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Problem Statement: 2
VoltSync:
Energy-Efficient OS Scheduling for Embedded Systems

DA-1 Project Report

Operating Systems (BCSE303L)

D1 + TD1 Slot

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VoltSync:
Energy-Efficient OS Scheduling for Embedded Systems

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1 Introduction and Problem Statement

Battery-powered embedded devices, such as IoT units, medical wearables, and smart sensors, require energy-aware task scheduling. Traditional schedulers focus only on time efficiency, ignoring power consumption.

The objective of this project is to develop an energy-aware OS scheduler, named **VoltSync**, that minimizes power consumption while successfully meeting task deadlines. According to the system requirements, the scheduler must dynamically scale CPU frequency, batch low-priority tasks, and enter low-power sleep states when idle.

2 Methodology and System Design

VoltSync utilizes a hardware-abstracted energy model to simulate power usage versus performance. The system defines three power states:

- **Sleep State (1.0W):** The system enters this low-power sleep state when idle to conserve battery.
- **Low Frequency (5.0W):** The CPU is throttled for low-priority tasks to save power, executing tasks at a reduced speed (batching/throttling).
- **Max Frequency (15.0W):** The CPU runs at maximum processing speed for tasks with strict, approaching deadlines.

The algorithm dynamically assesses the slack time of incoming tasks, dropping the frequency when deadlines are loose and ramping up only when mathematically necessary to prevent a deadline miss.

3 Implementation

3.1 Phase 1: Baseline Algorithms and System Parameters

This phase establishes the foundational task parameters and the baseline Earliest Deadline First (EDF) scheduler used for our comparative study.

```
1 from collections import deque
2
3 class Task:
4     def __init__(self, task_id, arrival_time, execution_time, deadline):
```

```
        self.task_id = task_id
        self.arrival_time = arrival_time
        self.execution_time = execution_time
        self.remaining_time = execution_time
        self.deadline = deadline
        self.completion_time = 0
        self.is_completed = False

class EnergyState:
    SLEEP = 1.0
    LOW_FREQ = 5.0
    MAX_FREQ = 15.0

def edf_scheduler(tasks):
    time = 0
    completed_tasks = []
    n = len(tasks)

    for t in tasks:
        t.remaining_time = t.execution_time
        t.is_completed = False

    while len(completed_tasks) < n:
        available_tasks = [t for t in tasks if t.arrival_time <= time and not t.
            is_completed]

        if not available_tasks:
            time += 1
            continue

        current_task = min(available_tasks, key=lambda x: x.deadline)
        current_task.remaining_time -= 1
        time += 1

        if current_task.remaining_time == 0:
            current_task.is_completed = True
            current_task.completion_time = time
            completed_tasks.append(current_task)

    return completed_tasks
```

Listing 1: phase1_baselines.py

3.2 Phase 2: VoltSync Energy-Aware Scheduler

Phase 2 contains the core logic for the modified scheduling algorithm. It implements the dynamic frequency scaling and energy metrics tracking.

```
from phase1_baselines import Task, EnergyState, edf_scheduler, calculate_metrics

def voltsync_scheduler(tasks):
    time = 0
    completed_tasks = []
    power_log = []
    total_energy = 0.0
    n = len(tasks)

    for t in tasks:
```

```
        t.remaining_time = float(t.execution_time)
        t.is_completed = False

    while len(completed_tasks) < n:
        available_tasks = [t for t in tasks if t.arrival_time <= time and not t.
            is_completed]

        if not available_tasks:
            power_log.append(EnergyState.SLEEP)
            total_energy += EnergyState.SLEEP
            time += 1
            continue

        current_task = min(available_tasks, key=lambda x: x.deadline)
        time_to_deadline = current_task.deadline - time

        if time_to_deadline <= current_task.remaining_time + 1:
            current_power = EnergyState.MAX_FREQ
            work_done = 1.0
        else:
            current_power = EnergyState.LOW_FREQ
            work_done = 0.5

        current_task.remaining_time -= work_done
        power_log.append(current_power)
        total_energy += current_power
        time += 1

        if current_task.remaining_time <= 0:
            current_task.is_completed = True
            current_task.completion_time = time
            completed_tasks.append(current_task)

    return completed_tasks, power_log, total_energy
```

