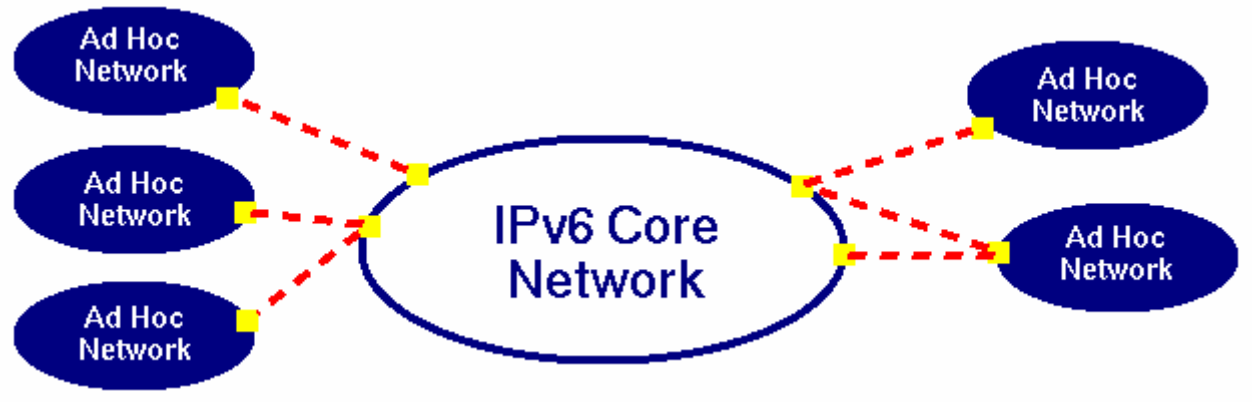
Modelling and Validation of Protocols for Internet Connectivity in Mobile Ad-hoc Networks



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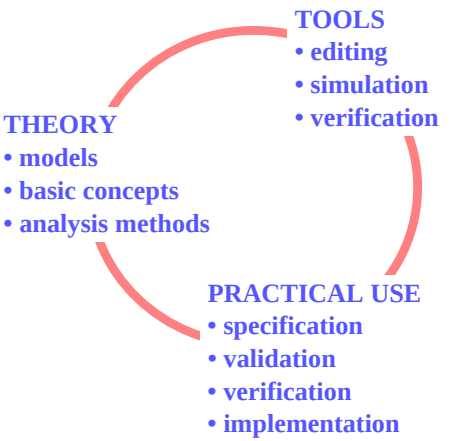
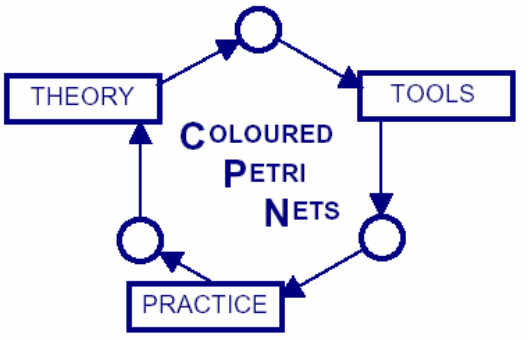


Project

Joint 3-year research project started in 2002:

- Ericsson Telebit A/S, Viby, Denmark.
- Coloured Petri Nets Group, University of Aarhus, Denmark.



Themes of the research project:

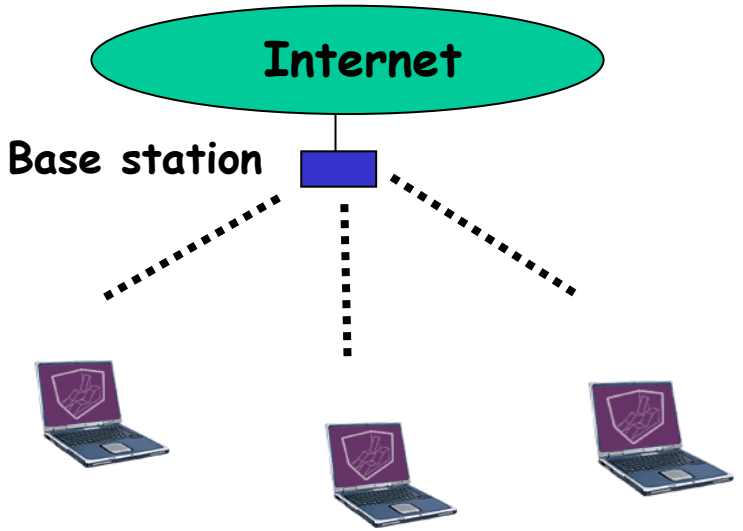
- Explore the use of the Internet Protocol version 6 (IPv6) protocol suite in the context of ad-hoc networking.
- Apply of Coloured Petri Nets (CP-nets) and supporting computer tools in the development of communication protocols.

Mobile Ad-hoc Networking

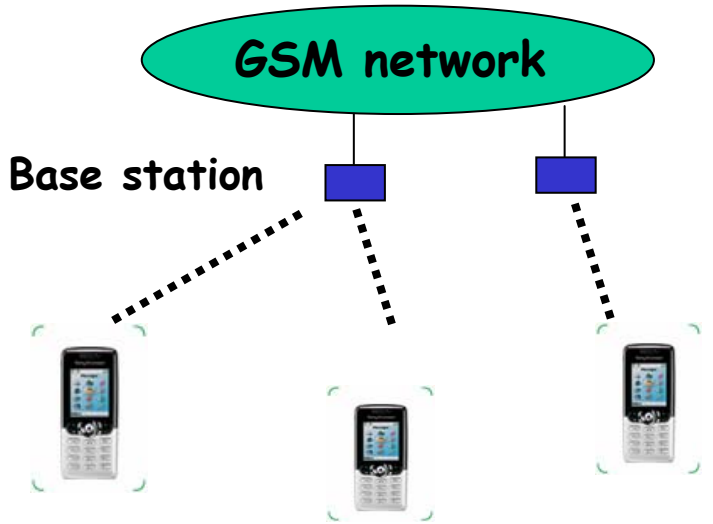
A very brief introduction

Wireless Communication and Mobility

Wireless LAN (e.g., 802.11b):



Cellular Networks:

