An Adaptive Data Forwarding Scheme for Energy Efficiency in Wireless Sensor Networks

IEEE Intelligent Systems 2010

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The problem

- Wireless Sensor Networks (WSN): a large number of nodes equipped with sensing communication and minimal computation capabilities.
  - Contextual data are collected by WSN towards a **sink**.
- Nodes have very limited resources, e.g., energy, computational power, data storage and bandwidth,
  - Hence, it is not a sound technical decision to forward **any** sensor data directly to a sink that does the corresponding processing.
- Concept: Take into consideration the **nature** of the sensed data in order to avoid significant energy consumption due to data transmission and improve bandwidth utilization.

The concept

- Each node **decides** whether to propagate the receiving data or not.

- A node i receives a new piece of data $p(t)$ at time t.
- The node i can
  - **either** forward $p(t)$ to a node j in the upstream path
  - **or** send a signal $u(t) \in \{0, 1\}$ to node j to reproduce the $p(t)$ value **without**, explicitly, receiving it.

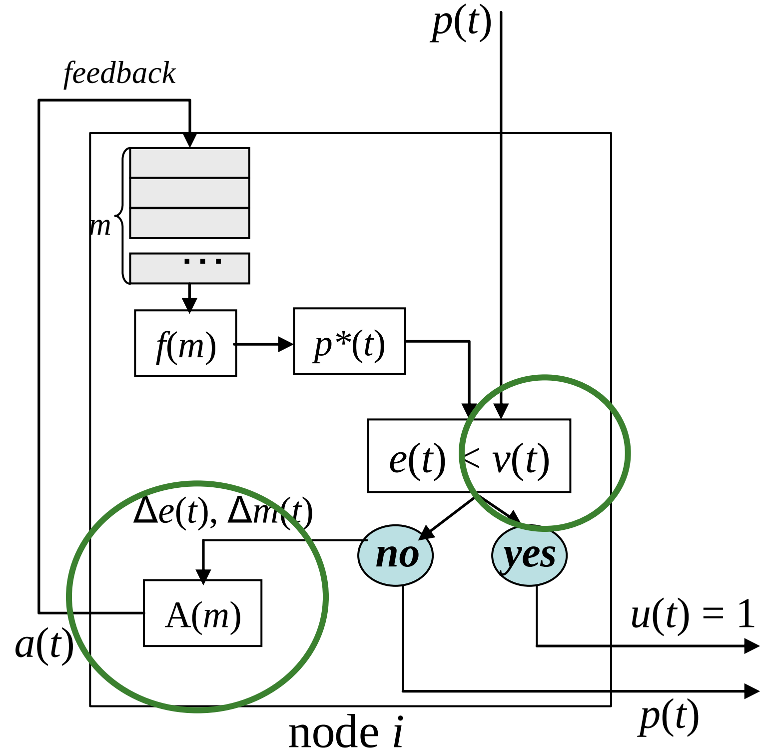
- The node i calculates an **extrapolated** value $p^*(t)$ for the piece of data $p(t)$ based on the previous m received measurements $p(t-m), \ldots, p(t-1)$, $m > 0$.
- The extrapolation scheme $f(m)$ **depends on such** m **values** (Lagrange Polynomial, Local Linear Regression)
- The reconstruction error $e(t) = p(t) - p^*(t)$ is obtained.
- The estimated **error level** is the decision on forwarding $p(t)$.

- If data is **not** transmitted upstream, then the node j performs the same extrapolation calculation f and considers the **locally** estimated $p^*(t)$ as the **new** received measurement.

m history length adaptation *error level* estimation

- m is **not a-priori known** and there is **no knowledge** about the received data distribution.
- At time $t+1$ the value of m is based on:
  - the reconstruction error $e(t)$,
  - the change in error $e(t)$ ($\Delta e(t) = e(t) - e(t-1)$)
  - the previous decision on m ($\Delta m(t) = m(t) - m(t-1)$)
- The **adaptation rule** is
  - $m(t+1) = m(t) + a(t)$, $a(t) \in \{-1, 0, 1\}$
- The controller A(m) produces $a(t)$ that minimizes $e(t)$ of the extrapolation.

