Using Process Algebra to Design Better Protocols

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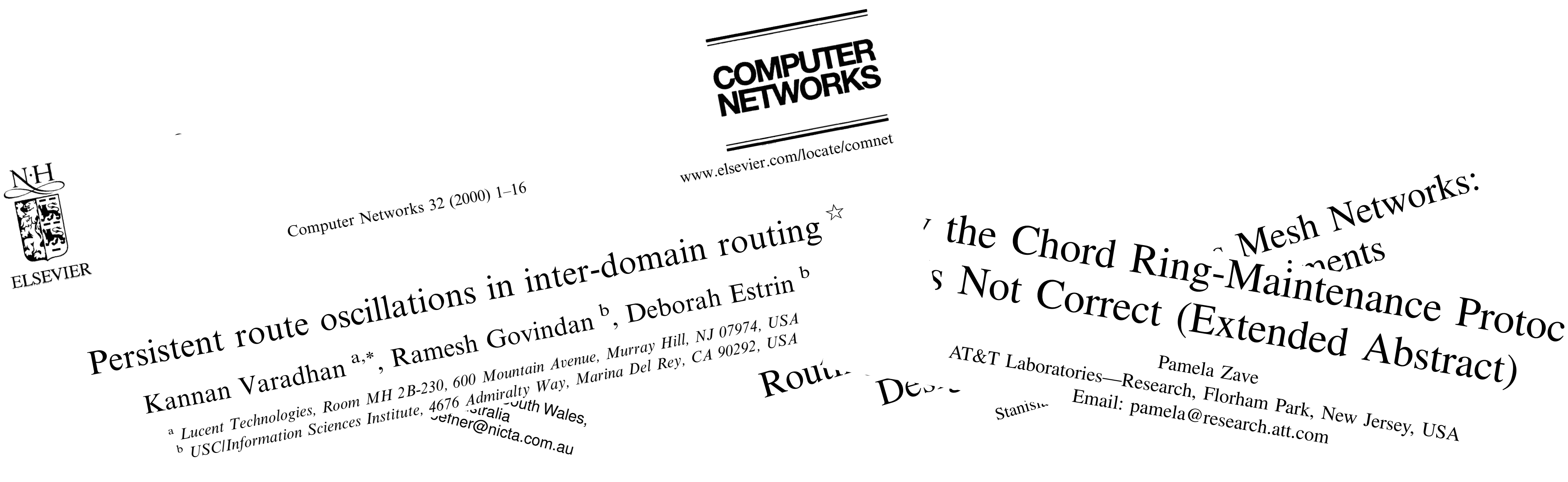
Why Better Protocols are Needed

Routing Protocols are Broken



Today's Protocol Development

IETF: "Rough Consensus and Running Code" (Trial and Error)

- start with a good idea
- build a protocol out of it (implementation)
  - run tests (over several years)
  - find limitations, flaws, etc…
  - fix problems
- build a new version of the protocol
- at some point people agree on an RFC (request for comments)

Beauvais Cathedral, France
(~300 years to build, at least 2 collapses)

Better Protocols are Needed Now!

We cannot afford this approach

- too expensive w.r.t. time
- too expensive w.r.t. money
- we are not working in a lab, i.e., sometimes we have one try only (e.g. BGP)

Is there a method which is more reliable and cost efficient ?

Opera House, Australia
(design was found structurally impossible to build)

What's the Problem? (1)

Specifications are (excessively) long

- Session Initiation Protocol (SIP) is 268 pages long (and not even self contained - by 2009 142 additional documents were required)
- IEEE 802.11 is 2.793 pages long

What’s the Problem? (2)

Specifications are

- underspecified
- contradictory
- erroneous, and
- ambiguous

What's the Problem? (3)

Specifications are written in English Prose

- in case of AODV there are 5 *different* implementations, all compliant to the standard

Aims

Provide complete and practical formal methods

- expressive
  (mobility, dynamic topology, types of communication,…)
- usable and intuitive
- description language + proof methodology + automation

Specification, verification and analysis of protocols

- formalise relevant standard protocols
- analyse the protocols w.r.t. key requirements
- analyse compliant implementations

Development of improved protocols

- assured protocol correctness
- improve reliability and performance

Developed Process Algebra

Description Language (Syntax)

