

Towards Practical Debugging of Wireless Sensor Networks

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CS407: Fourth Year Project

10–11AM Tuesday 7th May 2013

What is a Wireless Sensor Network

A wireless sensor network (WSN) is a collection of computing devices called motes, they have:

- a short range wireless radio
- an array of sensors such as light, heat and humidity
- a simple low powered CPU
- a battery with limited power supply

Motes communicate with each other to form a WSN. WSNs perform data gathering tasks such as environment monitoring.

The Problem of Debugging Distributed Systems

- Multiple tasks running simultaneously leads to non-deterministic interactions
- Traditional debugging tools are unsuited
- Timing and synchronisation issues

Complications to the Problem

- Motes are energy constrained
- Sending messages is the most expensive task
- Receiving messages is the next most expensive task [Shnayder et al., 2004]
- Motes have low computing power and a small memory
- WSNs deployed in hard to reach areas — physical access after deployment is difficult [Herbert et al., 2007]

- Global Predicate Detection [Garg and Waldecker, 1996]
- H-SEND [Herbert et al., 2007]
- NodeMD [Krunic et al., 2007]
- TinyOS [Levis et al., 2005], Contiki

Project Aims

- Develop tools to aid in debugging distributed programs running on WSNs.
- Implement libraries that check predicates, with a focus on correctly evaluating these predicates.
- Investigate if there are places in the network where evaluation is more efficient.
- Visualise some of the state of the network, as part of a tool to inform system users what state the network is in.

- Matthew — Group Leader
- Amit — Technical Manager
- Everyone was involved with development and research
- Bitbucket.org Git repository

Implemented Libraries

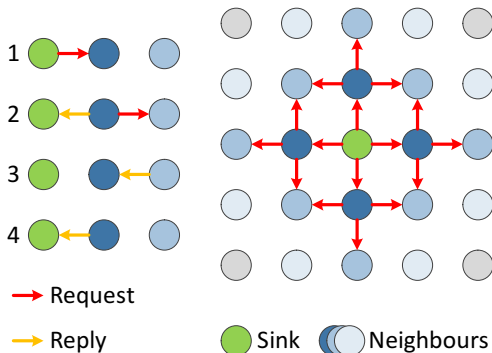
- Linked List
 - Ours: Standard linked list
 - Contiki's: Intrusive linked list
- Array List
- Unique Array
- Map
- Unit tests implemented for each

Benefits:

- Abstraction
- Reduced code duplication
- Simplified memory management

Implemented Libraries — N-Hop Request

- Used by predicate evaluation
- Floods request N hops away from sink
- Asks for mote's current state
- Returned along the chain created by the flooding stage



Implemented Libraries — N-Hop Flood

- Floods a given packet N hops
- Surprised that Contiki did not provide this as a library
 - Had to implement ourselves using TTLs in packet headers

Implemented Libraries — Event Update

- Used by predicate evaluation
- Periodically checks if node's data has changed
- If it has, floods the new data the required number of hops

Depends On:

- N-Hop Flood

Implemented Libraries — Multi-Packet Unicast

- Contiki packet size: 128 bytes
- This is too small for some of our data
- Alternative APIs Contiki implements are convoluted
 - Targeted towards sending file chunks
- We split packet up, send pieces and then reassemble

Implemented Libraries — Tree Aggregation

- ① Leaf node generates data, forwards to parent
- ② Parent waits for a period, aggregating received data
- ③ The node adds its own data to the aggregate
- ④ The node then forwards the message to its parent
- ⑤ Repeat until the aggregated message reaches the base station

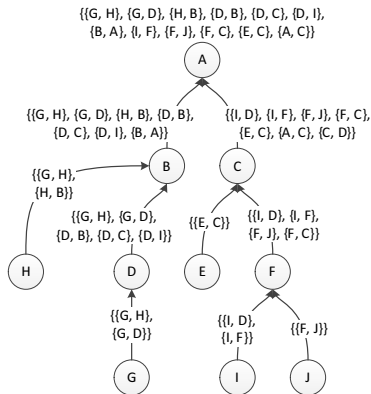
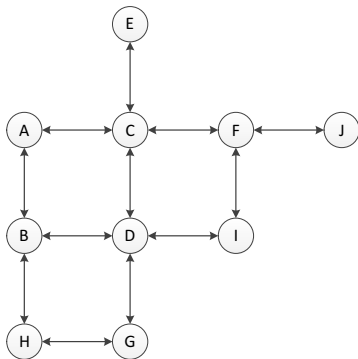
Again surprised that Contiki didn't have an implementation

