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

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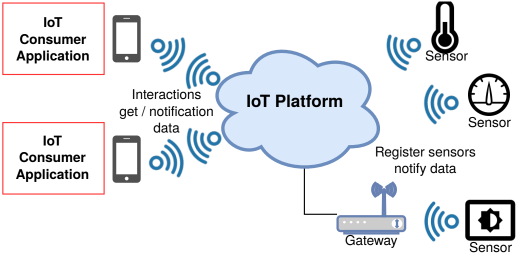
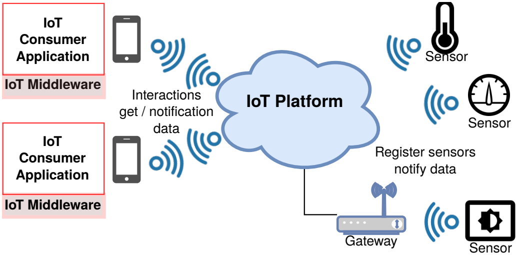
Outline

Introduction



- 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

Middleware Proposal



- 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

Outline

1. Introduction

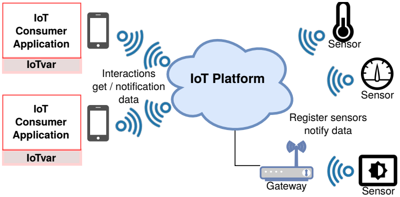
2. Mastering energy consumption with IoTvar

3. Conclusion and Future works

What is the IoTvar middleware?

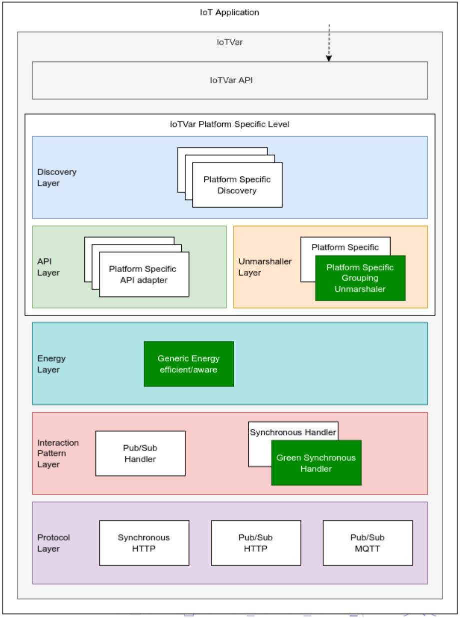
IoTvar
middleware [Borges et al., 2023]

- 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

Interaction pattern	Lines of code	
	With IoTvar	Without IoTvar
Synchronous	15	450
Publish-subscribe	15	600

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[1]

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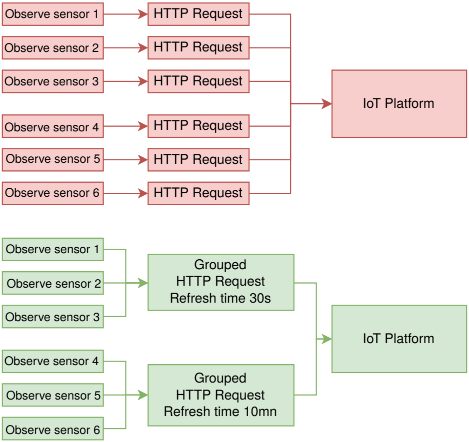
[1] Dell notebook i7-8665U CPU at 1.90GHz, with 32GB of volatile memory, OS Debian v9, Wifi network

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

$$E = \sum_{i=0}^{nb_G} \frac{(C_V * nb_{V_{G_i}}) + (C_{net} * M_{netS} * M_{netI}) + C_{cpu}}{R_{G_i}}$$

- Constants for the experiments on a laptop with a wifi interface[2]

$$E = \sum_{i=0}^{nb_G} \frac{(0,02 * nb_{V_{G_i}}) + (90 * M_{netS} * 10) + 87}{R_{G_i}}$$

- nb_G: Number of groups
- $nb_{V_{G_i}}$: Number of variables inside a group;
- R_{G_i}: The refresh time of a group in seconds;
- M_{netS}: Network status modifier;
- M_{netI}: Network interface modifier (WiFi, Ethernet, 5G . . .);

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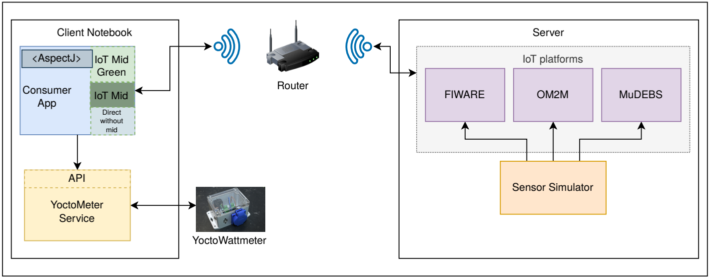
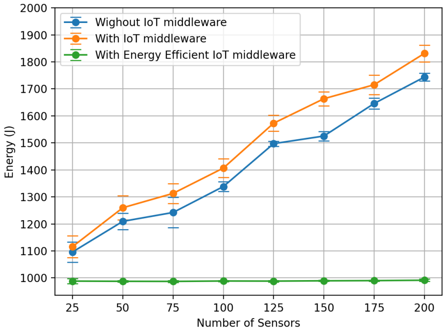
[1] Dell notebook i7-8665U CPU at 1.90GHz, with 32GB of volatile memory, OS Debian v9, Wifi network

Evaluation: Environmental setup



- 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)

Outline

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.

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