Creating Correct Network Protocols
PhD Defence Oskar Wibling

Ansgar Fehnker

Introduction

Opponent

- Ansgar Fehnker

Affiliation

- National ICT Australia
- Managing Complexity
- Formal Methods

Research Interests

- Model checking and static analysis to support embedded software development (C/C++)
- Model checking to support protocol design in the wireless network domain

Introduction

National ICT Australia

- Australian Government backed research institute
- 5 Laboratories:
  * ATP, Sydney
  * Canberra Research Laboratory
  * The Neville Roach Laboratory, Sydney
  * Queensland Research Laboratory
  * Victoria Research Laboratory

726 Staff

- PhD and Masters Students: 301
- Corporate Staff: 107
- Researchers: 244

Creating Correct Network Protocols

Thesis Oskar Wibling

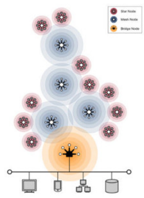
Content

- Networks
- Protocols
- Correctness
- Thesis
- Q&A

Networks

Applications

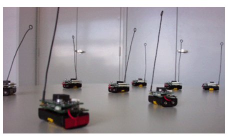
- Internet
- Home entertainment systems
- Power grid
- In-car network
- In-plane network
- Mobile phones
- WiFi
- Wireless sensor networks



Networks

Characteristics of Wireless Networks

- Ad-hoc
- Mobile
- Dynamic node creation
- Node failure
- Multi-hop communication
- Interference
- Resource constrained



Protocols

Protocols

NICTA

Purpose

- Protocols define the proper interaction between multiple components/ agents in a network.
- Protocols define the normal operating procedures
- Protocols should resilient to most failures

Protocols

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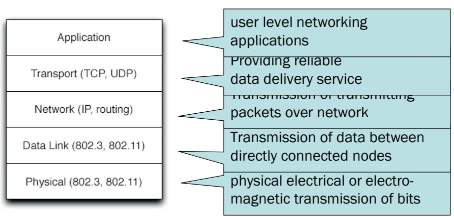
Characteristics

- Protocol are typically organized in layers, the so-called *protocol stack*.
- Lower layers deal with the physical aspects of the network.
- Upper layers with more abstract applications.
- Upper layers assume that lower layers work correctly.

Protocols

NICTA



Page 16, Figure 1.2 *TCP/IP protocol stack.*

Routing Protocols

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Aim

- Used to set up correct routes, to transmit data from one node to another.
- Needs to find a series of intermediate nodes if sender and receiver are not directly connected

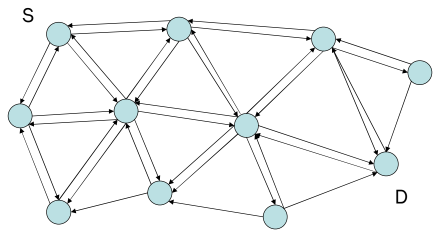
Routers

- Traditional networks uses router, i.e. dedicated nodes
- Routers provide a reliable “map” of the network.
- Ad hoc networks are more dynamic, no dedictaed routers.
- Every node has to act as a router.

