# Statistical Model Checking
of
# Wireless Mesh Routing Protocols

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# Wirless Mesh Networks

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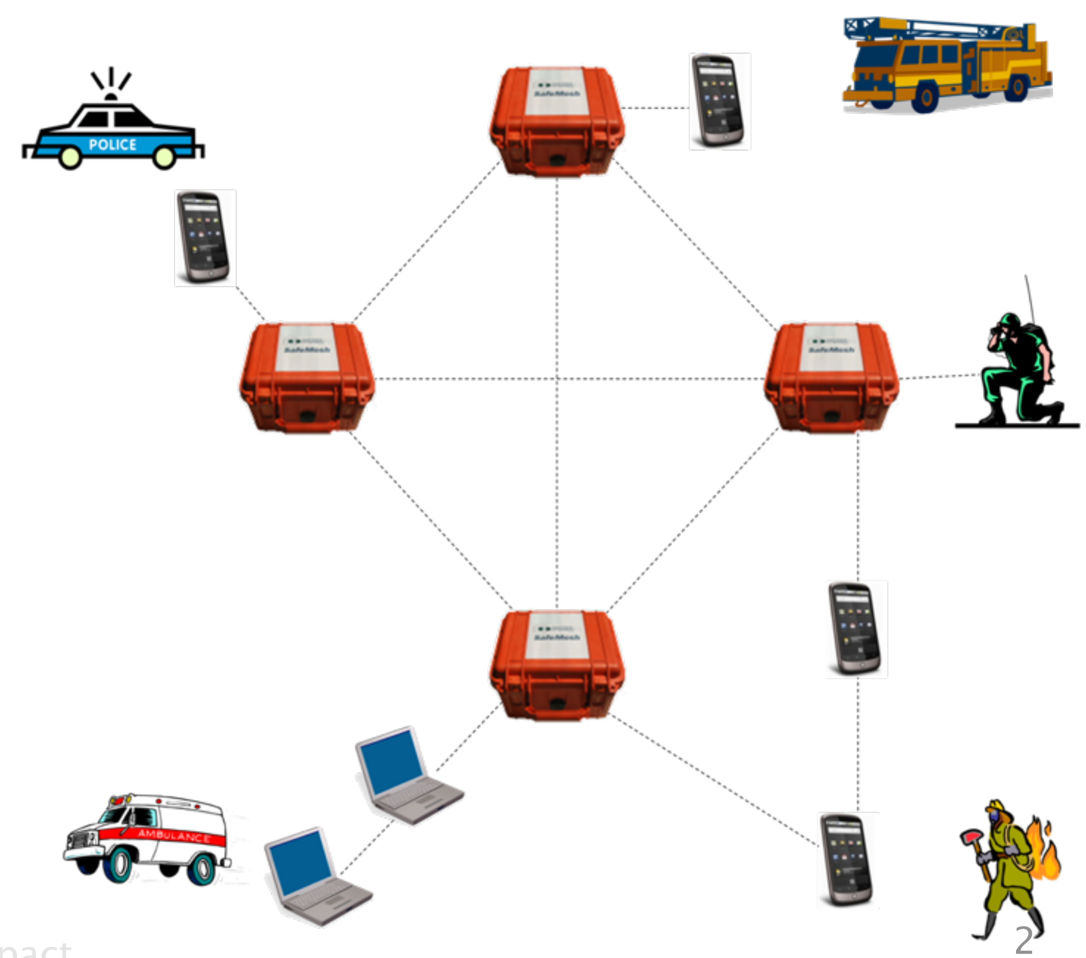
- wireless mesh networks (WMNs)
  - key features: mobility, dynamic topology, wireless multihop backhaul
  - quick and low cost deployment
- applications
  - public safety
  - emergency response, disaster recovery
  - transportation
  - smart grid
  - ...
- limitations in reliability and performance

