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Unifying and systematic system development methologies
with trustworthy embedded components

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OpenComRTOS: An Ultra-Small Network Centric Embedded RTOS Designed Using Formal Modeling

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Who is Open License Society?

- Privately funded R&D institute
  - Leuven (BE), Berdyansk (UA)
  - Industrial sponsors
  - IWT project funding for OpenComRTOS
- Why: 70 % of all SE projects do not deliver
- Objectives
  - Systematic & Unified Systems Engineering Methodology
  - ‘Interacting Entities’ paradigm at all levels:
    - OpenComRTOS as runtime environment (formally developed)
  - Implies ‘Trustworthy Components’
    - => Open License (source code + all design, test, …. docs)
- Focus:
  - Embedded Systems:
    - Constraints driven development
    - Real-time, distributed, hardware & software, …

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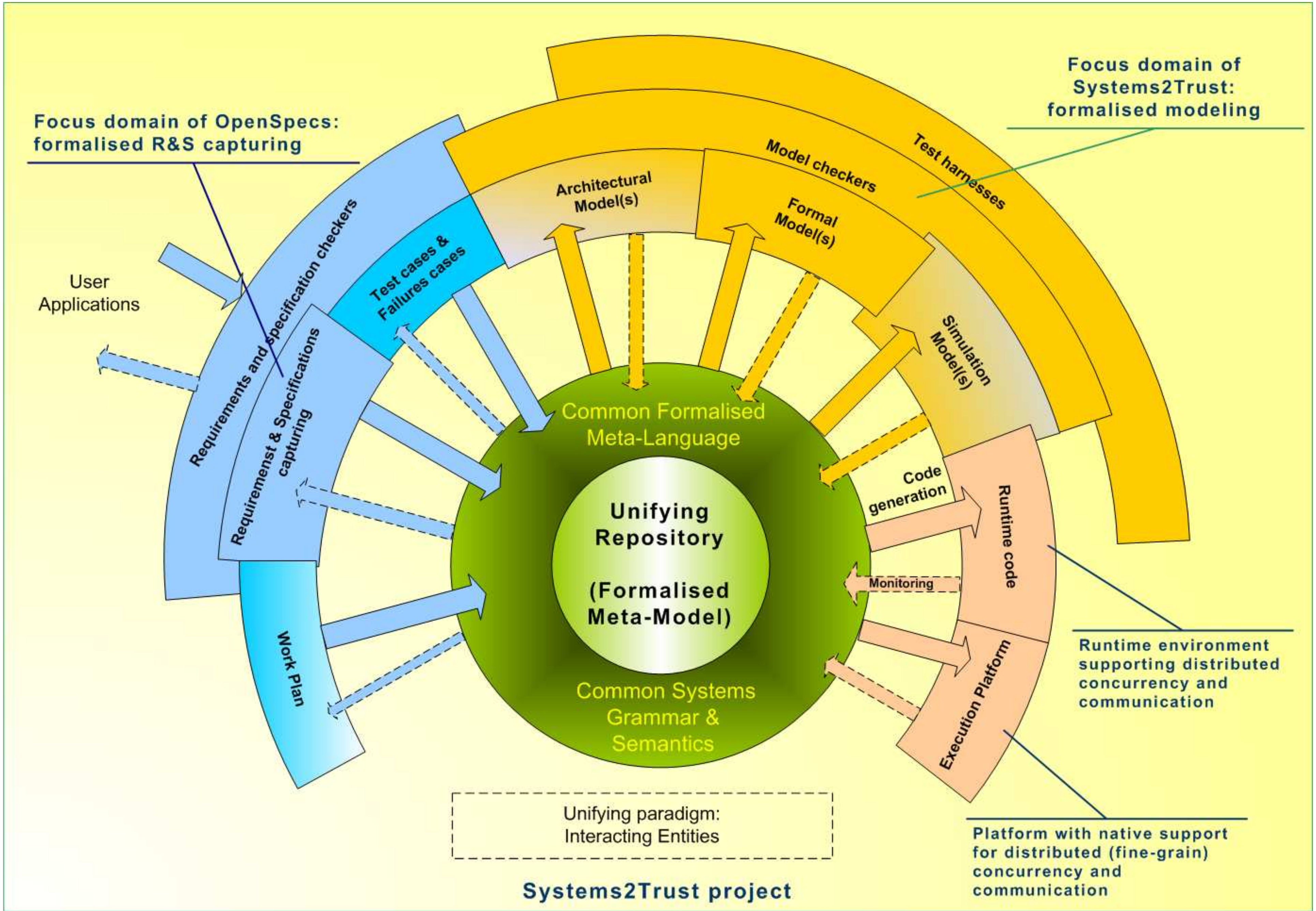
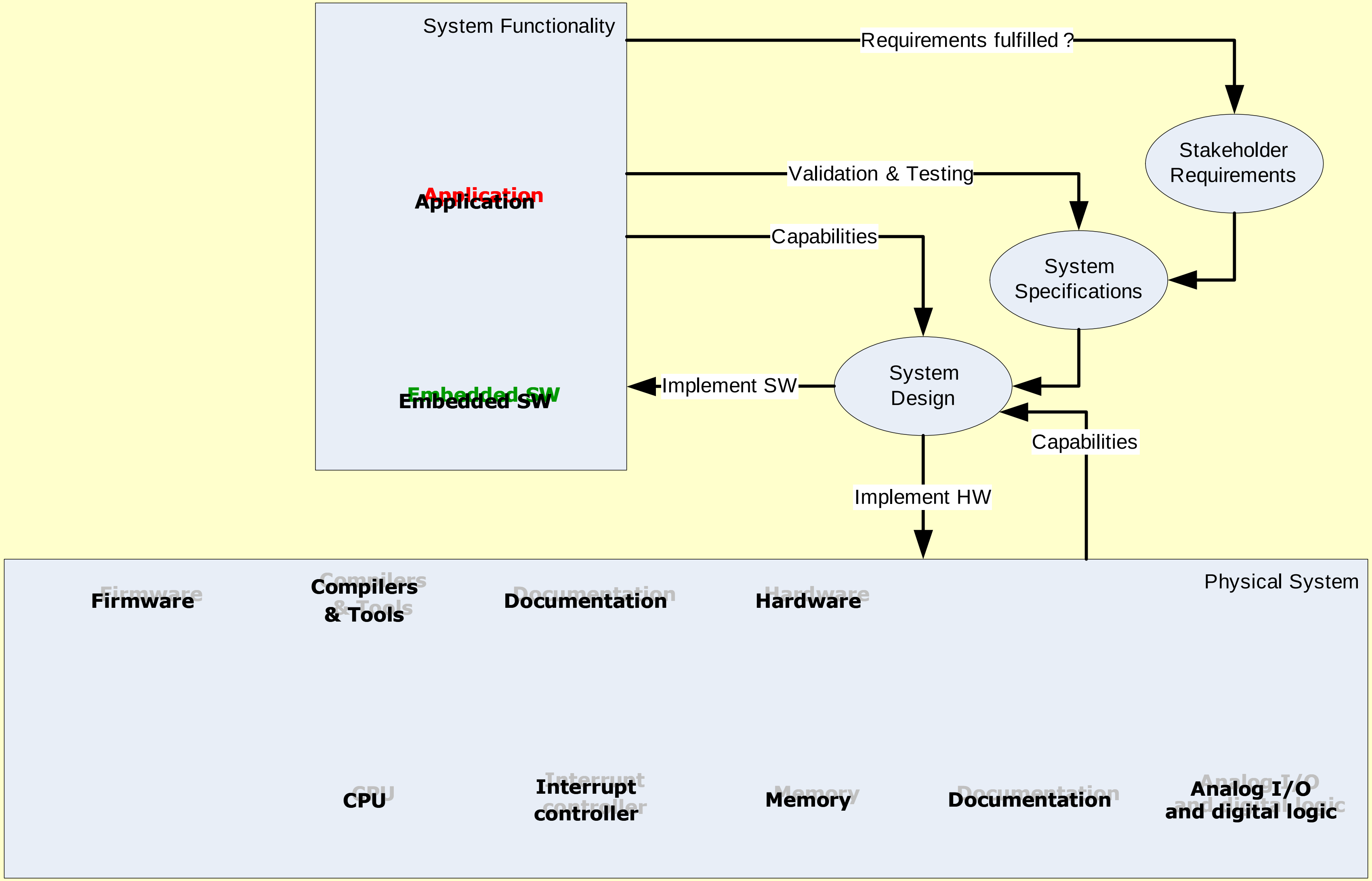
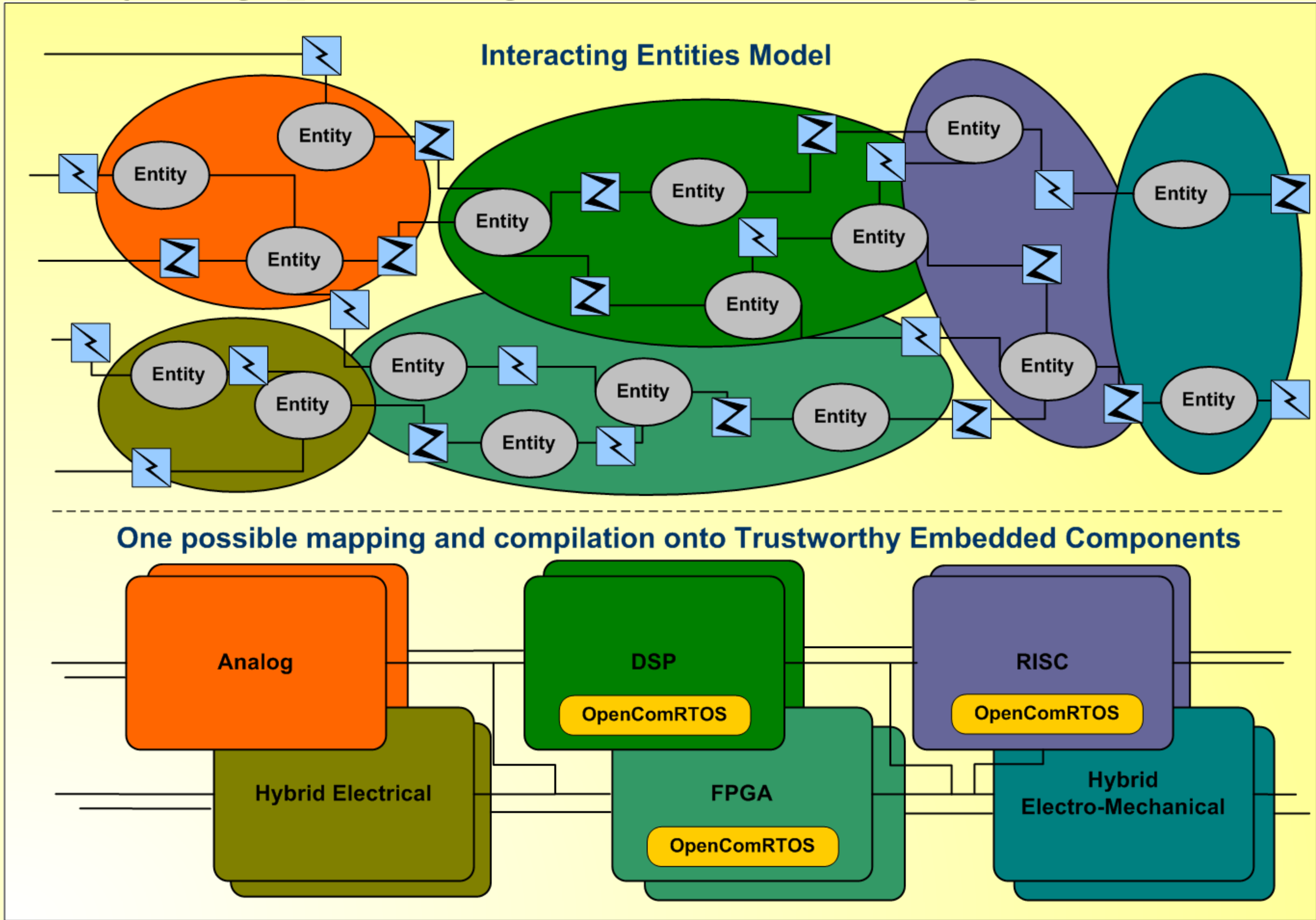