$X(exp_1, \ldots, \mathrm{exp}_n)$	process calls
$P + Q$	nondeterministic
$[\varphi]P$	if-construct (guard)
$[\![\mathtt{var} := exp]\!]P$	assignment followed
$\mathbf{broadcast}(ms).P$	broadcast
$\mathbf{groupcast}(dests, ms).P$	groupcast
$\mathbf{unicast}(dest, ms).P \blacktriangleright Q$	unicast
$\mathbf{send}(ms).P$	send
$\mathbf{receive}(\mathtt{msg}).P$	receive
$\mathbf{deliver}(data).P$	deliver

Developed Process Algebra

Description Language (Syntax)

$[\varphi]P + [\neg\varphi]Q$	deterministic choice
$P(n) = [\![n := n+1]\!].P(n)$	loops

Do we need more?

$P \langle\!\langle Q$	parallel operator on nodes
$P \parallel Q$	parallel operator between nodes

Developed Process Algebra

Semantics

- not used by a software engineer
- internal state determined by expression and valuation

$$\xi, \textbf{broadcast}(ms).p \xrightarrow{\textbf{broadcast}(\xi(ms))} \xi, p$$

$$\xi, \textbf{groupcast}(dests, ms).p \xrightarrow{\textbf{groupcast}(\xi(dests),\xi(ms))} \xi, p$$

$$\xi, \textbf{unicast}(dest, ms).p \blacktriangleright q \xrightarrow{\textbf{unicast}(\xi(dest),\xi(ms))} \xi, p$$

$$\xi, \textbf{unicast}(dest, ms).p \blacktriangleright q \xrightarrow{\neg\textbf{unicast}(\xi(dest))} \xi, q$$

$$\xi, \textbf{send}(ms).p \xrightarrow{\textbf{send}(\xi(ms))} \xi, p$$

$$\xi, \textbf{deliver}(data).p \xrightarrow{\textbf{deliver}(\xi(data))} \xi, p$$

$$\xi, \textbf{receive}(\texttt{msg}).p \xrightarrow{\textbf{receive}(m)} \xi[\texttt{msg} := m], p \qquad (\forall m \in \texttt{MSG})$$

Case Study: AODV

$+\,[\,(\texttt{oip},\texttt{rreqid}) \notin \texttt{rreqs}\,]$ /* the RREQ is new to this node */

$[\![\texttt{rt} := \texttt{update}(\texttt{rt},(\texttt{oip},\texttt{osn},\texttt{kno},\texttt{val},\texttt{hops}+1,\texttt{sip},\emptyset))]\!]$ /* update the route to oip in rt */

$[\![\texttt{rreqs} := \texttt{rreqs} \cup \{(\texttt{oip},\texttt{rreqid})\}]\!]$ /* update rreqs by adding (oip, rreqid) */

(

$[\,\texttt{dip} = \texttt{ip}\,]$ /* this node is the destination node */

$[\![\texttt{sn} := \max(\texttt{sn},\texttt{dsn})]\!]$ /* update the sqn of ip */

/* unicast a RREP towards oip of the RREQ */

unicast$(\texttt{nhop}(\texttt{rt},\texttt{oip}),\texttt{rrep}(0,\texttt{dip},\texttt{sn},\texttt{oip},\texttt{ip}))\,.\,\texttt{AODV}(\texttt{ip},\texttt{sn},\texttt{rt},\texttt{rreqs},\texttt{store})$

$\blacktriangleright$ /* If the transmission is unsuccessful, a RERR message is generated */

$[\![\texttt{dests} := \{(\texttt{rip},\texttt{inc}(\texttt{sqn}(\texttt{rt},\texttt{rip}))) \mid \texttt{rip} \in \texttt{vD}(\texttt{rt}) \wedge \texttt{nhop}(\texttt{rt},\texttt{rip}) = \texttt{nhop}(\texttt{rt},\texttt{oip})\}]\!]$

$[\![\texttt{rt} := \texttt{invalidate}(\texttt{rt},\texttt{dests})]\!]$

$[\![\texttt{store} := \texttt{setRRF}(\texttt{store},\texttt{dests})]\!]$

$[\![\texttt{pre} := \bigcup\{\texttt{precs}(\texttt{rt},\texttt{rip}) \mid (\texttt{rip},*) \in \texttt{dests}\}]\!]$