Routing Protocols

NICTA

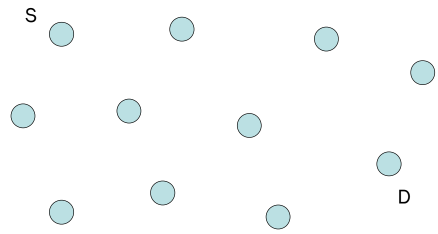
- Node S want to transmit to node D



Routing Protocols

NICTA

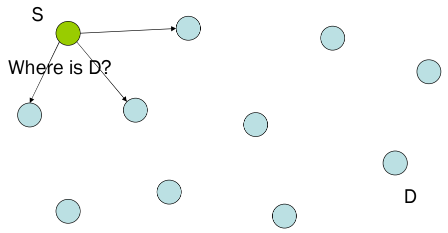
- Node S want to transmit to node D



Routing Protocols

NICTA

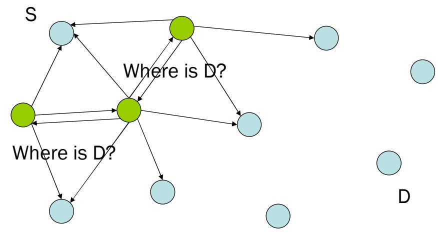
- Node S want to transmit to node D



Routing Protocols

NICTA

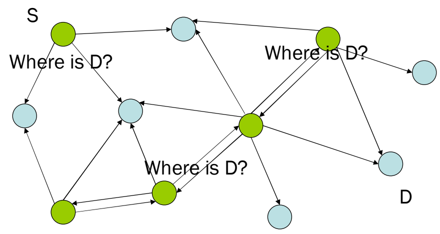
- Node S want to transmit to node D



Routing Protocols

NICTA

- Node S want to transmit to node D



Routing Protocols

NICTA

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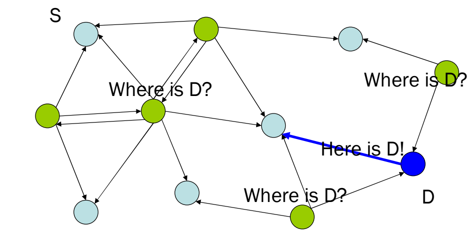

Routing Protocols

NICTA

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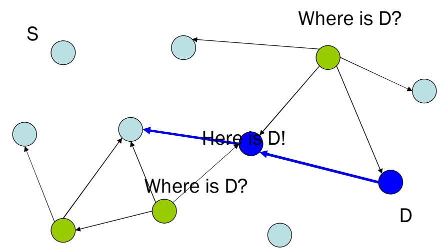
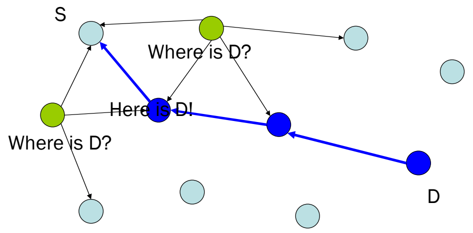


Routing Protocols

NICTA

- Node S want to transmit to node D



Routing Protocols

NICTA

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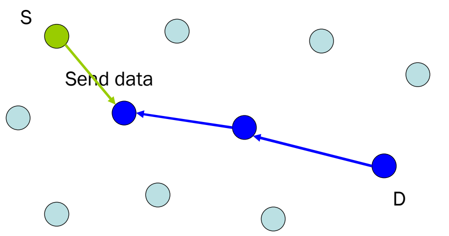

Routing Protocols

NICTA

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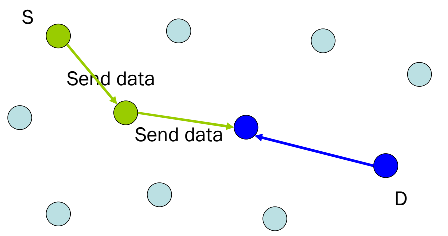

Routing Protocols

NICTA

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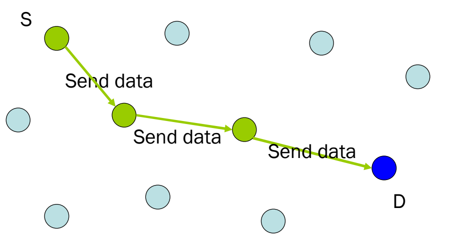

Routing Protocols

NICTA

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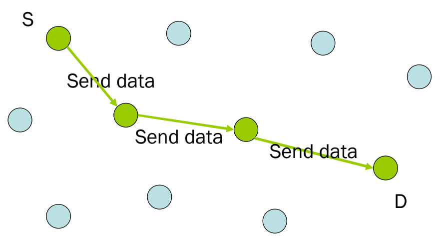

Routing Protocols

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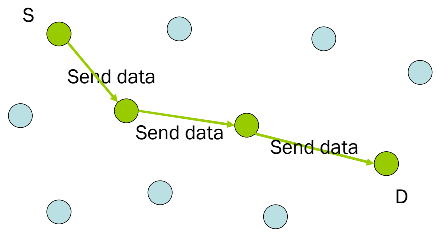
Challenges



Routing Protocols

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Challenges

- Nodes can move
- Nodes can fail
- Messages can get lost
- Messages can interfere/collide

Protocols

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Reactive protocols

- Create routing information as needed
- Examples are LUNAR and DYMO

Proactive

- Maintain routing information for later use.
- Examples are AODV, DSR, and OLSR

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Correctness

"We must not put mistakes into programs because of sloppiness, we have to do it systematically and with care."
(Edsger Dijkstra)

Correctness

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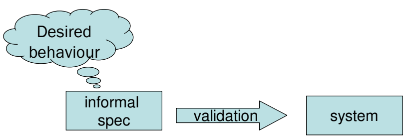
Definition 1

