Pro-Energy: a novel energy prediction model for solar and wind energy-harvesting Wireless Sensor Networks

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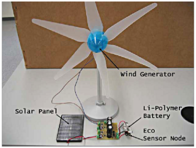
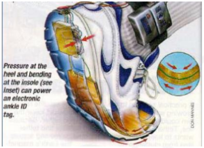
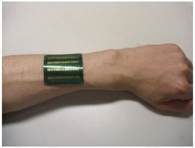
Energy Harvesting Wireless Sensor Nodes

Wireless motes that are capable of extracting energy from the environment and converting it into usable electrical energy.







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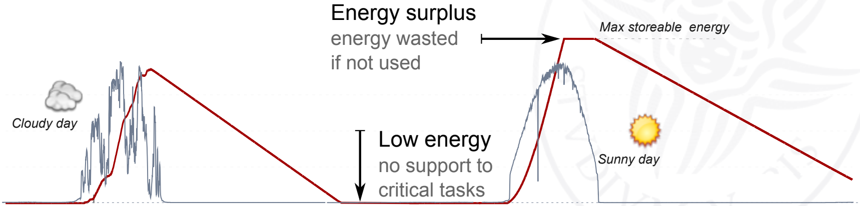
- ✔ Virtually unlimited lifetime to WSNs
- ✗ Energy availability is uncertain in time and value
- ▶ New challenges for harvesting-aware power-management

Why energy harvesting predictions?

- Energy predictions to mitigate uncertain energy availability
- Plan energy usage in advance: **proactive** vs reactive energy allocation
- Exploit available energy at best:
  1. Minimize the likelihood of running out of energy and missing high priority task
  2. Minimize the **waste** of energy (energy buffers limited in size and time)

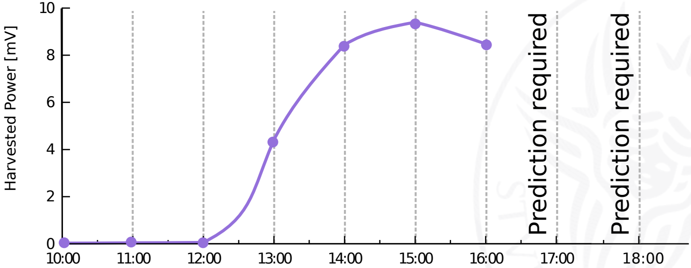


Outline

1. **Pro-Energy prediction algorithm**
2. Performance evaluation
3. Conclusion

Energy observations and predictions

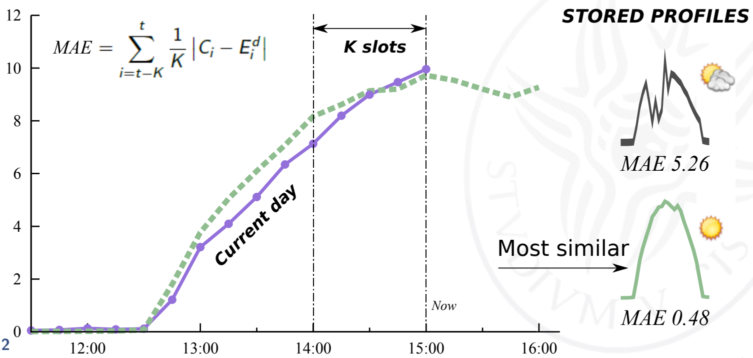
- Discretize each day into N equal lenght timeslots
- Periodically sample the current energy harvesting rate
- Perform predictions once per slot



0	0	0	4.8	8.7	9.8	8.6	???	???

Pro-Energy in a nutshell

- Keep track of energy profiles observed during D **typical** days
- Store traces representative of different weather conditions (sunny, windy, ...)
- Predict future energy intake by looking at the **most similar** stored profile



Pro-Energy energy predictions

At the beginning of timeslot t, provide energy predictions for timeslot $t + \delta$:

$$\hat{E}_{t+\delta} = (1 - \gamma_\delta) \cdot E^d_{t+\delta} \; + \; \gamma_\delta \cdot C_t$$

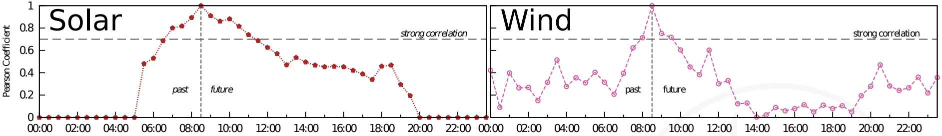
- δ prediction horizon
- C_t energy harvested during the current day at timeslot t
- $E^d_{t+\delta}$ energy harvested at timeslot $t + \delta$ during the stored day that is the most similar to the current day

Parameter γ_δ:

- Weighting factor balancing the contribution between stored profile and last energy observation
- Determines the influence of the last energy observation, adapt to current weather conditions
- Dynamically adapted to the required prediction horizon δ

Pro-Energy energy predictions

Influence of the last energy observation depends on correlation between energy harvested at time t and energy harvested at time $t + \delta$



- Correlation of the energy harvested at timeslot t and at timeslot $t + \delta$ decreases for increasing δ

G number of timeslots after which there is only little or no correlation with the current energy observation

