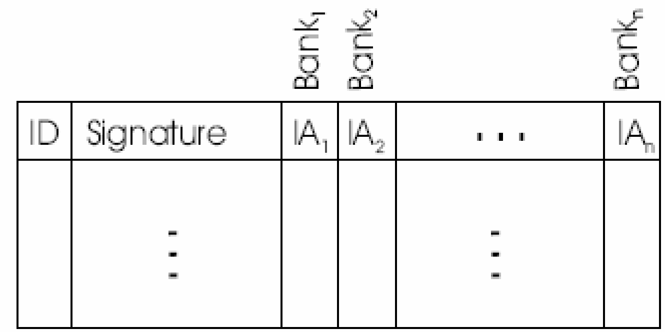
1 Understanding application behavior

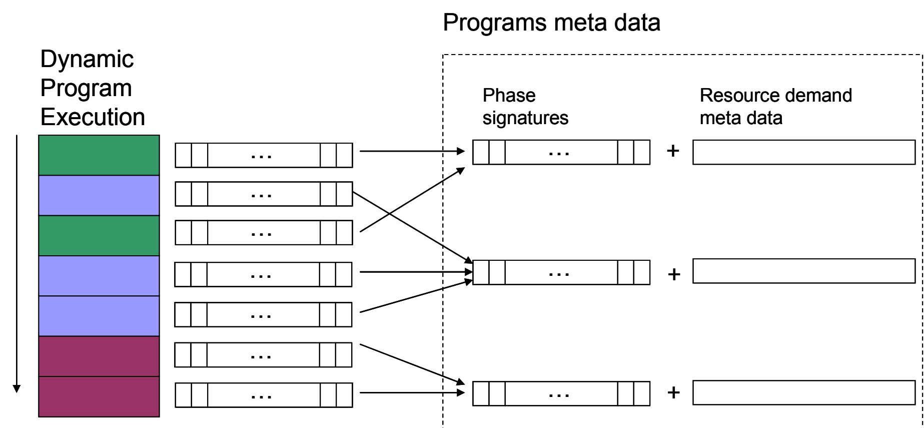
- Divide an application into phases of execution
  - A group of program intervals executing similar code
- Each phase has similar dema on resources
  - Similar code, similar resourc demands
- Demand for resources varies during the execution of application
  - As it moves from one phase to another.
- Phases identified using BBV or LBV
  - Keep track of loop branches



2 Offline analysis of application

- A data structure with the summary of the information of interest for each phase is attached to the program
  - Fixed location for the program metadata
  - OS support to access metadata.
- Also a signature of each phase is attached to the program.
  - No. of times the loops of the program are executed in the particular phase