$[\![\texttt{dests} := \{(\texttt{rip},\texttt{rsn}) \mid (\texttt{rip},\texttt{rsn}) \in \texttt{dests} \wedge \texttt{precs}(\texttt{rt},\texttt{rip}) \neq \emptyset\}]\!]$

groupcast$(\texttt{pre},\texttt{rerr}(\texttt{dests},\texttt{ip}))\,.\,\texttt{AODV}(\texttt{ip},\texttt{sn},\texttt{rt},\texttt{rreqs},\texttt{store})$

$+\,[\,\texttt{dip} \neq \texttt{ip}\,]$ /* this node is not the destination node */

(

$[\,\texttt{dip} \in \texttt{vD}(\texttt{rt}) \wedge \texttt{dsn} \leq \texttt{sqn}(\texttt{rt},\texttt{dip}) \wedge \texttt{sqnf}(\texttt{rt},\texttt{dip}) = \texttt{kno}\,]$ /* valid route to dip that is fresh enough */

/* update rt by adding precursors */

$[\![\texttt{rt} := \texttt{addpreRT}(\texttt{rt},\texttt{dip},\{\texttt{sip}\})]\!]$

$[\![\texttt{rt} := \texttt{addpreRT}(\texttt{rt},\texttt{oip},\{\texttt{nhop}(\texttt{rt},\texttt{dip})\})]\!]$

/* unicast a RREP towards the oip of the RREQ */

unicast$(\texttt{nhop}(\texttt{rt},\texttt{oip}),\texttt{rrep}(\texttt{dhops}(\texttt{rt},\texttt{dip}),\texttt{dip},\texttt{sqn}(\texttt{rt},\texttt{dip}),\texttt{oip},\texttt{ip}))\,.$

Case Study: AODV

Ad Hoc On-Demand Distance Vector Protocol

- routing protocol for wireless mesh networks
  (wireless networks without wired backbone)

- ad hoc (network is not static)
- on-Demand (routes are established when needed)
- distance (metric is hop count)

- developed 1997-2001 by Perkins, Beldig-Royer and Das
  (University of Cincinnati)

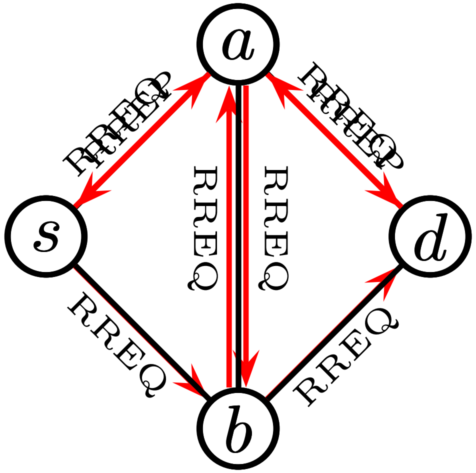
- one of the four protocols standardised by the
  IETF MANET working group (IEEE 802.11s)

Case Study

Main Mechanism

- if route is needed
  BROADCAST RREQ
- if node has information about a destination
  UNICAST RREP
- if unicast fails or link break is detected
  GROUPCAST RERR

- performance improvement via intermediate route reply



Case Study: AODV

```
+ [ (oip , rreqid) ∉ rreqs ]        /* the RREQ is new to this node */
  ⟦rt := update(rt,(oip, osn, kno, val, hops + 1, sip, ∅))⟧        /* update the route to oip in rt */
  ⟦rreqs := rreqs ∪ {(oip, rreqid)}⟧        /* update rreqs by adding (oip , rreqid) */
  (
    [ dip = ip ]        /* this node is the destination node */
      ⟦sn := max(sn, dsn)⟧        /* update the sqn of ip */
      /* unicast a RREP towards oip of the RREQ */
      unicast(nhop(rt,oip),rrep(0,dip,sn,oip,ip)) . AODV(ip,sn,rt,rreqs,store)
      ▶ /* If the transmission is unsuccessful, a RERR message is generated */
        ⟦dests := {(rip, inc(sqn(rt,rip))) | rip ∈ vD(rt) ∧ nhop(rt,rip) = nhop(rt,oip)}⟧
        ⟦rt := invalidate(rt,dests)⟧
        ⟦store := setRRF(store,dests)⟧
        ⟦pre := ⋃{precs(rt,rip) | (rip, ∗) ∈ dests}⟧
        ⟦dests := {(rip,rsn) | (rip,rsn) ∈ dests ∧ precs(rt,rip) ≠ ∅}⟧
        groupcast(pre,rerr(dests,ip)) . AODV(ip,sn,rt,rreqs,store)
    + [ dip ≠ ip ]        /* this node is not the destination node */
      (
        [ dip ∈ vD(rt) ∧ dsn ≤ sqn(rt,dip) ∧ sqnf(rt,dip) = kno ]        /* valid route to dip that is fresh enough */
          /* update rt by adding precursors */
          ⟦rt := addpreRT(rt,dip,{sip})⟧
          ⟦rt := addpreRT(rt,oip,{nhop(rt,dip)})⟧
          /* unicast a RREP towards the oip of the RREQ */
          unicast(nhop(rt,oip),rrep(dhops(rt,dip),dip,sqn(rt,dip),oip,ip)) .
```