Depends On:

- Multi-Packet

Implemented Libraries — Neighbour Detection

- To debug a WSN we need to know the network topology
- Uses Tree Aggregation to send neighbours to sink
- Contiki library does neighbour detection



Predicate Evaluation

Predicate Evaluation

- 1 Disseminate predicate to network
- 2 Evaluate predicate
- 3 Return response to base station

Consider:

- Where to evaluate: Local vs. Global
- When to propagate mote data: Periodic vs. Event
- How to respond to a failure or success

Predicate Evaluation — Libraries I

	Periodic	Event
Local	<p>PELP</p> <ul style="list-style-type: none">• Evaluated in-network• Data is requested when needed to evaluate predicate• Previous round's data is forgotten after a round completes	<p>PELE</p> <ul style="list-style-type: none">• Evaluated in-network• Data is sent by data sources, when it changes• Data is never forgotten, simply updated

Predicate Evaluation — Libraries II

	Periodic	Event
Global	<p>PEGP</p> <ul style="list-style-type: none">• Similar to PELP, except data is aggregated to the base station• Predicate evaluation at base station	<p>PEGE</p> <ul style="list-style-type: none">• Similar to PELE, except data is aggregated to the base station• Predicate evaluation at base station

Predicate Evaluation — Libraries Used

	Periodic	Event
Local	<p>PELP</p> <ul style="list-style-type: none">• N-Hop Request	<p>PELE</p> <ul style="list-style-type: none">• Event Update<ul style="list-style-type: none">• N-Hop Flood
Global	<p>PEGP</p> <ul style="list-style-type: none">• Neighbour Detect• Tree Aggregation	<p>PEGE</p> <ul style="list-style-type: none">• Neighbour Detect• Tree Aggregation

Predicate Evaluation — Response

Failure

- Only predicate failures are reported to the base station
- Cannot say much about the network state, either:
 - we have not been informed of a failure
 - we have been informed
- We chose this one due to the reduced traffic

Failure and Success

- Both failures and successes are reported
- Supports detecting the network is in the following states:
 - Unknown
 - Failed
 - Succeeded
 - Failed and then later succeeded
- Uses more energy

Note: Global PE may as well take advantage of "Failure and Success" messages, as the target of them is the node the predicates are evaluated on

Predicate Evaluation — Evaluation

- Implemented a virtual machine in C to evaluate predicates on the nodes
 - Optimised for low memory environment
 - Opcodes for high-level operations to reduce program size
- Implemented a DSL with a JavaCC parser and a Java compiler and assembler
 - Functional language
 - Expects a boolean output

$$\forall n \in \text{Nodes}.$$
$$\forall n' \in \text{Neighbours}(n, 2).$$
$$\text{slot}(n) \neq \text{slot}(n')$$

```
[all]  
function 1 as slot returning int in  
    using Neighbours(2) as twohopn in  
        @(x : twohopn ~  
            slot(x) != slot(this)  
        )
```

$\forall n \in \text{Nodes}.$

$\forall n' \in \text{Neighbours}(n, 1) \cup \{n\}.$

$\forall n'' \in \text{Neighbours}(n, 1) \cup \{n\}.$

$\text{addr}(n') \neq \text{addr}(n'')$

$\implies \text{slot}(n') \neq \text{slot}(n'')$

[all]

```
function 0 as addr returning int in
function 1 as slot returning int in
  using Neighbours(1) as ohn in
    @(a : ohn ~
      @(b : ohn ~ addr(a) != addr(b)
        => slot(a) != slot(b))
      & slot(a) != slot(this)
    )
```

