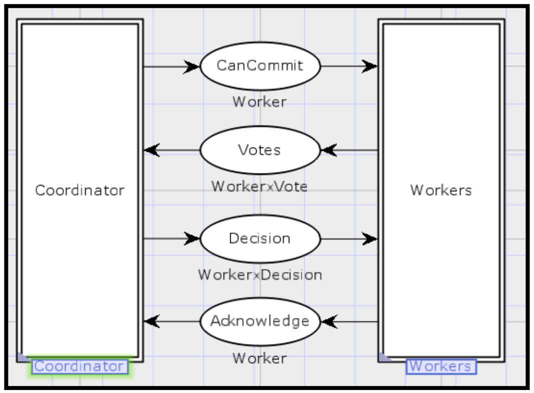
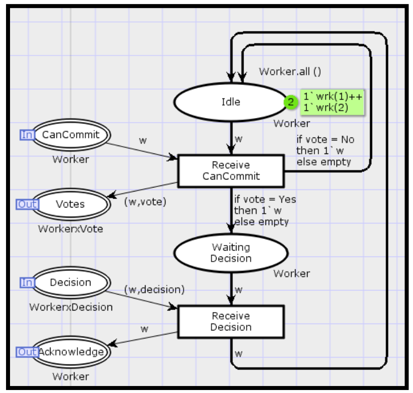
Implementing the WebSocket Protocol based on Formal Modelling and Automated Code Generation





Lars M. Kristensen

Bergen University College [1]

Norway

lmkr@hib.no / www.hib.no/ansatte/lmkr/

Kent I.F. Simonsen[1,2]

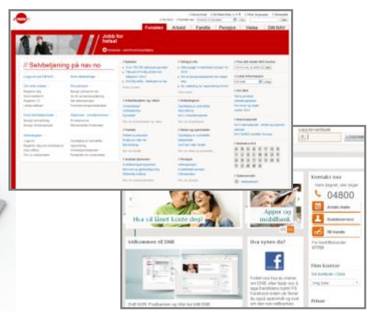
Technical University of Denmark [2]

Denmark

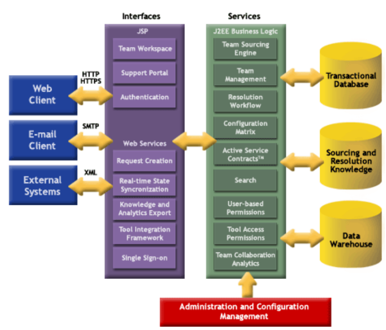
kifs@hib.no

Motivation - Distributed Systems

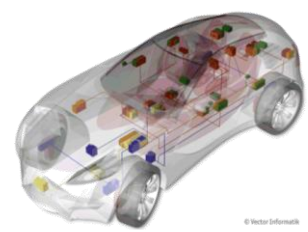
- **The vast majority of IT systems today can be characterised as distributed software systems:**
  - **Structured as a collection of concurrently executing software components and applications.**
  - **Operation relies inherently on communication, synchronisation, and resource sharing.**



Internet and Web-based applications, protocols



Multi-core platforms and multi-threaded software



Embedded systems and networked control systems

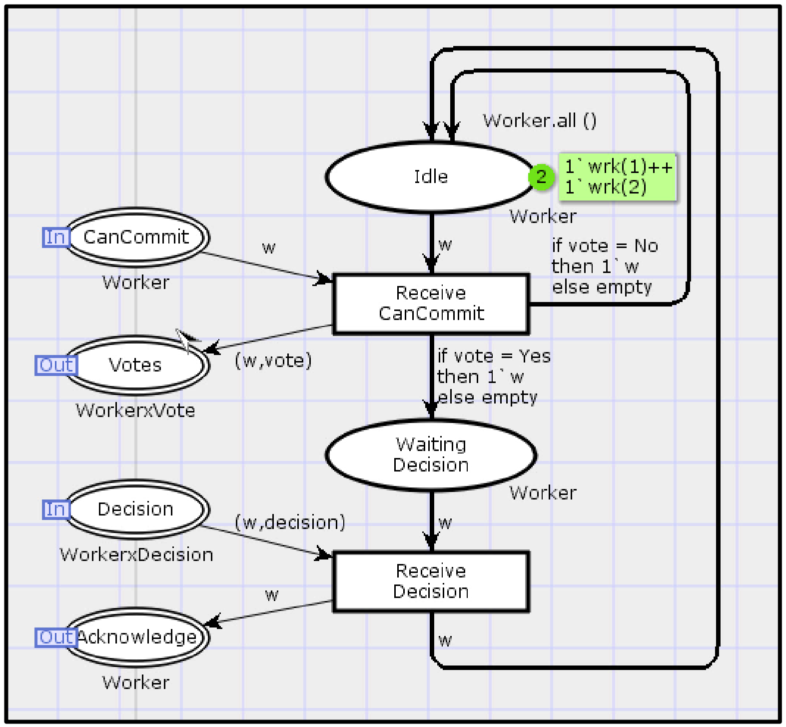
Challenges

- **The engineering of distributed software systems is challenging due to their complex behaviour:**
  - Concurrently executing and independently scheduled software components that need to synchronise.
  - Non-deterministic and asynchronous behaviour (e.g., timeouts, message loss, external events, …).
  - Challenging for software developers to have a complete understanding of the system behaviour.
  - Reproducing errors and conducting debugging is often difficult.