- Linearly decreases the influence of the last energy observation for longer prediction horizons

$$\gamma_\delta = \begin{cases} \alpha \cdot \left(1 - \frac{\delta - 1}{G}\right) & \text{if } \delta \leq G \\ 0 & \text{if } \delta > G \end{cases}$$

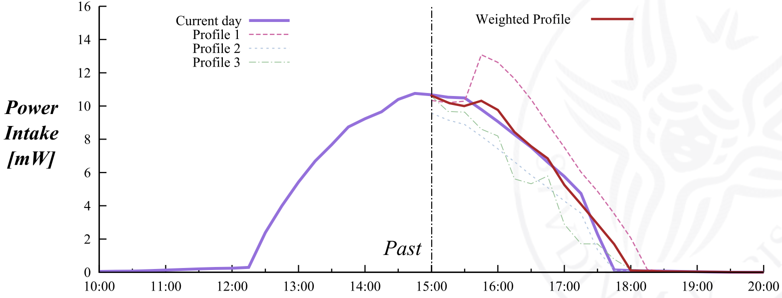
Improving predictions

- **Profile pool update**

Similarity Maintain only profiles representing different weather conditions

Aging Discard from the pool stored profiles that have become obsolete due to seasonal patterns

- **Multiple profiles combination** Combine multiple profiles together to account for possible different evolutions of the current day



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Benchmark energy prediction algorithms

- Exponentially Weighted Moving-Average (EWMA)

  Aman Kansal, Jason Hsu, Sadaf Zahedi, and Mani B. Srivastava.
  Power management in energy harvesting sensor networks.
  ACM Trans. Embed. Comput. Syst., 6(4):32, 2007.

  - simple, small overhead
  - significant prediction errors in mixed weather conditions
  - Assumption: energy harvested at time *t* during current day similar to energy harvested during the same timeslot in the past days

- Weather-Conditioned Moving Average (WCMA)

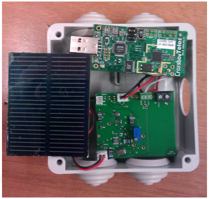
  Joaquin Recas Piorno, Carlo Bergonzini, David Atienza, and Tajana Simunic Rosing.
  Prediction and management in energy harvested wireless sensor nodes.
  Proc. of Wireless VITAE 2009, Aalborg, Denmark, May 17-20, 2009, pp. 6–10.

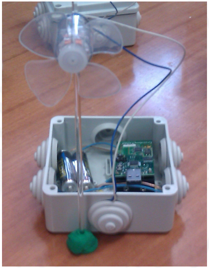
  - adapts well to frequently changing weather conditions
  - prediction error increases for longer prediction horizon

Solar and wind datasets

Real-life energy traces

- Telos B motes interfaced with solar cells and wind micro turbines
- Deployed outdoor: variable weather conditions, different locations
- Collecting data for up to 75 days





Other datasets

- Solar and wind traces from the National Renewable Energy Laboratory
- 90 days, one measurement per minute

Performance metric

- For each timeslot we compare the amount of energy predicted with the energy actually harvested
- Prediction error calculated as Mean Absolute Percentage Error (MAPE):

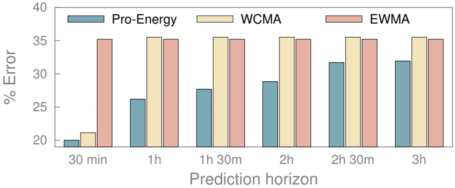
$$MAPE = \frac{1}{T} \sum \left| \frac{\overline{e}_t - \widehat{e}_t}{\overline{e}_t} \right|,$$

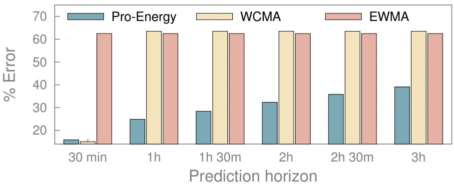
$\widehat{e}_t$ energy predicted for timeslot t;

$\overline{e}_t$ actual energy harvested during timeslot t;

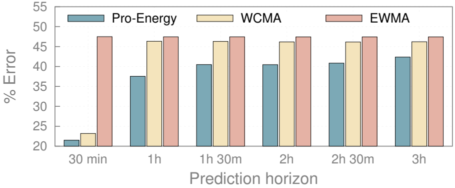
T total number of timeslots over which the error is computed.

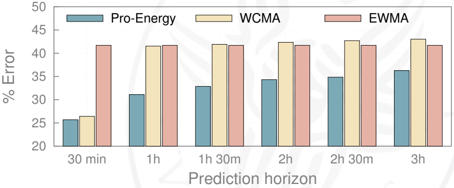
Prediction error for different forecasting horizons





Solar energy predictions: Pro-Energy performs up to **75% better** than EWMA and **60% better** than WCMA





Wind energy predictions: Pro-Energy performs up to **55% better** than EWMA and **10% better** than WCMA

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Conclusion

- Energy prediction algorithms allow to optimize harvesting-aware power-management
- Pro-Energy provides accurate estimation of future energy availability
- Targeting both solar and wind harvesting WSNs
- Allows to dynamically choose the time horizon of forecasting based on application needs
- Performs up to 75% better than SoA prediction algorithms

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