Focus domain of OpenSpecs:
formalised R&S capturing
Focus domain of
Systems2Trust:
formalised modeling
User
Applications
Requirements and specification checkers
Requirement & Specifications
capturing
Test cases &
Failures cases
Architectural
Model(s)
Model checkers
Test harnesses
Formal
Model(s)
Simulation
Model(s)
Code
generation
Runtime code
Monitoring
Execution Platform
Work Plan
Common Formalised
Meta-Language
Unifying
Repository
(Formalised
Meta-Model)
Common Systems
Grammar &
Semantics
Runtime environment
supporting distributed
concurrency and
communication
Platform with native support
for distributed (fine-grain)
concurrency and
communication
Unifying paradigm:
Interacting Entities
Systems2Trust project

SE Process dependency graph



Unifying paradigm: Interacting Entities



OpenComRTOS project objectives

- Funded R&D project (IWT, Flanders)
  - Lancelot Research: management, commercialisation
  - Open License Society: technology development
  - University Gent (INTEC, Prof. Boute): formal modeling
  - University Berdyansk: tools and formal validation
  - Melexis: co-sponsor and first user (16bit uC)
- GUI tools:
  - graphical modeling/development environment
- Goal:
  - Develop Trustworthy <u>distributed</u> RTOS
    - Follow OLS SE methodology
    - Formal verification & analysis: formal modelling
  - Scalable distributed RTOS
  - Verify benefits and issues of using Formal Modeling

Some requirements

- Targets:
  - Single chip, tightly coupled: multi-core
  - Multi-chip, tightly coupled: parallel processors on board
  - Multi-boards, multi-rack: using backplane interconnects
  - Distributed: using LAN and WAN
  - Host node
- Programming models:
  - "Interacting Entities"
  - "Virtual Single Processor":
    - transparent for topology
    - Supporting heterogenous targets
  - Distributed real-time
  - Safe, secure
  - Small code size, low latency (=high performance)

OpenComRTOS systems grammer

OpenComRTOS **IS_DEFINED_BY**

Configuration (1) // The root node of XML file

Configuration **IS_DEFINED_BY** // Nodes of configuration section

Parameters (1) **AND** // *Attributes* of the configuration section of XML file

SystemTasks (4) **AND** // Kernel, Idle, Rx or Tx

ApplicationTasks (1-N) **AND**

Ports (1-N) **AND**

Nodes (1-N) **AND**

Links (1-N)

Configuration **HAS_ATTRIBUTES** // Parameters

DataSize (1) **AND** // Packet data size (in bytes)

NodeIdSize (1) // Length of Node identifier (in bits)