- **Techniques to support the engineering of reliable distributed systems are important.**

Coloured Petri Nets (CPNs)

- **A graphical and formal modelling language for the engineering of distributed systems.**
- **Combines Petri Nets and a programming language:**



Petri Nets

graphical notation
concurrency
communication
synchronisation
resource sharing

Programming language

data types
data manipulation
compact modelling
parameterisable models

High-Level Petri Net

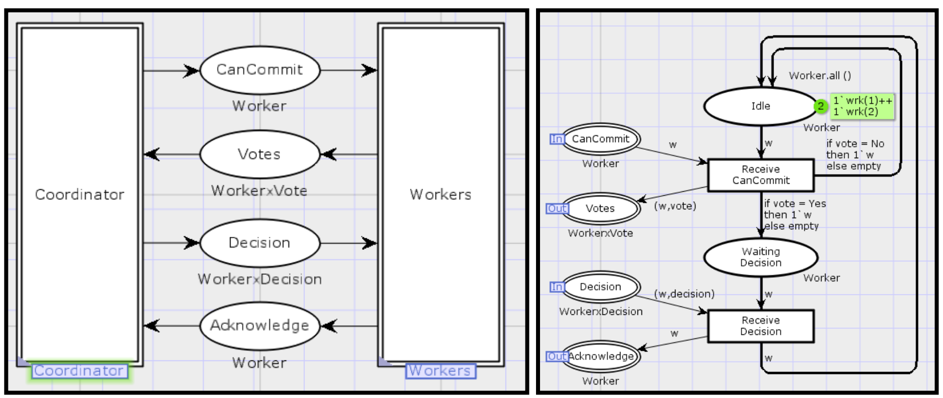
- **Supported by CPN Tools [www.cpntools.org]**

Application of CPNs

- **CPNs have been widely used for modelling and verification of communication protocols:**
  - Application layer protocols: IOTP, SIP, WAP, …
  - Transport layer protocols: TCP, DCCP, SCTP, …
  - Routing layer protocols: DYMO, AODV, ERDP, …

- **Limited work on automated code generation:**

CPN model



Source code

IETF WebSocket Protocol CPN model

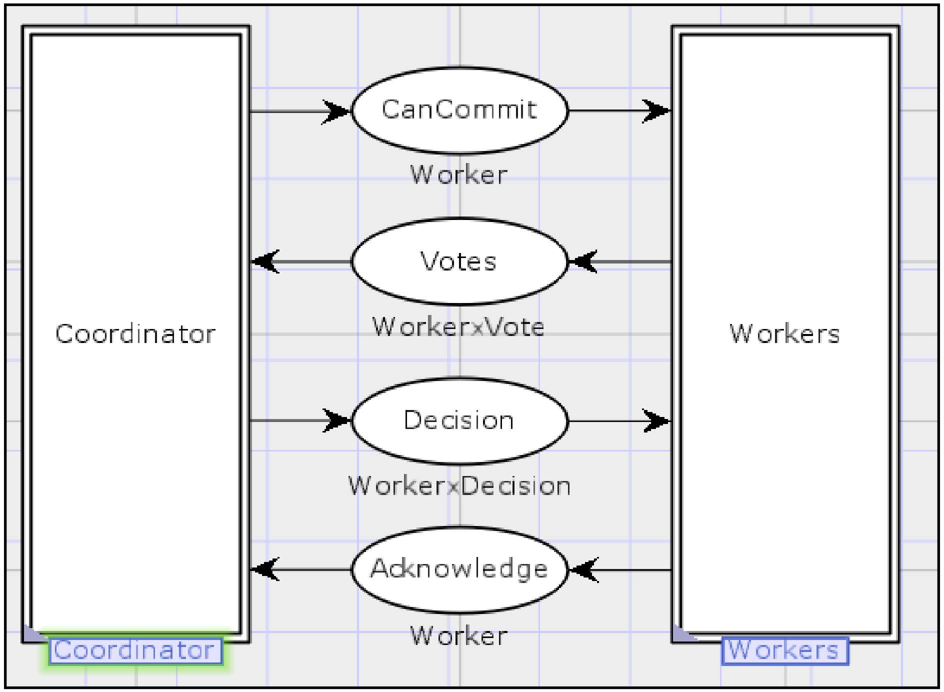
WebSocket Implementation

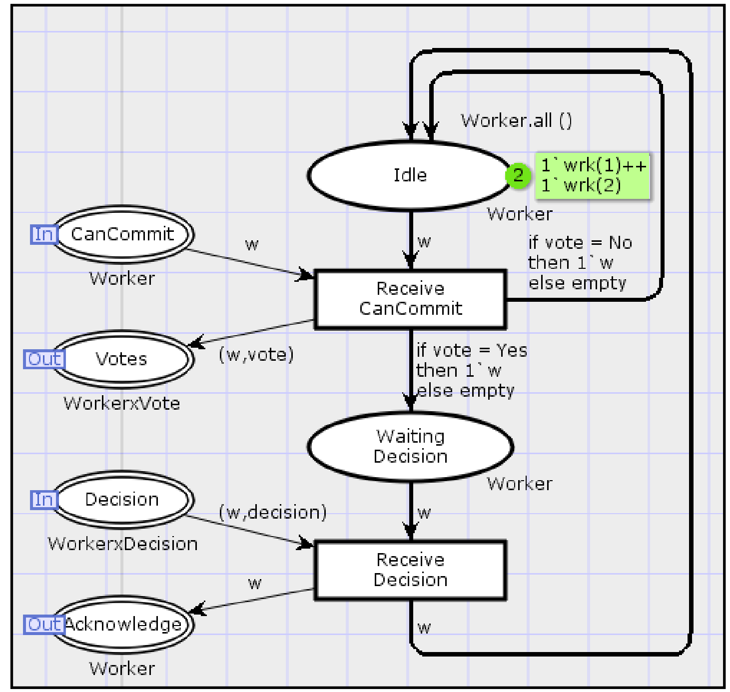
Outline of this Talk

- **Approach and WebSocket Protocol Modelling**
- **Model Verification and Code Generation**
- **Evaluation and Interoperability Tests**
- **Conclusions and Future Work**

Automated Code Generation

- **It is difficult (in general) to recognize programming language constructs in CPNs:**