- A system is correct if it cannot exhibit undesirable behaviour

Definition 2

- A system is correct if it exhibits only permissible behaviour



Correctness

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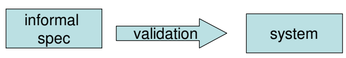
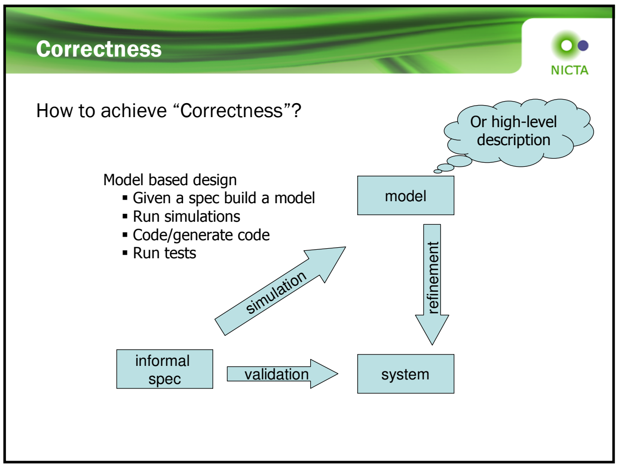
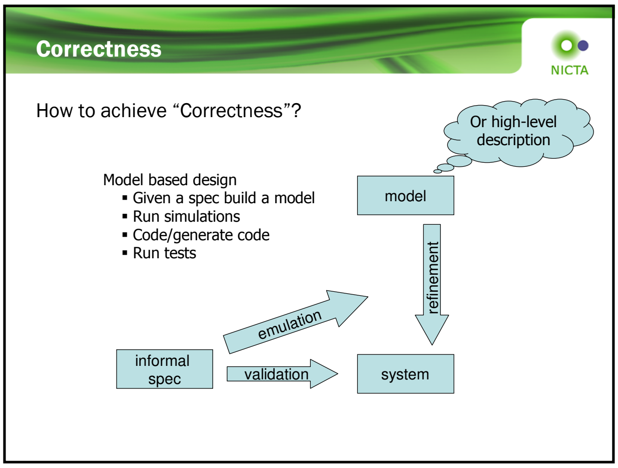
How to achieve "Correctness"?

"Traditional" software engineering practice

- Given a spec start coding
- Run test cases
- Code review
- Run more tests




Correctness
NICTA
How to achieve "Correctness"?
Or high-level description
Model based design
▪ Given a spec build a model
▪ Run simulations
▪ Code/generate code
▪ Run tests
model
simulation
refinement
informal spec
validation
system


Correctness
NICTA
How to achieve "Correctness"?
Or high-level description
Model based design
▪ Given a spec build a model
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model
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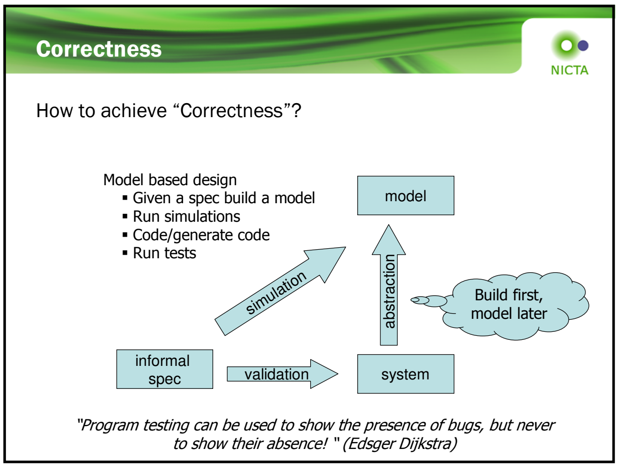
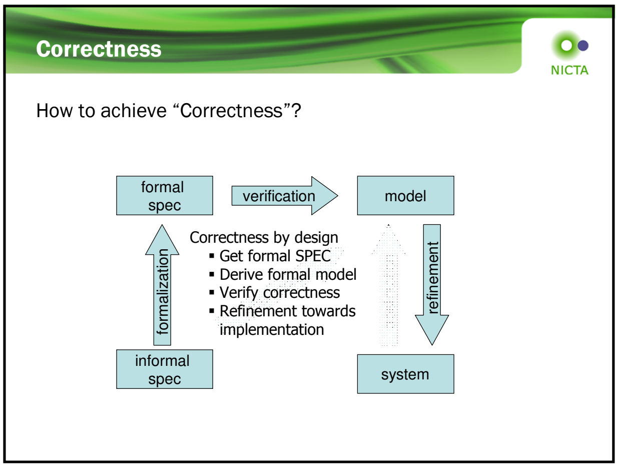
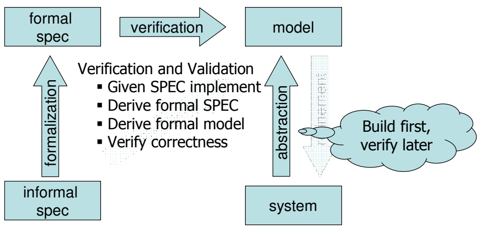