SystemTask **CAN_BE** // Type of system task

KernelTask **OR**

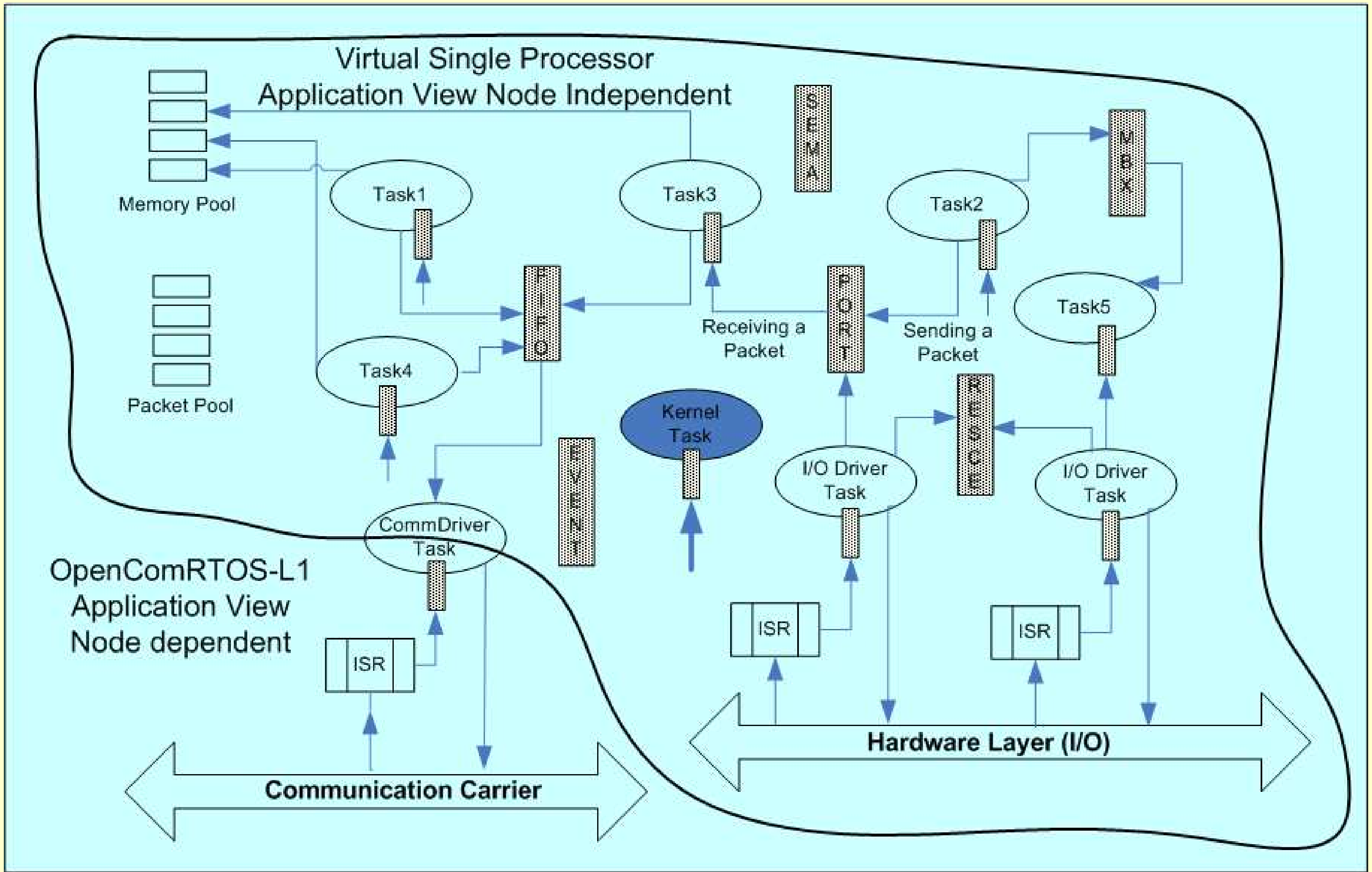
IdleTask **OR**

RxTask **OR**

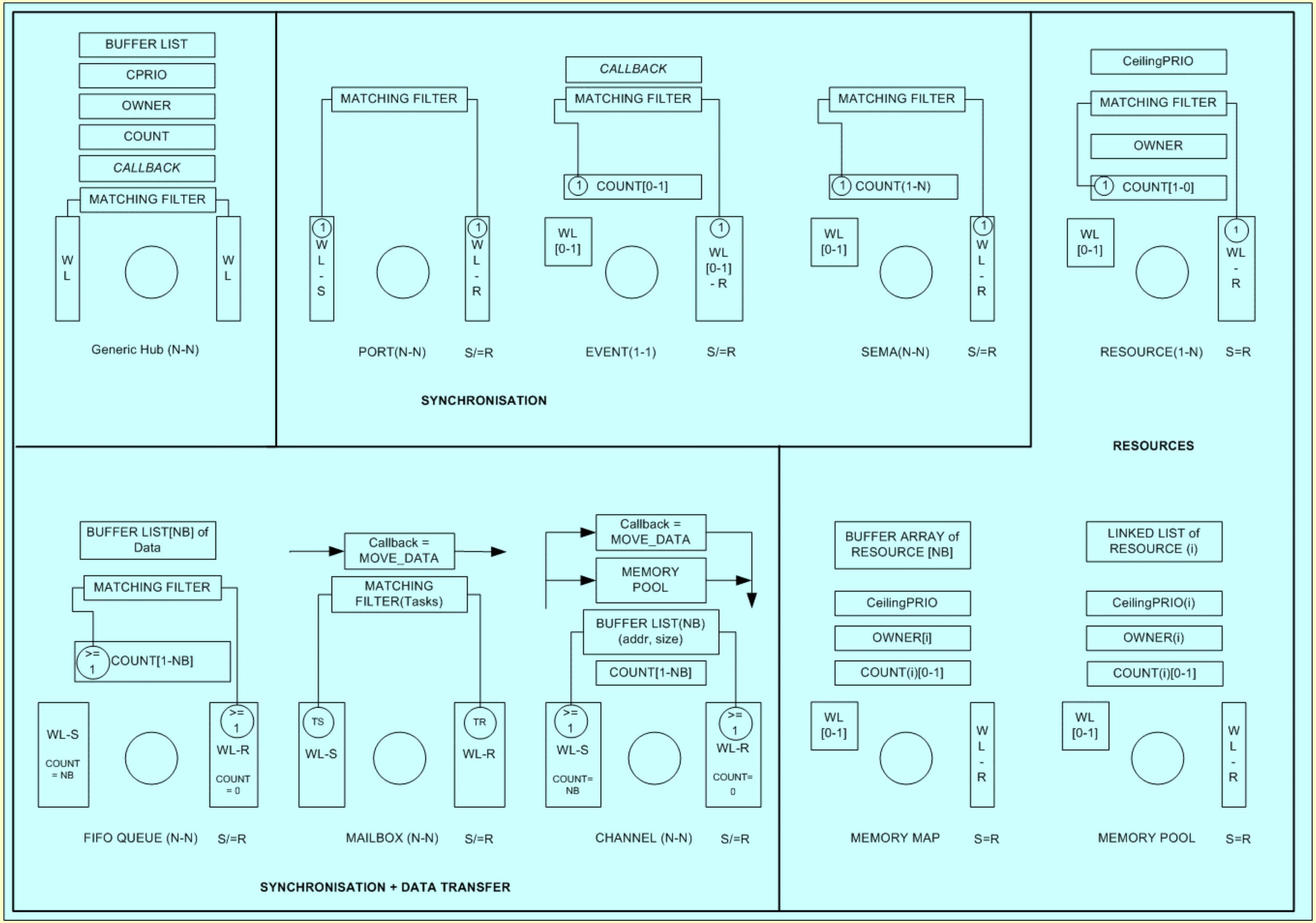
TxTask

Etc.