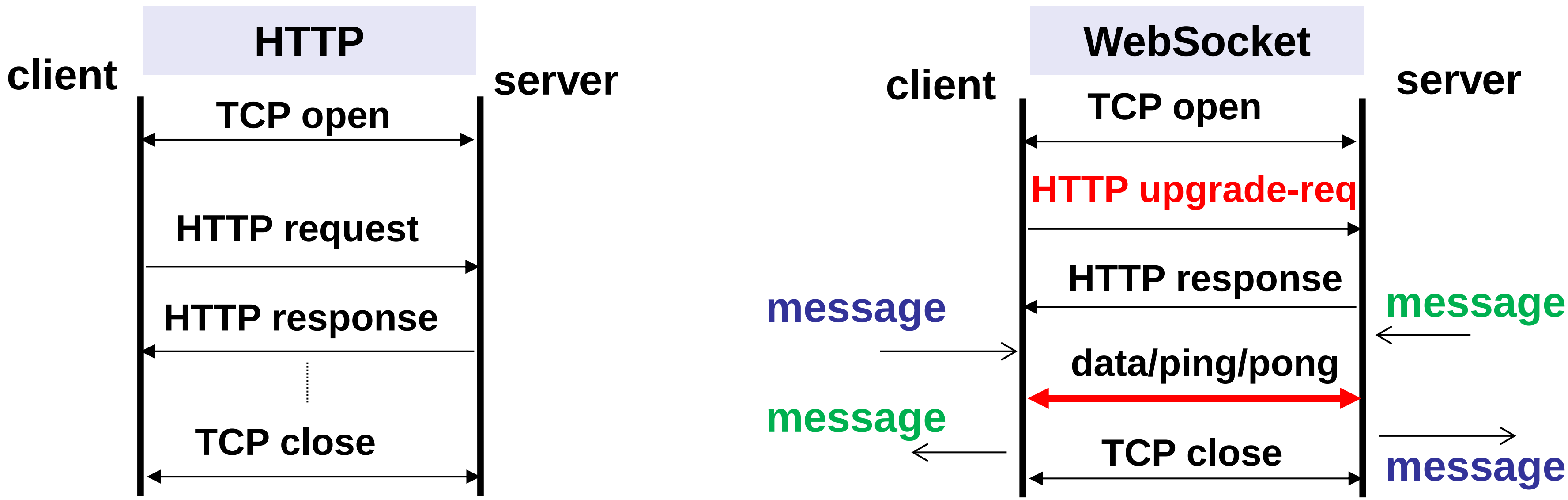
- **Conclusion:** **some additional syntactical constraints and/or annotations are required.**

Main Requirements

1. **Platform independence:**
   - Enable code generation for multiple languages / platforms.
2. **Integratebility of the generated code:**
   - Upwards integration: the generated code must expose an explicit interface for service invocation.
   - Downwards integration: ability for the generated code to invoke and rely on underlying libraries.
3. **Model checking and property verification:**
   - Code generation capability should not introduce complexity problems for the verification of the CPN models.
4. **Readability of the generated code:**
   - Enable code review of the automatically generated code.
   - Enable performance enhancements (if required).
5. **Scalability:**
   - Applicable to industrial-sized communication protocols.

The IETF WebSocket Protocol

- Provides a bi-directional and message-oriented service on top of the HTTP protocol:



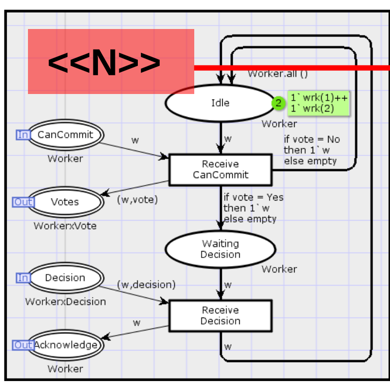
- Three main phases: connection establishment, data transfer, and connection close.

Overview of Approach

- **Modelling structure** requiring the CPN model to be organised into three levels:
  1. **Protocol system level** specifying the **protocol principals** and the **communication channels** between them.
  2. **Principal level** reflecting the **life-cycle** and **services** provided by each principal in the protocol system.
  3. **Service level** specifying the **behaviour** of the individual **services** provided by each principal.
- Annotate the CPN model elements with **code generation pragmatics** to direct code generation.
- Represent **concepts from the domain** of communication protocols and protocol software.
- A **template-based** model-to-text transformation for generating the protocol software (code).

Code Generation Pragmatics

- **Syntactical annotations (name and attributes) that can be associated with CPN model elements:**
  - Structural pragmatics designating principals and services.
  - Control-flow pragmatics identifying control-flow elements and control-flow constructs.
  - Operation pragmatics identifying data manipulation.
- **Template binding descriptors associating the pragmatics and code generation templates:**



CPN model

```
<%import static
org.k1s.petriCode.generation.CodeGenerator.removePr
ags%>class ${name} {
<%
      if(binding.variables.containsKey('lcvs')){
            for(lcv in lcvs){
            %>def ${removePrags(lcv.name.text)}
${lcv.initialMarking.asString() == '()' ? '= true' : ''}\n<%
            }
      }
      if(binding.variables.containsKey('fields')){
            for(field in fields){
            %>def ${removePrags(field.name.text)}<%
            }
      }
      %>
      %%yield%%
}
```

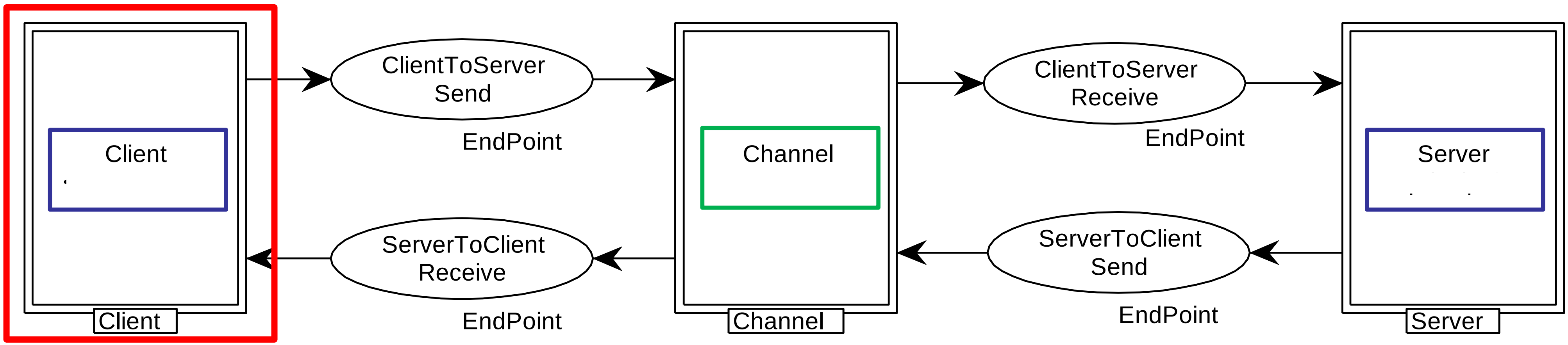
Template

```
def getMessage(){
  /*vars: [__TOKEN__:, message:]*/
  def __TOKEN__
  def message
  //getMessage
  if(inBuffer != null && inBuffer.size() > 0){
    message = inBuffer.remove(0)
    byte[] bArr = new byte[message.payLoad.size()]
    for(int i = 0; i < bArr.length; i++){
      bArr[i] = message.payLoad.get(i)
    }
    if(message.opCode == 1){
      message = new String(bArr)
     }else if(message.opCode == 2) {
       message = bArr
     }
  }else{
    message = null
  }
  return message
}
```