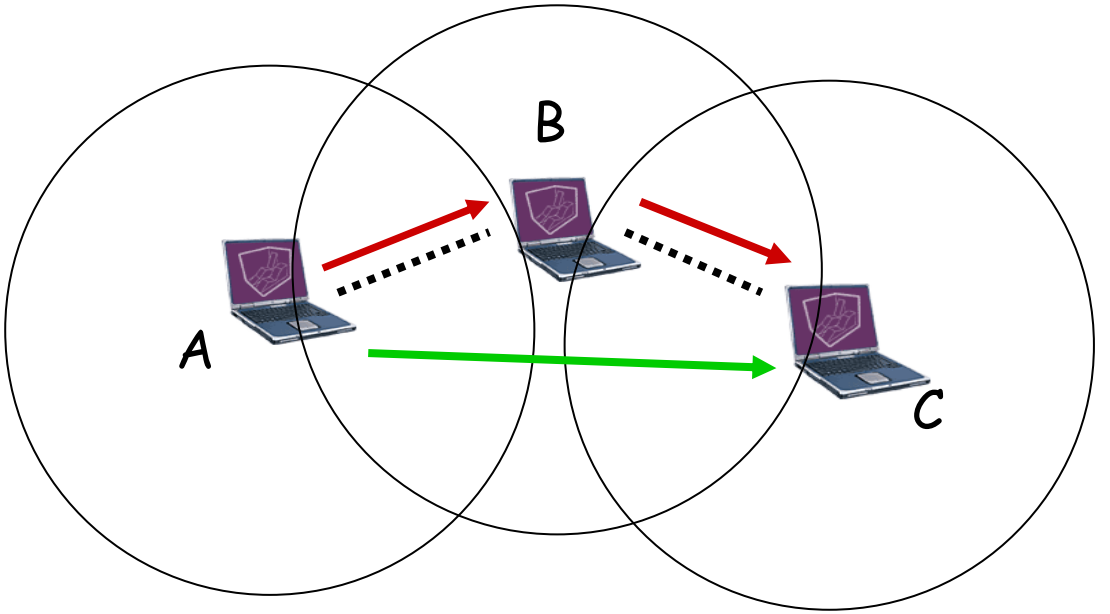


Key characteristics:

- Communication is based on a preexisting (fixed) infrastructure.
- No direct communication between mobile nodes.

Mobile Ad-hoc Networks (MANETs)

No preexisting infrastructure and peer-to-peer multi-hop communication:



Application areas:

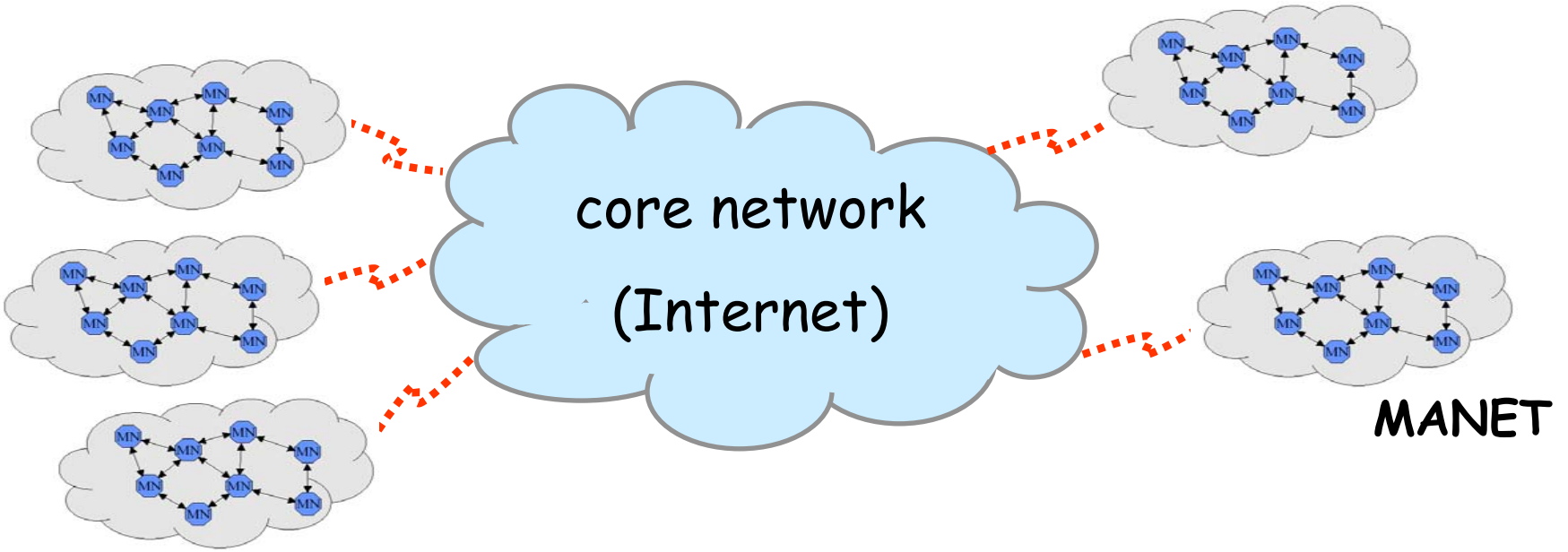
- Sensor networks.
- Search-and-rescue operations.
- Home networking.
- Traffic safety.

Challenges:

- Mobility and bandwidth.
- Power consumption.
- Security.
- Fully distributed operation.

Hybrid Network Architecture

A main topic of the project is protocols for integration of fixed core networks and mobile ad-hoc networks.



Mobility management (nodes and MANETs).

Connectivity management (address configuration, service discovery).

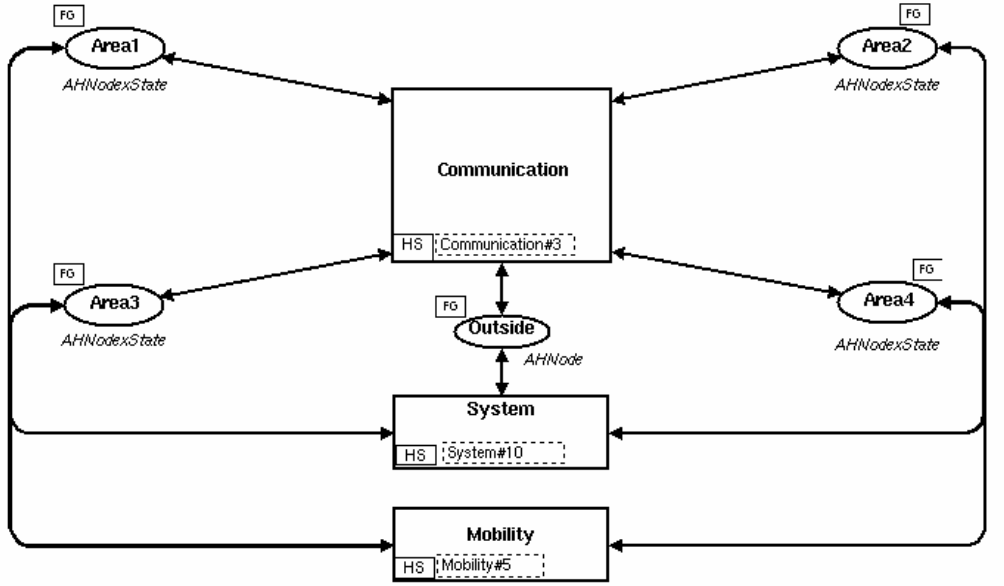
Routing (integration of core network and intra-MANET routing).

