
Anh-Dung Phan, Michael R. Hansen and Jan Madsen
Energy-harvesting-aware WSNs

- Thesis: protocols can be defined by (certain kinds of) many-sorted algebras
Energy-harvesting-aware WSNs

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- Behaviour of nodes and network is specified on that basis
Energy-harvesting-aware WSNs

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- Behaviour of nodes and network is specified on that basis

- Software is systematically derived from the specification
Overview

- Motivation
- A semantic framework capturing energy-harvesting-aware routing
- Simulation-based analysis of three protocols
- Conclusion
A WSN scenario

Purpose: To route observations from nodes to the base station.

Assumption: Node are zero-power devices with a solar panel
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Goal: To keep the node of the network alive as long as possible so that as many observations as possible reach the base station.
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Challenge: A dynamic adaption of routes avoiding that nodes on “bottleneck routes” get drained.
Some observations

- Nodes may be drained from energy, observations are lost.
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- Consistent use of shortest paths will drain critical nodes rapidly.
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- Consistent use of shortest paths will drain critical nodes rapidly.
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  Exchange of information consumes energy
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- Consistent use of shortest paths will drain critical nodes rapidly.
- Harvested energy at a fully charged node is free of charge.
- Minimization of energy consumption is not a goal.
- Knowledge of the state of other nodes can improve the routing.
- Exchange of information consumes energy.

The routing should adapt to dynamic changes of the available energy.
Some questions about the “global” behaviour

We search for answers to the following questions:

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- Will the network get fragmented (permanently)?
- What is the routing trend from the nodes?
- Will drained nodes get a chance to recover?

It is difficult to give clear-cut answers
they are “weather dependent”
An protocol example

Distributed Energy Harvesting Aware Routing

- An observation is forwarded to a neighbour with shorter distance to the base station

\[
\text{distance} = \text{simpleDistance} + \text{energyDeficit} + \text{energyFaithfulAdjustment}
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Fig. 5. DEHAR protocol with consistent nodes using energy-faithful adjustments
An protocol example

Distributed Energy Harvesting Aware Routing
- An observation is forwarded to a neighbour with shorter distance to the base station
- node $e$ is inconsistent using $\text{simpleDistance} + \text{energyDeficit}$

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Fig. 5. DEHAR protocol with consistent nodes using energy-faithful adjustments
Distributed Energy Harvesting Aware Routing

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The deficits of \( f \) and \( g \) influence the routing of (non-neighbour) \( d \)

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\text{distance} = \text{simpleDistance} + \text{energyDeficit} + \text{energyFaithfulAdjustment}
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Fig. 5. DEHAR protocol with consistent nodes using energy-faithful adjustments
Focus of this work

A generic modelling framework energy-harvesting-aware WSN

- Nodes (Basic operations, energy, cost-functions)
- Energy-harvesting aware routing
- Network (topology)
- Environment (energy harvesting, observation, communication medium)

Goal: A broad class of protocols can be modelled and analyzed
Focus of this work

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- A protocol is specified as a certain many-sorted algebra
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- A protocol is specified as a certain many-sorted algebra
- Underlying semantics is a labelled transition system
- Analysis is so far supported by discrete-event simulations
Some background

- Discrete-event simulation:
  Avrora (Cycle-accurate instruction-level)  Titzer et al 2005
  GLONEMO (ReactiveML) Addresses some global properties.
  Addresses energy consumption.      Samper et al 2006
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- Model-checking
  Real-Time Maude: Optimal Geographical Density Control algorithm for WSNs ÖIveczky et at. 2009
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These approaches address energy consumption but not energy production (harvesting)
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- Model-checking
  HyTech: Safety properties of a single node. Simulation of a network. \cite{Coleri2002}
  Real-Time Maude: Optimal Geographical Density Control algorithm for WSNs \cite{Oliveczky2009}
  ...  

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- Energy harvesting is typically studied by empirical approaches.

We have also experimented with verification using Uppaal and Uppaal SMC.
A Generic Modelling Framework
A Generic Modelling Framework

Environments:

- $id, t \vdash_O d, o$, where $t, d \in \mathbb{R}_{\geq 0}$: Node $id$ can make the observation $o$ at time $t + d$.