Code

WebSocket: Protocol System

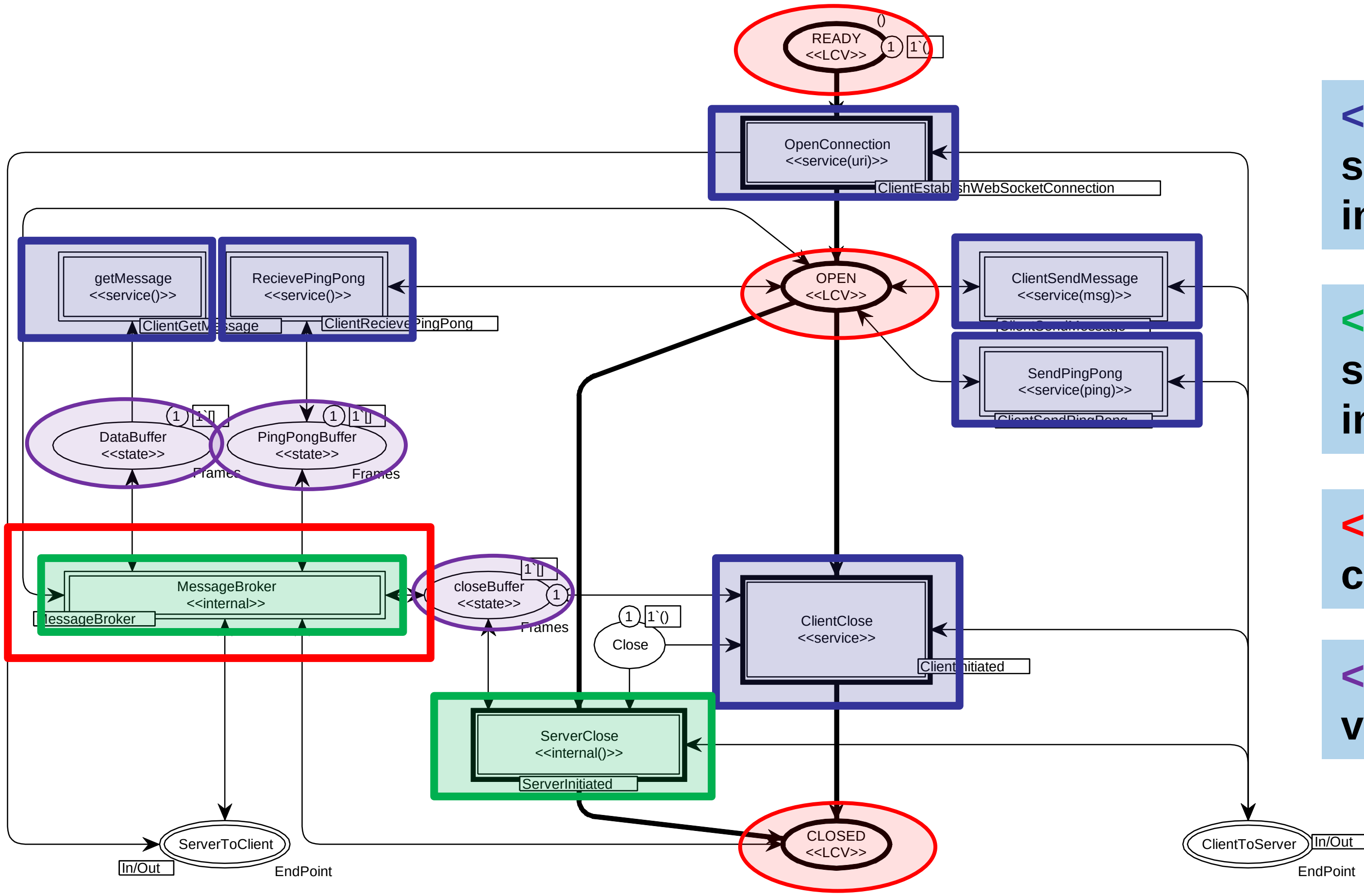
- The complete CPN model consists of 19 modules, 136 places, and 84 transitions:



- The <<principal>> pragmatic is used on substitution transitions to designate principals.
- The <<channel>> pragmatic is used to designate channels connecting the principals.

Client: Principal Level

- **Makes explicit the services provided and their allowed order of invocation (API life-cycle):**



