Assessing Security of Cyber-Physical Systems

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Outline

- Introduction
  - What is CPS/Example systems
  - Security Issues of CPS
- Tools/Experiment Environment for CPS Security Assessment
  - Run-time: Integration of multiple tools/Environment
    - Simulation, emulation, real testbed
  - Modeling-time, rapid configuration/deployment
    - Model integration
- Step I: Command and Control Wind Tunnel
  - Heterogeneous simulation integration
- Step II, Integration of DeterLab and C2WT
  - Simulation and emulation integration
- Step III – Future Directions

Cyber-Physical Systems

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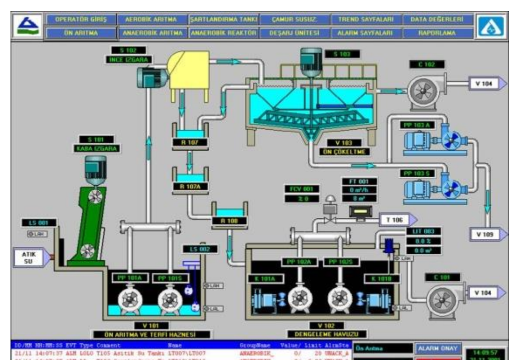
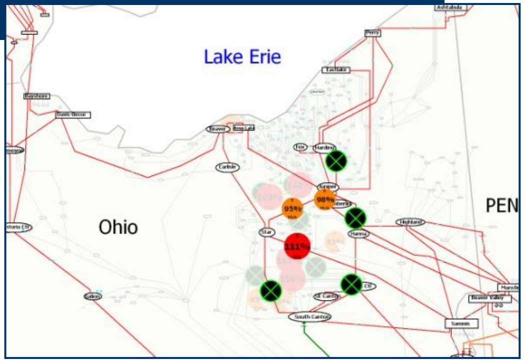
Cyber-physical systems (CPS) are tight integrations of communications, computational and physical processes

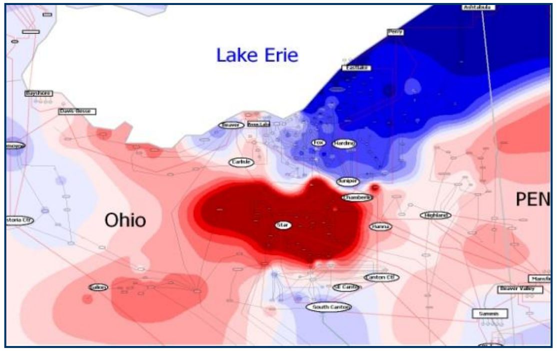
- CPS has extraordinary significance for the future of the U.S. industry and military superiority.
  - A 2007 report of the President's Council of Advisors on Science and Technology highlights CPS as the number one priority for federal investments in networking and information technology.
- Application Domains
  - Health-Care
  - Automotive Systems
  - Building and Process Controls
  - Defense and Aviation Systems
  - Critical Infrastructure

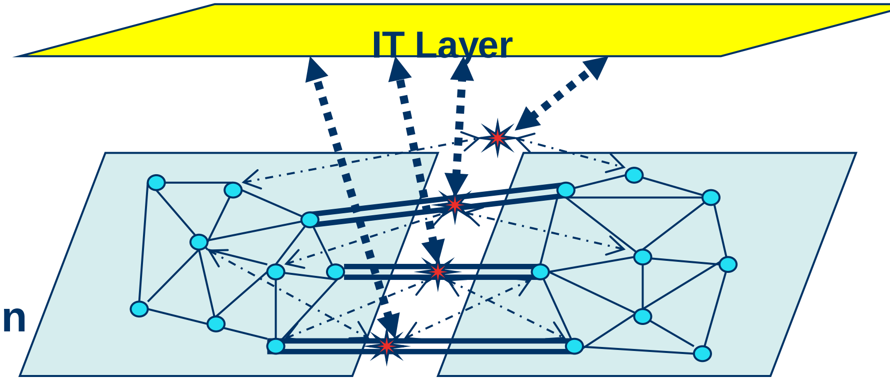


Example: Electric Power Grid

- Current picture:
  - **Equipment protection devices trip locally, reactively**
  - **Cascading failure: August (US/Canada) and October (Europe), 2003**
- Better future?
  - **Real-time cooperative control of protection devices**
  - **Or -- self-healing -- (re-)aggregate islands of stable bulk power (protection, market motives)**
  - **Ubiquitous green technologies**
  - **Issue: standard operational control concerns exhibit wide-area characteristics (bulk power stability and quality, flow control, fault isolation)**
  - **Technology vectors: FACTS, PMUs**
  - **Context: market (timing?) behavior, power routing transactions, regulation**







Images thanks to William H. Sanders, Bruce Krogh, and Marija Ilic

Example: Health Care and Medicine

- National Health Information Network, Electronic Patient Record initiative
  - Medical records at any point of service
  - Hospital, OR, ICU, …, EMT?
- Home care: monitoring and control
  - Pulse oximeters (oxygen saturation), blood glucose monitors, infusion pumps (insulin), accelerometers (falling, immobility), wearable networks (gait analysis), …
- Operating Room of the Future (Goldman)
  - Closed loop monitoring and control; multiple treatment stations, plug and play devices; robotic microsurgery (remotely guided?)
  - System coordination challenge
- Progress in bioinformatics: gene, protein expression; systems biology; disease dynamics, control mechanisms

Images thanks to Dr. Julian Goldman, Dr. Fred Pearce

CPS Characteristics

- Cyber capability in physical component
- Size and power of computational elements
- Networked at multiple and extreme scales
- High degrees of automation, control loops must close at all scales
- Enhance and leverage nature physical feedback at all levels
  - sensing technology
  - actuation technology
- Human-System Interaction, human in the control loop

Security Issues of CPS

- Trustworthiness of software and hardware for cyber-physical systems is an essential concern since such systems are routinely employed in critical settings.
- Existing systems are built without sufficiently formalized and analyzed properties and guarantees.
  - many existing systems have built-in vulnerabilities which, once identified and exploited by attackers, can lead to catastrophic consequences.
  - Most current systems cannot perform any self-diagnostics to test whether they have been compromised.
  - Even if attacks/intrusions are detected, existing systems cannot automatically contain, or heal themselves from consequences of, successful attacks.