Case Study: AODV

Full specification of AODV (IETF Standard)

Specification details

- around 5 types and 30 functions
- around 120 lines of specification
  (in contrast to 40 pages English prose)

Case Study: AOVD - Analysis

Properties of AODV

- route correctness ✓
- loop freedom ✓ (at least for some interpretations)
- route discovery ✗
- packet delivery ✗

Case Study: Analysis

Loop Freedom

- invariant proof
  based on about 35 invariants, e.g.

  If a route reply is sent by a node ip_c, different from the destination of the route, then the content of ip_c's routing table must be consistent with the information inside the message.

$$N \xrightarrow{R:\mathbf{*cast}(\mathtt{rrep}(hops_c,dip_c,dsn_c,*,ip_c))}_{ip} N' \;\wedge\; ip_c \neq dip_c$$
$$\Rightarrow\;\; dip_c \in \mathtt{kD}_N^{ip_c} \;\wedge\; \mathtt{sqn}_N^{ip_c}(dip_c) = dsn_c \;\wedge\; \mathtt{dhops}_N^{ip_c}(dip_c) = hops_c \;\wedge\; \mathtt{flag}_N^{ip_c}(dip_c) = \mathtt{val}$$

- ultimately we defined quality on routes
  the quality strictly increases

$$dip \in \mathtt{vD}_N^{ip} \cap \mathtt{vD}_N^{nhip} \;\wedge\; nhip \neq dip \;\Rightarrow\; \xi_N^{ip}(\mathtt{rt}) \sqsubset_{dip} \xi_N^{nhip}(\mathtt{rt})$$

- first rigorous and complete proof of loop freedom of AODV
  (for some interpretations)