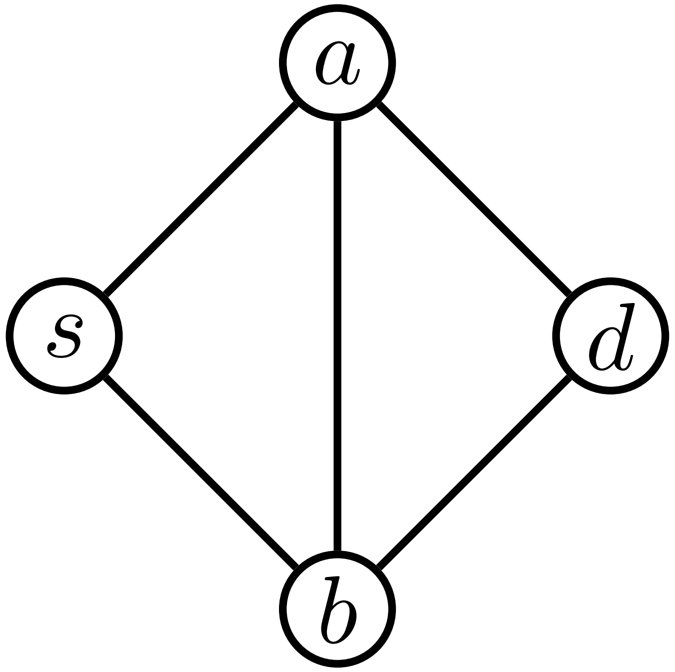


# Case Study: AODV vs DYMO

- AODV and DYMO are routing protocols for WMNs
  - ad hoc (network is not static)
  - on demand (routes are established when needed)
- Ad Hoc On-Demand Distance Vector (AODV)
  - 1997-2001 by Perkins, Beldig-Royer and Das (University of Cincinnati)
  - One of the four protocols currently standardised by the IETF MANET working group (IEEE 802.11s)
- Dynamic MANET On-demand (DYMO) Routing
  - successor of AODV
  - "supposed to be better"

# Case Study:

- main mechanism (AODV and DYMO)
  - if route is needed
    *broadcast* route request (RREQ)
  - if node has information about a destination
    *unicast* route reply (RREP)
  - if unicast fails or link break is detected
    *groupcast* route error (RERR)




- (no details for the purpose of this talk)

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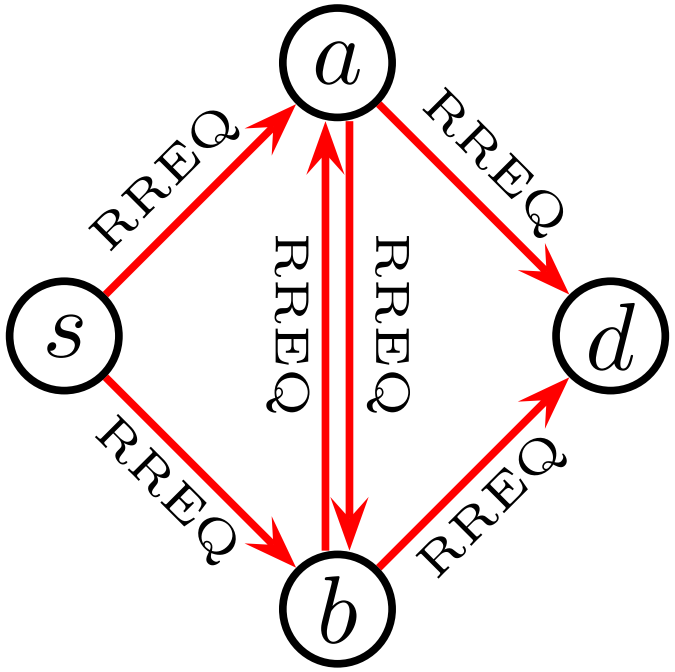