Correctness
NICTA
How to achieve "Correctness"?
Model based design
▪ Given a spec build a model
▪ Run simulations
▪ Code/generate code
▪ Run tests
model
simulation
abstraction
Build first, model later
informal spec
validation
system
"Program testing can be used to show the presence of bugs, but never to show their absence! " (Edsger Dijkstra)


Correctness
NICTA
How to achieve "Correctness"?
formal spec
verification
model
Correctness by design
▪ Get formal SPEC
▪ Derive formal model
▪ Verify correctness
▪ Refinement towards implementation
formalization
refinement
informal spec
system

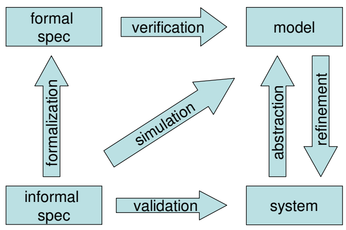
Correctness

Verification



Algorithmic Verification

How to achieve “Correctness”?



Creating Correct Network Protocols

Thesis Oskar Wibling

Thesis

Content and contributions

- Cross-platform protocol development
- Structured Live Testing
- Automata based protocol verification
- Graph-transformation system based (protocol) verification

Cross-Platform Protocol Development

LUNAR

- Lightweight Underlay Network Ad hoc Routing
- Discovers paths as needed
- Active paths are maintained
- Uses Propagating Localized Broadcast with Dampening (PLBD)
- Cross-platform implementation for Windows and Linux

Cross-Platform Protocol Development

Given

- User space implementation for Linux

Aim

- Kernel implementation for Windows and Linux

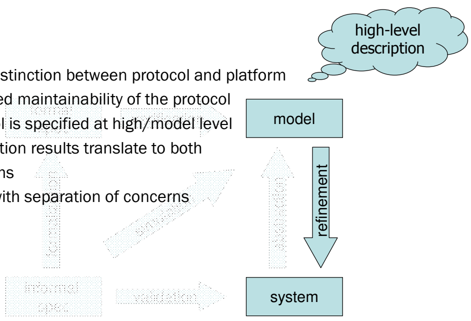
Approach

- Separate protocol logic from network and platform specific details
- Provide Windows versions of Linux kernel function calls

Cross-Platform Protocol Development

Benefits

- Clear distinction between protocol and platform
- Improved maintainability of the protocol
- Protocol is specified at high/model level
- Verification results translate to both platforms
- Helps with separation of concerns



Structured Live Testing

Comparative study

- Three different protocols: AODV, DSR and OLSR
- Three different evaluation methods: Simulation, emulation, real world testing
- Three different scenarios: End node swap, Relay node swap, Roaming node

=> Identified three ad hoc routing protocol problems: TCP backlash, Self Interference and Link cache poisoning

Structured Live Testing

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Simulation

- Simulating the protocol with ns-2
- No hardware
- Radio is simulated
- Mobility of nodes is simulated

Structured Live Testing

NICTA

Emulation

- Emulating the protocol using the APE testbed on identically configured laptops
- Stationary setup
- Uses actual radio and hardware
- Mobility is emulated using MAC filters
- Useful to study radio propagation effects when compared to simulation

Structured Live Testing

NICTA

Real World Testing

- Running the protocol using the APE testbed on identically configured laptops
- Uses actual radio and hardware
- Mobility is achieved by humans carrying laptops
- To ensure repeatability carefully choreographed and scripted

Structured Live Testing

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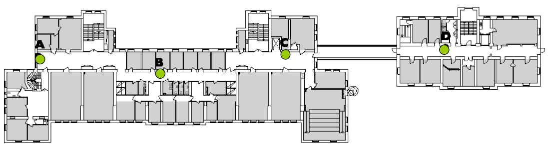
Scenarios