Project Overview

Subprojects

Subprojects

Subproject 1: Specification of mobility and communication scenarios in an Internet-MANET network architecture:



Subproject 2: Specification and Validation of an Edge Router Discovery Protocols for Mobile Ad-hoc Networks.

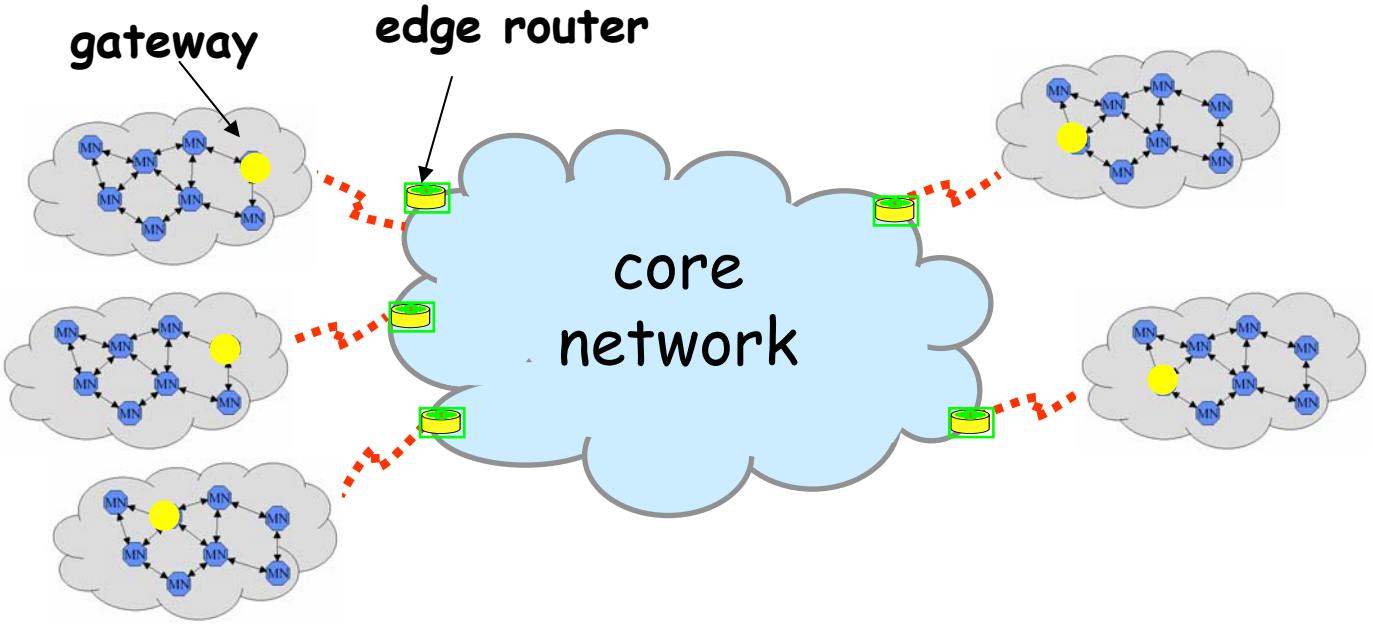
Subproject 3: Model-based Prototyping of Protocols for Internet-MANET Routing with Redundant Gateways.

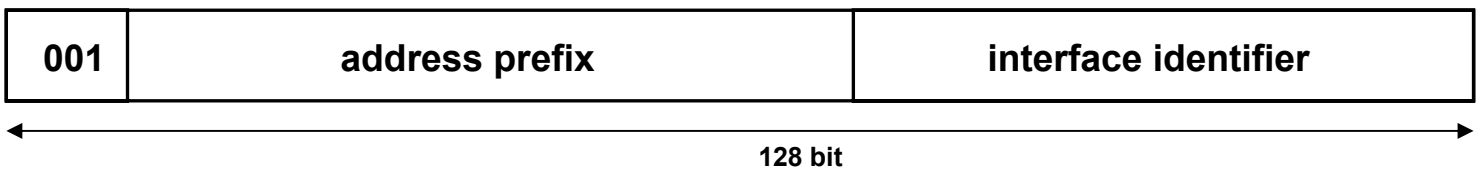
Specification and Validation of an Edge Router Discovery Protocols for Mobile Ad-hoc Networks

Subproject 2

Edge Router Discovery Protocol (ERDP)

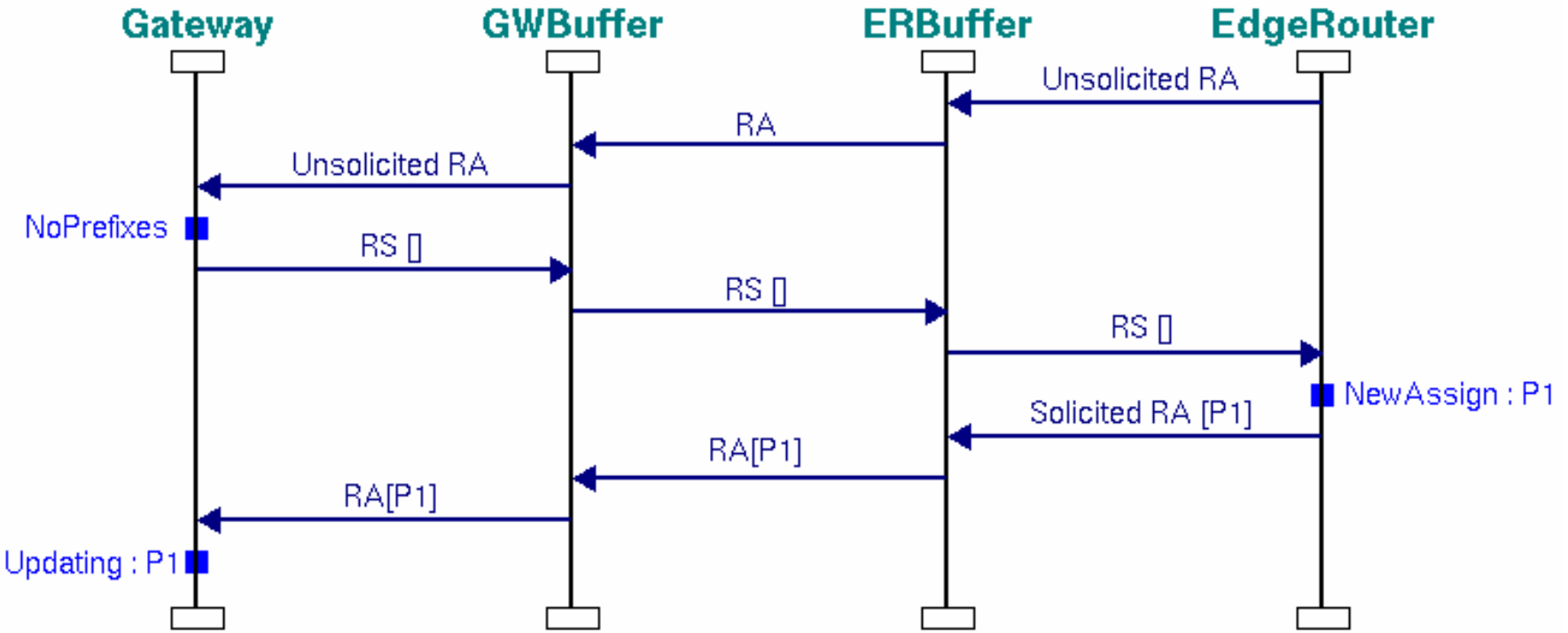
ERDP allow edge routers to configure gateways with address prefixes:





Based on extending the Neighbour Discovery Protocol (NDP) of IPv6.

Basic Operation of ERDP



ERDP requirements:

- mobility of gateways.
- expire of address prefixes.
- unreliable wireless links.

RA = Router Advertisement

RS = Router Solicitation

The Modelling Phase

CPN modelling applied for specification of ERDP:

- A natural language specification developed by protocol engineers from Ericsson Telebit A/S.
- CPN model reflecting the specification developed by researchers from the CPN Group.

Protocol developers from Ericcson Telebit A/S were given a 6-hours course enabling them to read and interpret CPN models.

ERDP and the CPN model was developed in an iterative process:

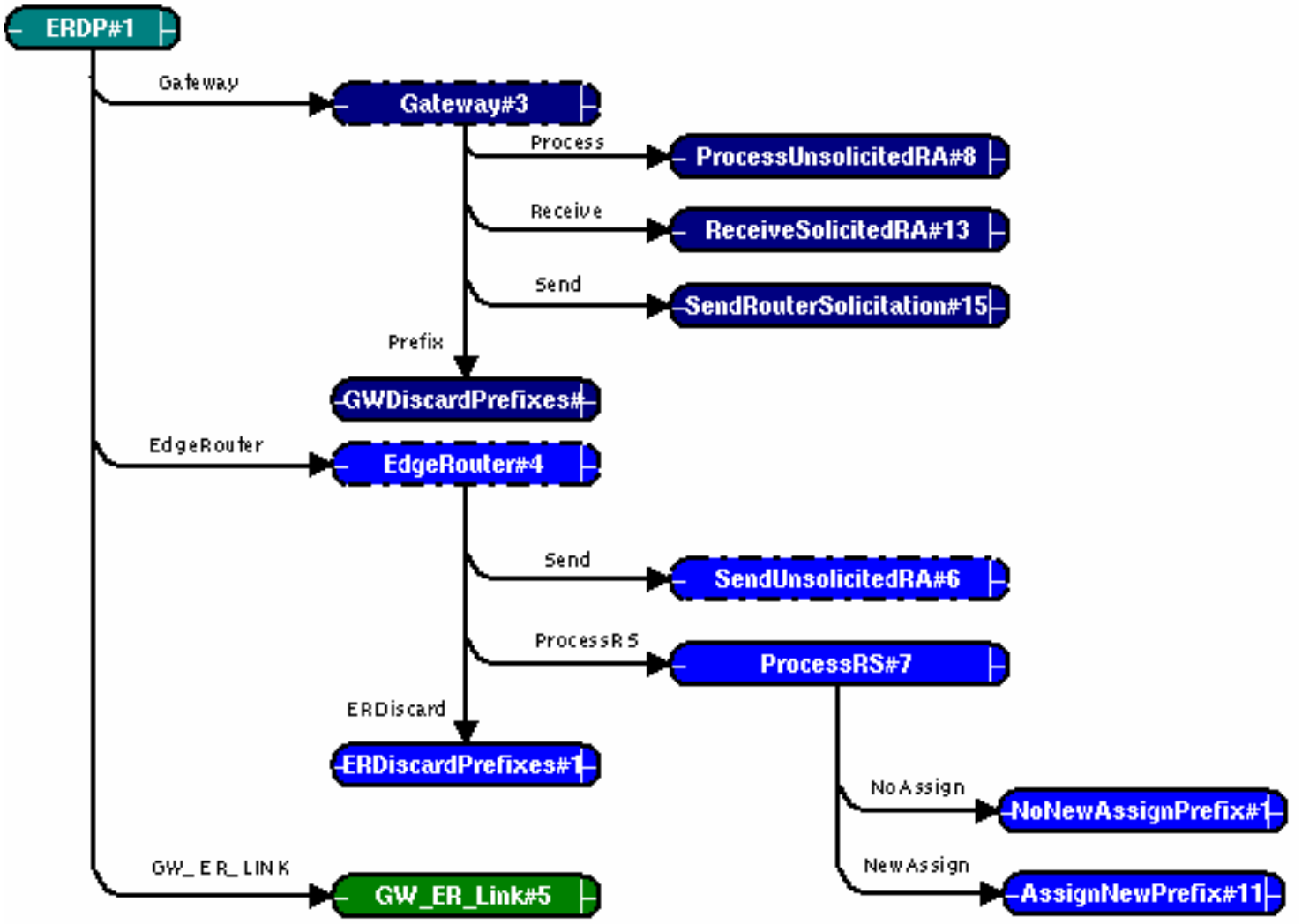
- CPN model discussed and reviewed in each iteration.
- CPN model used as a basis for discussion of protocol design.
- Single-step simulation of model used for detailed investigations.

Approximately 70 man-hours were used on CPN modelling and reviews.