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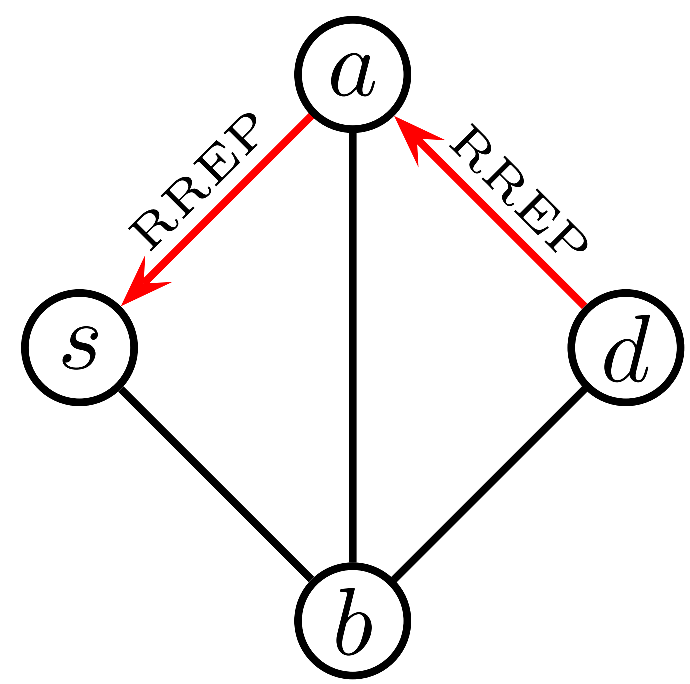


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# Model Checking WMN-protocols

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- exhaustive MC techniques often limited
  - state space explosion
    - limited to less than 10 nodes
    - dynamic topology decreases network size even more
  - quantitative reasoning
    - hardly possible
    - qualitative reasoning only indicated that there is a problem; but not how serious it is

- do we need real verification?
  - is high evidence/confidence sufficient?

# Example: Loop Free Protocol

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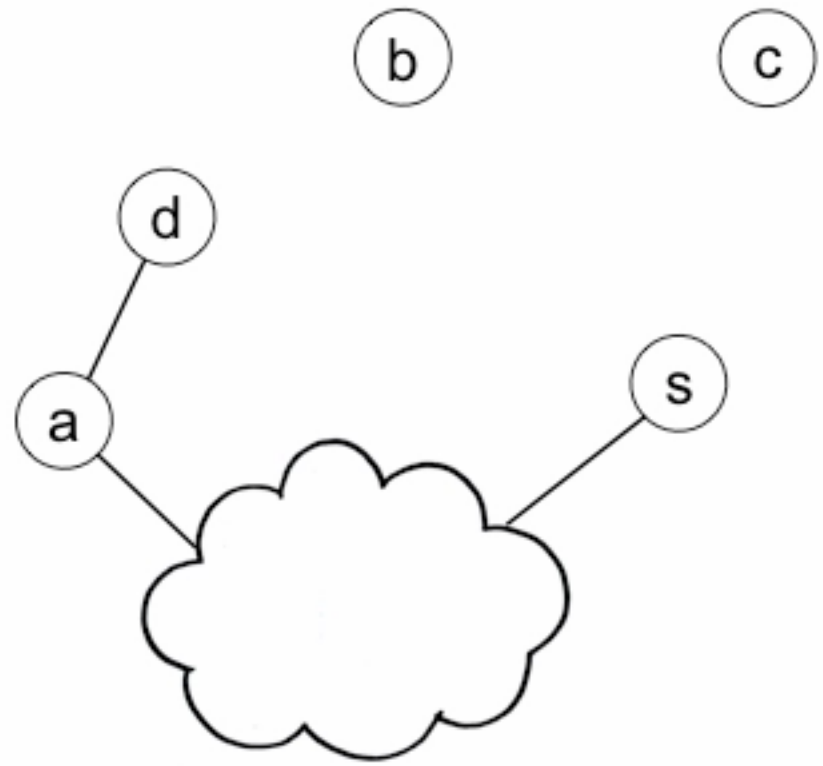
- idea (common belief):
  - sequence numbers guarantee loop freedom if increased monotonically
- depending on the reading of the standard AODV is (not) loop free
  - 6 nodes (2 highly dynamic)
  - 4 route request
- not possible to find with MC
  - but should we find it?
  - are the scenarios too rare?