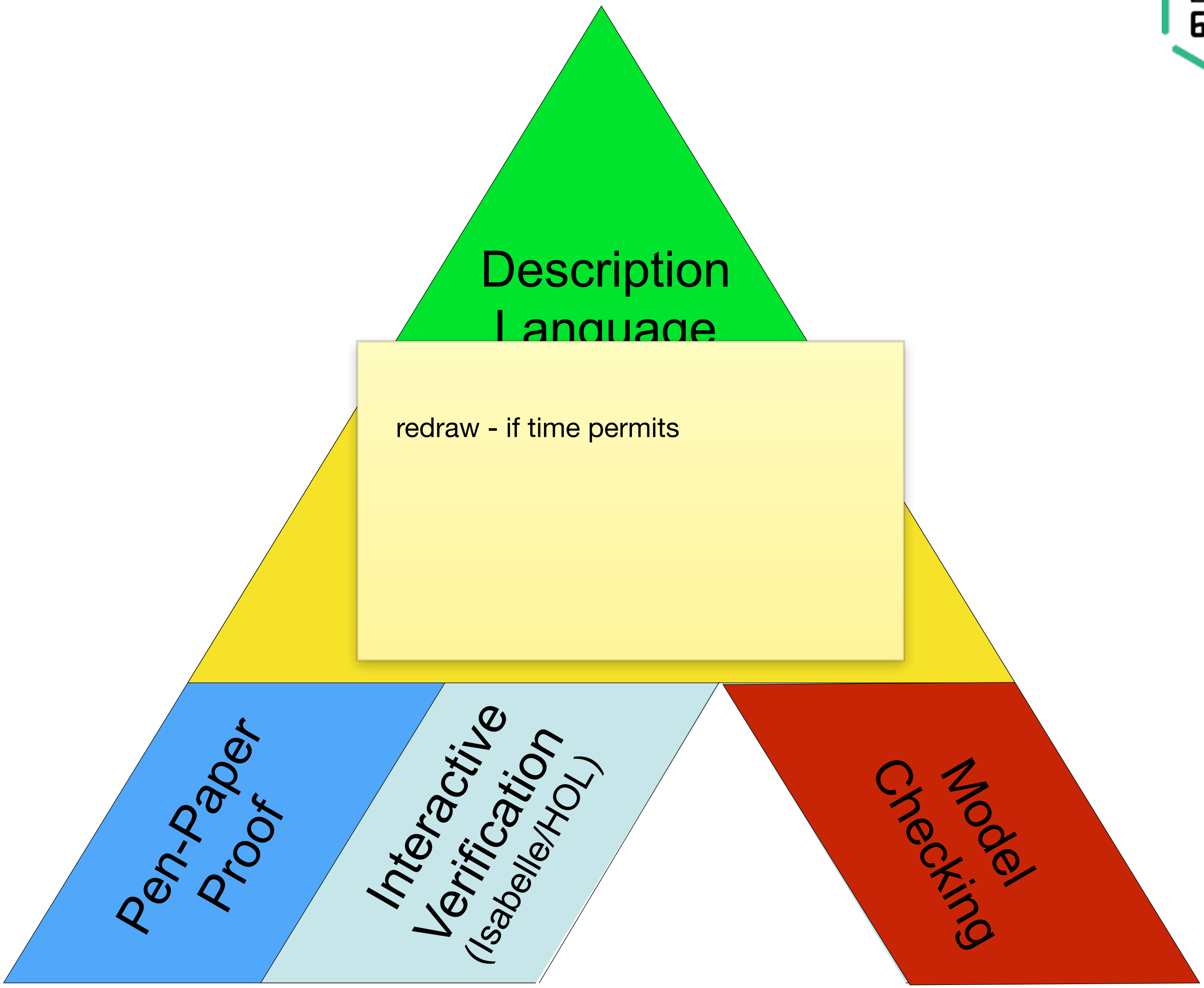
Case Study: Analysis

Loop Freedom

- 5184 possible interpretations due to ambiguities
- 5006 of these readings of the standard contain loops
- 3 out of 5 open-source implementations contain loops

Found other shortcomings

- e.g. non-optimal routing information
- we proposed solutions and proved them correct