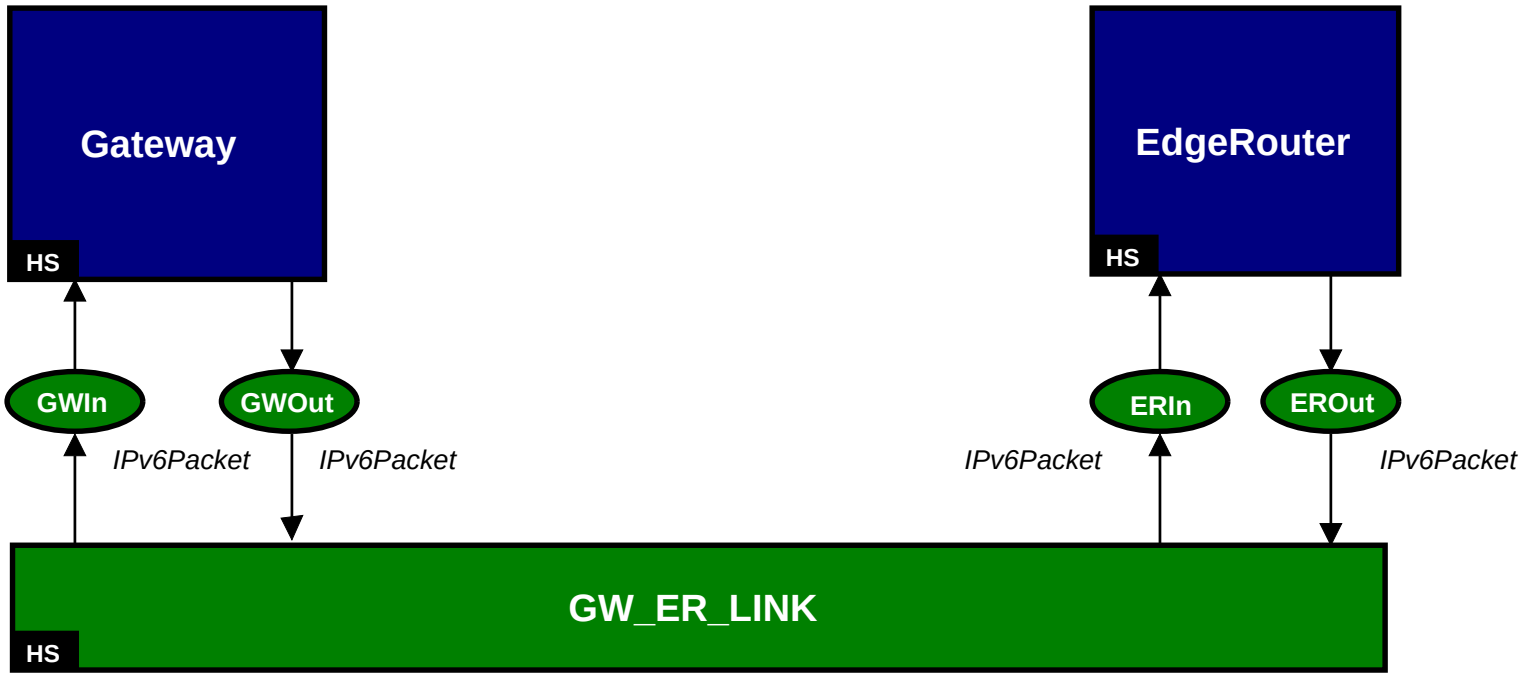
The ERDP CPN Model

Demo

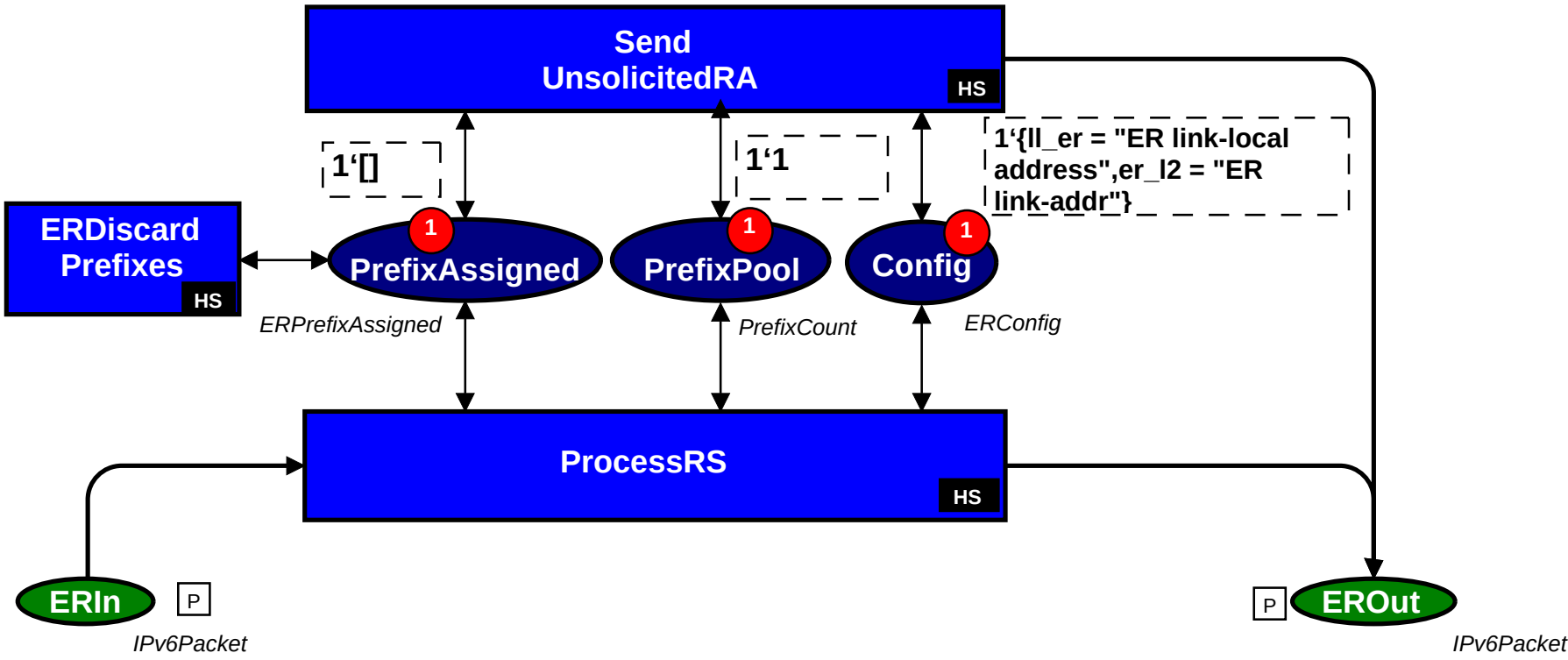
Overview of CPN model



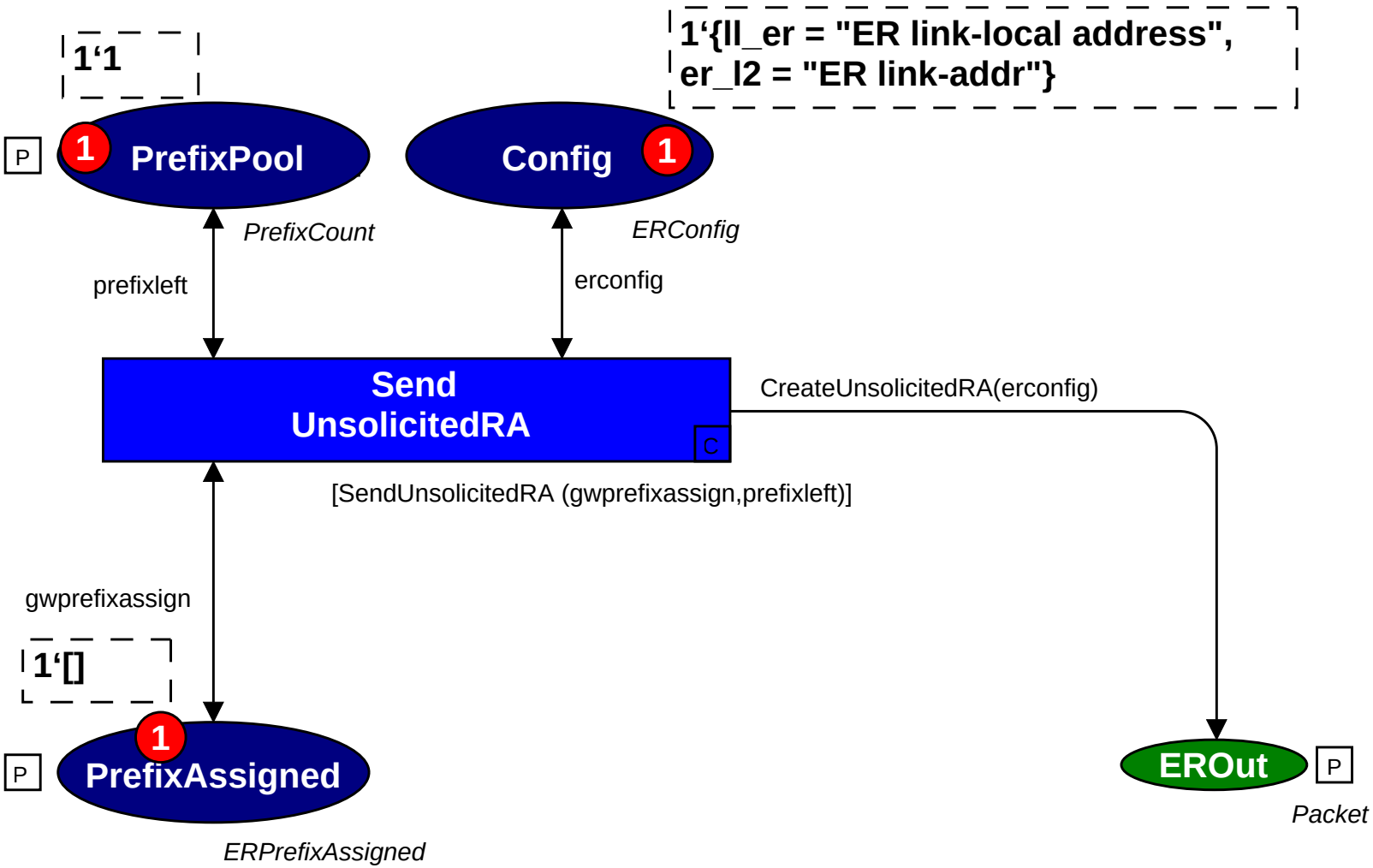
Edge Router Discovery Protocol



Modelling of the Edge Router



Sending Unsolicited RA



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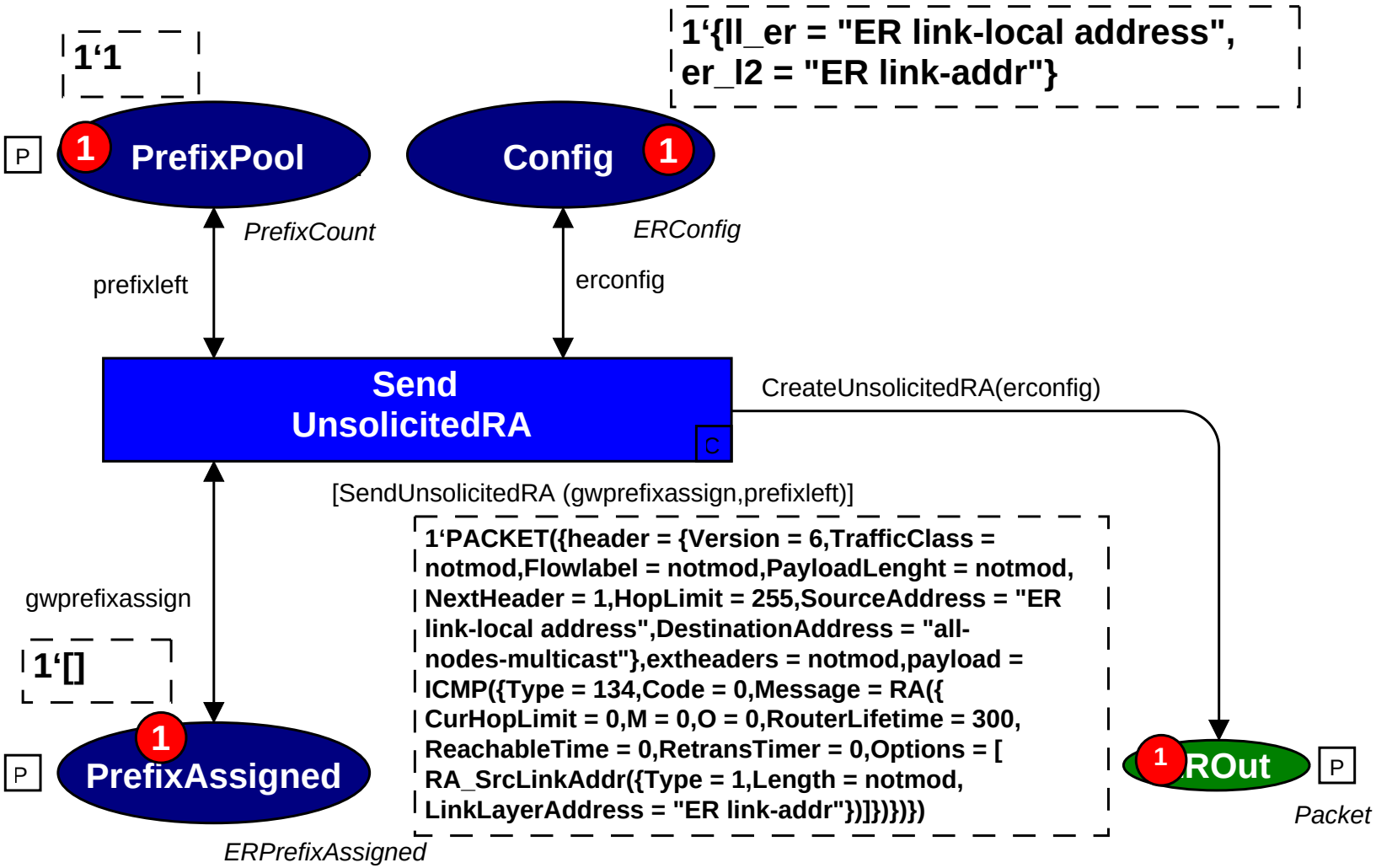


Results from Modelling

Several design issues were identified in the modelling phase:

Category	**Review 1**	**Review 2**	**Total**
Incompleteness and ambiguity in the ERDP specification	3	6	9
Errors in the protocol	2	7	9
Simplifications of the protocol	2	0	2
Additions	4	0	4
Total	11	13	24

State Space Analysis

Conducted after the three modelling and specification iterations.