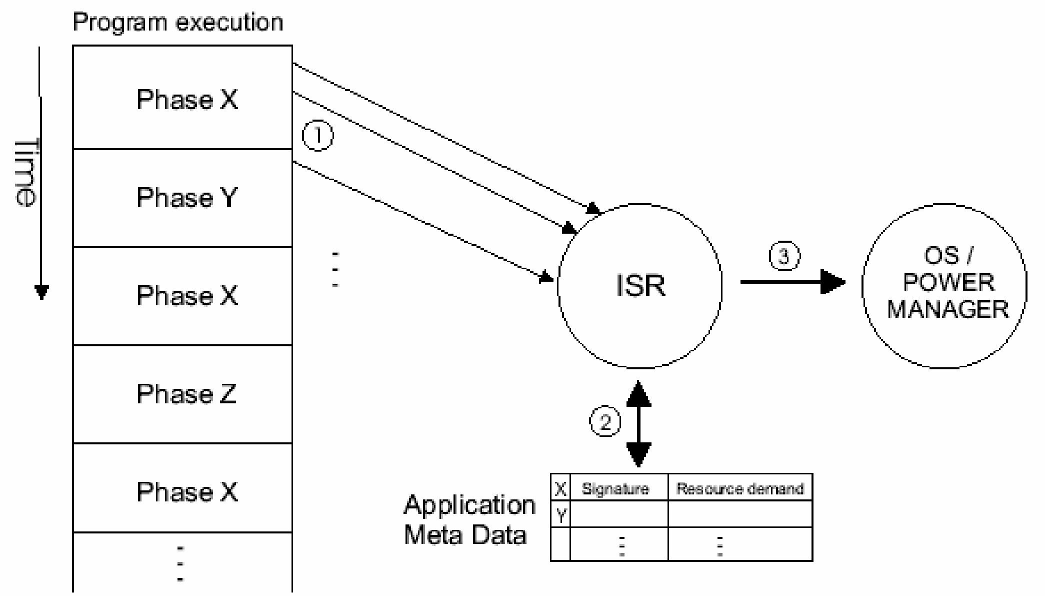




3 Runtime Analysis

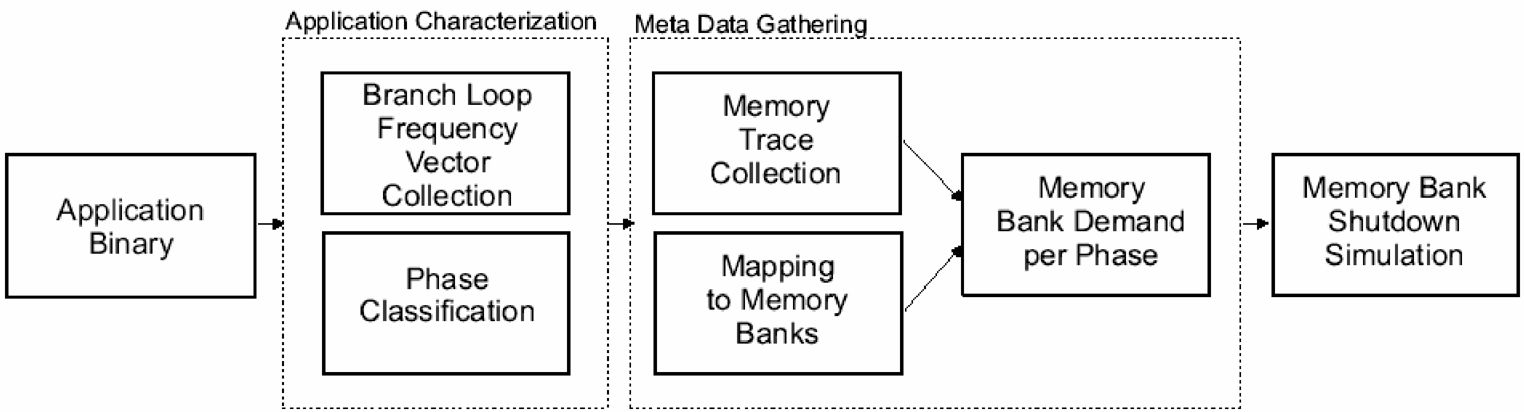
- Challenge:
  - Detect in which phase the program is running
- Learning, signature construction, partial matches
  - Match the signature created offline with a online signature using Manhattan distance.
    - If distance < threshold a match is found.
    - Threshold tells how similar two intervals of execution are.
  - The same technique used for splitting the program in phases offline is applied online but using partial signatures for matching with the offline computed signatures.

4 Matching signature at runtime



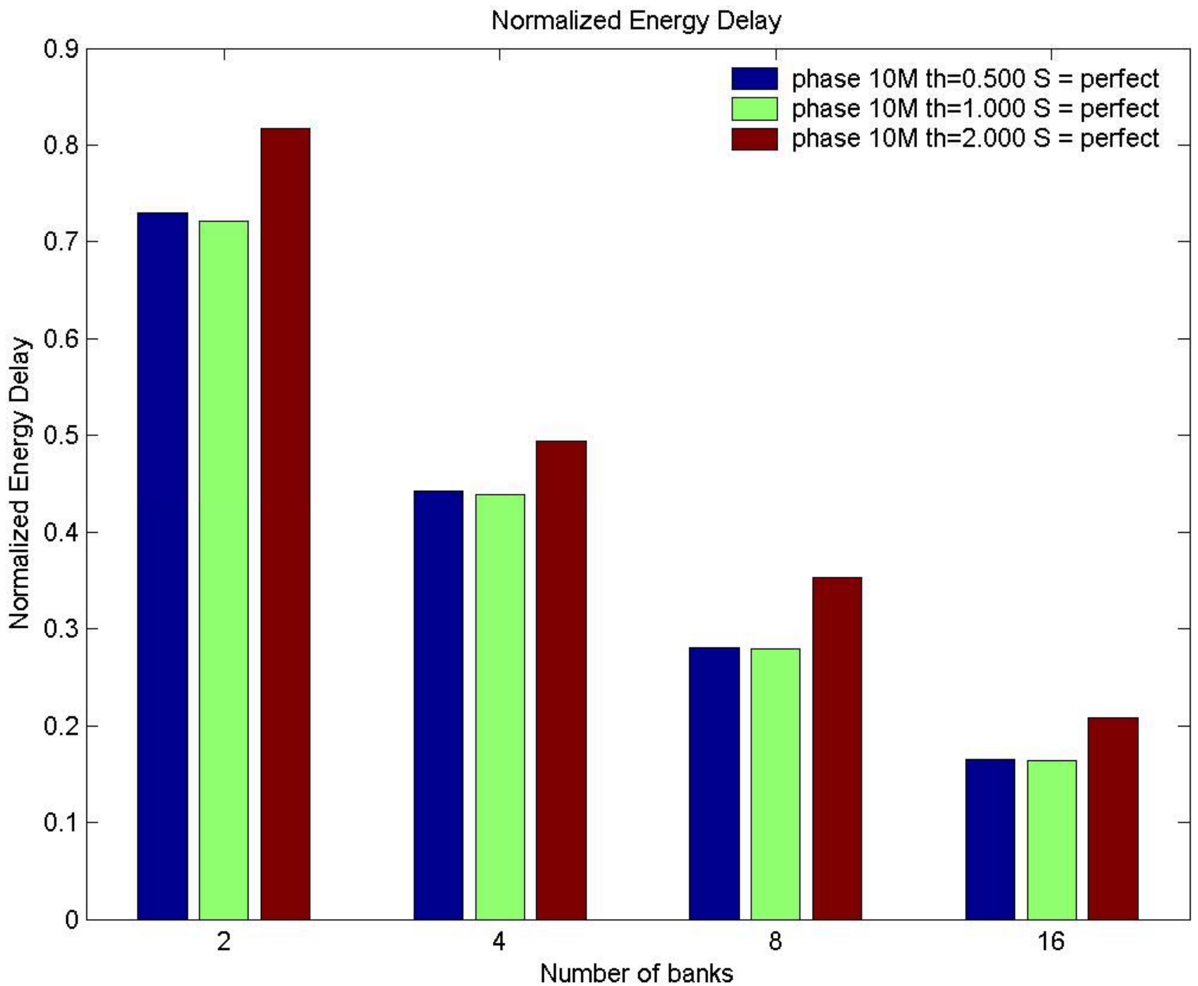
- Use performance counters:
  - Can be programmed to generate an interrupt on specified counts
- ISR provides matching with the meta data and mode changes
  - Every S*10,000 loop branches try a match
  - Phase matching can also be done in hardware
- Notify power manager to trigger proper action