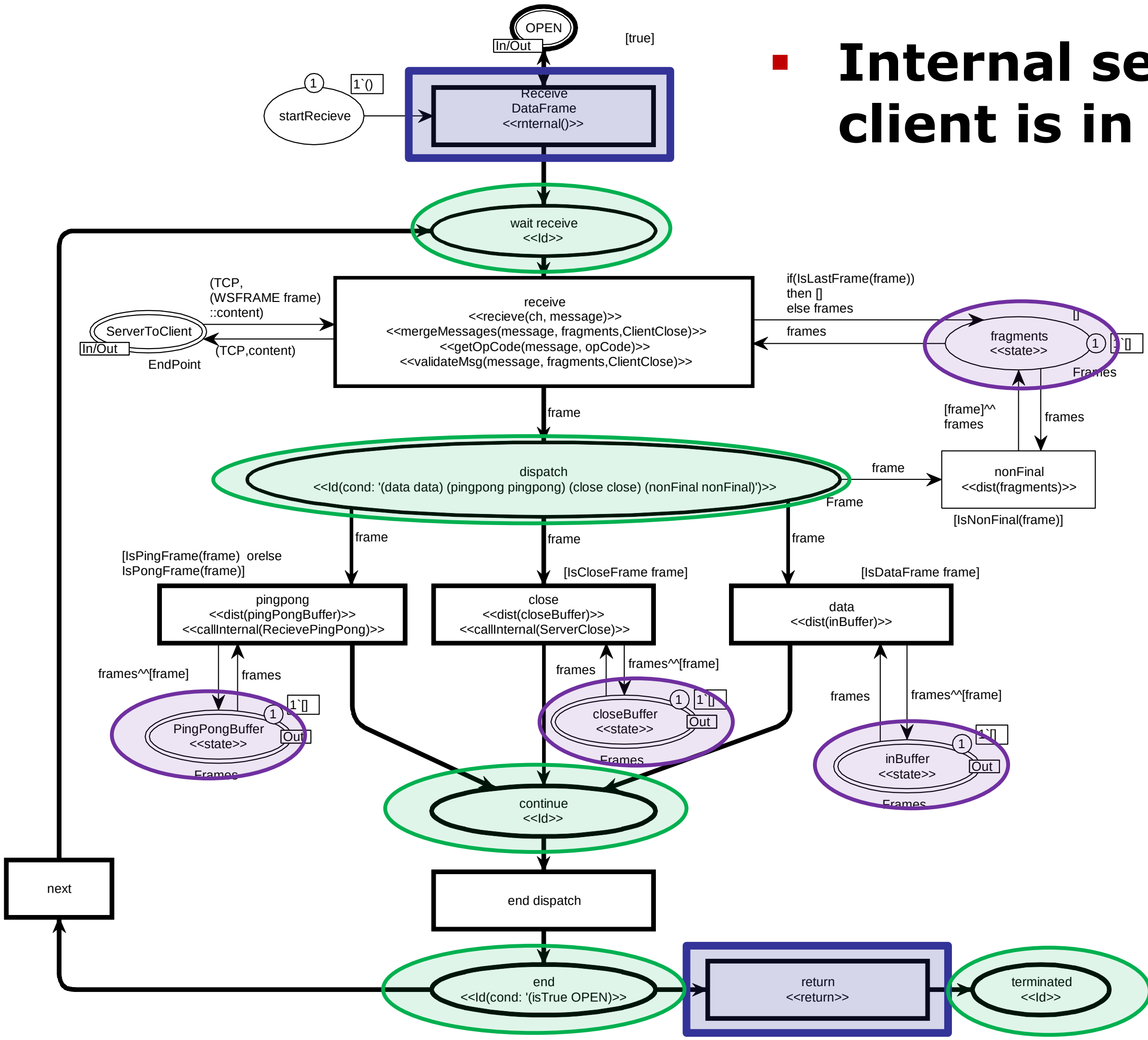
<<service>> specifies services that can be invoked externally.

<<internal>> specifies services that are invoked internally in the principal.

<<LCV>> specifies life-cycle for services.

<<state>> specifies state variables of the principal.

Client: MessageBroker Service



- **Internal service started when the client is in the OPEN state.**

Service entry point <<internal>>

Service-local state is specified using <<state>>

Control-flow locations is made explicit using <<ID>> pragmatic on places.

Service exit point <<return>>

Outline

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WebSocket Verification

- **State space exploration and model checking to automatically verify basic connection properties:**

P0 - From the initial state it is possible to reach states in which the WebSocket connection has been opened.

P1 - All terminal states correspond to states in which the WebSocket connection has been properly closed.

P2 - From any reachable state, it is always possible to reach a state in which the WebSocket connection has been properly closed.

ClientM	ServerM	#Nodes	#Arcs	Time (secs)	#Terminal states
+	-	2,747	9,544	1	2
-	+	2,867	9,956	2	2
+	+	39,189	177,238	246	4

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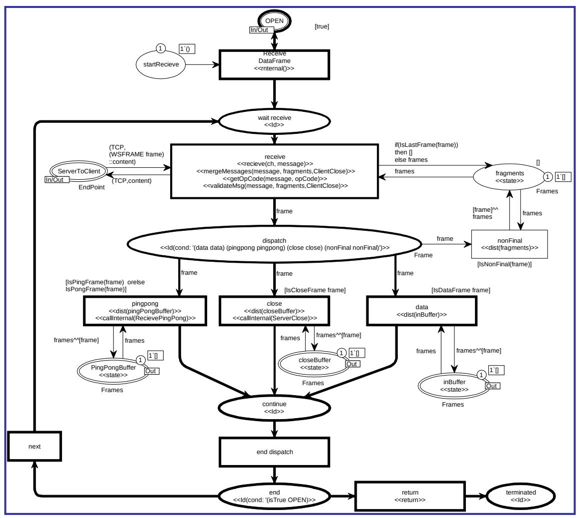
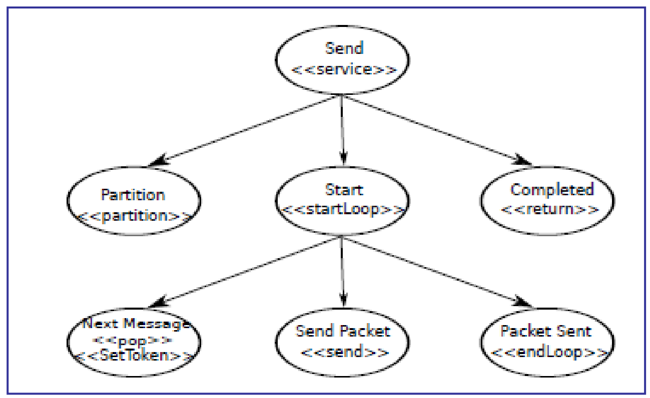
Automated Code Generation