L1 application view



All RTOS Entities: variation on a theme



Generic hub

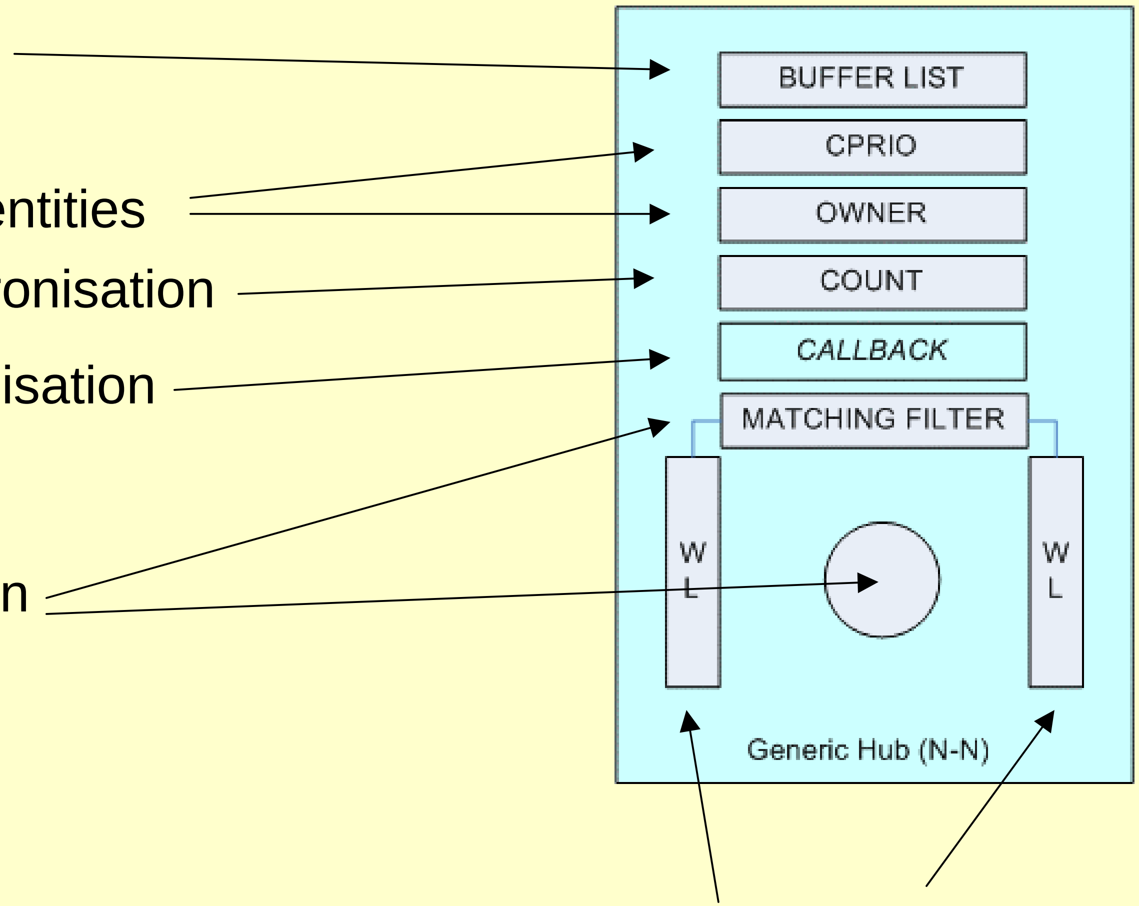
When buffering

With resource entities

Pending synchronisation

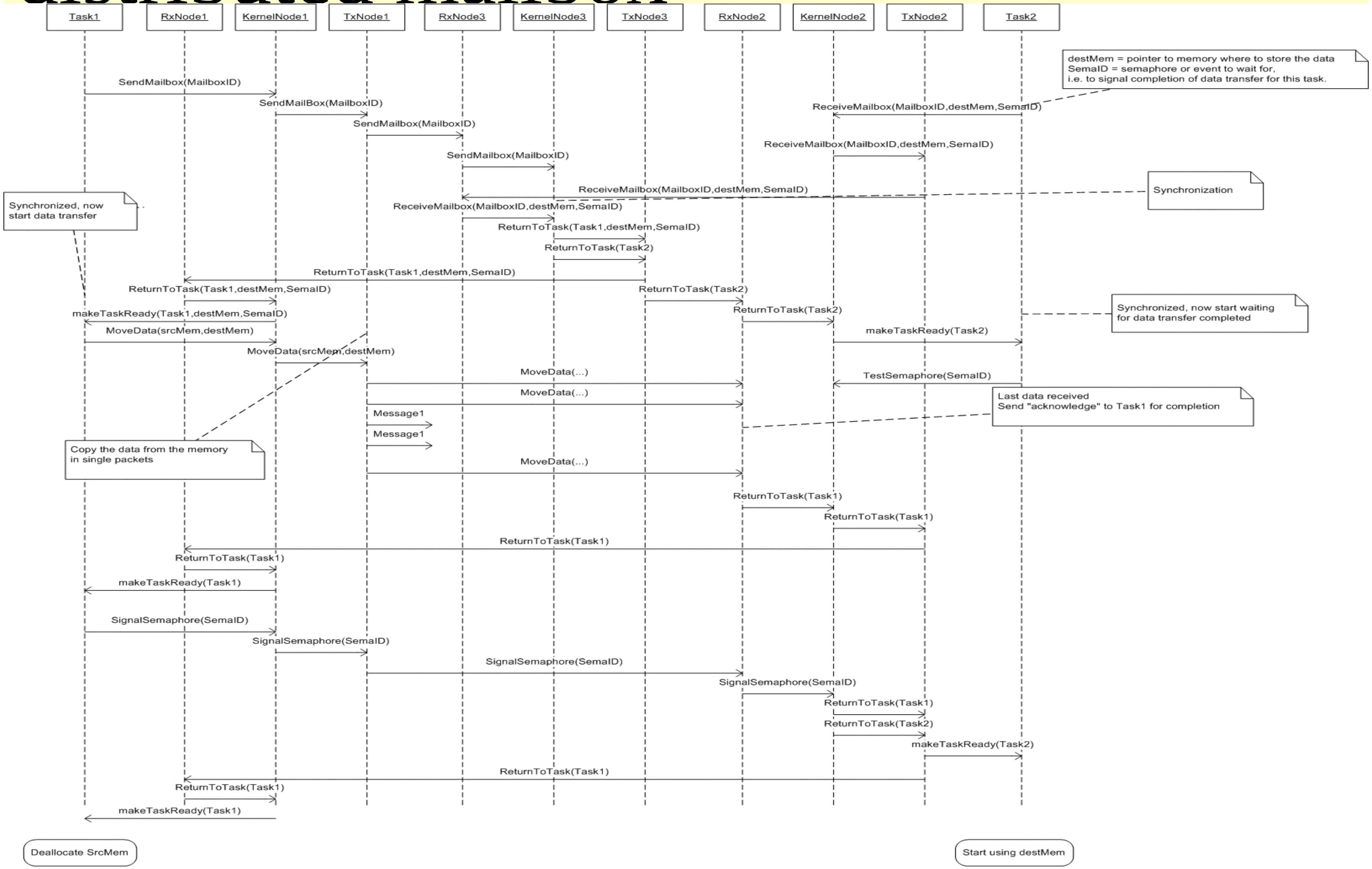
Upon Synchronisation

Synchronisation



Waiting lists “senders/receivers”

Example of Interaction diagram: distributed mailbox



Clean architecture gives small code

OpenComRTOS L1 code size figures (MLX16)				
	MP FULL		**SP SMALL**	
	L0	**L1**	**L0**	**L1**
L0 Port	162		132	
L1 Hub shared		574		400
L1 Port		4		4
L1 Event		68		70
L1 Semaphore		54		54
L1 Resource		104		104
L1 FIFO		232		232
L1 Resource List		184		184
Total L1 services		1220		1048
Grand Total	**3150**	**4532**	**996**	**2104**

<u>Smallest application</u>: 1048 bytes program code and 198 bytes RAM (data)
(SP, 2 tasks with 2 Ports sending/receiving Packets in a loop, ANSI-C)
Number of instructions : 605 instructions for one loop (= 2 x context switches, 2 x L0_SendPacket_W, 2 x L0_ReceivePacket_W)

Results (ctd)

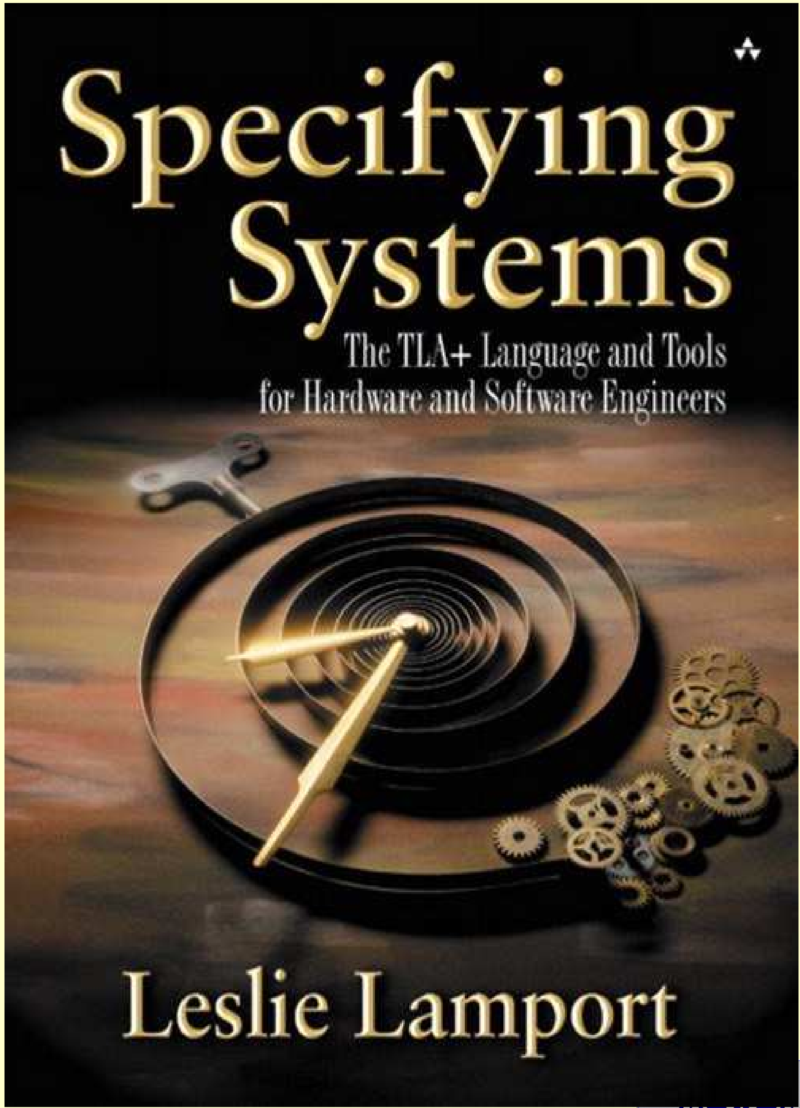
- Break-through results in well-known domain
  - 100’s of RTOS with such support
  - 15 years of experience, 3 generations of RTOS design
  - Typically CPU dependent, use of assembler and async operation

- Small, scalable, distributed and maintainable code
  - SP(L0): < 1000 machine instructions
  - MP(L1): < 2000 - 5000 machine instructions
  - Needs a few 100 bytes of data RAM
  - Fully in ANSI-C, MISRA-C compliant
  - Runs on MelexCM (16 bit) and Windows
  - Scheduling algorithm can be improved to reduce worst-case rescheduling latency and blocking time
  - All RTOS Entities are variations of a generic « hub » object
    - => less but faster code: 5 KBytes vs. 50 KBytes before

Formal TLA models of OpenComRTOS entities

TLA

- **TLA** (the **Temporal Logic of Actions**) is a logic for specifying and reasoning about concurrent and reactive systems.



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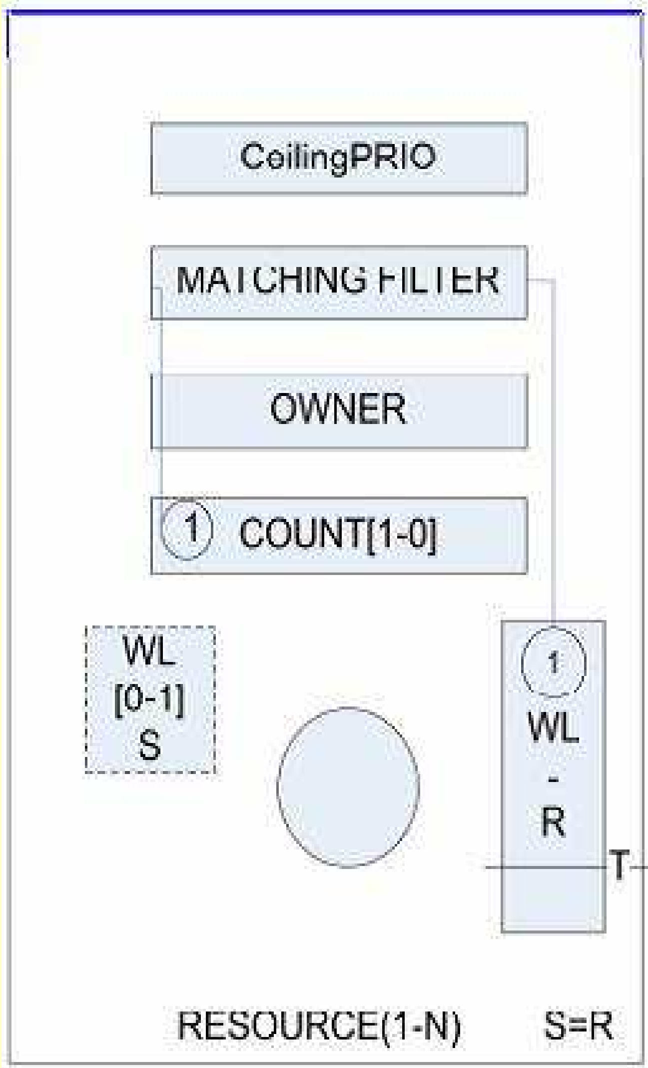
TLA modelling results