Adaptation for Memory Behavior



- Number of engineering optimizations
  - Frequency of adaptation
  - Granularity of analysis (phase granularity)
  - Tradeoff against cost of adaptation.

Results – Normalized to NAP



Average among bzip, mpeg, ghostscript and ADPCM

Results - overheads

- Approx. 350K instructions for every 10,000 loop branch instructions
- Number of instructions executed by the match algorithm at every 10,000 loop branches to match a partial signature (500 instructions per phase)

# of phases	# instructions	overhead
5	2,580	0.7%
10	4,500	1%
20	8,280	2%
30	12,060	3%

- Size overhead. 4 bytes per inter arrival estimate per bank / phase. 4 x 16 x 10 = 640 bytes assuming 16 banks and 10 phases.
- The signatures take1280 bytes for 10 phases. Total of 2KB of meta data

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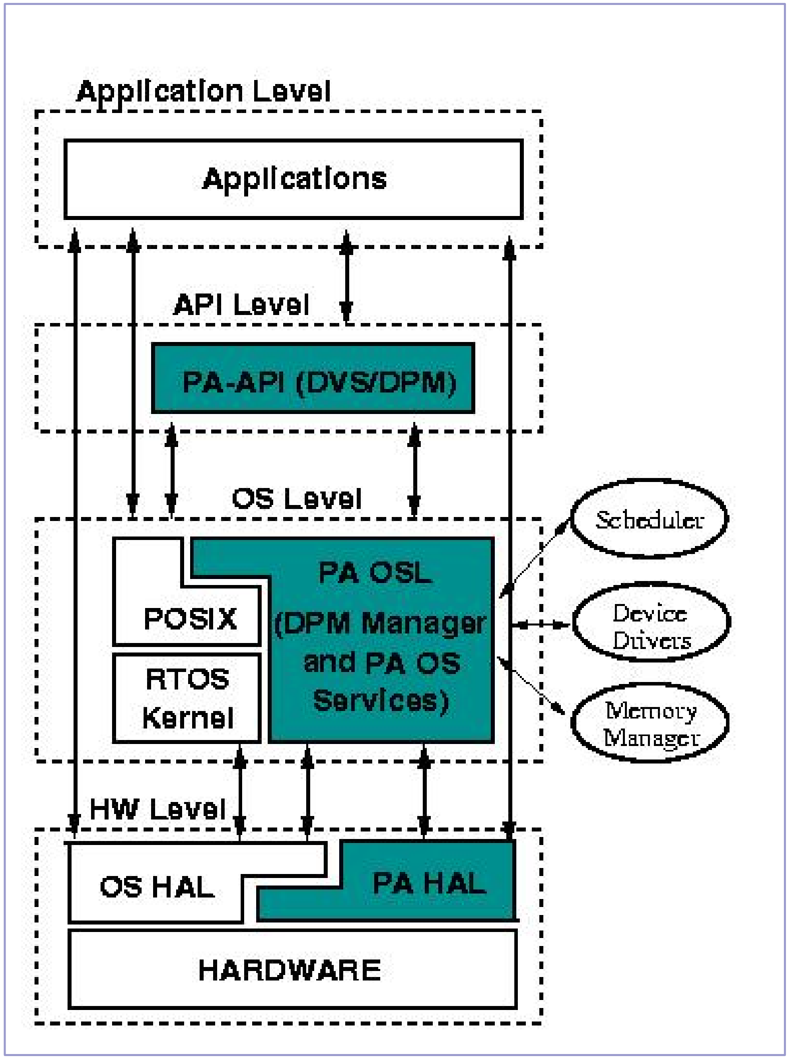
Power Aware OS and Middleware

- Make it adaptive to respond to application requirements
  - and to dynamically smooth the imbalances between demand and availability of energy resource
- Use reflectivity enable dynamic scaling of data, choice of algorithms or parameters
  - (e.g., transcoding algorithms, compression parameters)
- Use brokerage service to negotiate quality demands

Enable Power/Energy Dialogue

- Application can tell OS task information (type, deadlines, WCET estimates)
- OS can update these estimates based on runtime conditions.
- To do this, we need
  - API: Provide ways by which Application, OS and Hardware can exchange energy/power and performance related information efficiently.
  - Middleware: Facilitate a continuous dialogue / adaptation between OS / Applications.
  - HAL: Facilitate the implementation of power aware OS services by providing a software interface to low power devices

Power Aware Parts



- PA-API (Power Aware API)
  - interfaces applications and OS making the power aware OS services available to the application writer.
- PA-OSL (Power Aware Operating System Layer)
  - implements modified OS services and active components such as a DPM manager.
- PA-HAL (Power Aware Hardware Abstraction Layer)
  - interfaces OS and Hardware making the power control knobs available to the OS programmer.