- **Template-based code generation consisting of three main steps:**

Step 1	Step 2	Step 3



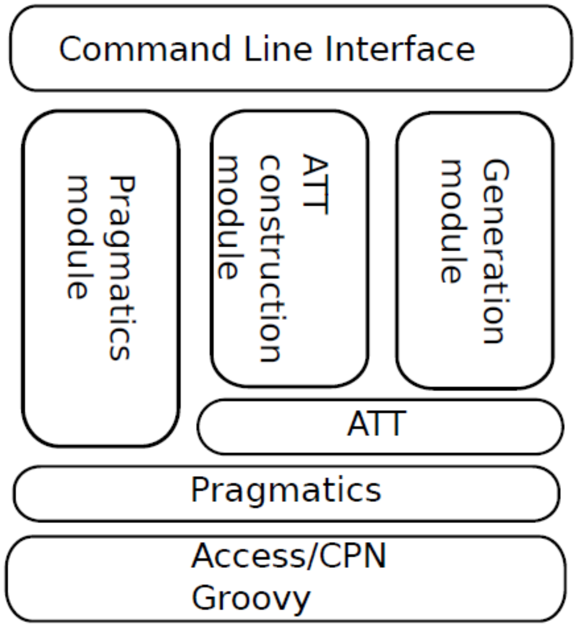



```
def getMessage(){
  /*vars: [__TOKEN__:, message:]*/
  def __TOKEN__
  def message
  //getMessage
  if(inBuffer != null && inBuffer.size() > 0){
    message = inBuffer.remove(0)
    byte[] bArr = new byte[message.payLoad.size()]
    for(int i = 0; i < bArr.length; i++){
      bArr[i] = message.payLoad.get(i)
    }
    if(message.opCode == 1){
      message = new String(bArr)
     }else if(message.opCode == 2) {
       message = bArr
     }
  }else{
    message = null
  }
  return message
}
```

Computing Derived Pragmatics	Abstract Template Tree (ATT) Construction	Pragmatics binding and emitting code

PetriCode [www.petricode.org]

- **Command-line tool reading pragmatic-annotated CPN models created with CPN Tools:**



Pragmatic module: parses CPN models and computes derived pragmatics.

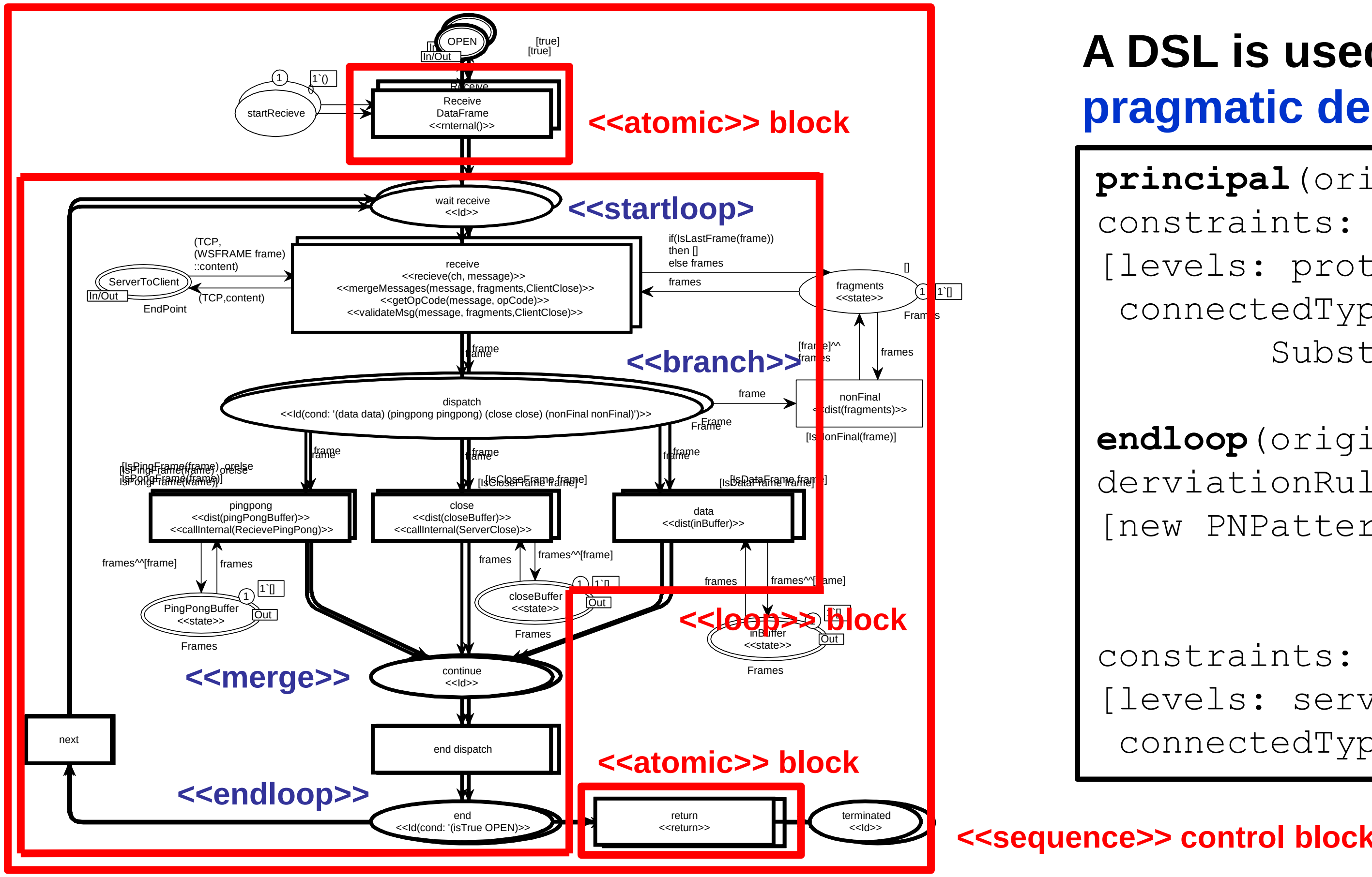
ATT construction module: performs block decomposition and constructs the ATT.

Code generation module: binds templates to pragmatics and generates source code via ATT traversal.