- If $\Delta e < 0$, then we should **reward** the **past** decision on m since there is an improvement depicted by the negative change in error.
- a represents a reward on the previous decision Δm. That is,
  - if $\Delta m(t) = 1$, we should increase m ($a = 1$);
  - Otherwise, we should decrease m ($a = -1$).



The error level $v(t)$ is based on the **current** standard deviation $s(t)$ of the received data.

- High $s(t)$: High frequencies in the data stream: $f(m)$ has to be very precise to capture such high frequencies
- Low $s(t)$: Low variability in the data stream, thus, a relaxation of $v(t)$ can be obtained.

$$v(t) = b/s(t),\ b \in (0, 1].$$

Performance assessment

- The Adaptive Data Forwarding (ADF) is compared against the Simple Data Forwarding (SDF) that simply forwards all received data.
- Real data streams of **temperature** and **wind speed** data sampled at 1Hz;
- Adopt the **Mica2** energy consumption model (a pair of AA batteries, 3V), the packet header is 7 bytes (MAC header+ CRC) and the preamble overhead is 20 bytes.
- The temperature and wind speed data payload is **4 bytes** (float) and the signal u is only **one bit**.

Performance assessment

- Incorporation of the energy cost for implementing LLR, LP and A(m).
- The **total cost** $c(t)$ in Joule at time t for a node is accumulated as:

$$cc(t) = c(t-1) + c\mathrm{R}(t) + c\mathrm{T}(t) + c\mathrm{I}(t) + c0(t)$$

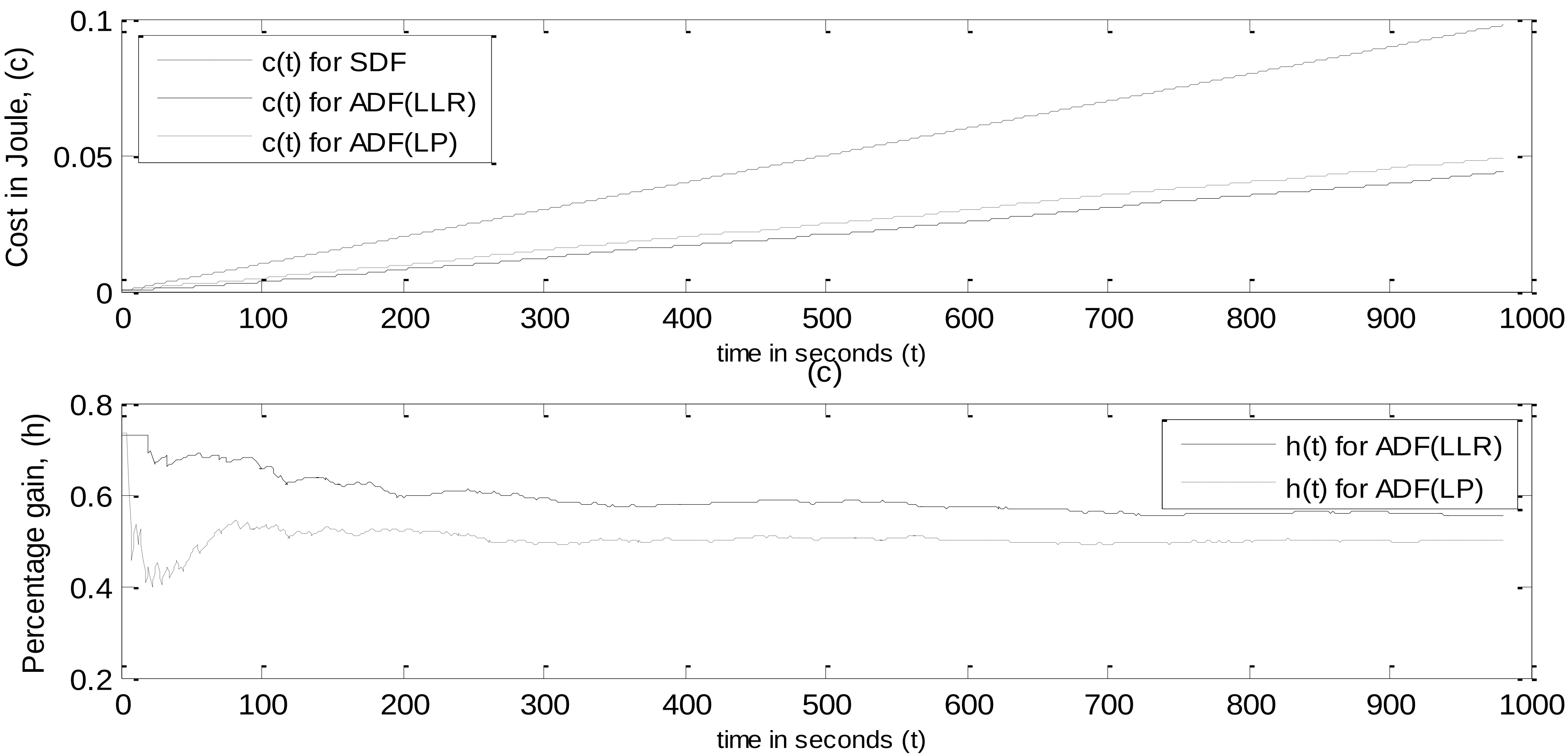
- $c\mathrm{R}(t)$, $c\mathrm{T}(t)$ are receive (rx) and transmit (tx) costs either for data $p(t)$ or for signal $u(t)$, respectively, and $c\mathrm{I}(t)$ is the energy **cost for the CPU** instructions of $f(m)$ mechanism. $c0(t)$ is the state transition cost for node i.
- We conserve energy once the $c\mathrm{R}(t) + c\mathrm{T}(t)$ cost **refers more to signal transmissions** rather than to **data transmissions** at the expense of additional $c\mathrm{I}(t)$ and data accuracy.
- The percentage cost gain $h(t) \in [0, 1]$ when applying ADF w.r.t. SDF is

$$h(t) = \frac{c_{\mathbf{SDF}}(t) - c_{\mathbf{ADF}}(t)}{c_{\mathbf{SDF}}(t)}$$

Percentage energy gain

•We obtain 48.6% and 57.1% **increase** in the life time of the network, respectively for ADF(LP) and ADF(LLR).

•ADF(LLR) (ADF(LP)) **replaces** 81% (72%) of the transmitted messages with data reconstruction signals ($u(t)$) between nodes.