OS Services

- PA-API - Power aware function calls available to the application writer.
  - Some functions of this layer are specific to certain scheduling techniques.
- PA-Middleware - Power aware services
  - implemented on the top of the OS (power management threads, data handling, etc...).
- POSIX - Standard interface for OS system calls.
  - This isolates PA-API and PA-Middleware from OS.
- PA-OSL - Power aware OS layer.
  - Calls related to modified OS services should go through this level. Also isolates OS from PA-API and PA-Middleware.
- PA-HAL - Power Aware Hardware Abstraction Layer.
  - Isolates OS from underlying power aware hardware.
- Modified OS services
  - Implementation / modification of OS services in a power related fashion. Ex: scheduler, memory manager, I/O, etc.

Layer Functionality

Layer	Function name
PA-API	paapi_dvs_create_thread_type(), paapi_dvs_create_thread_instance() paapi_dvs_app_started(), paapi_dvs_get_time_prediction() paapi_dvs_set_time_prediction(), paapi_dvs_app_done(), paapi_dvs_set_adaptive_param() paapi_dvs_set_policy(), paapi_dpm_register_device()
PA-OSL	paosl_dvs_create_task_type_entry(), paosl_dvs_create_task_instance_entry(), paosl_dvs_killer_thread(), paosl_dvs_killer_thread_alarm_handler(), paosl_dpm_register_device(), paosl_dpm_deamon()
PA-HAL	pahal_dvs_initialize_processor_pm(), pahal_dvs_get_frequency_levels_info() pahal_dvs_get_current_frequency(), pahal_dvs_set_frequency_and_voltage() pahal_dvs_pre_set_frequency_and_voltage(), pahal_dvs_post_set_frequency_and_voltage() pahal_dvs_get_lowpower_states_info(), pahal_dvs_set_lowpower_state() pahal_dpm_device_check_activity(), pahal_dpm_device_pre_switch_state() pahal_dpm_device_switch_state(), pahal_dpm_device_post_switch_state() pahal_dpm_device_get_info(), pahal_dpm_device_get_curr_state() pahal_battery_get_info()

B

DVS Related Functions

paapi_dvs_create_thread_type(), paapi_dvs_create_thread_instance()

creates type and instance of a task respectively

paapi_dvs_app_started(), paapi_dvs_app_done()

delimits execution of useful work in a thread. Tell the OS whether the task has finished execution or not.

paapi_dvs_get_time_prediction(), paapi_dvs_set_time_prediction()

get current execution time prediction for a given thread

paapi_dvs_set_adaptive_param()

set the paremeters of the adaptive policy (it will be described later) for a given task.

paapi_dvs_set_policy()

choses the policy to be using for DVS

DVS Related Functions (contd.)

- paosl_dvs_create_task_type_entry(), ...
  - create a type and an instance of a thread in the kernel internal tables of type and instance respectively
- paosl_dvs_killer_thread()
  - kills a thread that missed a deadline
- pahal_dvs_initialize_processor_pm()
  - initialize structures for processor power management
- pahal_dvs_get_current_frequency(), pahal_dvs_set_frequency_and_voltage() pahal_dvs_pre_set_frequency_and_voltage(), pahal_dvs_get_frequency_levels_info() pahal_dvs_post_set_frequency_and_voltage()
  - functions to switch processor among possible frequencies levels
- pahal_dvs_get_lowpower_states_info(), pahal_dvs_set_lowpower_state()
  - functions to switch processor among low power states

DPM Functions

- paapi_dpm_register_device()
  - just register the device to be power managed
- paosl_dpm_deamon()
  - implements the actual policy for a specific device. This deamon uses PA-HAL functions to decide on how to switch devices among all possible states.
- pahal_dpm_device_switch_state()
  - switch device's state
- pahal_dpm_device_check_activity()
  - check whether the device has been idle and for how long. This functions needs support from the device driver.
- pahal_dpm_device_get_info(), pahal_dpm_device_get_curr_state()
  - gets information about the device and about its current state respectively
- Others
  - functions for helping implementing power policies. For example:
    - pahal_battery_get_info() – gets battery status

Prototype Implementation

- Platforms
  - eCOS RTOS:
    - open source, Object oriented and highly configurable RTOS (by means of scripting language)
  - Hardware platforms we are currently working with:
    - Linux-synthetic (emulation of eCos over Linux - debugging purposes only)
    - Compaq iPaq Pocket PC, Accelent IDP
    - alu