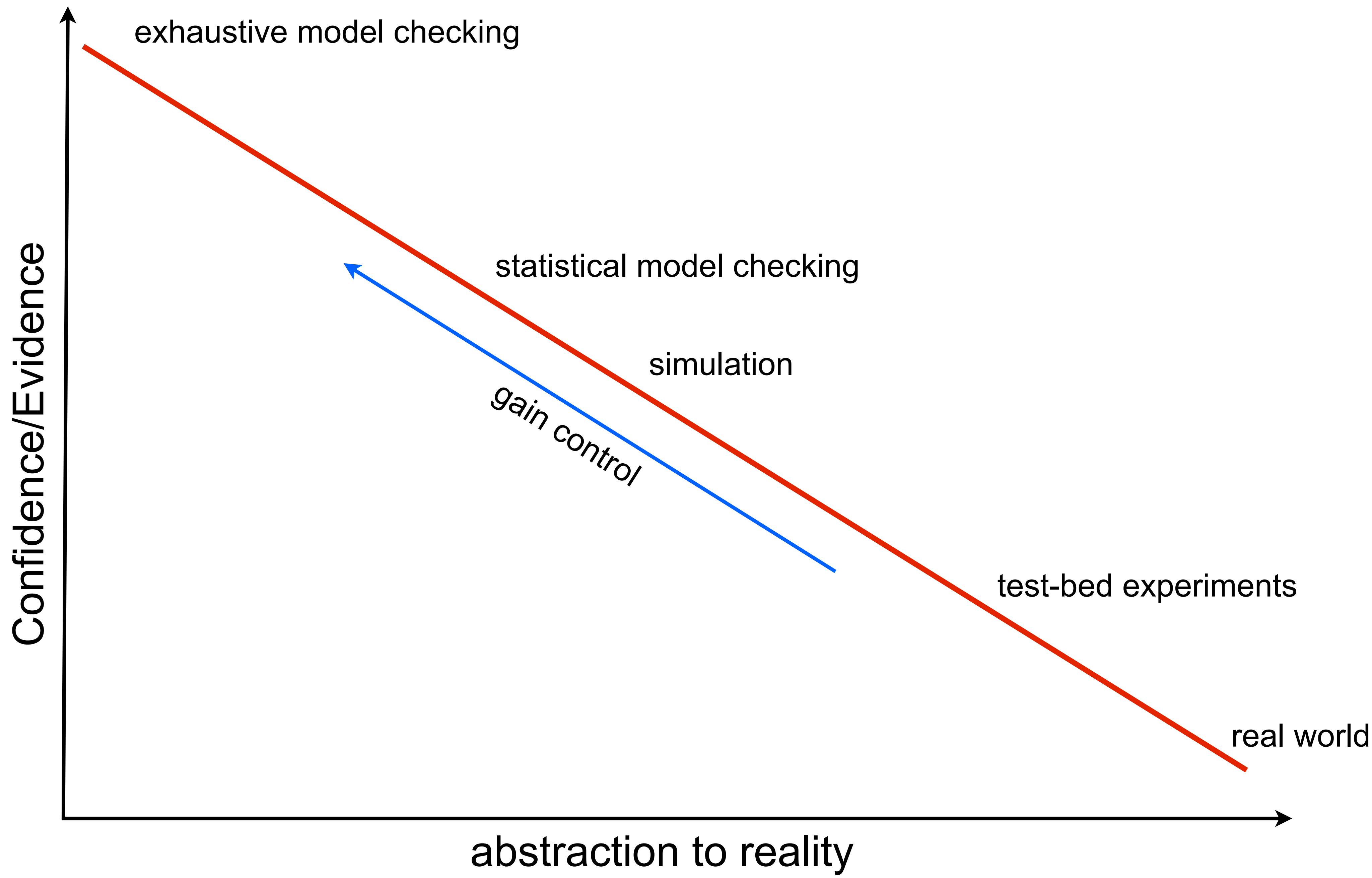


# Statistical Model Checking

- combines ideas of model checking and simulation
- supports quantitative analysis
- overcomes size barrier