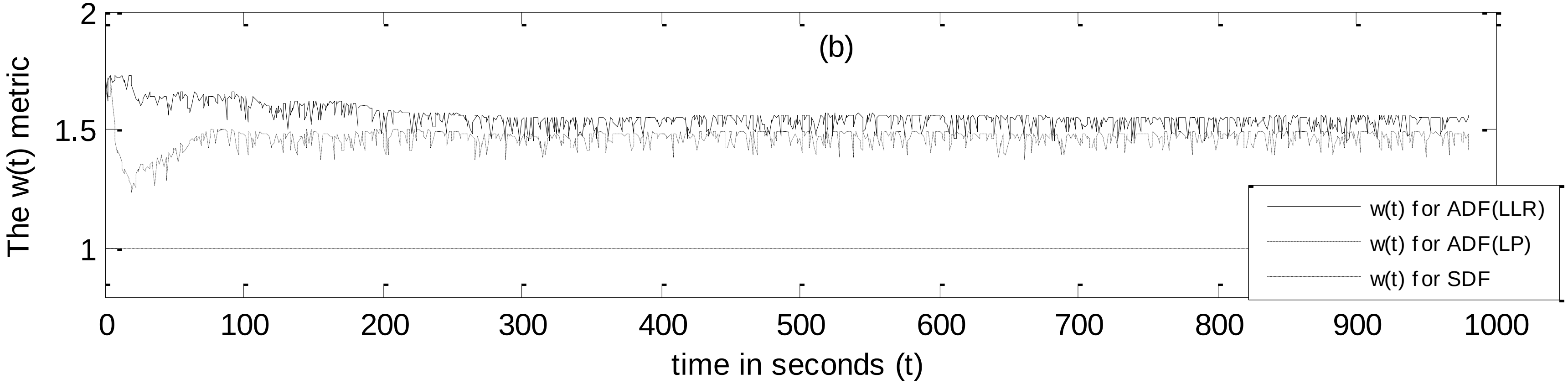
Holistic metric

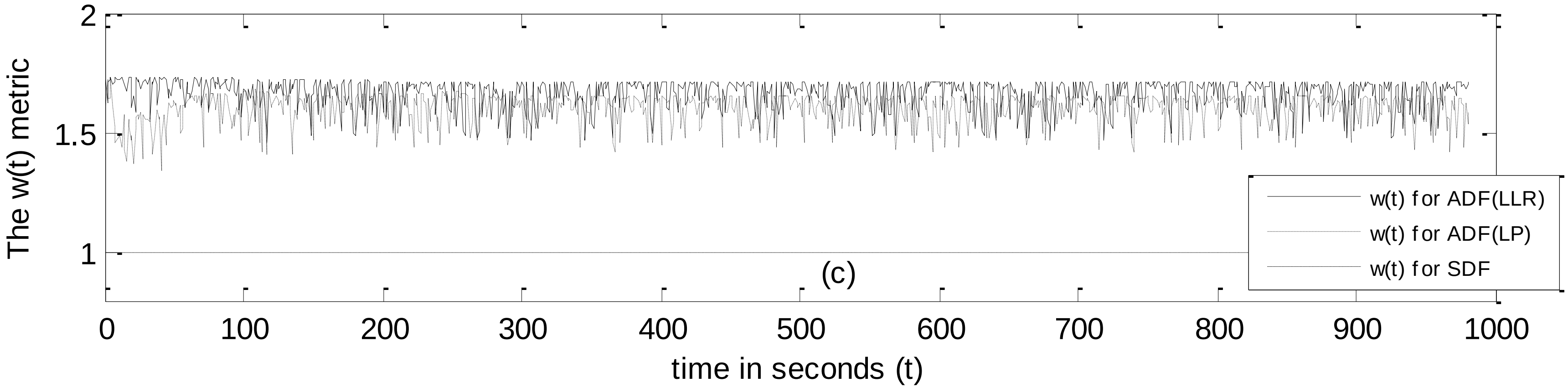
- We have to assess the benefit of ADF by taking into account **both** the **energy savings** and the **induced reconstruction error**.
- We define the metric $w(t) \in [0, 2]$ which combines the percentage of gain $h(t)$ **and** the relative reconstruction error:

$$w(t) = h(t) + \left| \frac{p(t)}{p(t) + e(t)} \right|$$

- $w(t)$ should get values close to 2, i.e., **promote energy efficiency** ($h(t) \to 1$) **with minimum error** ($e(t) \to 0$).
- For the SDF forwarding scheme we obtain $w(t) = 1$.

Holistic metric





- The ADF model assumes $w = 1.58$ and $w = 1.7$ for $b = 0.3$ and 0.5, respectively, w.r.t SDF model ($w = 1$).
- A low b value indicates that the WSN application has strict requirements for reproducing the data stream through estimations.

- **ADF prolongs the network life time while keeping reconstruction error at very low levels**

Future directives

- Include intelligent dimensionality **reduction** schemes.
  - Such schemes may significantly reduce the upstream communication requirements by transmitting **only** the **basic** components of a vector of values to the upstream node and **not** all the values.

Thank you.

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