Formal Verification and Simulation for Performance Analysis for Probabilistic Broadcast Protocols

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The PEWNA project

Wireless sensor networks

Aggregate of small, portable devices

- battery-operated computing power
- gather sensor information in a distributed fashion
- wireless communications
- multi-hop communication

The PEWNA project

Project Goals

- Notations and tools for wireless network protocols.
- Model checking techniques for performance evaluation.
- Abstraction techniques to scale model checking techniques.

The Content

- Method
- Problem
- Protocol
- Results
- Future work

The Method

Model Checking

Model Checking

Basic Idea

- Given a model of the system
  - Kripke structure, FSM, Petri net, Probabilistic system…
- Given a formal specification
  - LTL, CTL, mu-calculus, PCTL, …
  - another simpler model
- Calculate whether model satisfies specification

Model Checking

Characteristics

≠ testing
Explores the behavior of a system model

≠ simulation
Explores (symbolically) all infinite behaviours

≠ theorem proving
Proves correctness automatically

Model Checking

PRISM

A Probabilistic Symbolic Model Checker (Uni Birmingham)

Supports:
- Discrete-Time Markov Chains (DTMCs)
- Continuous-Time Markov Chains (CTMCs)
- Markov Decision Processes (MDPs)

Checks:
- Probabilistic temporal logic (PCTL)
- Example: node 7 receives a message with probability > 0.8

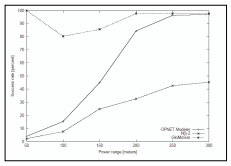
The problem

Simulation is imperfect

Related Work

On the Accuracy of MANET Simulators
Cavin, Sasson and Schiper (2002)

- Different simulators give different answers
- Even for simple protocols
- Semantics defined by simulator.
- Low level details as important as high level protocol



Related Work

Experimental Evaluation of Wireless Simulation Assumptions
Kotz, Newport et al. (2004)

- Assumptions render results useless
- Common assumptions:
  1. The earth is flat
  2. The transmission area is circular.
  3. All radios have equal range.
  4. If I can hear you, you can hear me.
  5. If I can hear you at all, I can hear you perfectly.
  6. Signal strength is a simple function of distance.

The Problem

Common Solution

- More details
- Hardware in the loop simulation
- Precise specific assumptions
- Specific results for very specific instances of a system

What about the general properties of a protocol?

The Problem

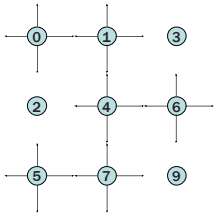
Our Approach

- More abstract model
- Formal model with well defined semantics
- Precise assumptions
- General results for a generic protocol

The Protocol

Gossiping and Flooding

Flooding and Gossiping



Gossiping protocol
- listen to medium
- if you receive a message
  - send message with probability p
- go to sleep

Properties of gossiping
- simple
- reduced redundancy
- reduced collisions
- improves efficiency

Common assumption

Common assumptions

- Absence of collisions
- Perfectly synchronous execution
- No clock drift
- Perfect medium

The basic model

Formal Model

Prism Model

- Well defined semantics,
- Abstraction from low level detail

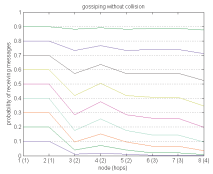
```
module node4
act4:  bool init true;
send4: bool init false;

[tick]  act4 & !send4 & (send1|send3|send5|send7)
        -> psend: (act4'=true)&(send4'=true) + (1-psend):(act4'=false)&(send4'=false);
[tick]  act4 & !send4 & !(send1|send3|send5|send7)-> (act4'=true) & (send4'=false);
[tick]  act4 &  send4 -> (act4'=false) & (send4'=false);
[tick] !act4          -> (act4'=false) & (send4'=false);
endmodule
```

PRISM model of gossiping protocol

Performance Evaluation

Model checking results

- PRISM results for gossiping w/o collision
- Results are exact probabilities rather than approximations



Common assumption

Common assumptions

- *Absence of collisions*
- **Perfectly synchronous execution**
- No clock drift
- *Perfect medium*

Synchronization

Model protocols as formal models

- Clean understanding of concurrency
- Simulation in contrast often implicitly synchronous

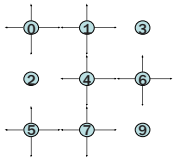
```
for i=find(sending) %for all nodes that are sending

   if(rand <= p)
        for j=1:4
            if(C(i,j) ~= 0) % if it has a neighbour
                        receive(C(i,j)) = 1; %then neighbour receives a msg
            end
        end;
   end;
end;
```

Matlab code for Monte-Carlo simulation: *implicitly synchronous*

Synchronization

Model protocols as formal models

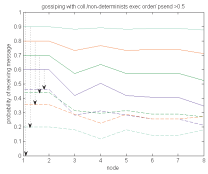
- Clean understanding of concurrency



Synchronization

Model protocols as formal models

- Model with non-deterministic execution order
- Minimal and maximal probability cover all execution orders



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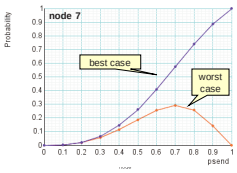


Common assumption

Common assumptions

- *Absence of collisions*
- Perfectly synchronous execution
- **No clock drift**
- *Perfect medium*

Timing

Unreliable timing

- Modelled as probabilistic waiting
- Compared different variants of the timing model

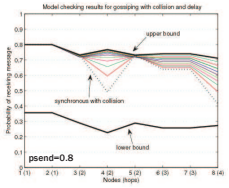
```
[tick] active4=1 & send4=0 & send1+send3+send5+send7 =1
                           ->   (1-psend):        (active4'=0)&(send4'=0)
                           +    psend*(1-pdelay): (active4'=1)&(send4'=1)
                           +    psend*   pdelay:  (active4'=2)&(send4'=0);
[tick] active4=2 ->(1-pdelay): (active4'=1)&(send4'=1)
                           +    pdelay:  (active4'=2)&(send4'=0);
```

PRISM model of simple delay

Timing

Unreliable timing

- Effect of collisions vanishes with an increasing delay
- Upper and lower bound provided by non-deterministic model



Intermediate Summary

Results

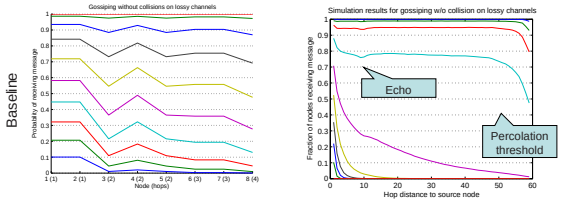
- Prism model for gossiping protocols
- Well defined semantics
- Abstraction from low level detail
- Verification produces exact answers
- Deals with non-determnism by under specification
- Results for small networks (up to 20 nodes)

What about large networks (1000 nodes)?

Matlab model

Monte-Carlo simulation

- Derived a simulation model (manually) from PRISM model
- Observed effects that are only visible for large models/models



Summary

Verification **vs** Simulation

Verification
- all infinite behaviour
- for a generic protocol
- for small networks

Simulation
- a few finite behaviours
- for a specific instance
- for large networks

Observations

Verification **and** Simulation

- Simulation complements model checking
- Formal model serves as "golden" model
- We are currently maintaining two models (artefacts)
- Future work: PRISM to of-the-shelf simulator translation

The End

Thanks