redraw - if time permits

Computer-Aided Verification

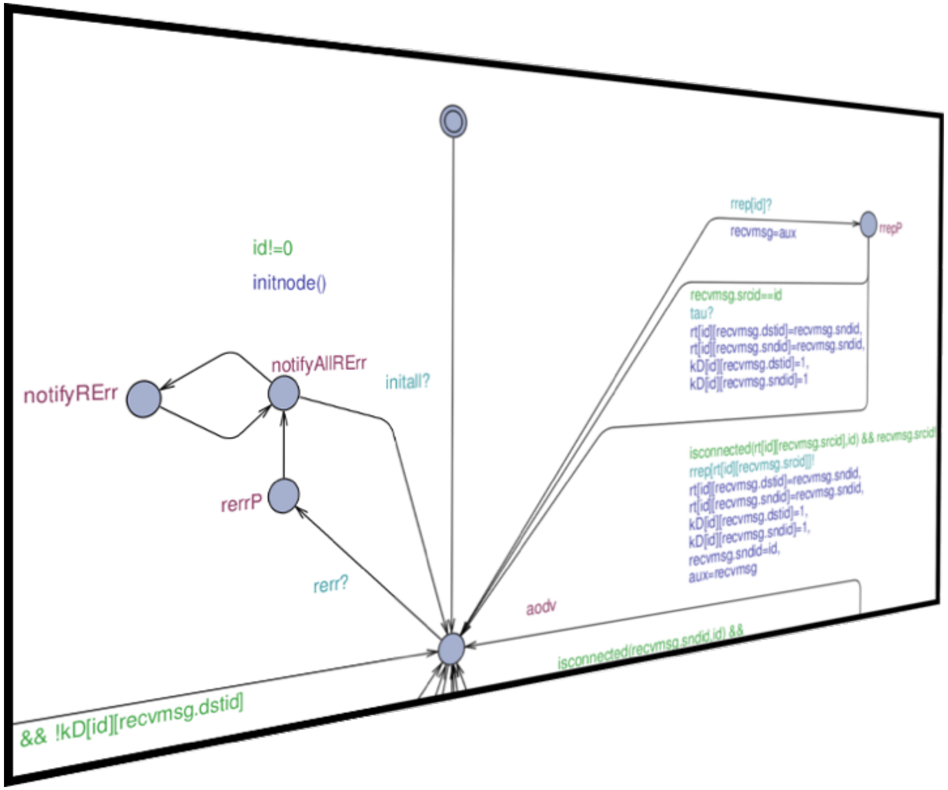
Model Checking

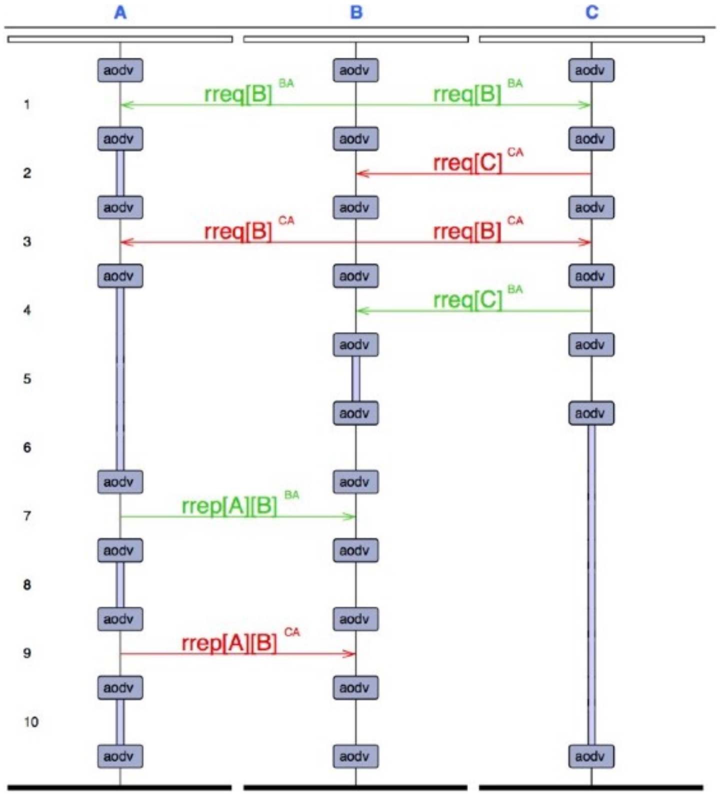
- quick feedback for development
- cannot be used for full verification (not yet)

(Interactive) Theorem Proving

- Isabelle/HOL
- replay proofs
  - proof verification
  - robust against small changes in specification

Model Checking





Model Checking

Model checking routing algorithms

- executable models
- generated from process-algebraic specification
- translation function needs to be correct