We modeled entities of OpenComRTOS:

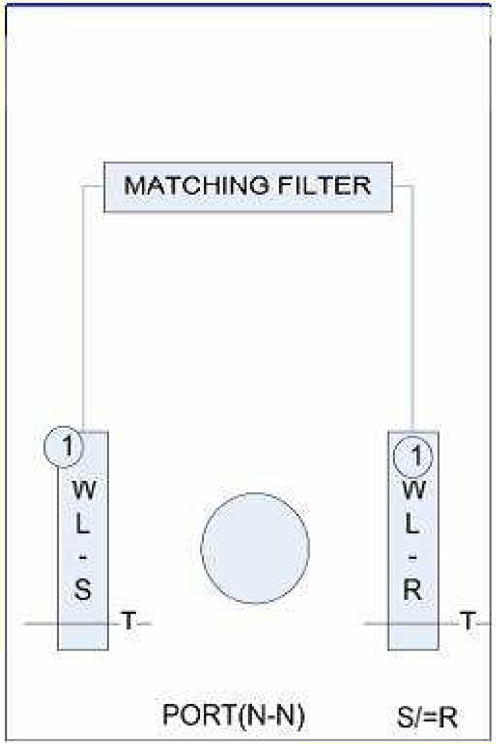
- Port
- Event
- Semaphore
- Resource
- Packet Pool
- Memory Pool
- FIFO
- Mailbox



Port

Verified Properties:

- There are never more Tasks on the ready list than there are Tasks in the system
- There are never more Tasks in the Port's waiting list then there are Tasks in the system
- All Tasks waiting on an Port, either waiting to send a Packet, either waiting to receive a Packet are of the same type in each waiting list

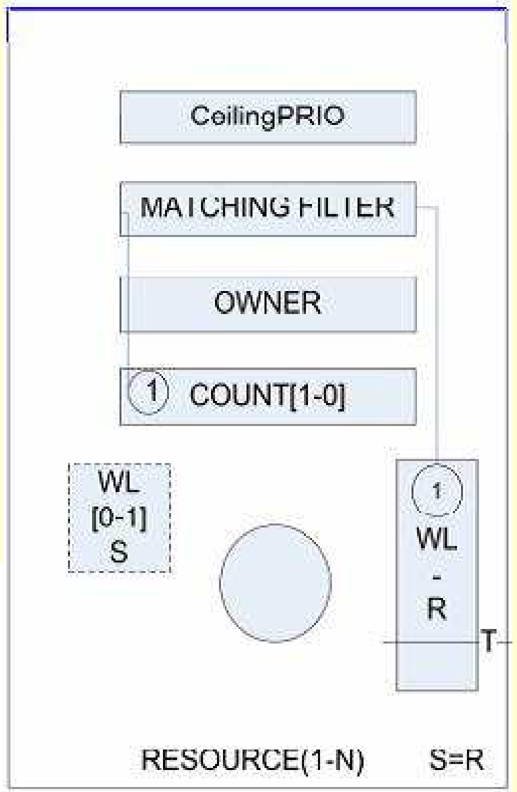


$$
\begin{aligned}
&TypeInvariant \triangleq \\
&\wedge\ Cardinality(ReadyList) \leq Cardinality(TaskId) \\
&\wedge\ \forall\, p \in PortId : \\
&Len(PortWL[p]) \leq Cardinality(TaskId) \\
&\wedge\ \forall\, p \in PortId : \\
&\forall\, i, j \in 1 \,..\, Len(PortWL[p]) : \\
&PreallocatedPacket[PortWL[p][i]].type = PreallocatedPacket[PortWL[p][j]].type
\end{aligned}
$$

Resource

Verified Properties:

- No Task waiting for an Resource can be ready
- Any Task that is ready cannot be in a waiting condition
- When the resource is free, then no Task will be waiting for it



$$
\begin{aligned}
&\land \forall p \in ResourceId : \\
&\forall i \in 1 \,..\, Len(ResourceWL[p]) : \\
&ResourceWL[p][i] \notin ReadyList \\
&\land \forall t \in TaskId : \\
&(t \in ReadyList) \Rightarrow (\forall i \in ResourceId : \\
&\forall j \in 1 \,..\, Len(ResourceWL[i]) : \\
&PreallocatedPacket[ResourceWL[i][j]].RequestingTaskID \neq t) \lor \\
&(\forall i \in 1 \,..\, Len(KernelPortWL) : \\
&PreallocatedPacket[KernelPortWL[i]].RequestingTaskID \neq t) \\
&\land \forall p \in ResourceId : \\
&\land isResourceAvailable(p) \Rightarrow List\_isEmpty(ResourceWL[p])
\end{aligned}
$$

Packet Pool

Checking Properties:

- Packets from the Packet Pool can only be allocated once
- If a Packet has been allocated from the Pool, then it must be in a Packet List of a Task and vice versa, if a Packet is not in any Task Packet List then it must be in the Packet Pool.
- If we have any packet in the Packet Pool, then no Task will be waiting for a Packet

$$
\begin{aligned}
&\wedge \forall\, i, j \in TaskId : \\
&(i \neq j) \Rightarrow (task[i].packetlist \cap task[j].packetlist = \{\}) \\
&\wedge \forall\, t \in TaskId : \forall\, dp \in DynamicalPacketId : \\
&\vee (dp \in task[t].packetlist) \Rightarrow (dp \notin PacketPoolPacketList) \\
&\vee (dp \in PacketPoolPacketList) \Rightarrow (dp \notin task[t].packetlist) \\
&\wedge isPacketAvailable \Rightarrow Len(PacketPoolWL) = 0
\end{aligned}
$$

RTOS Metamodel

- Based on Interacting Entities Paradigm
- Application can be constructed from various entities (*kernel entities*) and interactions between them (*kernel services*).
- The Metamodel allows extensions to different sets of kernel entities and services of other RTOSes.
- Expression of the Metamodel in XML format

OpenComRTOS Entities’ Metamodel = RTOS hub instances

```xml
<?xml version="1.0" encoding="UTF-8" standalone="yes" ?>
<Metamodel>
    <Entity Name="Task" SvgPath="Task.svg">
        <Attribute Name="Name" Type="String"/>
        <Attribute Name="Priority" Type="Integer" MinValue="1" MaxValue="255"/>
        <Attribute Name="Arguments" Type="String" DefaultValue="NULL"/>
        <Attribute Name="Status" Type="Enum" Values="L0_INACTIVE:L0_STARTED" DefaultValue="L0_STARTED"/>
        <Attribute Name="Node" Type="Node"/>
        <Attribute Name="StackSize" Type="Integer" DefaultValue="170"/>
        <Function  Name="EntryPoint"/>
    </Entity>
    <Entity Name="Port" SvgPath="Port.svg">
        <Attribute Name="Name" Type="String"/>
        <Attribute Name="Node" Type="Node"/>
    </Entity>
    <Entity Name="Event" SvgPath="Event.svg">
        <Attribute Name="Name" Type="String"/>
        <Attribute Name="Node" Type="Node"/>
    </Entity>
    <Entity Name= "Semaphore" SvgPath="Semaphore.svg">
        <Attribute Name="Name" Type="String"/>
        <Attribute Name="Node" Type="Node"/>
    </Entity>
```

```xml
    <Entity Name="Hub" SvgPath="Hub.svg">
        <Attribute Name="Name" Type="String"/>
        <Attribute Name="Node" Type="Node"/>
        <Attribute Name="Type" Type="Enum" Values="L1_PORT:L1_EVENT:L1_SEMAPHORE:L1_RESOURCE:L1_FIFO:L1_P
        <Function Name="UpdateFunction"/>
        <Function Name="SyncFunction"/>
    </Entity>
```