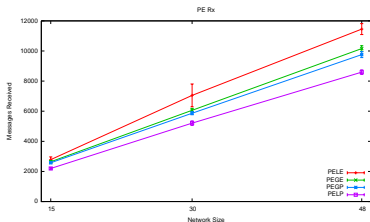

Predicate Evaluation — DSL

```
//TARGETING all      INEQ      //slot(a[*1])
//FUNC 0 AS addr     JZ end2    end2: VIF AFC 1 255 1
//FUNC 1 AS slot     //addr(a[*1]) //slot(this)
//STORING 1 IN ohn   VIF AFC 1 255 0 THISC 1
IVAR 1              //addr(b[*2]) INEQ
IPUSH 1             VIF AFC 2 255 0 AND
IPUSH 0             INEQ      AND
ISTORE 1            //slot(a[*1]) VIINC 1
start1: AL EN 255   VIF AFC 1 255 1 JMP start1
INEQ               //slot(b[*2]) end1: HALT
JZ end1            VIF AFC 2 255 1 //VD 1 = 255
IVAR 2            INEQ
IPUSH 1           IMPLIES
IPUSH 0           AND
ISTORE 2          VIINC 2
start2: AL EN 255 JMP start2
```

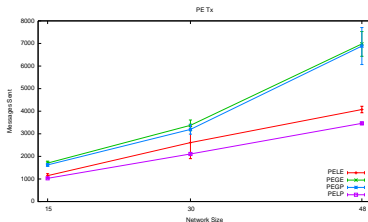
Results

- Run and measure energy usage of TDMA algorithm
- Measure energy cost of predicate evaluation algorithm
 - Checking for slot collisions
 - Vary predicate distance (1-hop and 2-hop)
 - Vary predicate evaluation algorithm
- Network was laid out as a grid
- N, S, E, W communication possible
- 5 minutes setup time for PE, start TDMA
- 35 minutes total runtime

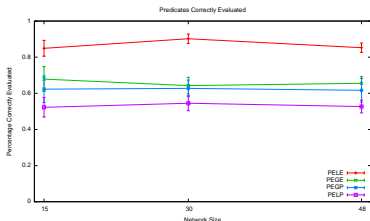
Results when period=4.0 minutes using a 1-hop predicate



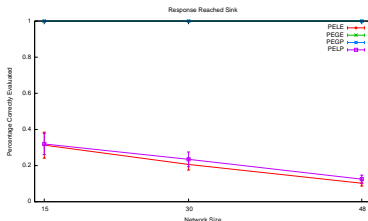
(a) Rx



(b) Tx

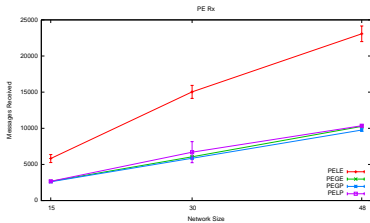


(c) Percentage of predicates correctly evaluated

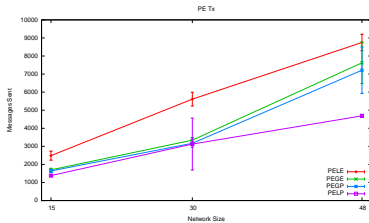


(d) Percentage of responses received

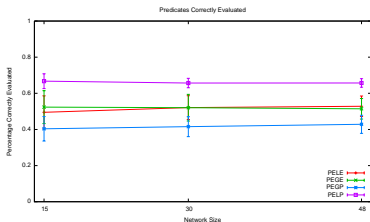
Results when period=4.0 minutes using a 2-hop predicate



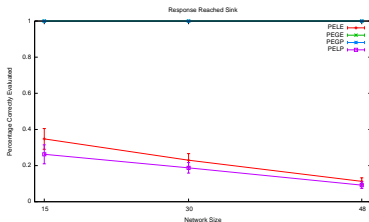
(e) Rx



(f) Tx



(g) Percentage of predicates correctly evaluated



(h) Percentage of responses received

Demo

Visualisation Tool and Network Interface

Features:

- Creating and compiling predicates to monitor
- Deploying predicates to the WSN
- Recording history of evaluation results
- Use of `serialdump-linux` to interface with sink mote

Views:

- Predicate view
- Network view

Conclusions

- Improve memory management
- Improve C containers developed
- Stateful predicates
- Handle mote mobility
- Improve failure response message deliver ratio

Developed:

- Libraries for use in Contiki (Container and Network)
- Predicate Evaluation Libraries (Global and Local)
- GUI tool to interface with network

Found:

- In-network, event-based evaluation suitable for “small” predicates
- Global, periodic evaluation more suitable for “large” predicates



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The End

Any Questions?