Using Power Aware OS

- The scheduler adapts frequency according to the real time parameters passed in as parameter on the thread type.
- The frequency is adjusted by means of slowdown factors (a factor can also speed up the processor if it is > 1).

```
void main()
{
  mpeg_decoding_t =
    paapi_dvs_create_thread_type(100,30,100,hard);

    paapi_dvs_set_policy(SHUTDOWN | STATIC
     DYNAMIC | ADAPTIVE);
    paapi_dvs_create_thread_instance(
      mpeg_decoding_t, mpeg_decode_thread);
}
...
```

period — WCET — deadline

Selects the DVS policy for all threads

Kills the thread instance when deadline is missed

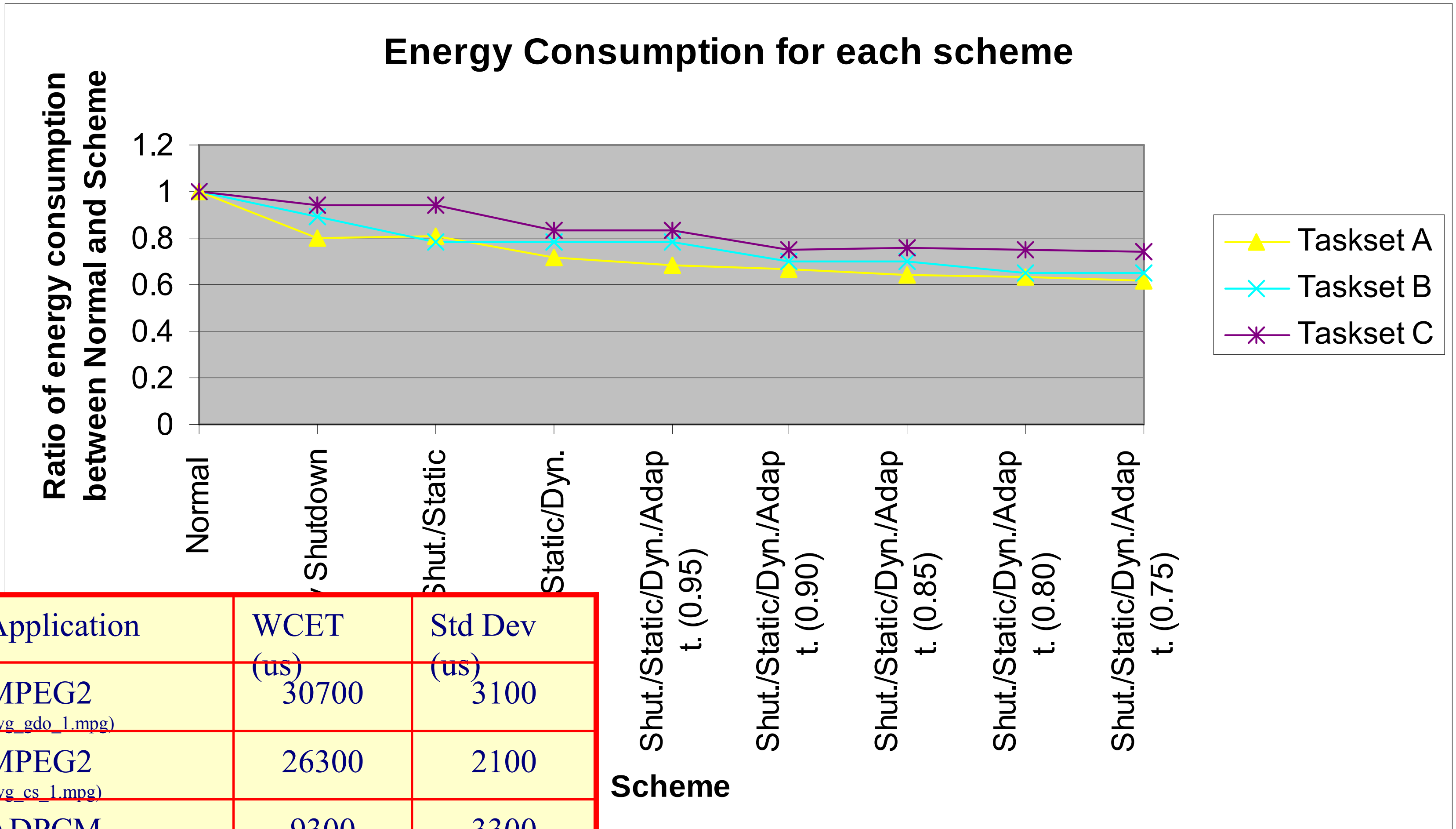
```
void mpeg_decode_thread()
{
 for (;;) {
   paapi_dvs_app_started();
   /* original code */
   mpeg_frame_decode()
   paapi_dvs_app_done();
 }
}
```

B

Directing DPM (and DVS)

```
void threshold_policy_deamon(device_info_t dev){
  unsigned idleness;
  for (;;) {
    /* check for how long the device has been idle */
    idleness = dev->check_activity(dev);
    /* if idle for longer than the threshold switch to next state */
    if ( idleness > dev->check_state()->threshold ) {
      dev->check_state()->switch_state(dev, dev->check_state,
                                       dev->check_state()->next); }
    /* sleep until next period for checking idleness */
    sleep(dev->policy_info->th_policy->period); }}
```

OS-directed DVS Results



Task	Application	WCET (us)	Std Dev (us)
T1	MPEG2 (wg_gdo_1.mpg)	30700	3100
T2	MPEG2 (wg_cs_1.mpg)	26300	2100
T3	ADPCM	9300	3300
T4	FFT	15900	0
T5	FFT (gaussian distribution)	13600	800