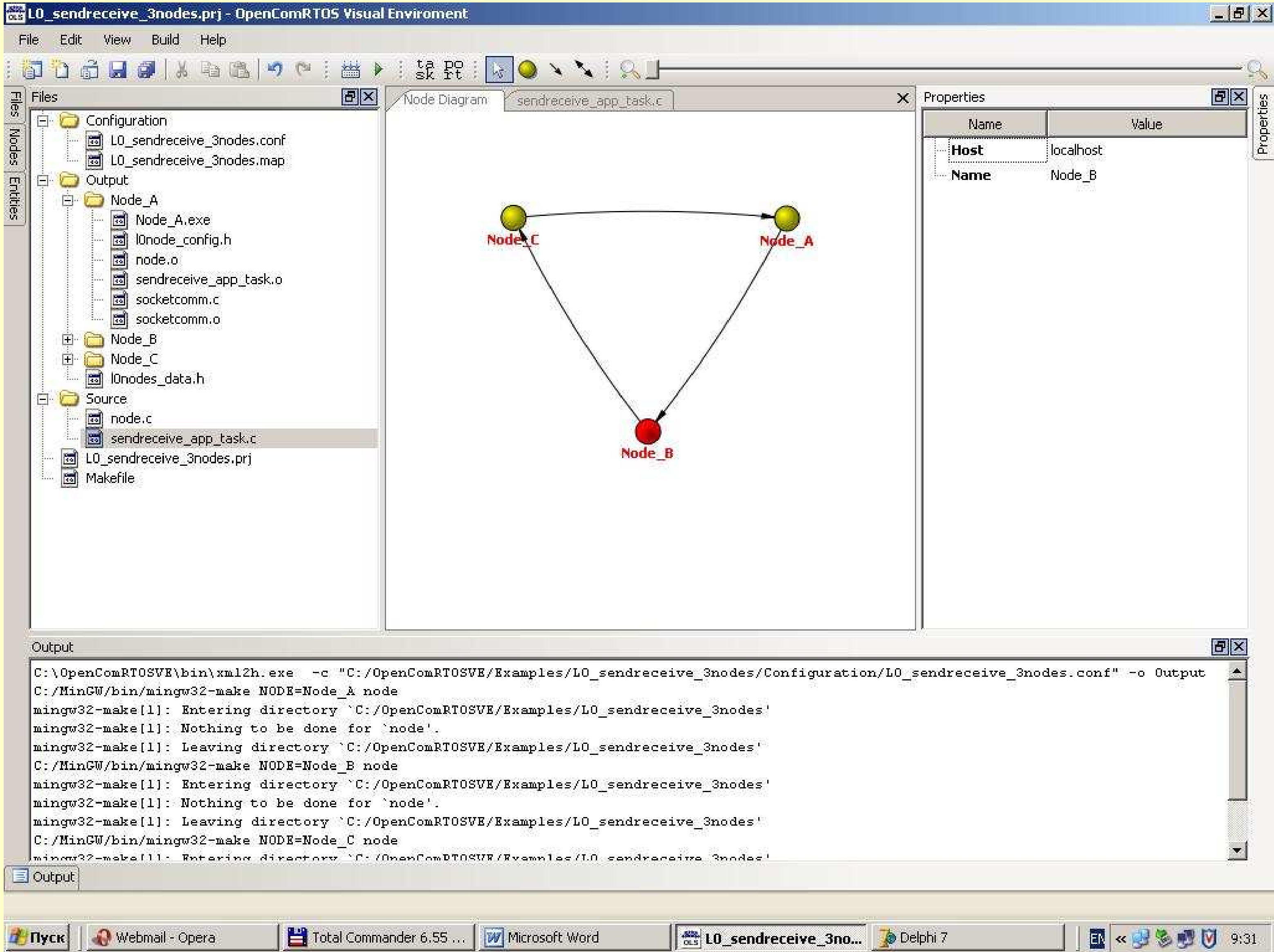
OpenComRTOS Interactions' Metamodel = kernel services

```
<Interaction Name="L1_StartTask_W" Subject="Task" Object="Task" />
<Interaction Name="L1_StopTask_W" Subject="Task" Object="Task" />
<Interaction Name="L1_SuspendTask_W" Subject="Task" Object="Task" />
<Interaction Name="L1_ResumeTask_W" Subject="Task" Object="Task" />
<Interaction Name="L1_SendPacket_W" Subject="Task" Object="Port" />
<Interaction Name="L1_ReceivePacket_W" Subject="Task" Object="Port" />
<Interaction Name="L1_SendPacket_NW" Subject="Task" Object="Port" />
<Interaction Name="L1_ReceivePacket_NW" Subject="Task" Object="Port" />
<Interaction Name="L1_SendPacket_WT" Subject="Task" Object="Port" />
<Interaction Name="L1_ReceivePacket_WT" Subject="Task" Object="Port" />
<Interaction Name="L1_SendPacket_A" Subject="Task" Object="Port" />
<Interaction Name="L1_ReceivePacket_A" Subject="Task" Object="Port" />
<Interaction Name="L1_AllocatePacket" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_DeallocatePacket_W" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_AllocatePacket_W" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_WaitForPacket" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_WaitForPacket_W" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_AllocatePacket_NW" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_WaitForPacket_NW" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_AllocatePacket_WT" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_WaitForPacket_WT" Subject="Task" Object="PacketPool" />
<Interaction Name="L1_SendPacket_W" Subject="Task" Object="Port" />
<Interaction Name="L1_ReceivePacket_W" Subject="Task" Object="Port" />
<Interaction Name="L1_RaiseEvent_W" Subject="Task" Object="Event" />
<Interaction Name="L1_TestEvent_W" Subject="Task" Object="Event" />
<Interaction Name="L1_SignalSemaphore_W" Subject="Task" Object="Semaphore" />
<Interaction Name="L1_TestSemaphore_W" Subject="Task" Object="Semaphore" />
<Interaction Name="L1_LockResource_W" Subject="Task" Object="Resource" />
<Interaction Name="L1_UnlockResource_W" Subject="Task" Object="Resource" />
<Interaction Name="L1_EnqueueFifo_W" Subject="Task" Object="Fifo" />
<Interaction Name="L1_DequeueFifo_W" Subject="Task" Object="Fifo" />
<Interaction Name="L1_SendPacket_NW" Subject="Task" Object="Port" />
```

Stages of application development in OpenComRTOSVE

1. Nodes (processors) topology definition
2. RTOS application structure definition
3. Tasks coding
4. Compiling and running
5. Tracing