- SMC trades certainty for approximation
  - using Monte Carlo style sampling, and hypothesis testing
  - we use SMC-Uppaal

# Simulation vs SMC vs MC




- SMC allows more control on an abstract level
- for example abstracts from other network layers

# Uppaal Models

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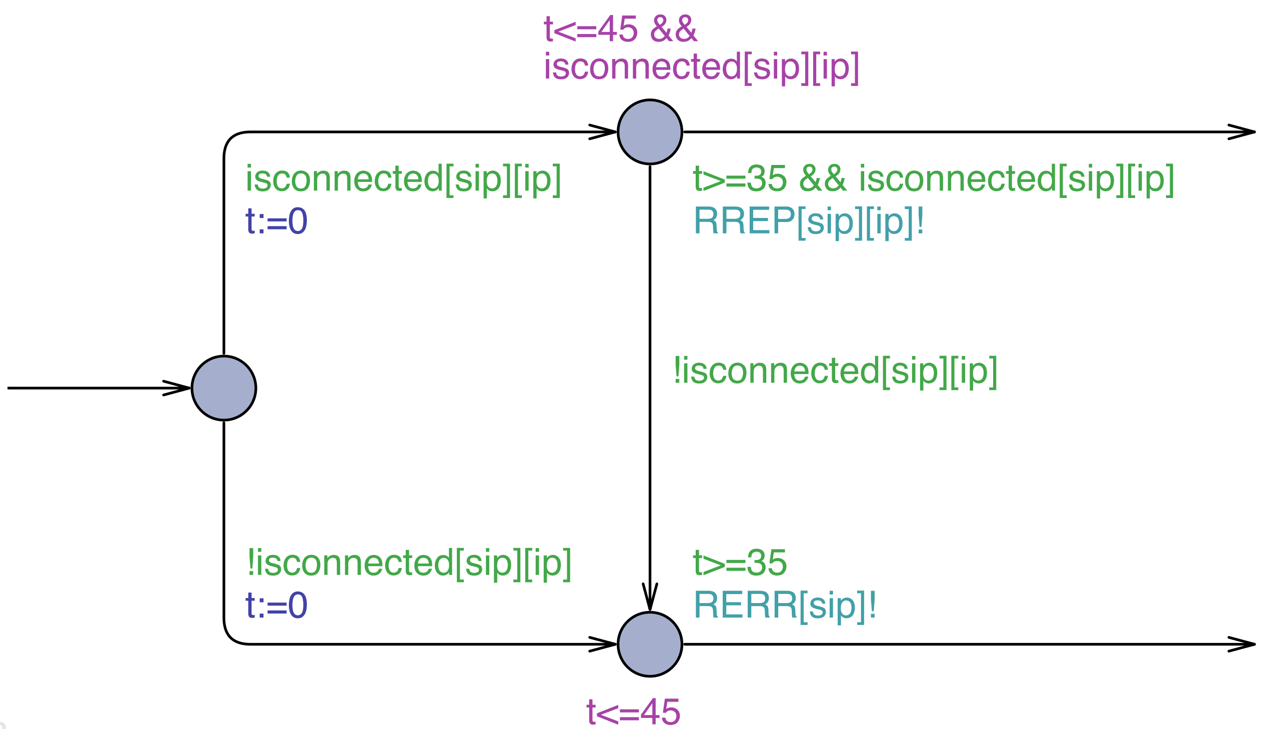
- created Uppaal models for AODV and DYMO
  - from unambiguous algebraic specification
  - each node runs two processes
    - message queue
    - main processes, handling the received messages (takes time)
  - time only elapse while sending messages (some randomness)
  - technicality
    - SMC-Uppaal only allows broadcast



