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A Mechanized Proof of Loop Freedom of the (untimed) AODV routing protocol

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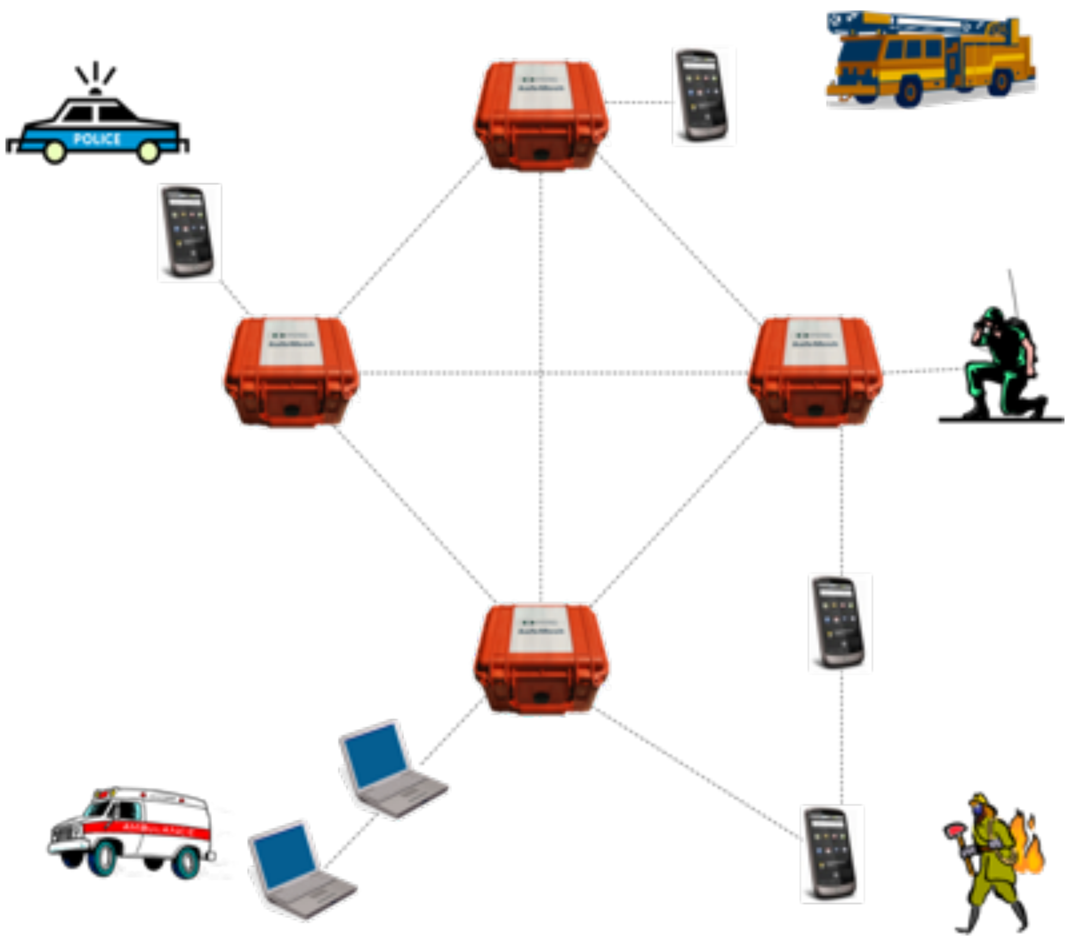
Wireless Mesh Networks

- Wireless Mesh Networks (WMNs)
  - key features: mobility, dynamic topology, wireless multihop backhaul
  - quick and low cost deployment
- Applications
  - public safety
  - emergency response, disaster recovery
  - transportation
  - mining
  - smart grid
  - ...
- Limitations in reliability and performance