Nodes → Reachable states

Arcs → Actions/events

Paths → Executions

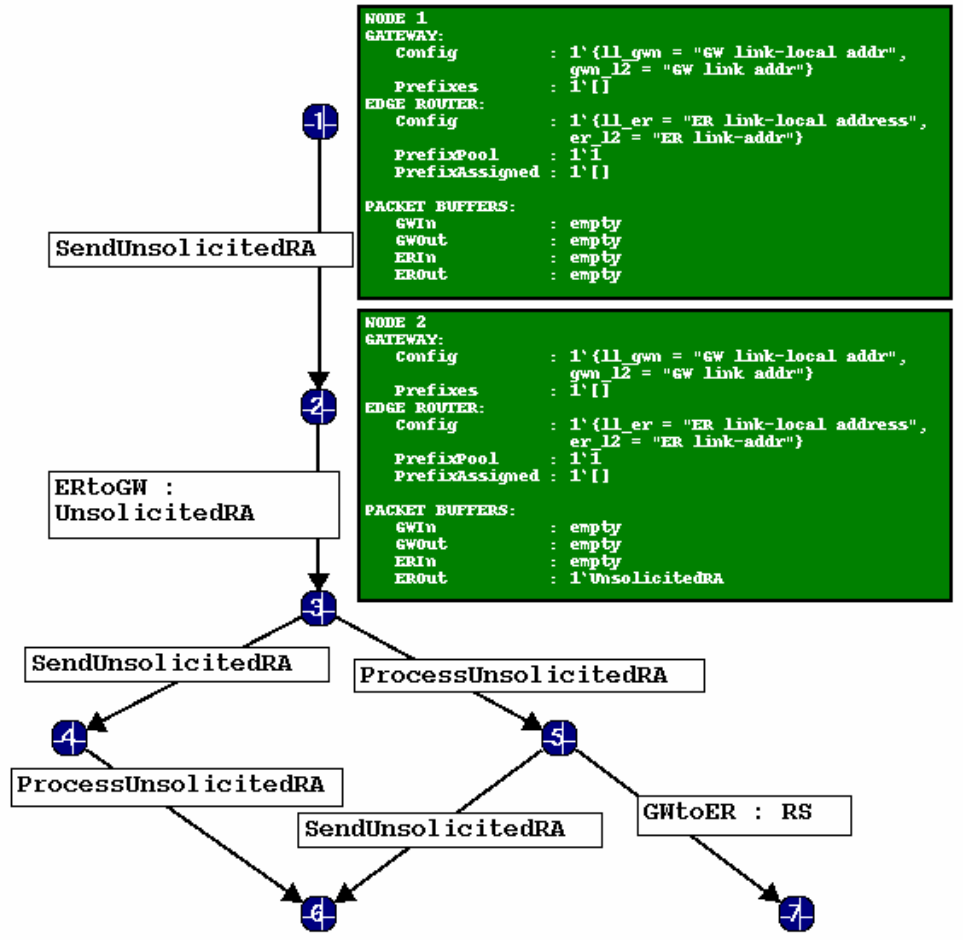
Advantages:

Highly automatic.

Counter examples.

Main disadvantage:

State explosion problem.



State Space Analysis Approach

State space analysis was based on full state spaces:

1. Compute full state space.
2. Generation of the state space report.
3. Verification of properties using query functions.

Key property (consistent configuration always possible):

From any state with a non-configured prefix P it is possible to reach a state where P is consistently configured.

The state space analysis proceeded in three steps:

1. Basic configurations: no packet loss and no expire of prefixes.
2. Packet loss on wireless link added.
3. Expire of prefixes added.

State Space Analysis

Demo

Example

Configurations with packet loss and expire of prefixes:

Prefixes	Nodes	Arcs	Generation Time	Analysis Time
1	173	531	0.34	0.02
2	714	2,404	1.80	0.17
3	2,147	7,562	6.34	0.67
4	5,390	19,516	18.65	2.09
5	11,907	43,976	48.56	6.39
6	23,905	89,654	121.07	15.36
7	44,550	169,169	289.91	33.14
8	78,211	300,072	671.24	64.12
9	130,732	505,992	1560.73	123.81
10	209,732	817,903	3586.23	229.70

Results from State Space Analysis

Step 1 [no packet loss and no expire of prefixes]:

- Synchronisation error between edge router and gateway.
- Properties verified:
  1. Consistent configuration always possible.
  2. Persistent consistently configured.
  3. Eventual consistent configuration.

Step 2 [packet loss on wireless link added]:

- Synchronisation error when certain unsolicited RAs was lost.
- Error in processing of router advertisement in gateway (livelock).
- Properties verified:
  1. Consistent configuration always possible.
  2. Persistent consistently configured.
  3. Eventual consistent configuration if only finitely many packets lost.

Step 3 [expire of prefixes added]:

- Property verified: Consistent configuration always possible.

Conclusions

CPN modelling and analysis applied in development of ERDP:

- The act of constructing the CPN model provided valuable input to the ERDP specification.
- Simulation and graphical feedback using message sequence charts added further insight into the operation of the protocol.
- State space analysis revealed 3 additional errors and the key properties for the revised ERDP could be verified.