Nodes topology definition



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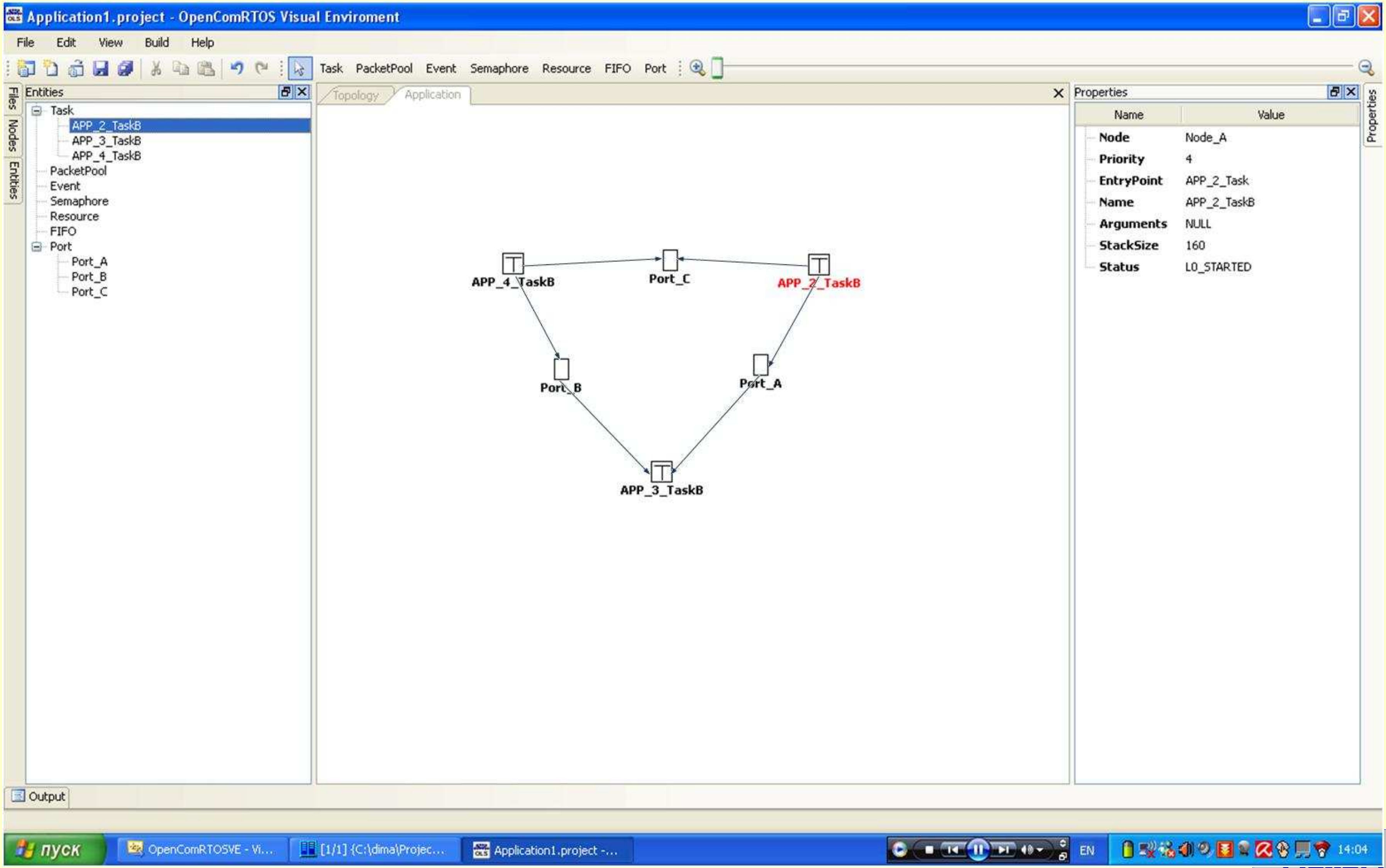
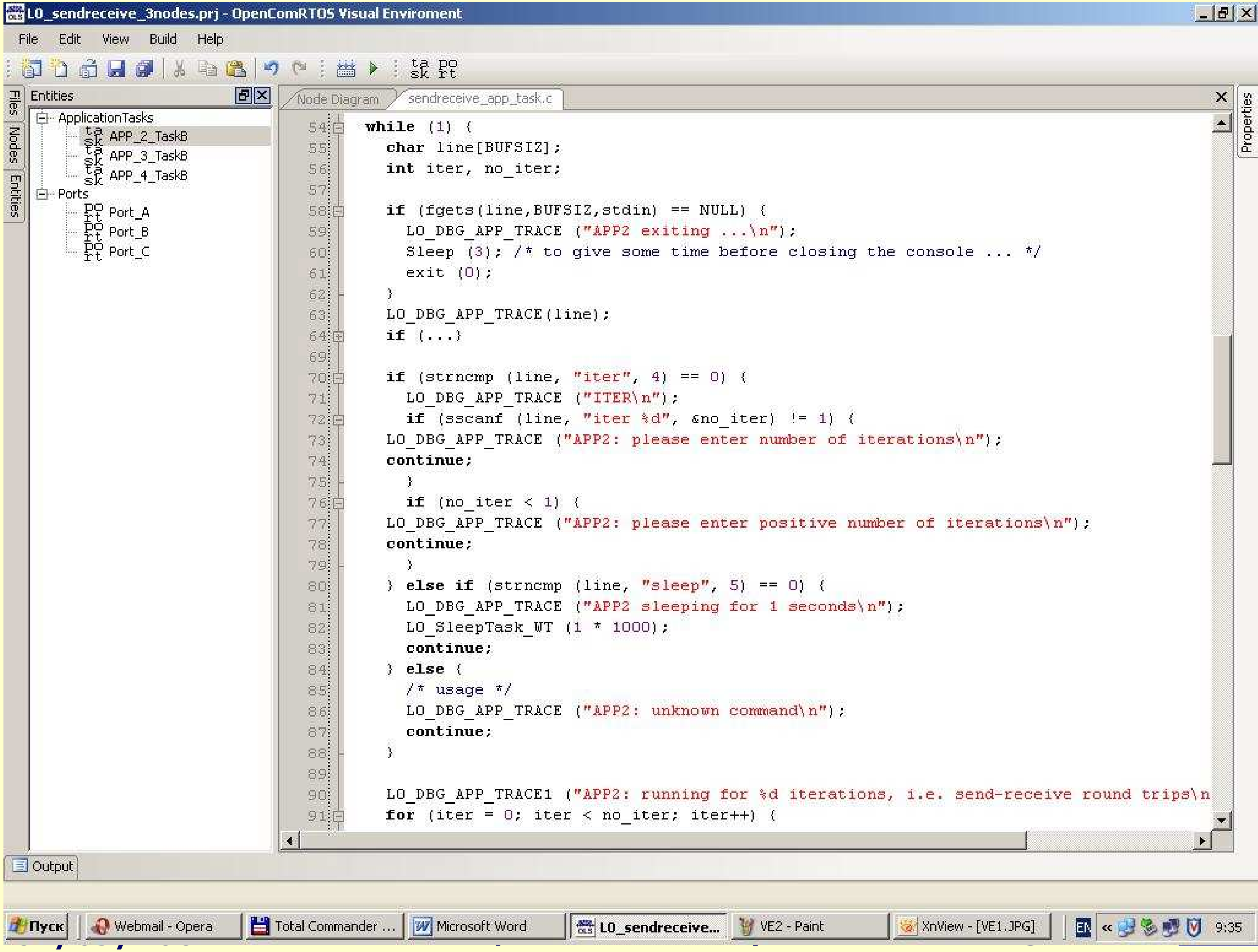
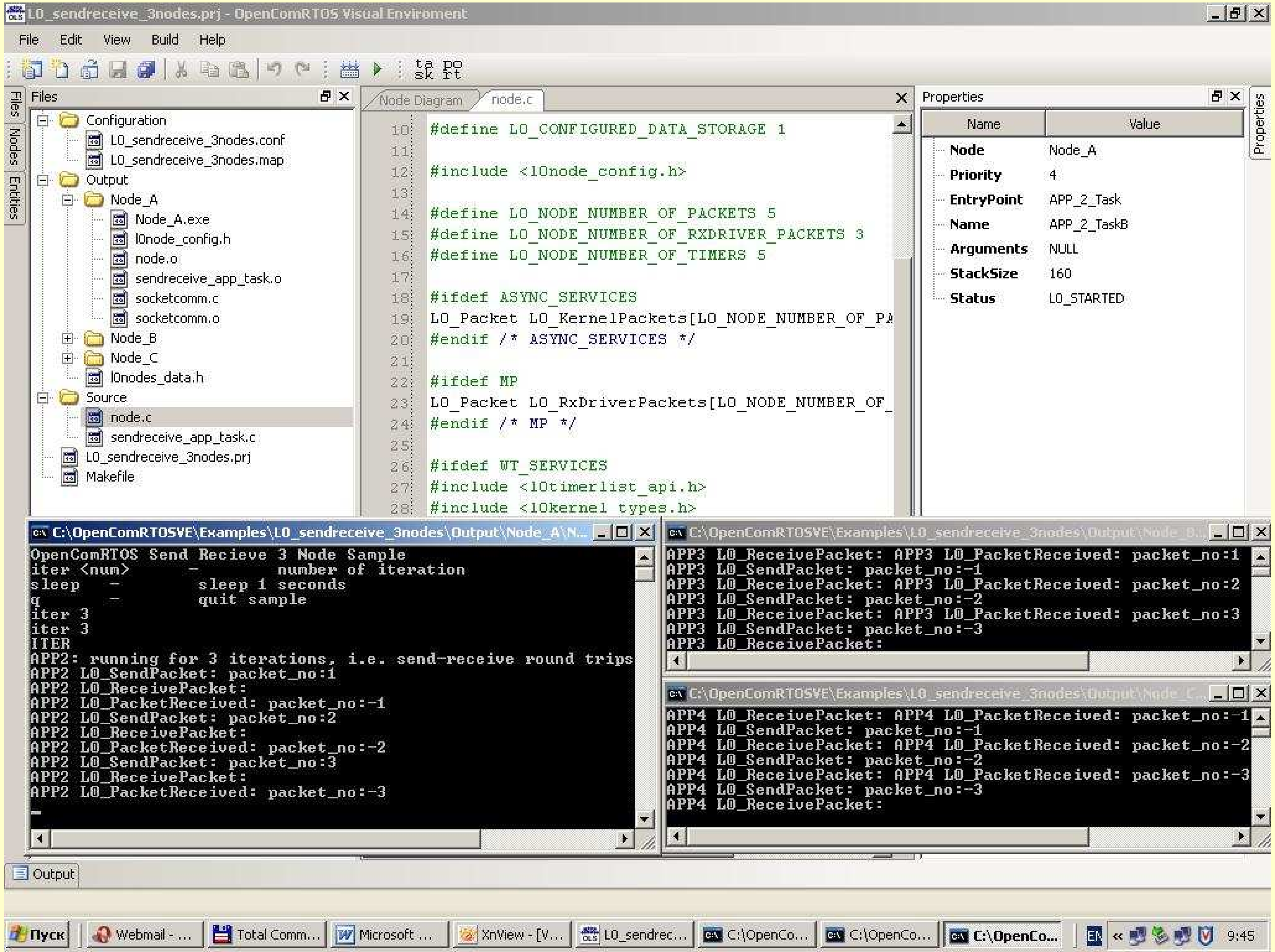
Application structure definition