# Experiments

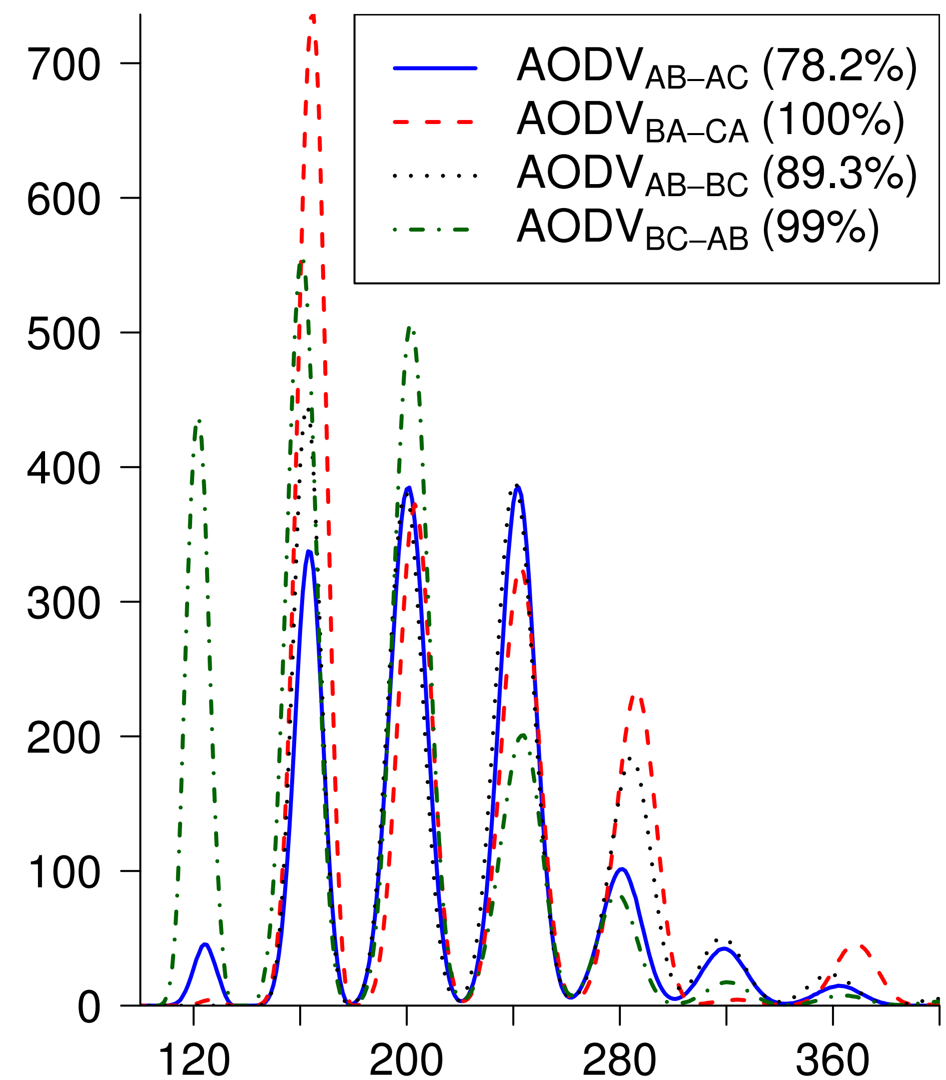
- a timing analysis of AODV
- a comparison between AODV and DYMO
- a quantitative analysis of AODV and DYMO
- pushing the limits of network size

# A Timing Analysis of AODV

- AODV fails to establish some routes
  - in 47% of all scenarios
    - from exhaustive (non-timed) MC
    - non-quantitative values
      (does not state how often failure happens)
  - might depend on missing time
- replay some of the experiments
  - all topologies up to 5 nodes
    (similar to former experiments)
  - about 4000 experiments on 444 topologies
  - two requests, one topology change