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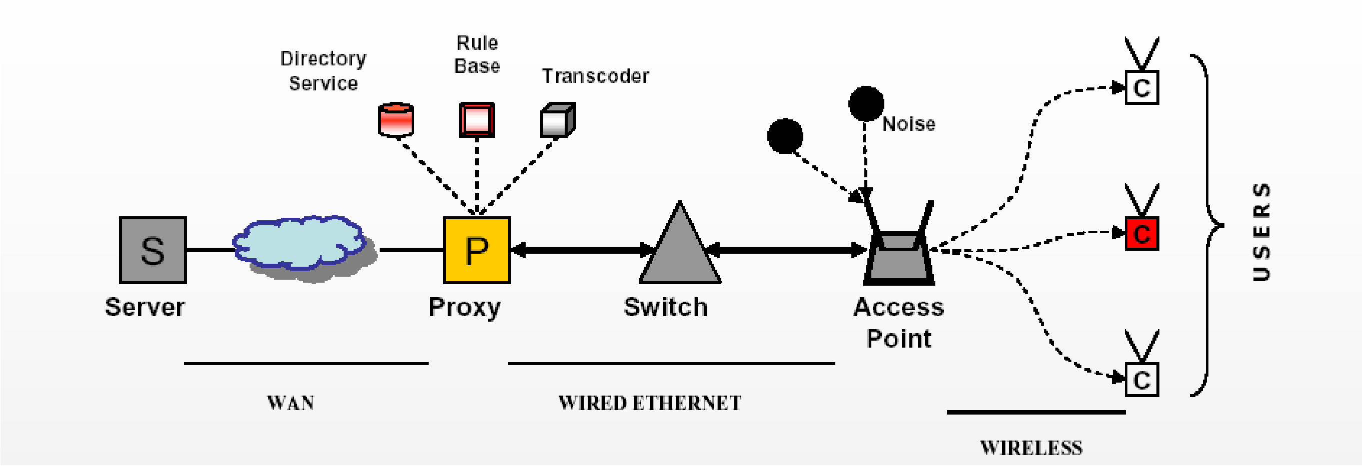
Energy Aware Middleware in FORGE

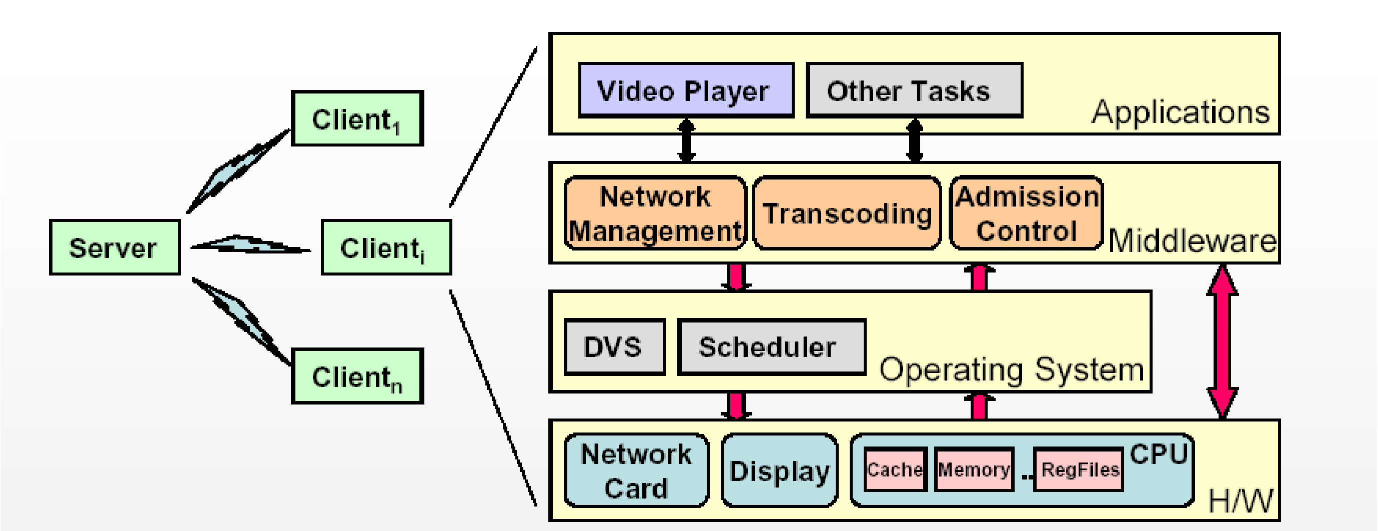
[Jointly with Nalini Venkatsubramaniam, UC Irvine.]

- Use reflective middleware services to continuously monitor and keep track of application needs
  - Use a rule base and directory service to carry out its functions.
- Example:
  - multimedia streaming from a server to a set of mobile “nodes”
  - Use a proxy server to adapt video stream to specific nodes



  - Node device: sends device info to proxy, connects video stream and network parameters to lower layers
  - Proxy: admission control, real-time transcoding, network traffic regulation.