Ad Hoc On-Demand Distance Vector Protocol

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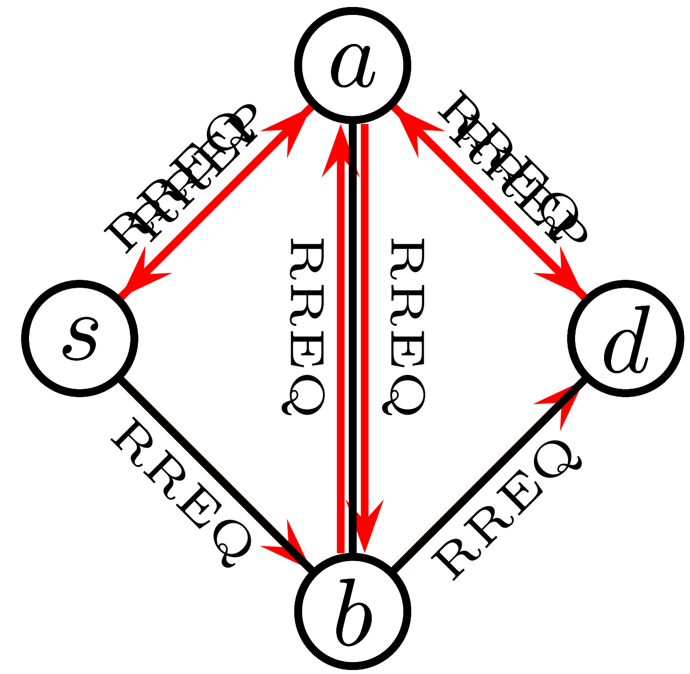
- Main Mechanism
  - if route is needed
    BROADCAST RREQ
  - if node has information about a destination
    UNICAST RREP
  - if unicast fails or link break is detected
    GROUPCAST RERR
- Essential Data structure
  - a routing table
    - local knowledge
    - entries:
      $(dip, dsn, dsk, val, hops, nhip, pre)$



Ad Hoc On-Demand Distance Vector Protocol

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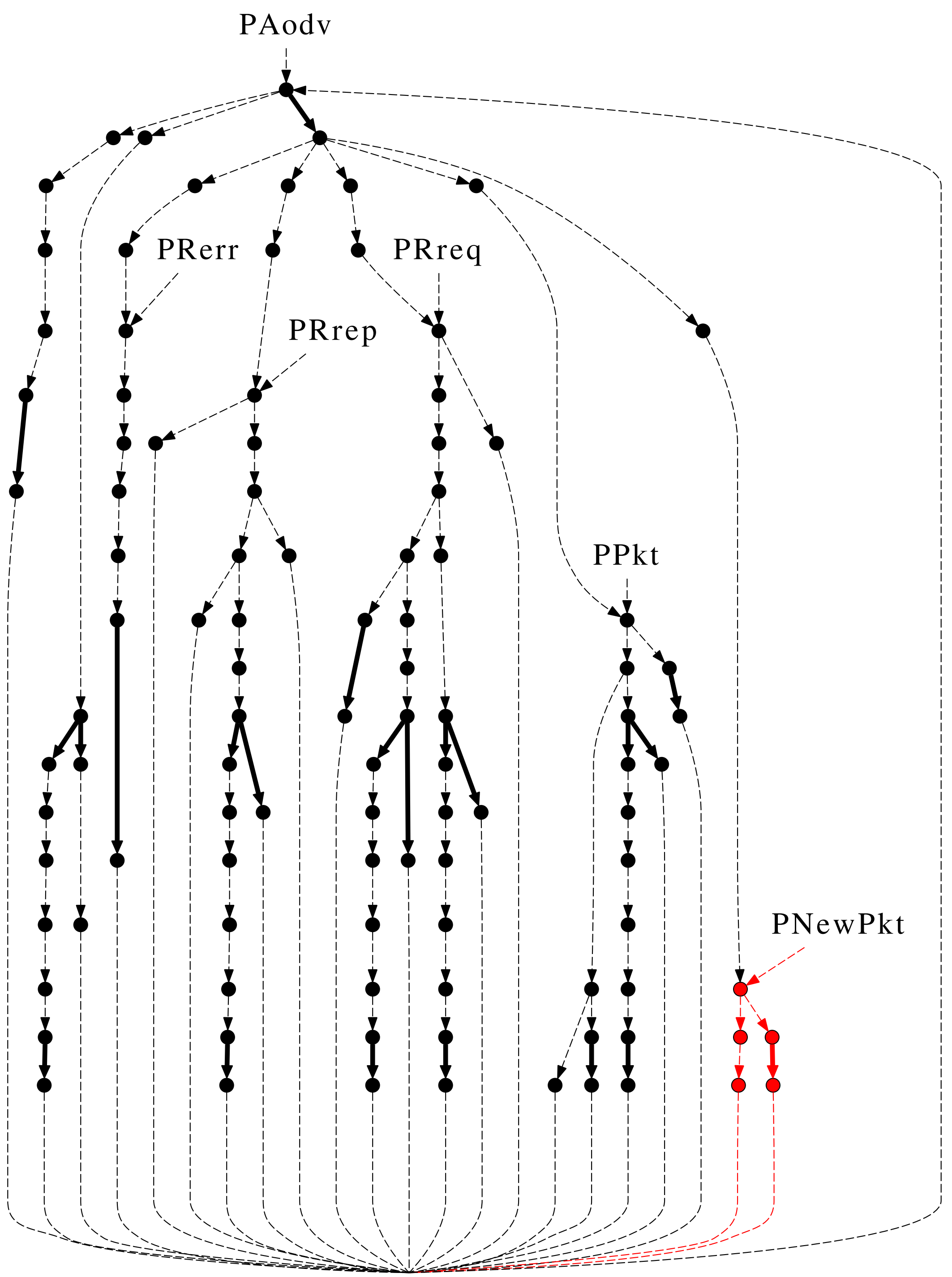
- Properties of AODV
  - route correctness ✓
  - loop freedom
  - route discovery ✗
  - packet delivery ✗