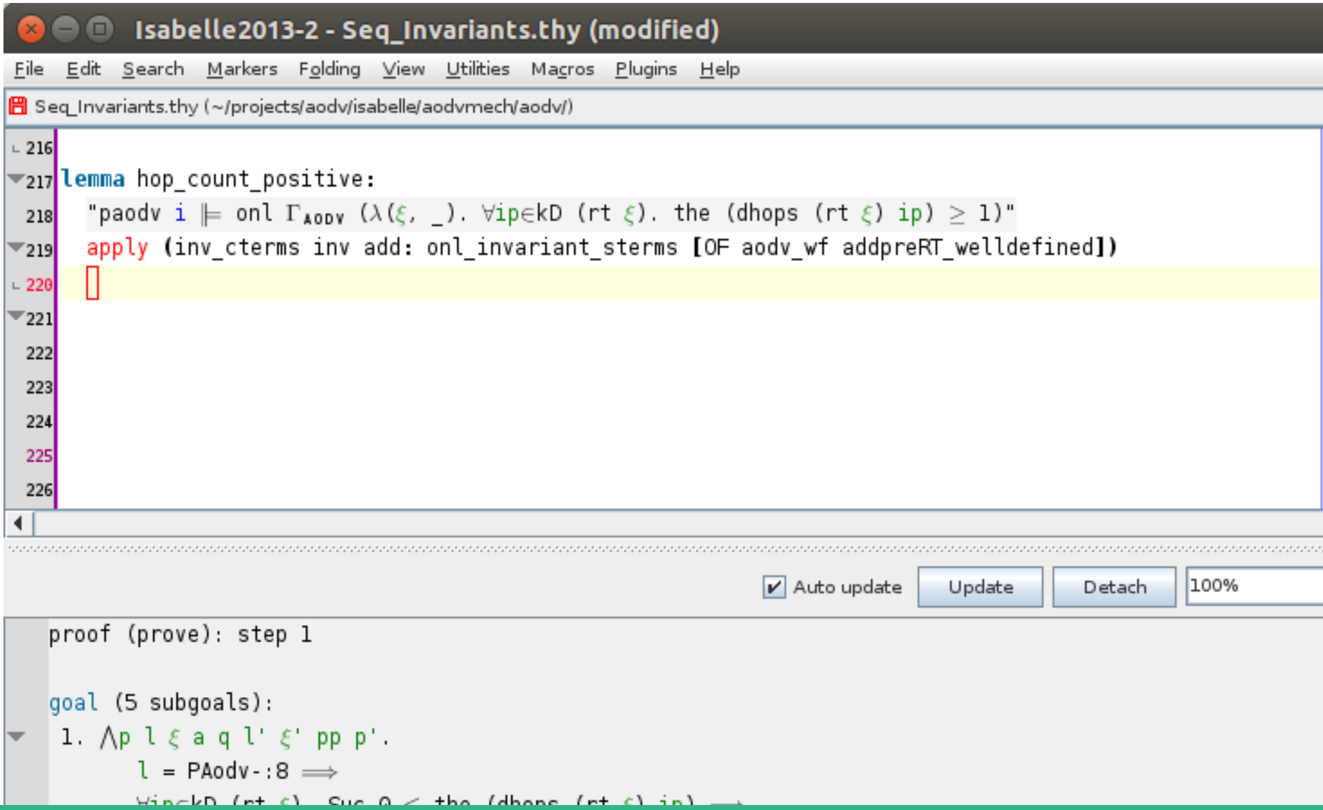
Complementary to process algebra

- find bugs and typos in process-algebraic model
- check properties of specification applied to particular topology
- easy adaption in case of change
- automatic verification

Achievements

- implemented process algebra specification of AODV
- found/replayed shortcomings

Isabelle/HOL



Isabelle/HOL

Generic proof assistant

We implemented

- developed process algebra
- AODV invariant proofs

Advantages

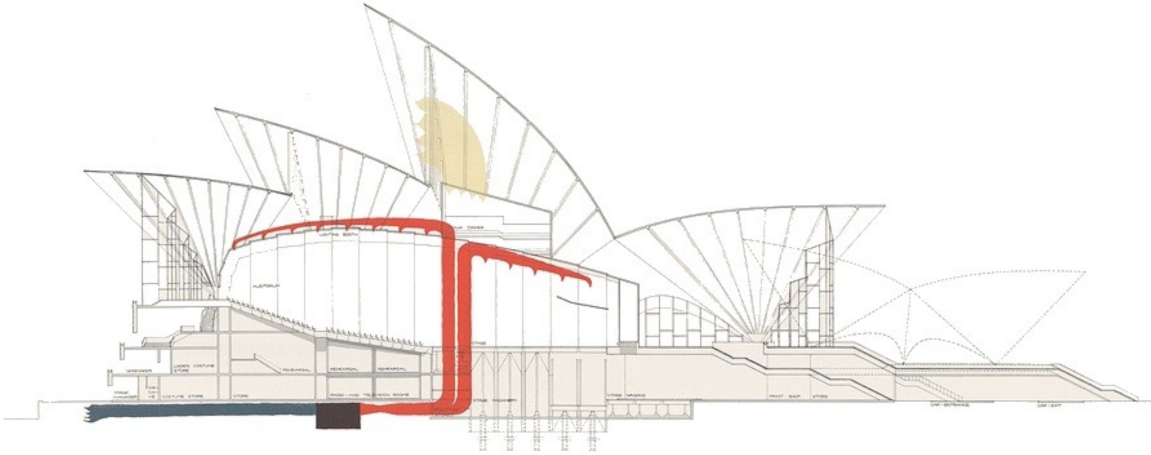
- proof verification
- speed up of analysis of protocol variants
  – analysed variants/improvements more or less automatically
- quick proof adaption
  – reply of proofs
  – necessary for protocol development