The application of CPNs was a success for three main reasons:

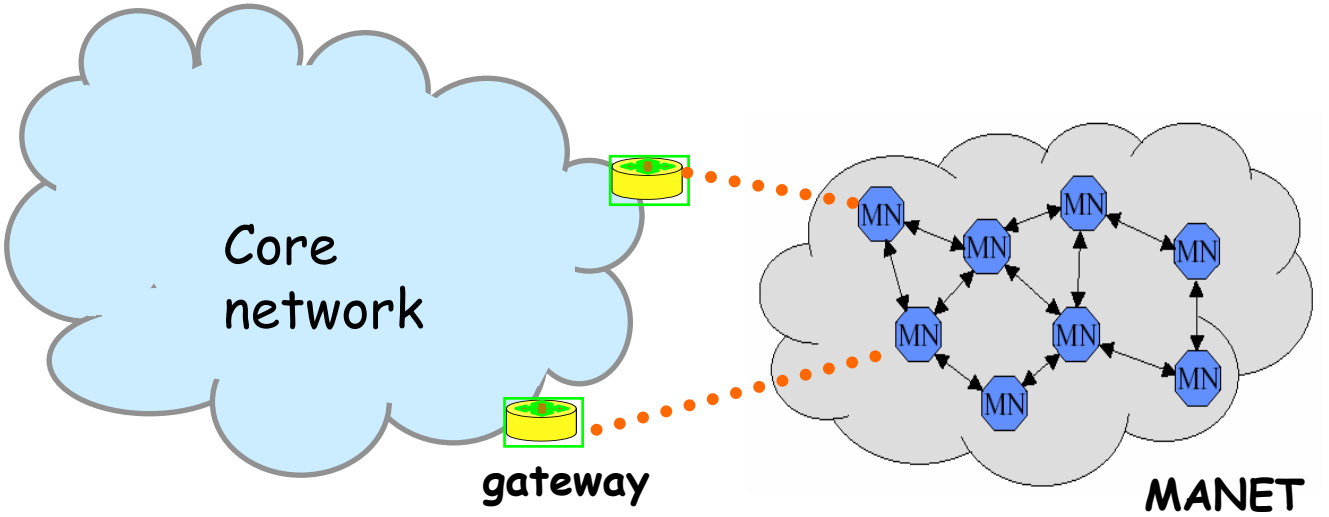
- CPN modelling language and supporting computer tools powerful enough to specify and validate a real-world protocol.
- Several non-trivial design issues and errors were identified and fixed in the course of modelling and analysis.
- Approximately 100 man-hours over a period of 4-months were invested in modelling and state space analysis.

Model-based Prototyping of Protocols for Internet-MANET Routing with Redundant Gateways

Subproject 3

Network Architecture

Routing between core network and MANETs in presence of multiple gateways



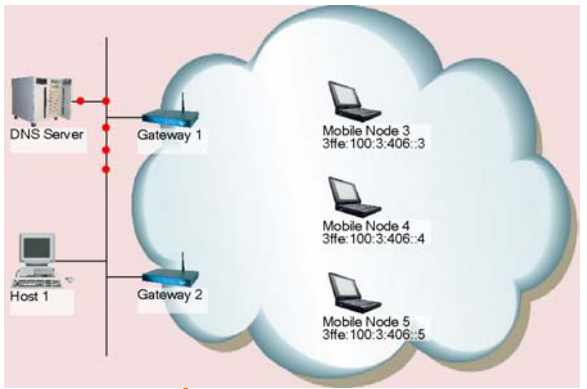
Possible solutions:

1. Mobile host routes injected by gateways into the core network.
2. **Dynamic DNS and renumbering.**
3. Mobile IP.
4. Host Identity Protocol (HIP).

Model-based Prototyping: Approach

.. based on constructing an executable model of the design:

Domain-specific graphic/GUI

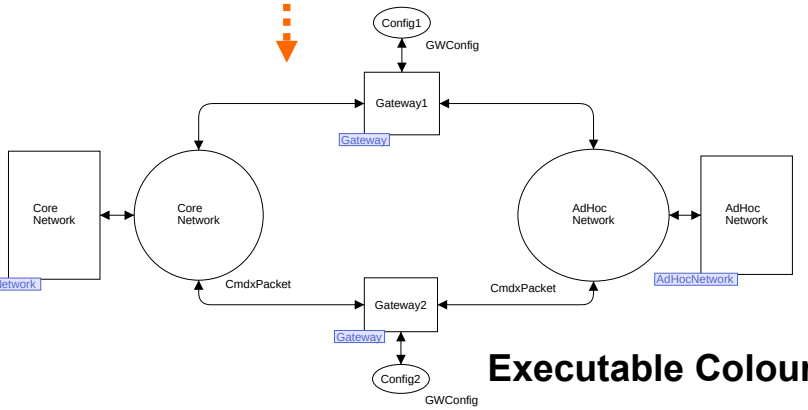


Explore and demonstrate

Input

feedback

Protocol engineer

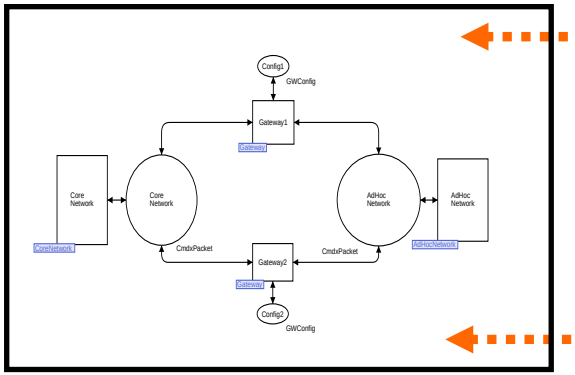


Executable Coloured Petri Net model

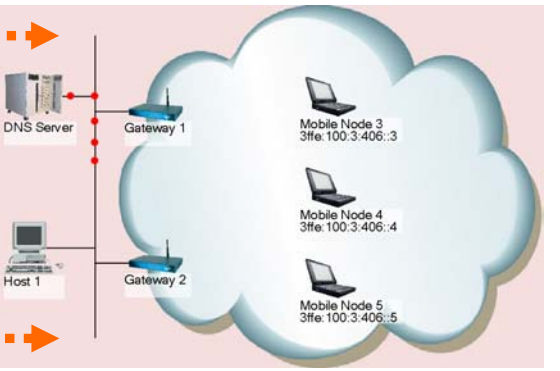
Modelling

Protocol specification

Prototype Architecture



CPN Simulation Engine



CPN Tools GUI

SceneBeans

DMO

XML-RPC

TCP/IP

BETA

Standard ML

JAVA

CPN RGW model

Demo

Domain-Specific GUI

Demo

Discussion

Prototype can be explored via domain-specific graphics:

- Behaviour is as defined by the CPN model.
- CPN knowledge is not required to explore the prototype.

Advantages (compared to building a physical prototype):

- Easier to control and reproduce scenarios.
- Implementation details can be abstracted away.
- Setup of physical network equipment is not required.
- Larger scenarios can be investigated.

References

L.M. Kristensen, J.B. Jørgensen and K. Jensen. Application of Coloured Petri Nets in System Development. Lectures on Concurrency and Petri Nets - Advanced in Petri Nets. Proc. of 4th Advanced Course on Petri Nets. Vol. 3098 of Lecture Notes in Computer Science, pp. 626-685. Springer-Verlag, 2004.

L.M. Kristensen and K. Jensen. Specification and Validation of an Edge Router Discovery Protocols for Mobile Ad Hoc Networks. In Integration of Software Specification Techniques for Applications in Engineering. Vol 3147 of Springer Lecture Notes in Computer Science, pp. 248-269. Springer-Verlag, 2004.