Specification in Process Algebra

- AODV in Process Algebra AWN
  - standard process algebra
  - with data structure
  - network-specific primitives, such as
    - (local) broadcast
    - (conditional) unicast
  - layered structure (processes, nodes, network of nodes, encapsulation)



- Model of AODV
  - 6 processes
  - about 150 lines of specification

Snippet of AODV

```
+ [ (oip, rreqid) ∉ rreqs ]        /* the RREQ is new to this node */
  /* update the route to oip in rt */
  [[rt := update(rt, (oip, osn, valid, hops + 1, sip, ∅))]]
  /* update rreqs by adding (oip, rreqid) */
  [[rreqs := rreqs ∪ {(oip, rreqid)}]]
  (
    [ dip = ip ]        /* this node is the destination node */
      /* update the sqn of ip by setting it to max(sqn(rt, ip), dsn) */
      [[rt := update(rt, (ip, dsn, valid, 0, ip, ∅))]]
      /* unicast a RREP towards oip of the RREQ; next hop is sip */
      unicast(sip, rrep(0, dip, sqn(rt, ip), oip, ip)) . AODV(ip, rt, rreqs, queues)
      ▶ /* If the packet transmission is unsuccessful, a RERR message is generated */
        [[dests := {(rip, rsn) | (rip, rsn, valid, ∗, sip, ∗) ∈ rt}]]
        [[pre := ⋃{precs(rt, rip) | (rip, ∗) ∈ dests}]]
        [[for all (rip, ∗) ∈ dests : invalidate(rt, rip)]]
        groupcast(pre, rerr(dests, ip)) . AODV(ip, rt, rreqs, queues)
    + [ dip ≠ ip ]        /* this node is not the destination node */
      (
        [ dip ∈ aD(rt) ∧ dsn ≤ sqn(rt, dip) ∧ sqn(rt, dip) ≠ 0 ]        /* valid route to dip that is
        fresh enough */
          /* update rt by adding sip to precs(rt, dip) */
          [[r := addpre(σ_route(rt, dip), {sip}); rt := update(rt, r)]]
```

A Pen-and-Paper Proof for the RFC 3561

- There existed a pen-and-paper proof
  - around 20 pages
  - about 40 invariants
    - state invariants
    - transition invariants
    - talking about one or more nodes

Mechanizing the Proof

- done in Isabelle/HOL
- Mechanization of the process algebra AWN
  - details see ITP’14
  - some crucial parts are discussed below
- Mechanization of the loop-freedom proof
  - 360 lemmas of which 40 are invariants
  - “usual” overhead

Node Properties

- Often straight forward

- Example:
  "all routing table entries have a hop count greater than or equal to one"

$$(*, *, *, *, hops, *, *) \in \xi_N^{ip} \;\Rightarrow\; 1 \leq hops$$

$$\mathsf{paodv}\ \mathsf{i} \mathrel{|\!\!\models} \mathsf{onl}\ \Gamma_{\mathsf{aodv}}\ (\lambda(\xi, \text{-}).\ \forall \mathsf{ip} \in \mathsf{kD}(\mathsf{rt}\ \xi).\ 1 \leq \mathsf{the}\ (\mathsf{dhops}\ (\mathsf{rt}\xi)\ \mathsf{ip}))$$

Network Properties for Single Nodes

- stating network properties already gets complicated
- proving even more sophisticated
  (but also for the pen-and-paper proof)

Network Properties for Single Nodes

- Example:
  "the quality of the routing table entries for a destination *dip* is strictly increasing along a route towards *dip*"