Listing 2: phase2_voltsync.py

3.3 Phase 3: Visualization Engine

Phase 3 utilizes Matplotlib to programmatically generate the required deliverables, including the dynamic power state step-graph and the comparative study dashboards.

```
import matplotlib.pyplot as plt
from phase1_baselines import Task, EnergyState
from phase2_voltsync import voltsync_scheduler, edf_scheduler

def run_visualization():
    tasks_edf = [Task("T1", 0, 4, 10), Task("T2", 1, 2, 5), Task("T3", 2, 1, 12)]
    tasks_vs  = [Task("T1", 0, 4, 10), Task("T2", 1, 2, 5), Task("T3", 2, 1, 12)]

    edf_results = edf_scheduler(tasks_edf)
    edf_total_time = max([t.completion_time for t in edf_results])
    edf_active_time = sum([t.execution_time for t in tasks_edf])
    edf_energy = edf_total_time * EnergyState.MAX_FREQ
    edf_cpu_util = (edf_active_time / edf_total_time) * 100
    edf_tat = sum([t.completion_time - t.arrival_time for t in edf_results]) / len
        (edf_results)

```

```
    vs_results, power_log, vs_energy = voltsync_scheduler(tasks_vs)
    vs_total_time = len(power_log)
    vs_sleep_time = power_log.count(EnergyState.SLEEP)
    vs_cpu_util = ((vs_total_time - vs_sleep_time) / vs_total_time) * 100
    vs_tat = sum([t.completion_time - t.arrival_time for t in vs_results]) / len(
        vs_results)

    energy_saved_pct = ((edf_energy - vs_energy) / edf_energy) * 100
    time_steps = list(range(len(power_log)))

    fig = plt.figure(figsize=(14, 8))

    ax1 = plt.subplot(2, 1, 1)
    ax1.step(time_steps, power_log, where='post', color='teal', linewidth=2)
    ax1.fill_between(time_steps, power_log, step='post', color='teal', alpha=0.2)
    ax1.set_title('VoltSync Scheduler: Dynamic Power State vs Time', fontsize=14,
        fontweight='bold')
    ax1.set_xlabel('Time (Seconds)', fontsize=12)
    ax1.set_ylabel('Power Draw (Watts)', fontsize=12)
    ax1.set_yticks([1, 5, 15])
    ax1.set_yticklabels(['Sleep (1W)', 'Low Freq (5W)', 'Max Freq (15W)'])
    ax1.grid(axis='y', linestyle='--', alpha=0.7)

    ax2 = plt.subplot(2, 3, 4)
    labels = ['Baseline EDF', 'VoltSync']
    bars = ax2.bar(labels, [edf_energy, vs_energy], color=['#e74c3c', '#2ecc71'])
    ax2.set_title('Total Energy (Joules)', fontsize=12)
    ax2.text(1, vs_energy + 2, f"-{energy_saved_pct:.1f}%!", ha='center', color='
        green', fontweight='bold')

    ax3 = plt.subplot(2, 3, 5)
    ax3.bar(labels, [edf_tat, vs_tat], color=['#3498db', '#f1c40f'])
    ax3.set_title('Avg Turnaround Time (Sec)', fontsize=12)

    ax4 = plt.subplot(2, 3, 6)
    ax4.bar(labels, [edf_cpu_util, vs_cpu_util], color=['#9b59b6', '#34495e'])
    ax4.set_title('CPU Utilization (%)', fontsize=12)
    ax4.set_ylim(0, 110)

    plt.tight_layout()
    plt.show()

if __name__ == "__main__":
    run_visualization()
```

Listing 3: phase3_visualizer.py

4 Simulation Results and Comparative Study

A simulation was executed to conduct a comparative study with EDF, and to perform a strict deadline-miss analysis.

