V-EDGE: FAST SELF-CONSTRUCTIVE POWER MODELING OF SMARTPHONES BASED ON BATTERY VOLTAGE DYNAMICS

Fengyuan Xu, Yunxin Liu, Qun Li, and Yongguang Zhang
Introducing Power Model

- Power model - relationship between power draw & system activities
- It is foundation to power management & optimization
Introducing Power Model

- Power model - relationship between power draw & system activities
- It is foundation to power management & optimization

\[ F_{\text{cpu}}(30\%) + F_{\text{bl}}(150) + F_{\text{...}}(x) \ldots = 1400 \text{ mW} \]
Introducing Power Model

- Power model - relationship between power draw & system activities
- It is foundation to power management & optimization
How to Build Power Models?

- Power consumption
- Controlled resource usage

Input

Regression

Output

Models

<table>
<thead>
<tr>
<th>Resource usage</th>
<th>Power consumption</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampled CPU utilizations</td>
<td>Voltage</td>
<td>Linear</td>
</tr>
<tr>
<td>Sampled Screen backlight levels</td>
<td>Discharging current</td>
<td>Nonlinear</td>
</tr>
<tr>
<td>...</td>
<td>$P = V \times I$</td>
<td>...</td>
</tr>
</tbody>
</table>
Requirements of Power modeling

Every phone is unique  ➔  Personalized models

1. User activities are not expected
   In training stage
2. Model adaptation is needed
   ➔  Fast training
External Metering

- Measure $V$ and $I$ from external hardware
  - Calculate power from $V \times I$

- Drawbacks
  - Labor-intensive
  - Inflexible/inaccurate
  - Expert knowledge required

Monsoon power monitor

BattOr power monitor
Self Metering

- Measure $V$ and $I$ from interior battery interfaces
  - Battery interfaces are registers exposed by battery fuel gauge IC

- Disadvantage
  - A large number of existing phones cannot support, e.g., Galaxy Nexus
Self metering with SOD (State of Discharge)

- SOD: percentage of energy left in battery
- Calculate power from the SOD changes

Limitations
- Slow
  - There are only 100 discrete SOD values
  - Wait a long time period to observe value changes
- Inaccurate
Leverage battery characteristics

- Instantaneous current changes lead to instantaneous output voltage dynamics

![Diagram](image)
Battery Dynamics

- Discharging current changes lead to output voltage dynamics

\[ V_{\text{out}} = OCV - V_r = OCV - I \times R \]

Observed by battery interface

\[ \Delta I = \frac{1}{R} \times \Delta V_{\text{out}} \]

we can infer current from voltage dynamics
**Theory vs. Experiment**

- **V-edge**: voltage difference before and after an operation

\[ V_{\text{edge}} = V_1 - V_2 \]
V-edge is Accurate

- Stable linear relationship between V-edge and current change
  - Test on 8 batteries of two phones
  - Various current change cases
  - Coefficient of Determination $R^2 > 0.995$
V-edge is Fast and Sensitive

- Fast
  - As fast as battery interface update rate
    - E.g., on Nexus S, ¾ sec (V-edge) V.S. 15 min (SOD)

- Sensitive
  - Detect 4% CPU usage change with 100% success ratio

- Fine-grained V-edge resolution
V-edge Implementation

- training stage
- only needed in training stage
- estimation stage
Model Considered

- **CPU**
  - Frequency $f$ and utilization $U$
    - $P = a_f \times U + b_f$

- **Screen**
  - Backlight level $L$ and average pixel color $RGB$
    - $P = F(L) \times (c_r \times R + c_g \times G + c_b \times B)$

- **Wi-Fi**
  - Throughput $D$
    - $P = d \times D + e$

- **GPS**
  - Service status $S$
    - $P = f \times S$
Evaluation

- **Training overhead**
  - 400+ training programs ➔ 1.2 h building time
  - 100X faster than SOD

- **Accuracy**
  - Real energy consumption error
    - Stricter than model parameter comparison
  - Component model
    - Random benchmarks on CPU, screen, …
  - Real applications
    - Include video playback, VoIP call, web browsing …
Accuracy

Comparison:
• **G**: ground truth measurement
• **V,P**: estimations using models
  - **V**: V-edge
  - **P**: external-metering-based
Accuracy – CPU and Screen

The graph shows the normalized energy cost of different devices at various CPU frequencies. The graph compares the energy cost across different devices, with bars representing V-edge, power meter, and ground truth.

- **CPU**: The graph indicates that the energy cost varies with the CPU frequency, with higher frequencies leading to higher energy costs.
- **Screen**: Similarly, the energy cost for the screen also varies with frequency, though the pattern is not as pronounced as for the CPU.

The graphs suggest that at higher CPU frequencies, the energy cost increases significantly for both the CPU and the screen, with the ground truth showing the highest energy cost, followed by the power meter, and then the V-edge.
Accuracy – CPU and Screen

- error: V-edge error compared to ground-truth
- diff.: V-edge value difference compared to external-metering-based power modeling

Normalized energy cost

<table>
<thead>
<tr>
<th>Photo index</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>error</td>
<td>5.8%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>diff.</td>
<td>3.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Accuracy – WiFi, GPS, and Apps

- WiFi
- GPS
- Apps

Normalized energy cost

V-edge model, meter model, ground truth

GALLERY, BROWSER, ANGRY BIRDS, VIDEO, SKYPE, GPS STATUS

Real Apps
Accuracy – WiFi, GPS, and Apps

- WiFi: error 14%, diff. 3.8%
- GPS: error 10%, diff. 6.5%

For real Apps: error 10%, diff. 3.8%
Conclusions

- Key finding on battery powered devices
  - Current change can be determined from instantaneous voltage change

- A new self-constructive power model building with only V readings
  - Works for most phones
  - 100X faster than SOD method
  - Within 4% difference to models using external metering

- Evaluations demonstrated the effectiveness in power modeling
Thank you

- Any questions?