- $id, t \vdash_H d, ps$, where $t, d \in \mathbb{R}_{\geq 0}$: Node $id$ has physical state $ps$ at time $t + d$.

- $\bar{s}, id \vdash_M id'$: Node $id'$ can receive a message from $id$ in the network state $\bar{s}$.
A Generic Modelling Framework

Environments:
- \( id, t \vdash_o d, o \), where \( t, d \in \mathbb{R}_{\geq 0} \): Node \( id \) can make the observation \( o \) at time \( t + d \).
- \( id, t \vdash_h d, ps \), where \( t, d \in \mathbb{R}_{\geq 0} \): Node \( id \) has physical state \( ps \) at time \( t + d \).
- \( \bar{s}, id \vdash_M id' \): Node \( id' \) can receive a message from \( id \) in the network state \( \bar{s} \).

Basic interactions of a node \( id \):

A node \( id \) can broadcast a message \( m \in \text{Msg} \): \( \text{send}_{id}(m) \).

A node \( id \) can react to the following input events:
- Sample the physical state: \( \text{samplePS}_{id} : S_{id} \times \text{PhysState} \rightarrow S_{id} \)
- Sense observation: \( \text{senseObs}_{id} : S_{id} \times \text{Observation} \rightarrow S_{id} \)
- Receive message: \( \text{treatMsg}_{id} : S_{id} \times \text{Msg} \rightarrow S_{id} \)

The semantics of a network (a LTS) is established on that basis.
### Fundamental types and operations of a Node

<table>
<thead>
<tr>
<th>Symbol</th>
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</tr>
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<tr>
<td>$o \in \text{Observation}$</td>
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<tr>
<td>$ps \in \text{PhysState}$</td>
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<td>$m \in \text{Msg}$</td>
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<td>observation message with node $dst \in \text{Id}$ as destination</td>
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next : CompState → Id
updateEnergyState : CompState × PhysState → CompState
updateRoutingState : CompState → CompState
consistent? : CompState → {true, false}
abstractView : CompState → AbsState
updateNeighbourView : CompState × Id × AbsState → CompState
transmitChange? : CompState × CompState → {true, false}

Property: consistent?(updateRoutingState(cs))
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### Operations

- **next**: $\text{CompState} \rightarrow \text{Id}$
- **updateEnergyState**: $\text{CompState} \times \text{PhysState} \rightarrow \text{CompState}$
- **updateRoutingState**: $\text{CompState} \rightarrow \text{CompState}$
- **consistent?**: $\text{CompState} \rightarrow \{\text{true, false}\}$
- **abstractView**: $\text{CompState} \rightarrow \text{AbsState}$
- **updateNeighbourView**: $\text{CompState} \times \text{Id} \times \text{AbsState} \rightarrow \text{CompState}$
- **transmitChange?**: $\text{CompState} \times \text{CompState} \rightarrow \{\text{true, false}\}$

### Property:

$$\text{consistent?}(\text{updateRoutingState}(cs))$$

with associated cost functions: $\text{costf} : \text{PhysState} \rightarrow \text{PhysState}$
The generic behaviour of node $id$

- Input events are defined by function composition
- The must preserve the consistency of the computational state

\[
samplePS_{id}((cs, ps), ps') = \cdots
\]
\[
senseObs_{id}((cs, ps), o) = \cdots
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The generic behaviour of node \( id \)

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\begin{align*}
samplePS_{id}((cs, ps), ps') &= \cdots \\
senseObs_{id}((cs, ps), o) &= \cdots \\
treatMsg_{id}((cs, ps), m) &= \text{case } m \text{ of} \\
&\quad \text{obsMsg}(dst, o) \rightarrow \text{TreatObsMsg}_{id}(dst, o, cs, ps) \\
&\quad \text{nbMsg}(src, as) \rightarrow \text{TreatNbMsg}_{id}(src, as, cs, ps)
\end{align*}
\]