- **Implemented in Groovy and uses the Groovy template engine for code generation.**

Step 1: Derived Pragmatics

- **Derived pragmatics computed for control-flow constructs and for data (state) manipulation.**



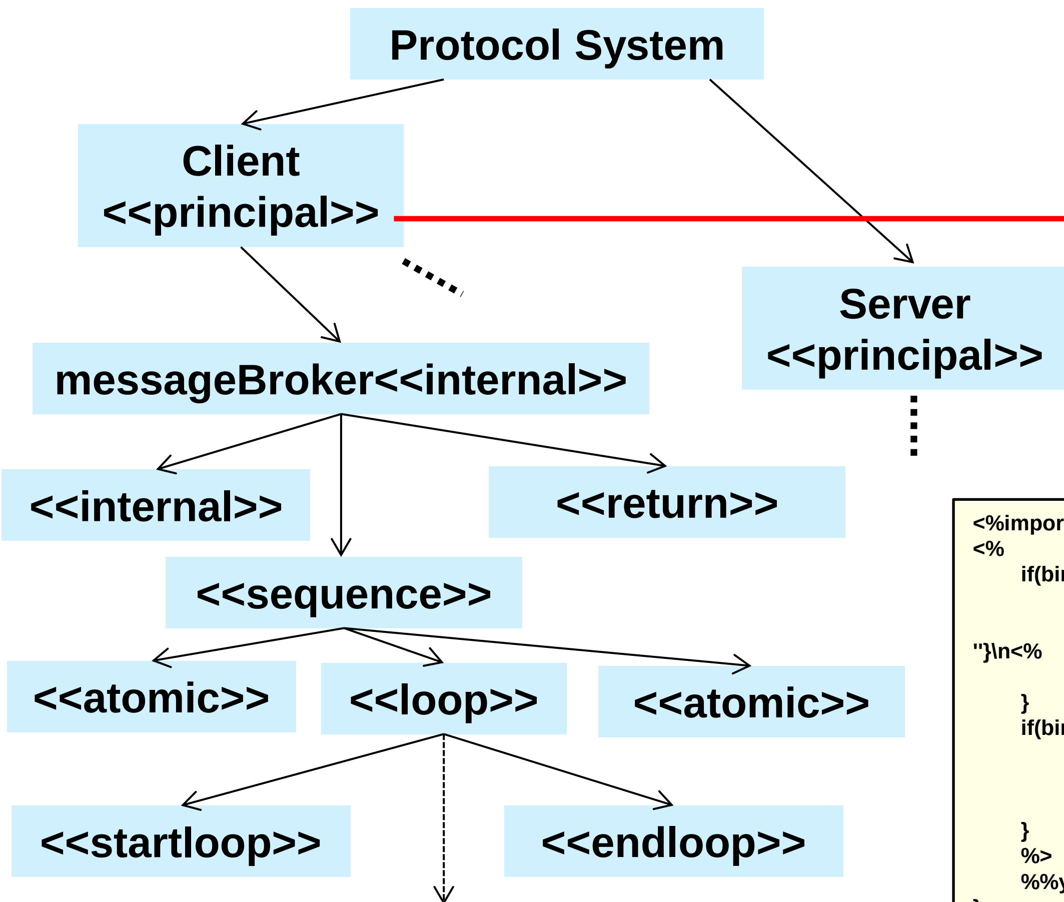
A DSL is used for specifying pragmatic descriptors.

```
principal(origin: explicit,
constraints:
[levels: protocol,
 connectedTypes:
        SubstitutionTransition])

endloop(origin: derived,
derviationRules:
[new PNPattern(pragmatics: [Id],
               minOutEdges: 2,
               backLinks: 1)],
constraints:
[levels: service,
 connectedTypes:Place])
```

Step 2: Abstract Template Tree

- **An intermediate syntax tree representation of the pragmatic-annotated CPN model:**



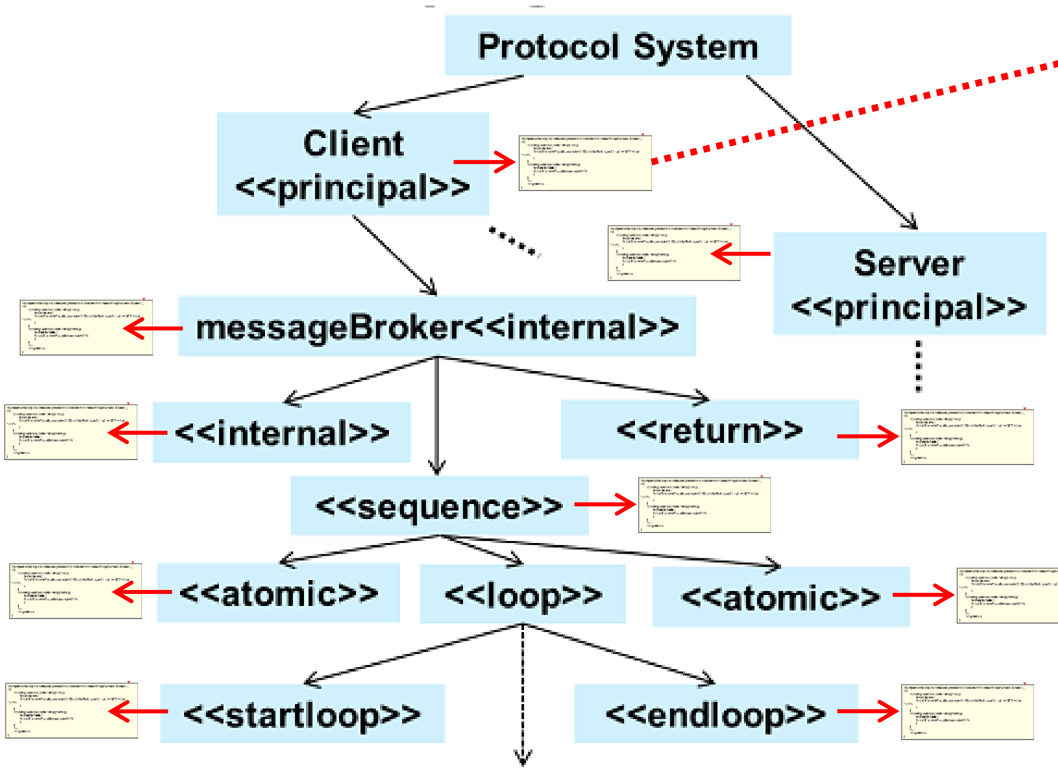
A DSL for template bindings and linkage to the target platform.

```
classTemplate(
pragmatic: 'principal',
template: './groovy/mainClass.tmpl',
isContainer: true)
endloop(
pragmatic: 'endloop',
template: './groovy/endLoop.tmpl')
```

```
<%import static org.k1s.petriCode.generation.CodeGenerator.removePrags%>class ${name} {
<%
	if(binding.variables.containsKey('lcvs')){
		for(lcv in lcvs){
		%>def ${removePrags(lcv.name.text)} ${lcv.initialMarking.asString() == '()' ? '= true' : ''}\n<%
		}
	}
	if(binding.variables.containsKey('fields')){
		for(field in fields){
		%>def ${removePrags(field.name.text)}<%
		}
	}
	%>
	%%yield%%
}
```