1. End node swap

Structured Live Testing

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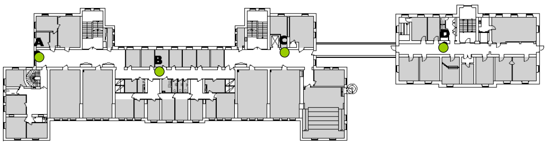
Scenarios



1. End node swap
2. Relay node swap

Structured Live Testing

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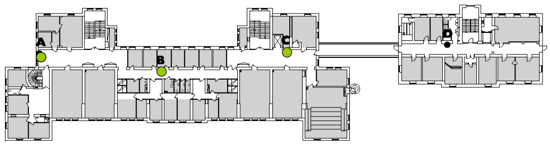
Scenarios



1. End node swap
2. Relay node swap
3. Roaming node

Structured Live Testing

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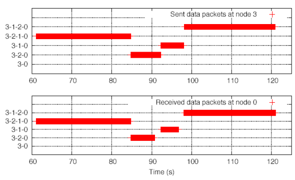
Results

- Comparing Simulation and Real-World points to sources for routing problems



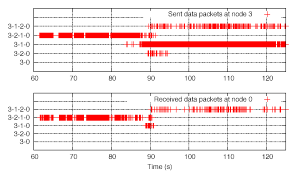
- Simulation for relay swap and DSR

Structured Live Testing

NICTA

Results

- Comparing Simulation and Real-World points to sources for routing problems



Link cache poisoning

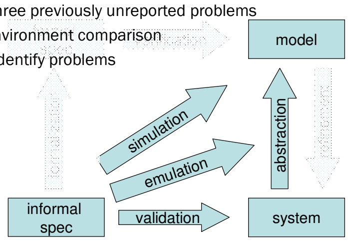
- Real world result for relay swap and DSR

Structured Live Testing

NICTA

Summary

- Used three different approaches to compare protocls
- Found three previously unreported problems
- Cross-environment comparison help to identify problems



Automata-based protocol verification

NICTA

Verification of LUNAR using SPIN and Uppaal

- Study protocol for network with finite number of nodes
- Subject to changes in topology.
- Correctness defined as guarantee that (1) the route will be set up and (2) the initial packet will be delivered
- Use time model in Uppaal to derive upper bounds for initial packet delivery

Automata-based protocol verification

NICTA

LUNAR

- The sender sends out a route request with Propagating Localized Broadcast with Dampening (PLBD)
  1. The initiating node tags the broadcast message with a unique ID
  2. Nodes ignore packets that they have received before
  3. Otherwise, if the node is not the destination, it will propagate the broadcast message.
- Once the destination node receives the request, it will send a unicast route reply along the discovered path.
- If the initiator receive the route reply it starts sending along the discovered path

Automata-based protocol verification

NICTA

Correctness property

- If there at one point in time exists a path between two nodes, then the protocol must be able to find some path between the nodes.
- When a path has been found, it is possible to send packets along the path from the source node to the destination node, as long as the path remains valid.

Automata-based protocol verification

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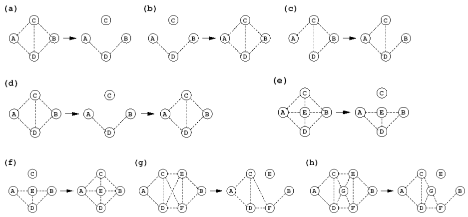
Changes in topology

Prove that the protocol is resilient to changes in topology, due to link and/or node failure.



Automata-based protocol verification

NICTA

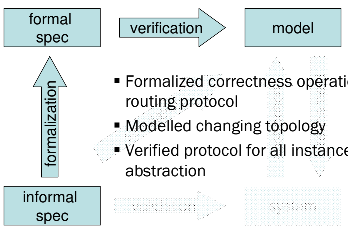
Broadcast Abstraction

- Improving the performance of model-checking by modelling PLBD as primitive operation, discarding many intermediate states and interleaving.
- Proving that the so-called “broadcast abstraction” is sound by provided
  - There exists a PLBD path
  - The PLBD path is unique
- Paper 3 gives proof that this is the case.

Automata-based protocol verification

NICTA

Summary



- Formalized correctness operation of an ad hoc routing protocol
- Modelled changing topology
- Verified protocol for all instances after broadcast abstraction

Graph Transformation System Verification

NICTA

Verification of DYMO and Heap operations using GBT

- A technique for modelling and verification based on graph transformation systems
- System configurations are modelled as hypergraphs
- Actions are modelled as graph rewrite rules
- Specification modelled as patterns
- Use backward reachability semi-algorithm to prove correctness
- Implemented as tool GBT

Graph Transformation System Verification

NICTA

Hypergraphs

- A hypergraph is a set of nodes with a set of hyperedges
- A hyperedge is a pair of an action label and an ordered tuple of nodes.