# A Timing Analysis of AODV

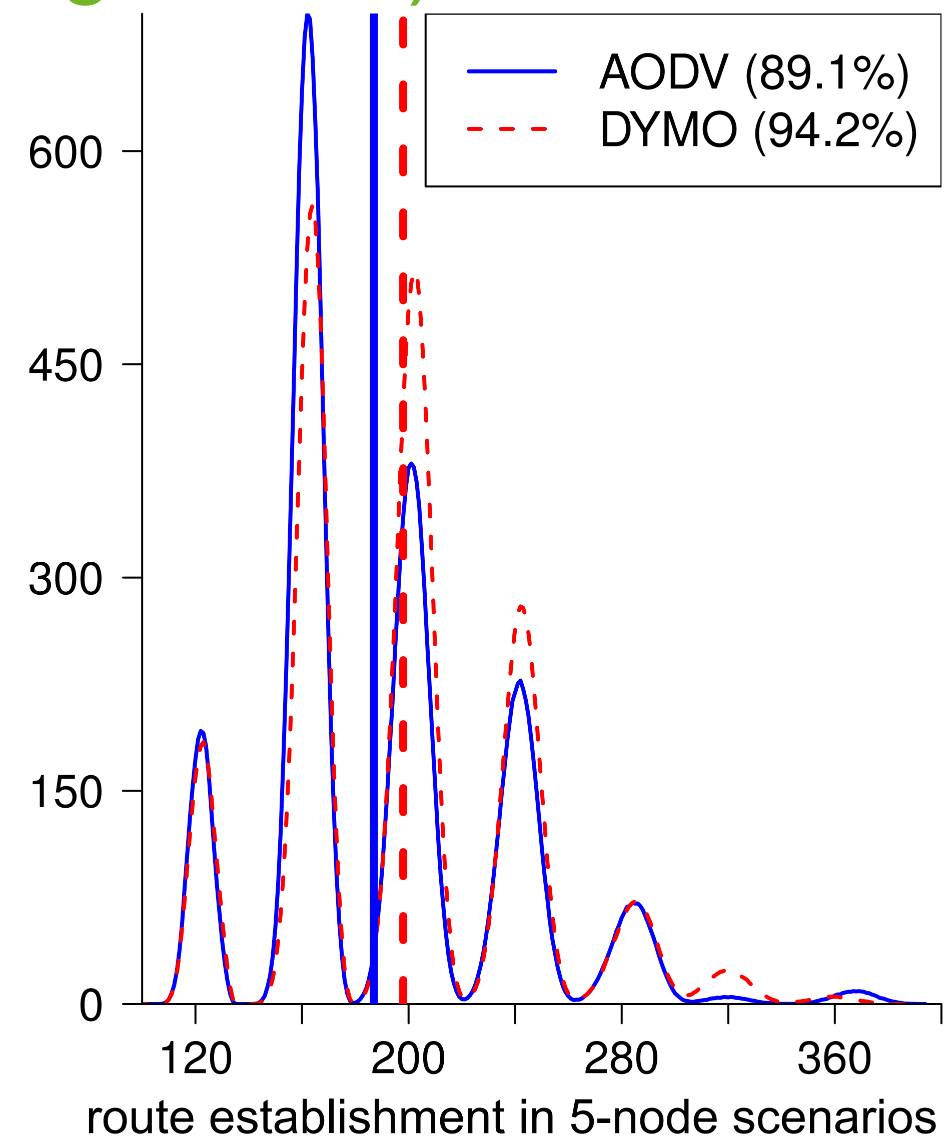
- results
  - failure rate around 10%
  - dependent on scenario
  - reasons
    - time has been added
    - we now have quantitative measurement




route establishment and protocol termination in 5-node scenarios

# Comparison AODV vs DYMO

- protocols vary in details, e.g.
  - different handling of sequence numbers
  - path accumulation
    (to decrease the number of messages sent)
- experiments show that
  - DYMO behaves better
  - AODV behaves better
- results
  - DYMO fails less often



# Quantitative Comparison AODV vs DYMO

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- quantitative measurements
  - route quantity
    - nodes gain knowledge by received messages
  - route quality
    - how good/useful is the knowledge learned
- results
  - DYMO establishes fewer routes
    - that was a surprise since it uses path accumulation
    - fewer messages sent means fewer opportunities to learn alternative routes
  - DYMO's route quality is worse than that for AODV
    - assumption: big consequences in larger networks

| | 3 nodes | 4 nodes | 5 nodes |
|---|---|---|---|
| AODV | 5.28 | 8.83 | 13.99 |
| DYMO | 5.25 | 7.87 | 11.94 |
| max | 6 | 12 | 20 |