Key Research Outcomes

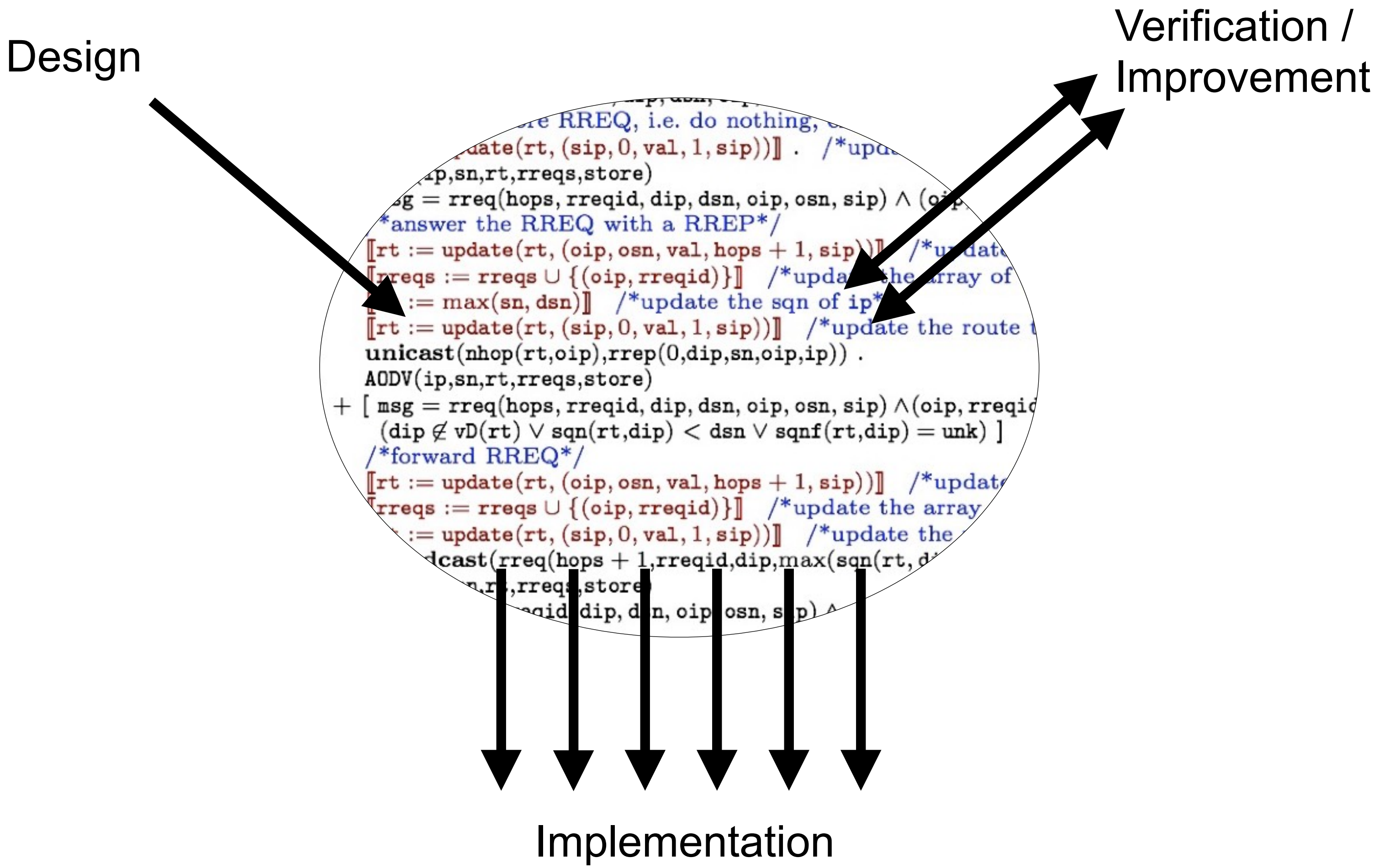
New languages and proof methodologies

- process algebra

- **Case Study AODV**
  - complete and detailed model (including time)
  - model checking: quick check for counterexamples
  - theorem proving: verification and proof automation



Vision - Practical Protocol Engineering



Future Work

Research (1)

- probabilistic analysis
- build tool suite
- better tool support (more proof automation)

Research (2)

- code generation
- code verification

Training

- train network engineers to use our approach
- hardest to achieve

Questions?

"Despite the maturity of formal description languages and formal methods for analyzing them, the description of real protocols is still overwhelmingly informal. The consequences of informal protocol description drag down industrial productivity and impede research progress".

Pamela Zave (AT&T)

Trustworthy Systems
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