4.1 Terminal Output Metrics

```
================================================
 BASELINE TEST: Earliest Deadline First (EDF)
```

```
================================================
--- Metrics for EDF Scheduler ---
Task ID     | Turnaround Time     | Waiting Time     | Deadline Status
-----------------------------------------------------------------------------------------
T2          | 2                   | 0                | Met
T1          | 6                   | 2                | Met
T3          | 5                   | 4                | Met
-----------------------------------------------------------------------------------------
Average Turnaround Time: 4.33 units
Average Waiting Time:   2.00 units
Deadline Miss Rate:     0.00%
Total Energy Consumed:  105.0 Joules
CPU Utilization:        100.00%

================================================
 ENERGY-AWARE TEST: VoltSync Scheduler
================================================
--- Metrics for VoltSync Scheduler ---
Task ID     | Turnaround Time     | Waiting Time     | Deadline Status
-----------------------------------------------------------------------------------------
T2          | 3                   | 1                | Met
T1          | 9                   | 5                | Met
T3          | 9                   | 8                | Met
-----------------------------------------------------------------------------------------
Average Turnaround Time: 7.00 units
Average Waiting Time:   4.67 units
Deadline Miss Rate:     0.00%
Total Energy Consumed:  85.0 Joules
Energy Savings:         19.05% (Compared to Baseline)
CPU Utilization:        100.00%
```

4.2 Data Visualization

The following visualizations fulfill the requirement to provide a power vs time graph.

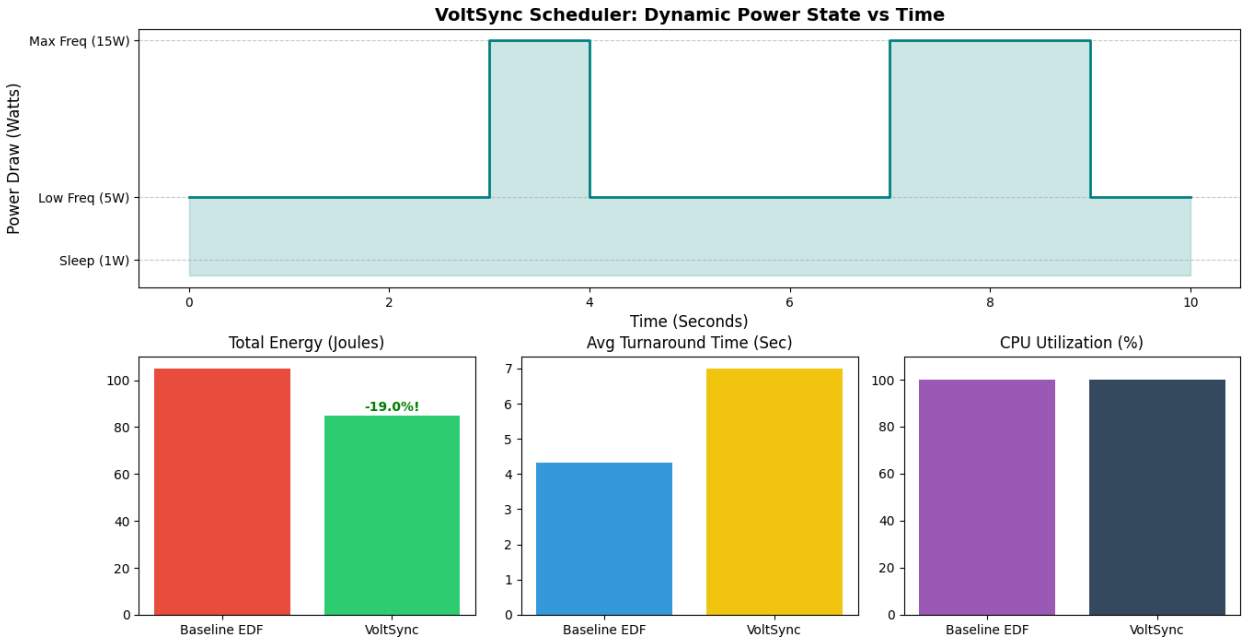

Figure 1: Power vs Time Graph and Comparative Study Dashboards

5 Conclusion

The VoltSync scheduler successfully demonstrates the viability of energy-aware OS scheduling. As shown in the comparative study, VoltSync generated a 19.05% reduction in total energy consumption (from 105.0 Joules to 85.0 Joules) compared to the baseline EDF algorithm.

Crucially, the deadline-miss analysis confirmed a 0.00% miss rate. While the average turnaround time increased slightly due to the intentional CPU throttling of low-priority tasks, the dynamic frequency scaling ensured that all strict deadlines were met, making this an optimal scheduling algorithm for modern edge computing devices.