Average number of routes established

# Experiments (Intermediate) Summary

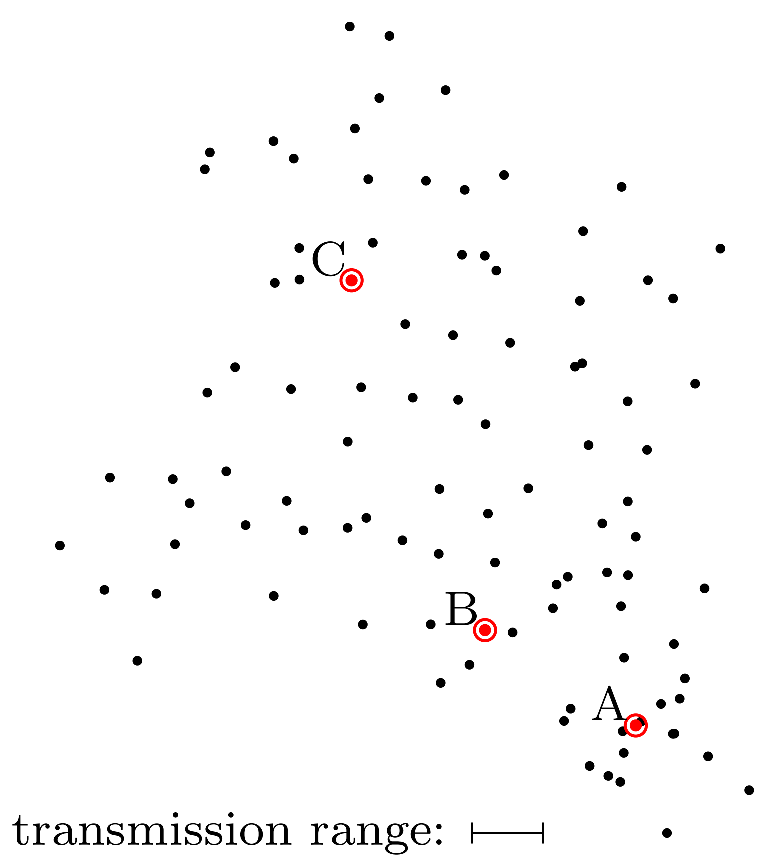
- exhaustive analysis of topologies up to 5 nodes
  - could be handled by exhaustive MC
  - allowed quantitative analysis
  - some surprising insights in AODV and DYMO
    - although these protocols have been implemented and analysed for years
- can SMC really can overcome the size barrier
  - last experiment

# Networks of Realistic Size

- WMNs consist of 20-100 nodes
  - some problems seem to occur only in larger networks
- analysis of topologies with 100 nodes feasible
  - problem: topology choice
  - node placement algorithm for realistic topologies (NPART)

| #nodes | 50 | 75 | 100 |
|---|---|---|---|
| memory (Gb) | 14 | 30 | 80 |
| run time (m) | 270 | 328 | 1777 |

Memory consumption




a network with 100 nodes

# The Other Side of the Coin

- we can analyse realistic size networks
  - which topology to be chosen (there are too many)
    - (small network topologies can be iterated)
  - dynamic topology
    - link failures could be modelled by probabilities
    - mobile nodes should be modelled

# Conclusion

- timed models of AODV and DYMO
  - systematic analysis across all small networks
  - examine reasons for observed differences in performance

- examined the feasibility of SMC w.r.t. scalability
  - first you analyses WMNs of realistic size

- what's next
  - catalogue of topology (shape, density, ...)
  - mobility model

THE END

# Problems

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- Standards (IETF RFCs) are not precise
  - written in English
  - ambiguous (sometimes incomplete)
  - no formal specification
- Compliant implementations
  - have different behaviours
  - are not compatible
  - have serious flaws
- Traditional evaluation techniques: simulation and test-bed
  - expensive
  - limited to (a small number of) specific scenarios
  - errors found after years of evaluation

# Why Formal Specification?

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