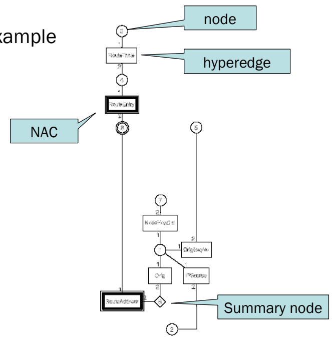
Patterns

- A pattern is a hypergraph, and represents all hypergraphs that have it as a subgraph.
- A pattern may include *negative application conditions,* which exclude all hypergraphs that have it as subgraph
- Introduction of *summary nodes*, to represent a non-empty set of nodes that have the same node type.

Graph Transformation System Verification

NICTA

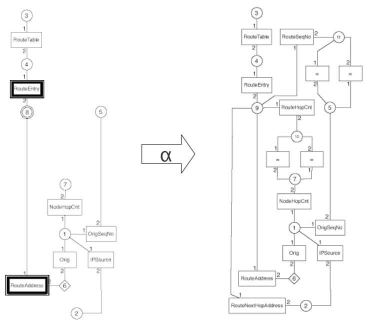
Example



Graph Transformation System Verification

NICTA

Example



Graph Transformation System Verification

NICTA

Backward Reachability

- Given a pattern representing all bad configurations (e.g. networks with loops)
- Compute the predecessor patterns, given all actions.
- Check if predecessor pattern is subsumed by a previously explored pattern.
- Stop if the initial configuration matches a predecessor pattern => Bad configurations are reachable.
- Stop if reachability analysis reaches a fix-point, i.e. find no new patterns => Bad configurations not reachable

Graph Transformation System Verification

NICTA

Verification Results

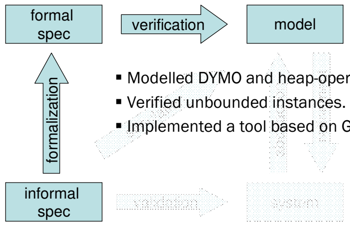
- Used the tool GBT to verify that the protocol DYMO guarantees absence of routing loops
- Verification took less than an hour
- Result holds for a network with an arbitrary number of network nodes.

- Verified the correctness of a heap-operation
- Made possible by introduction of summary nodes
- Verification took less than 20 minutes.
- Demonstrates the genral use of verification via Graph Transformation Systems

Graph Transformation System Verification

NICTA

Summary



- Modelled DYMO and heap-operations as GTS
- Verified unbounded instances.
- Implemented a tool based on GTS

Summary

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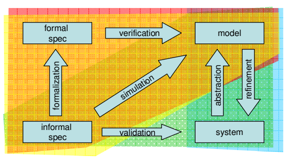
The thesis achieved the following

- Cross-platform implementation of the LUNAR protocol
- Structured testing of 3 routing protocols
- Verification of bounded instances of a routing protocol using existing tools
- Developed a new tool to verify unbounded instances.



NICTA

Questions

Re: Verification results of paper II, III, V, VI.

Re: Correctness property in Definition 1, paper II and III.

Informal spec

- If there at one point in time exists a path between two nodes, then the protocol must be able to find some path between the nodes.
- When a path has been found, it is possible to send packets along the path from the source node to the destination node, as long as the path remains valid.

Formal spec

- A <> Lunar0.unic_rrep_rec
- A <> Lunar1.ip_rec_ok

Re: Results for GBT, table 5.3. p83.

Re: Correctness property for DYMO as hypergraph

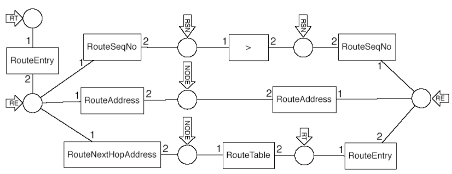


Figure 5.10: Pattern, φ, with node labels added.

Re: Paper IV, p 8. “The real world experiments suffer from (...) logging”.

Re: Page 40, Model checking. Classification of SPIN

Re: Paper III, p 3, “When using PLBD, the only possible paths (...) are disjoint.”

Re: p 90, paper VI, p15, CEGAR for GTS.

Re: Gap between simulation and real world experiment, p 57

Re: S/W development, p 25

Re: Impact of Network failure, p 15. “Driving to work or school”

Thanks