A Middleware Architecture for Mastering Energy Consumption in Internet of Things Applications

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Outline

1. Introduction

2. Mastering energy consumption with IoTvar

3. Conclusion and Future works
- IoT: identified as one among 5 main factors of TIC energy consumption growth [Ferreboeuf et al., 2021]

- 67 Zettabytes of data generated by IoT devices in 2020 [Ferreboeuf et al., 2021]

- IoT: Distributed systems

- Focus on **IoT Consumer applications**
  - Energy consumption of the interactions
- IoT middleware “*Software that resides between applications, services, and their underlying distributed architecture and platforms*” [Blair et al., 2016]
  - Manage the interactions between the components of an IoT system
  - Abstract and move the complexity from application to the middleware.

- **Proposal:** Introduce into an IoT middleware for consumer applications
  - **Energy efficiency:** strategies to reduce energy consumption
  - **Energy awareness:** energy consumption knowledge through an energy model
Objectives: energy concerns in IoT middleware

- **Energy efficiency**
  - Define strategies to be proposed by an IoT middleware to reduce the energy consumption of IoT consumer applications
  - Evaluate the (positive) impact in terms of energy consumption

- **Energy awareness**
  - Define an energy consumption model for the IoT interactions
  - At runtime: provide energy consumption estimations to IoT applications / end users
  - Manage an energy budget
Energy-efficiency in IoT middleware

Strategies

- **Network adaptation**
  - Protocols, interaction optimizations

- **Task offloading**
  - Transfer processes or data to other locations

- **Active node selection**
  - Nodes of a network (connected objects, cloud, fog, etc.) can be selected to process data

- **Machine Learning**
  - Build a model based on input data (network conditions, CPU load, etc.)

- **Data filtering**
  - Reduce the amount of transmitted data
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**What is the IoTvar middleware?**

**IoTvar**

middleware [Borges et al., 2023]

- Applications define
  - IoT variables with required refresh time
  - Maximum energy budget
- Proxy design pattern [Shapiro, 1986]
  - Manage the interactions between consumer IoT applications and IoT platforms
IoTvar architecture

- Platform specific
  - Discovery
  - API adaptation
  - Data model adaptation: Marshalling/unmarshalling

- Energy-efficiency/awareness handling

- Interaction handling (req/reply, pub/sub)

- Protocol handling (MQTT/HTTP)
### IoTvar outcomes

#### First outcome: reduce the development effort

<table>
<thead>
<tr>
<th>Interaction pattern</th>
<th>Lines of code With IoTvar</th>
<th>Lines of code Without IoTvar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous</td>
<td>15</td>
<td>450</td>
</tr>
<tr>
<td>Publish-subscribe</td>
<td>15</td>
<td>600</td>
</tr>
</tbody>
</table>

#### Second outcome: energy efficiency/awareness at the middleware level

- Energy efficiency and energy awareness is managed by the middleware and shared by applications
Results of experiments concerning IoT protocols and interaction patterns

- Energy consumption of IoT consumer applications [Canek et al., 2022]

- **Impact on energy consumption** for different interaction (patterns and protocols):
  - For the same update frequency, Pub/sub has lower energy consumption than req/rep (around 92% lower)
    - Favor the Publish-Subscribe interaction pattern
  - Payload has a low impact on energy consumption: x10 payload (from 24 to 3120 bytes) ~ 9% overhead
    - Group several variables in one message

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1Dell notebook i7-8665U CPU at 1.90GHz, with 32GB of volatile memory, OS Debian v9, Wifi network
Strategies

- Group several variables in one message
- Adapt refresh-time to network status
- Adapt refresh-time to energy budget
- Choose the best interaction pattern according to the refresh-time and notification frequency
## Message grouping

- **Group** several sensor observations in one message
  - **Increase** the payload sent in each request
  - **Decrease** the number of interactions
IoTvar interaction energy model

\[ E = \sum_{i=0}^{n_{bG}} \left( C_V \times n_{bV_{Gi}} \right) + \left( C_{net} \times M_{netS} \times M_{netI} \right) + C_{cpu} \]

- Constants for the experiments on a laptop with a wifi interface\(^2\)
  \[ E = \sum_{i=0}^{n_{bG}} \left( 0,02 \times n_{bV_{Gi}} \right) + \left( 90 \times M_{netS} \times 10 \right) + 87 \]

- \( n_{bG} \): Number of groups
- \( n_{bV_{Gi}} \): Number of variables inside a group;
- \( R_{Gi} \): The refresh time of a group in seconds;

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1\(^{\text{Dell notebook i7-8665U CPU at 1.90GHz, with 32GB of volatile memory, OS Debian v9, Wifi network}}\)
Test at the method level with aspect weaving using and not using the energy-efficient strategies

Objective: measure interaction energy consumption

- **Without** IoT middleware
- With IoT middleware (without energy efficiency strategies)
- With energy efficient IoT middleware
IoTvar energy consumption experiments

- Each point is the energy used in Joules during a 5 minute testing.
- Without energy efficiency strategies, middleware has a cost (orange above blue).
- Middleware with efficiency strategies lowers the energy usage (up to 45% less with 200 grouped variables) (green under blue).
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Conclusion and Future works

Conclusion

■ Energy efficiency

- IoT middleware can help to reduce development complexity while introducing energy-efficiency and energy-awareness into IoT application
- Clear difference between **using and not using** the energy-efficient strategies shown through an experimentation with statistical analysis
  - Maximum percentage change of around 45% **less** energy consumption
  - For a regular laptop battery with around **360 KiloJoules**:
    - Energy-efficient strategies could lead to a lifetime of around **31 hours**
    - Without the strategies: **16 hours** of battery

■ Energy awareness

- Energy interaction model: used to **estimate the energy consumption** of the middleware
- Energy budget: **Automatically** modify the refresh time to **balance** the consumption based on the required budget
Lessons and limitations

- Model constants are specific to a given computer hardware
  - Experimental measures have to be redone for each computer/network interface
- Depends on the availability of message grouping on the IoT platform
- What is the part of CPU cost in the interaction cost?
Future works

- Put the stress on energy awareness
  - Keep the users in the loop
  - Keep the developers in the loop

- Support distributed applications efficiency and enable IoT middleware-level cooperation to provide energy-awareness in a multi-component system.