Cross-layer Energy Awareness



- Experiments using iPAQs demonstrate viability of dynamic adjustments of video quality
  - based on changing battery conditions and client devices.
  - [Mohapatra et al, ACM MM03]

Reducing Backlight for Lower Power

- Identify “Groups of Scenes” with little variance in luminosity
- **SBC: Simple Backlight Compensation**
  - **Only identify GOS, reduce backlight on handheld**
  - **No video stream contrast enhancement**
- **CBVLC: Constant Backlight with Video Luminosity Compensation**
  - **Backlight level set once at start of video stream**
  - **Video stream is enhanced (dynamically at the proxy)**
- **DCA: Dual Compensation Approach**
  - Backlight level is dynamically changed based on GOS
  - Video stream is enhanced based on Backlight level decision

Backlight Modes	Power Consumed (in Watts)
Super Bright	2.80
High Bright	2.51
Medium Bright	2.32
Low Bright	2.16
Power Save	1.72

Power consumed at various backlight levels during streaming multimedia playback on the Compaq iPAQ

bipolar.mpg iceegg.mpg intro.mpg simpsons.mpg

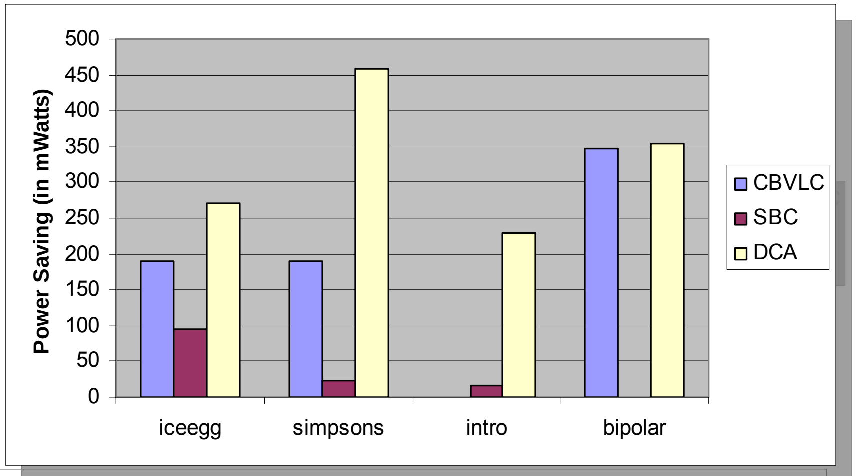
Snapshots of MPEG-1 video streams used in experiments

MPEG Video	Resolution	FPS	Duration (sec)	Luminosity Variation	Video Type
bipolar.mpg	320 x 240	30	41	Little	Dark, 3D animation
iceegg.mpg	240 x 136	30	59	Moderate	Bright, 3D animation
intro.mpg	160 x 120	30	59	Very High	Flashy, TV show clip
simpsons.mpg	192 x 144	30	27	High	Colorful, 2D animation

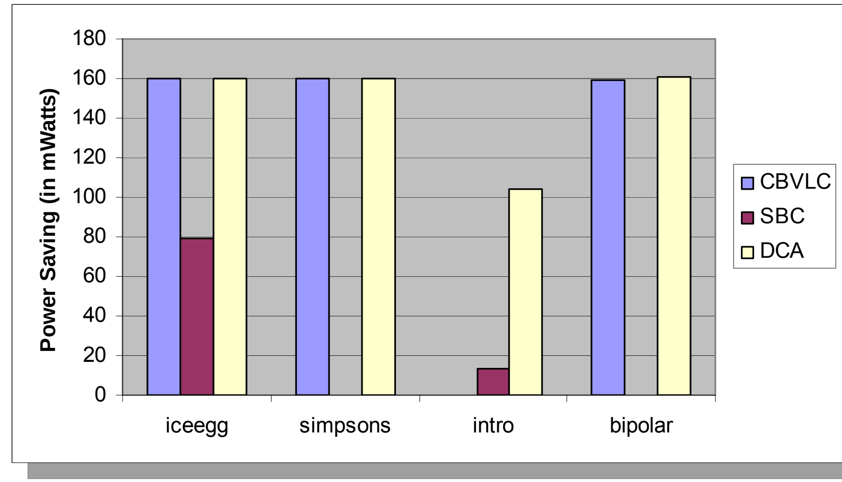
Characteristics of video streams used in experiment