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

$$\begin{aligned}
&\mathsf{opaodv\ i} \Vdash (\mathsf{otherwith}\ (\mathsf{op} =)\ \{\mathsf{i}\} \\
&\qquad (\mathsf{orecvmsg}\ (\lambda\sigma\ m.\ \mathsf{msg_fresh}\ \sigma\ m\ \wedge\ \mathsf{msg_zhops}\ m)), \\
&\qquad \mathsf{otherquality_increases}\{\mathsf{i}\}\ \rightarrow) \\
&\qquad \mathsf{onl}\ \Gamma_{\mathsf{aodv}}\ (\lambda(\sigma, \text{-}).\ \forall \mathsf{dip}.\ \mathsf{let\ nhip} = \mathsf{the}\ (\mathsf{nhop}\ (\mathsf{rt}(\sigma\ \mathsf{i}))\ \mathsf{dip}) \\
&\qquad\qquad \mathsf{in\ dip} \in \mathsf{vD}\ (\mathsf{rt}\ (\sigma\ \mathsf{i}))\ \cap\ \mathsf{vD}\ (\mathsf{rt}\ (\sigma\ \mathsf{nhip})) \\
&\qquad\qquad\quad \wedge\ \mathsf{nhip} \neq \mathsf{dip} \\
&\qquad\qquad\quad \longrightarrow (\mathsf{rt}\ (\sigma\ \mathsf{i}))\ \sqsubset_{\mathsf{dip}}\ (\mathsf{rt}\ (\sigma\ \mathsf{nhip})))
\end{aligned}$$

Why Mechanisation?

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- Did we waste our time
  - there was a pen-and-paper proof before
  - took about 1 person-year
    (building up infrastructure for AWN, etc.)
  - more confidence
  - found one missing case and some typos
- Do we gain anything when we analyse variants

Variants

- Variants might occur
  - change in specification
    (not yet standardized)
  - optimizations found
  - different Interpretations of the Specification
    (written in English)

Change in Specifications

```
+ [ (oip, rreqid) ∉ rreqs ]      /* the RREQ is new to this node */
  /* update rreqs by adding (oip, rreqid) */
  [[rreqs := rreqs ∪ {(oip, rreqid)}]]
  /* update the route to oip in rt */
  [[rt := update(rt, (oip, osn, valid, hops + 1, sip, ∅))]]
  (
   [ dip = ip ]      /* this node is the destination node */
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       [[for all (rip, ∗) ∈ dests : invalidate(rt, rip)]]
       groupcast(pre, rerr(dests, ip)) . AODV(ip, rt, rreqs, queues)
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       fresh enough */
         /* update rt by adding sip to precs(rt, dip) */
         [[r := addpre(σ_route(rt, dip), {sip}); rt := update(rt, r)]]
```

Different Reading of a Standard

Analysing Variants

- Overview
- Analysed 5 Variants
  - from simple optimisations
  - to “bug fixing”
- An Interactive Theorem Prover can try to replay the proof
  - points a points where proofs/invariants break down
  - hope it’s easy to fix
  - if you cannot fix it, you don’t know anything

Variants of AODV

- Variant A: Skipping route request identifiers
  - small optimisation
  - RFC uses unnecessary data structure

  - modification in specification took about 5 minutes
  - proof went basically through

Variants of AODV

- Variant B: Forwarding route replies
  - “bug” fix of RFC
  - modification includes deletion of 3 lines of the spec
  - out of 400-odd lemmas only 7 broke down
    - 4 were easily fixed (broken references to line numbers)
    - about 3 hours to repair (for a novice)

Variants of AODV

- Variant C: From groupcast to broadcast
  - groupcast failed to inform some nodes
  - using boadcast is (in some sense) more efficient
  - as a consequence: simplifying data structure

  - modification includes new guard
  - about 75 lemmas broke down
  - 74 simple fixes
    - delete references to dropped data structure
    - fix line references
  - basically 1 lemma broke which could be fixed

Variants of AODV

- Variant D: Forwarding route requests
  - requests are not send to all nodes
  - missed opportunity to establish routes
  - performance improvement (maybe)

  - 8 lines were changed in the specification
  - 17 lemmas broke down
  - one proof needed major rework

Variants of AODV

- Variant E: All changes discussed above
  - basically merging all proof changes
  - no conflicting proofs/conditions showed up

The Other Side of the Medal

- Is every variant fix so simple
  - probable yes, IF the lemmas/invariants stay valid
    (which was the case for the presented variants)
  - no, IF lemmas do not hold any longer
    Variant F: Updating with the Unknown Sequence Number
    - since lemmas are not valid any more deep expertise is needed
      to see that the lemma is incorrect
      to provide an alternative repair

Conclusion/Future Work

- Mechanised Proof of AODV and variants
  - based on process algebra
  - mechanised in Isabelle
  - about 1 hour verification time (with 4 cores)
  - both mechanisation of process algebra and AODV can be found in the Archive of Formal Proofs
- Variants are often so small that the proof can be “replayed”

- Optimise Mechanisation
  - simple changes might be automated (e.g. reference to line numbers)
- Extend Formalism and Model
  - add time
  - add probabilities and quantities

Questions

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