where \( \text{TreatObsMsg}_{id}(dst, o, cs, ps) = \)
\[
\begin{cases}
    \text{if } id \neq dst & \text{then } (cs, ps) \\
    \text{else } \text{initSend}_{id}((cs, \text{costSend}($\text{costNext}(ps)$)), \text{obsMsg}(next(cs), o))
\end{cases}
\]

and \( \text{TreatNbMsg}_{id}(src, as, cs, ps) = \)
\[
\begin{align*}
    &\text{let } cs' = \text{updateNeighbourView}(cs, src, as) \\
    &\text{let } cs'' = \text{updateRoutingState}(cs') \\
    &\text{let } ps' = \text{costUpdateNeighbourView}(\text{costUpdateRoutingState}(ps)) \\
    &\text{if } \neg \text{transmitChange}(cs, cs'') \wedge \text{consistent}(cs', ps') \text{ then } (cs', ps') \\
    &\text{else } \text{let } m = \text{nbMsg}(id, \text{abstractView}(cs'')) \\
    &\quad \text{initSend}_{id}((cs'', \text{costSend}(\text{costAbstractView}(ps'))), m)
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A discrete-event simulator is implemented in F#
Three protocols

Directed Diffusion (DD):
- Uses shortest path (no of hops) only

Intanagonwiwat et al 2003 reference model

![Diagram of network nodes and base station with shadow areas]

- Node
- Base station
- Strong shadow
- Light shadow
Three protocols

Directed Diffusion (DD): Intanagonwiwat et al 2003
- Uses shortest path (no of hops) only reference model

- A neighbour with a shorter distance is chosen probabilistically based on energy levels of immediate neighbours.
Three protocols

Directed Diffusion (DD):
- Uses shortest path (no of hops) only

Energy-Aware Routing (EAR):
- A neighbour with a shorter distance is chosen probabilistically based on energy levels of immediate neighbours.

Distributed Energy-Harvesting-Aware Routing (DEHAR):
- routing is based on energy levels and faithful adjustments

\[
\begin{array}{c|c|c|c|c|c|c|c}
\hline
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & & & & & & & \\
2 & \times & & & & & & \\
3 & & & & & & & \\
4 & & & & & & & \\
5 & & & & & & & \\
6 & & & & & & & \\
7 & & & & & & & \\
\hline
\end{array}
\]

- Node
- Base station
- Strong shadow
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Intanagonwiwat et al 2003
Shah et al 2002
Experiments: Settings

- Simulation time: 720 hours (30 days)
  A day consists of 12 hours full light and 12 hours of no light
  Light shadow: 75% harvesting. Dark shadow: 25% harvesting.

- Observations (\(\overline{O}\)). Mean: 900 s. Standard derivation: 10s

- Energy sampling (\(\overline{H}\)). Mean 1800 s. Standard derivation 10s

The protocols are using the same uniform cost functions.
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- DEHAR harvest about 50% more energy than DD and about
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- DD protocol drained $1.5 \times$ as many nodes as EAR did and $3.5 \times$ as many as DEHAR did.
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- DD protocol drained $1.5 \times$ as many nodes as EAR did and $3.5 \times$
  as many as DEHAR did.

- Drained nodes recovered in DEHAR experiments.
  This was not observed for DD and EAR.
Experiments: Energy Levels

Figure: All experiments at $t = 0$

Figure: DD nodes at $t = 720h$
Experiments: Energy Levels

Figure: All experiments at $t = 0$

Figure: DD nodes at $t = 720h$

Figure: EAR nodes at $t = 720h$
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Figure: DD nodes at $t = 720h$

Figure: EAR nodes at $t = 720h$

Figure: DEHAR nodes at $t = 720h$
Experiments: Routing Trends

DEHAR nodes at $t = 720h$:

Figure: Amount of messages

- detour is taken (with advantage)
- messages are lost
- drained nodes recover

Figure: Routing trends
Conclusion

Summary:

- A conceptual framework for studying energy-harvesting-aware protocols
- Analysis based on discrete-event simulation
- Simple analysis of three routing protocols
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Next:
- more case studies and experiments (protocols)
- formal verification (e.g. statistical model checking)
  - Real-time Maude, PAL, Uppaal, Cyber-application framework,