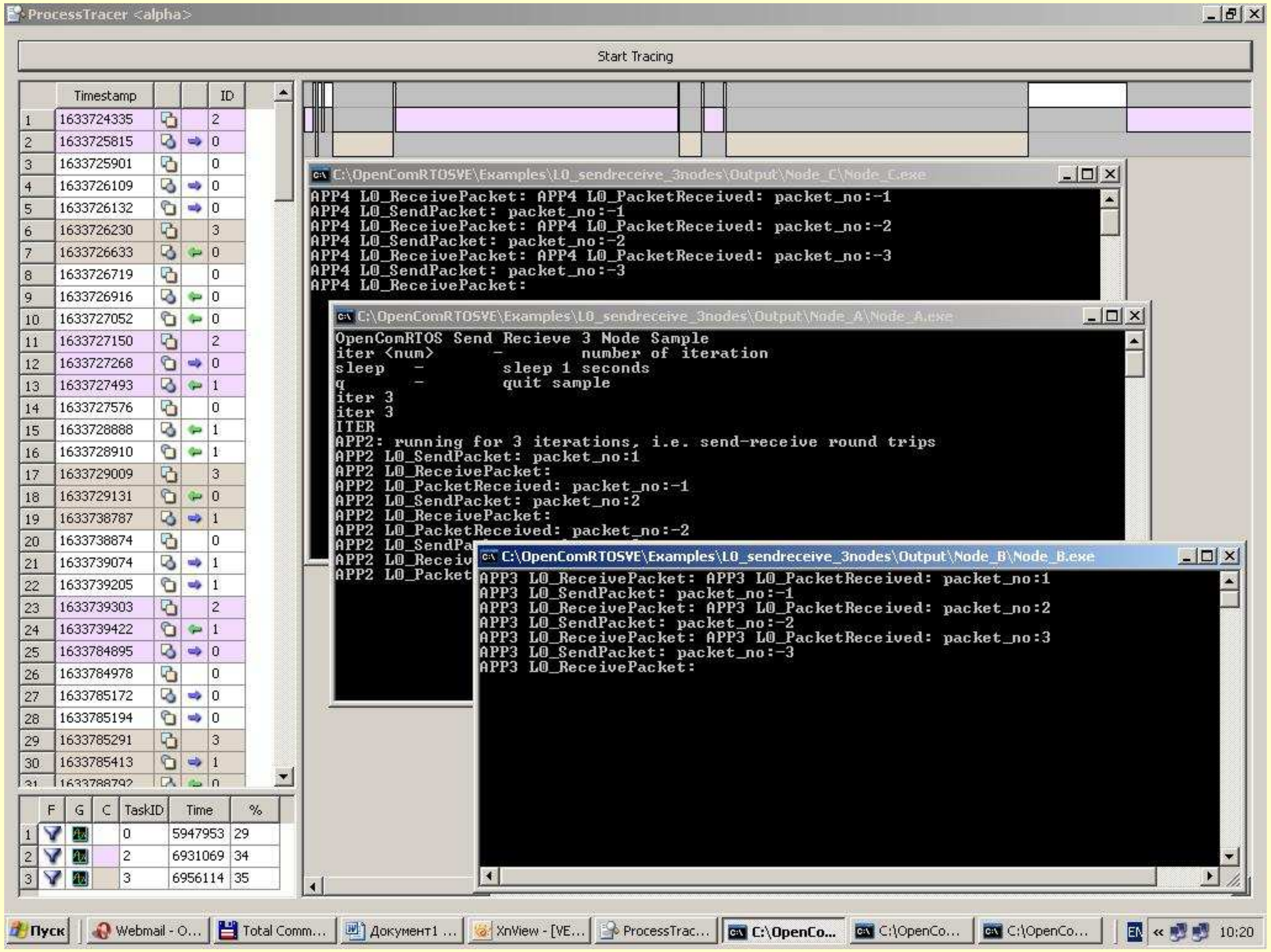
Task source coding



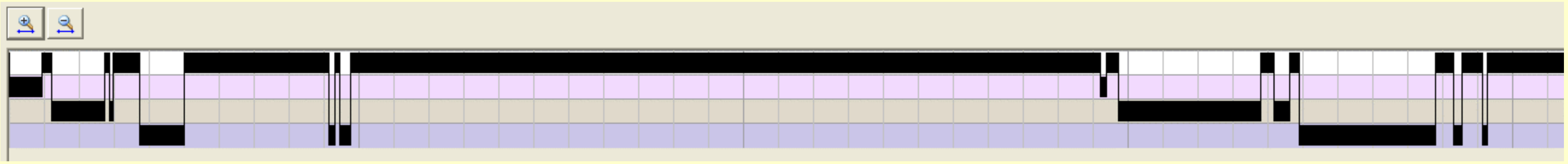
Compiling and running

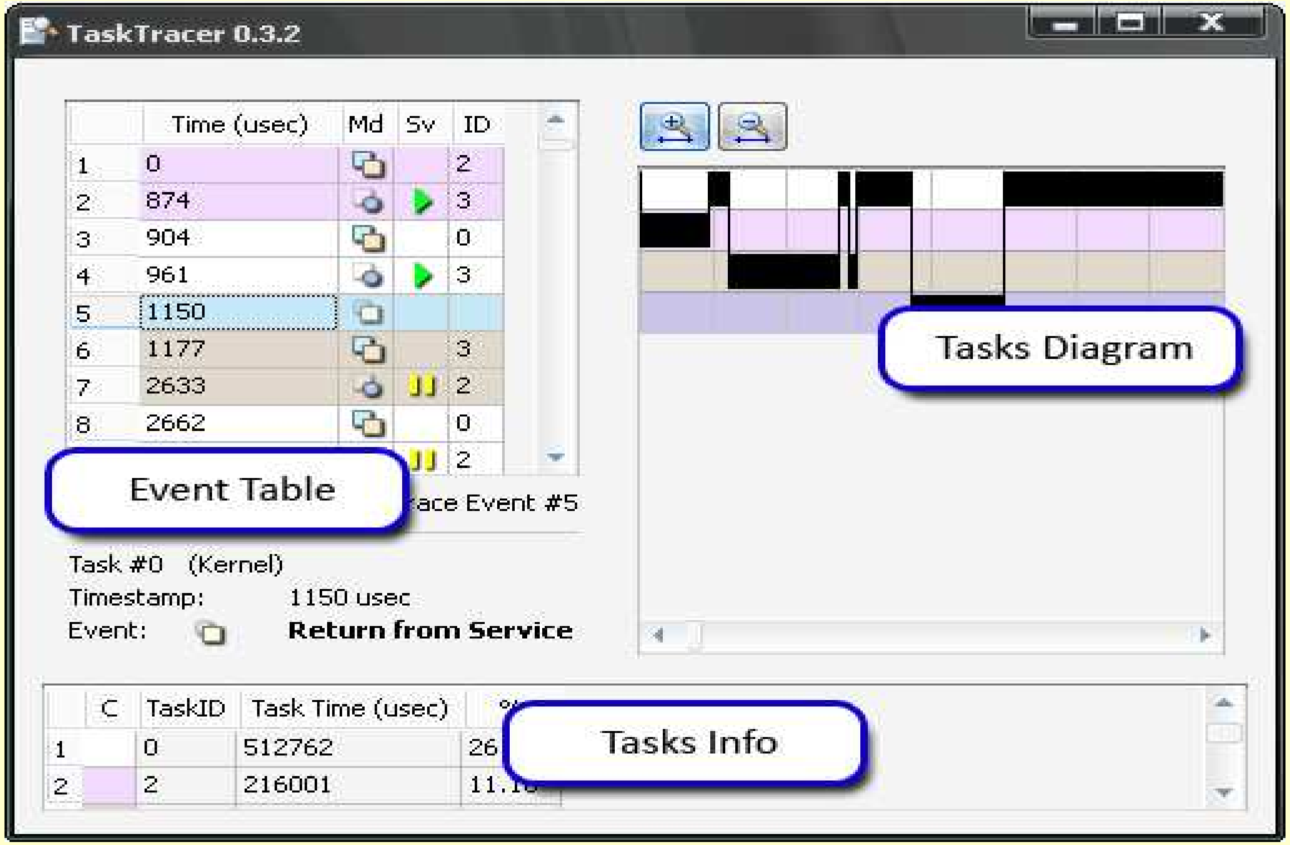


Tracing


ProcessTracer <alpha>
Start Tracing
Timestamp ID
1 1633724335 2
2 1633725815 0
3 1633725901 0
4 1633726109 0
5 1633726132 0
6 1633726230 3
7 1633726633 0
8 1633726719 0
9 1633726916 0
10 1633727052 0
11 1633727150 2
12 1633727268 0
13 1633727493 1
14 1633727576 0
15 1633728888 1
16 1633728910 1
17 1633729009 3
18 1633729131 0
19 1633738787 1
20 1633738874 0
21 1633739074 1
22 1633739205 1
23 1633739303 2
24 1633739422 1
25 1633784895 0
26 1633784978 0
27 1633785172 0
28 1633785194 0
29 1633785291 3
30 1633785413 1
F G C TaskID Time %
1 0 5947953 29
2 2 6931069 34
3 3 6956114 35
C:\OpenComRTOSVE\Examples\L0_sendreceive_3nodes\Output\Node_C\Node_C.exe
APP4 L0_ReceivePacket: APP4 L0_PacketReceived: packet_no:-1
APP4 L0_SendPacket: packet_no:-1
APP4 L0_ReceivePacket: APP4 L0_PacketReceived: packet_no:-2
APP4 L0_SendPacket: packet_no:-2
APP4 L0_ReceivePacket: APP4 L0_PacketReceived: packet_no:-3
APP4 L0_SendPacket: packet_no:-3
APP4 L0_ReceivePacket:
C:\OpenComRTOSVE\Examples\L0_sendreceive_3nodes\Output\Node_A\Node_A.exe
OpenComRTOS Send Recieve 3 Node Sample
iter <num> - number of iteration
sleep - sleep 1 seconds
q - quit sample
iter 3
iter 3
ITER
APP2: running for 3 iterations, i.e. send-receive round trips
APP2 L0_SendPacket: packet_no:1
APP2 L0_ReceivePacket:
APP2 L0_PacketReceived: packet_no:-1
APP2 L0_SendPacket: packet_no:2
APP2 L0_ReceivePacket:
APP2 L0_PacketReceived: packet_no:-2
C:\OpenComRTOSVE\Examples\L0_sendreceive_3nodes\Output\Node_B\Node_B.exe
APP3 L0_ReceivePacket: APP3 L0_PacketReceived: packet_no:1
APP3 L0_SendPacket: packet_no:-1
APP3 L0_ReceivePacket: APP3 L0_PacketReceived: packet_no:2
APP3 L0_SendPacket: packet_no:-2
APP3 L0_ReceivePacket: APP3 L0_PacketReceived: packet_no:3
APP3 L0_SendPacket: packet_no:-3
APP3 L0_ReceivePacket:
Пуск Webmail - O... Total Comm... Документ1 ... XnView - [VE... ProcessTrac... C:\OpenCo... C:\OpenCo... C:\OpenCo... 10:20

OpenComRTOS Event Tracer





Conclusion

- OpenComRTOS breaks new grounds for distributed real-time processing:
  - Developed using formal methods
  - Based on packet switching
  - Ultra-small, still same functionality
  - Scalable and extensible by use of meta-model
  - From multicore to widely distributed systems
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  - www.OpenLicenseSociety.org