Step 3: Emitting Code

- **Traversal of the ATT, invocation of code generation templates, and code stitching:**




```
def getMessage(){
  /*vars: [__TOKEN__:, message:]*/
  def __TOKEN__
  def message
  //getMessage
  if(inBuffer != null && inBuffer.size() > 0){
    message = inBuffer.remove(0)
    byte[] bArr = new byte[message.payLoad.size()]
    for(int i = 0; i < bArr.length; i++){
      bArr[i] = message.payLoad.get(i)
    }
    if(message.opCode == 1){
      message = new String(bArr)
     }else if(message.opCode == 2) {
       message = bArr
     }
  }else{
    message = null
  }
  return message
}
```

```
def SendPingPong(ping){ ... }
def ClientClose(){ ... }
def getMessage(){ ... }
}
```

Outline

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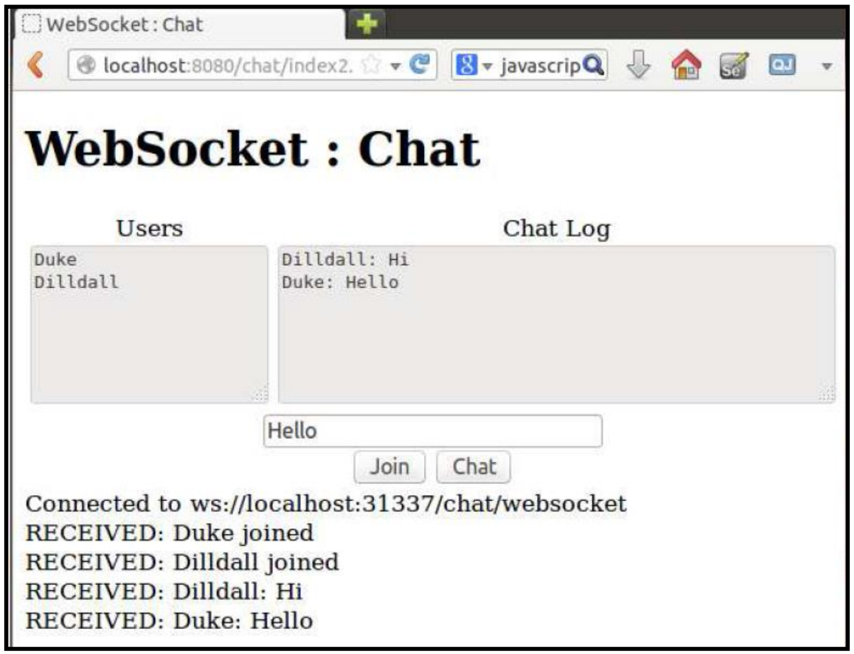
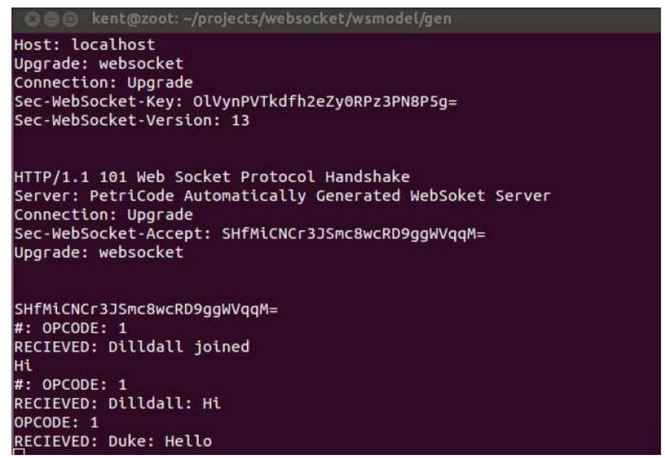
Chat Application

- **WebSocket tutorial example provided with the Java EE 7 GlassFish Application Server:**

Chat Server [CPN WebSocket model]



Web-based Chat Client [WebSocket Browser]



Chat Client [CPN WebSocket model]

Autobahn Testsuite [autobahn.ws/testsuite/]

Autobahn

- **Test-suite used by several industrial WebSocket implementation projects** (Google Chrome, Apache Tomcat,..).
- **Errors encountered with the generated code:**
  - **One protocol logical error related to the handling of fragmented messages (CPN model change).**
  - **Several local errors in the code-generation templates were encountered (template change).**

Tests	Server Passed	Client Passed
1. Framing (text and binary messages)	16/16	16/16
2. Pings/Pongs	11/11	11/11
3. Reserved bits	7/7	7/7
4. Opcodes	10/10	10/10
5. Fragmentation	20/20	20/20
6. UTF-8 handling	137/141	137/141
7. Close handling	38/38	38/38
9. Limits/Performance	54/54	48/54
10. Auto-Fragmentation	1/1	1/1

http://t.k1s.org/wsreport/

Conclusions

- **An approach enabling CPN models to be used for code generation of protocol software:**
  - Pragmatic annotations and enforcing modelling structure.
  - Binding of pragmatics to code generation templates.
- **Implemented in the PetriCode tool to allow for practical applications and initial evaluation.**
- **Scalability of the approach has been evaluated via application to the IETF WebSocket Protocol:**
  - State space-based verification was feasible for verifying basic connection properties prior to code generation.
  - The implementation was tested for interoperability against a comprehensive benchmark test-suite with promising results.
  - A proof-of-concept on the scalability and feasibility of the approach for the implementation of real protocols.

Thank you for your attention!