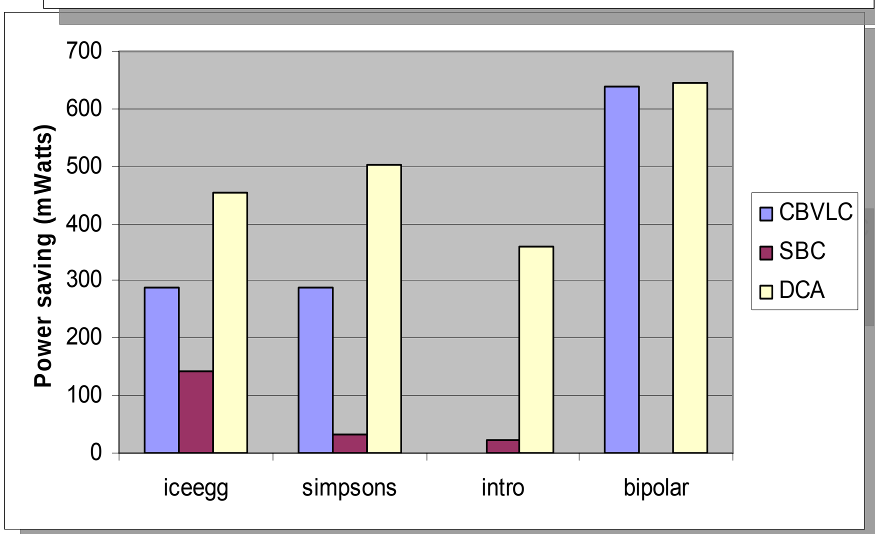
Results for Backlight Compensation

Super Bright



High Bright





Medium Bright

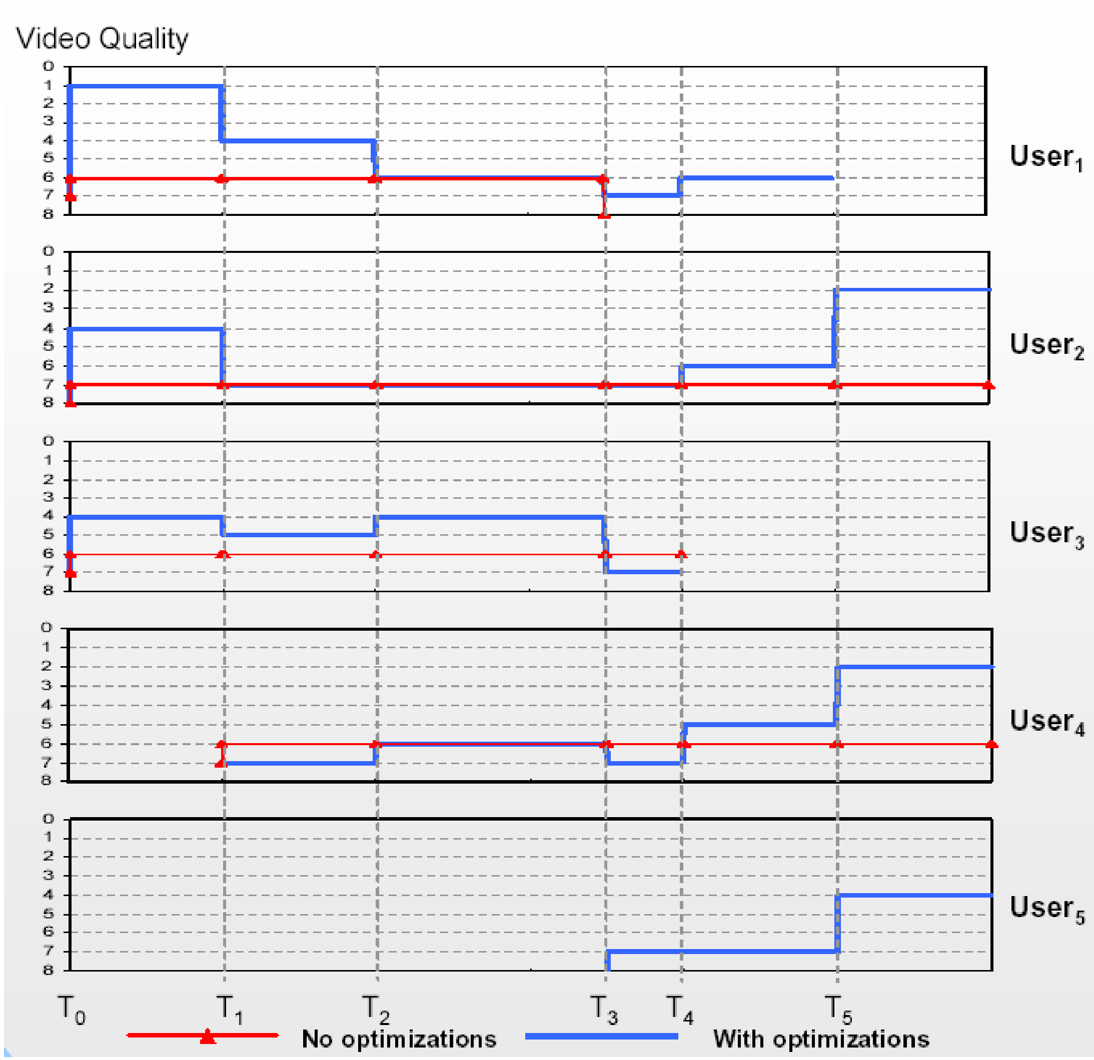
Backlight Modes	Power Consumed (in Watts)
Super Bright	2.80
High Bright	2.51
Medium Bright	2.32
Low Bright	2.16
Power Save	1.72

New Computing Spaces & Fabrics

- New Computing Spaces challenge energy efficiency
  - Computers with radios, mobility
- New Computing Fabrics challenging architectures
  - To enable high hardware integration, and yet allow for reasonable software development across multiple heterogeneous processors
  - Yet, not fast enough. With the multiple processor cores on chip, the interaction of application behavior with core utilization will be even more critical to maintain energy profile.
- Awareness (environmental, location, QoS) may make it possible to achieve extreme dutycycles.

► Systematic understanding and use of awareness is crucial to engineering optimization.

Example



- T_0: 3 users (1, 2, 3)
- T1: user 4 joins
  - System readjusts quality levels
- T2: residual power on user 1 decreases
  - Quality level is decreased for 1
- T3: user 5 joins
  - All levels go down to accommodate 5
- T4: user 3 finishes streaming
  - Quality levels rise back
- T5: user 1 finishes streaming
  - Even higher levels