Core CPS Programmatic Themes

- There is a pressing need to design and evaluate both cyber- and physical systems (CPS) together and holistically
  - Scientific foundations for building verifiably correct and safe cyber-physical systems
  - Scalable infrastructure and components with which cyber-physical systems can be deployed
  - Tools and Experimental Testbed
  - Education that encompasses both the cyber and the physical domains

Tools for Design & Implementation of CPS

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	Control Design: Continuous State	Control Implementation: Discrete State/Events
Models	differential equations, transfer functions, etc.	automata, Petri nets, statecharts, etc.
Analytical Tools	Lyapunov functions, eigenspace analysis, etc.	Boolean algebra, formal logics, recursion, etc.
Software Tools	MATLAB, Matrix_X, VisSim, etc.,	Statemate, NS-2, OMNeT++, etc.

Need for Security Assessment Tool and Experiment Environment

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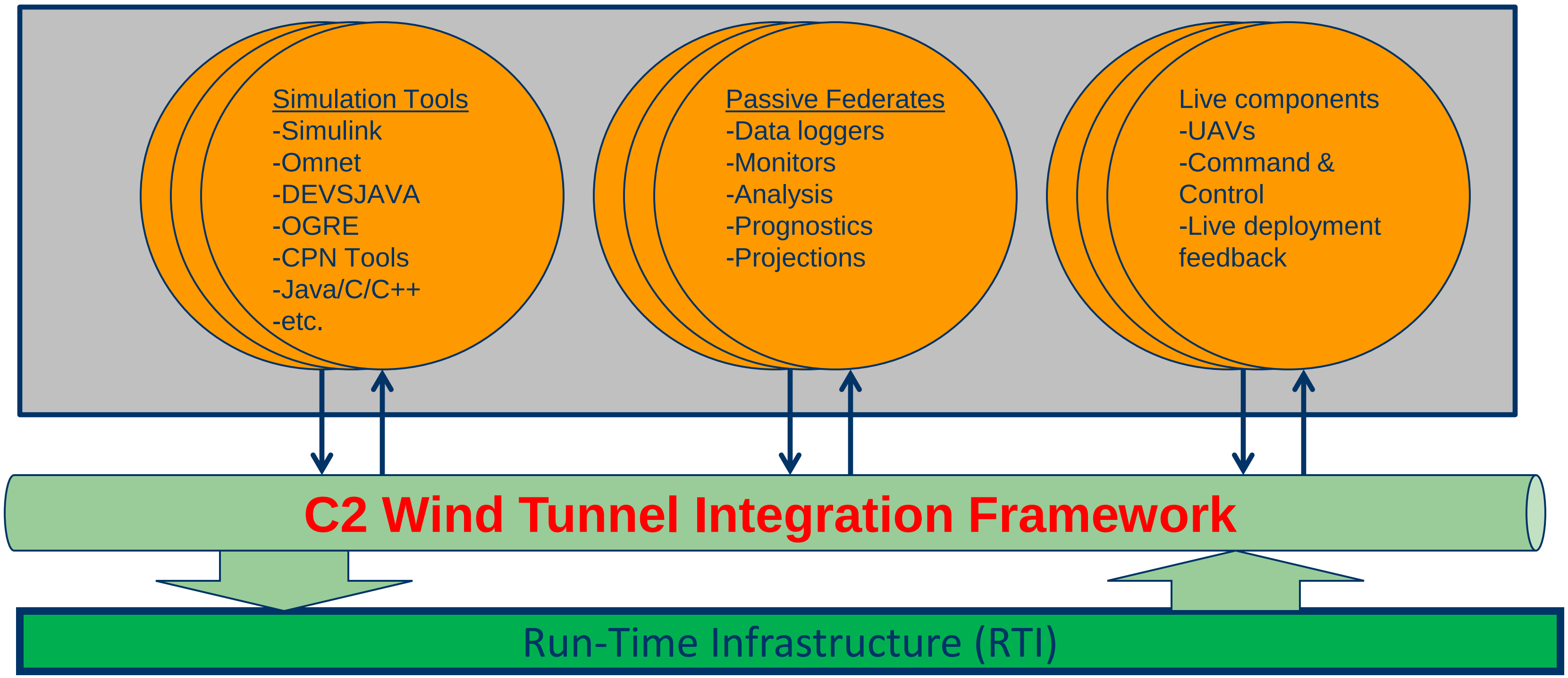
- Evaluation of CPS security requires a sophisticated modeling and simulation, experiment infrastructure that allows for the concurrent modeling, simulation and evaluation of
  - the CPS system architecture (advanced system-of-systems modeling)
  - running environment (scenario modeling and generation)
  - attack scenario (threat modeling and generation).
- This requires the integration at two levels
  - Run-time: Integration of multiple tools/Environment
    - Simulation, emulation, real testbed so that they can interact in a coordinated way.
  - Modeling-time: Model integration
    - rapid configuration/deployment

Our Approach

- Step I: Command and Control Wind Tunnel
  - Heterogeneous simulation integration
- Step II, Integration of DeterLab and C2WT
  - Simulation and emulation integration
- Step III – Future Directions

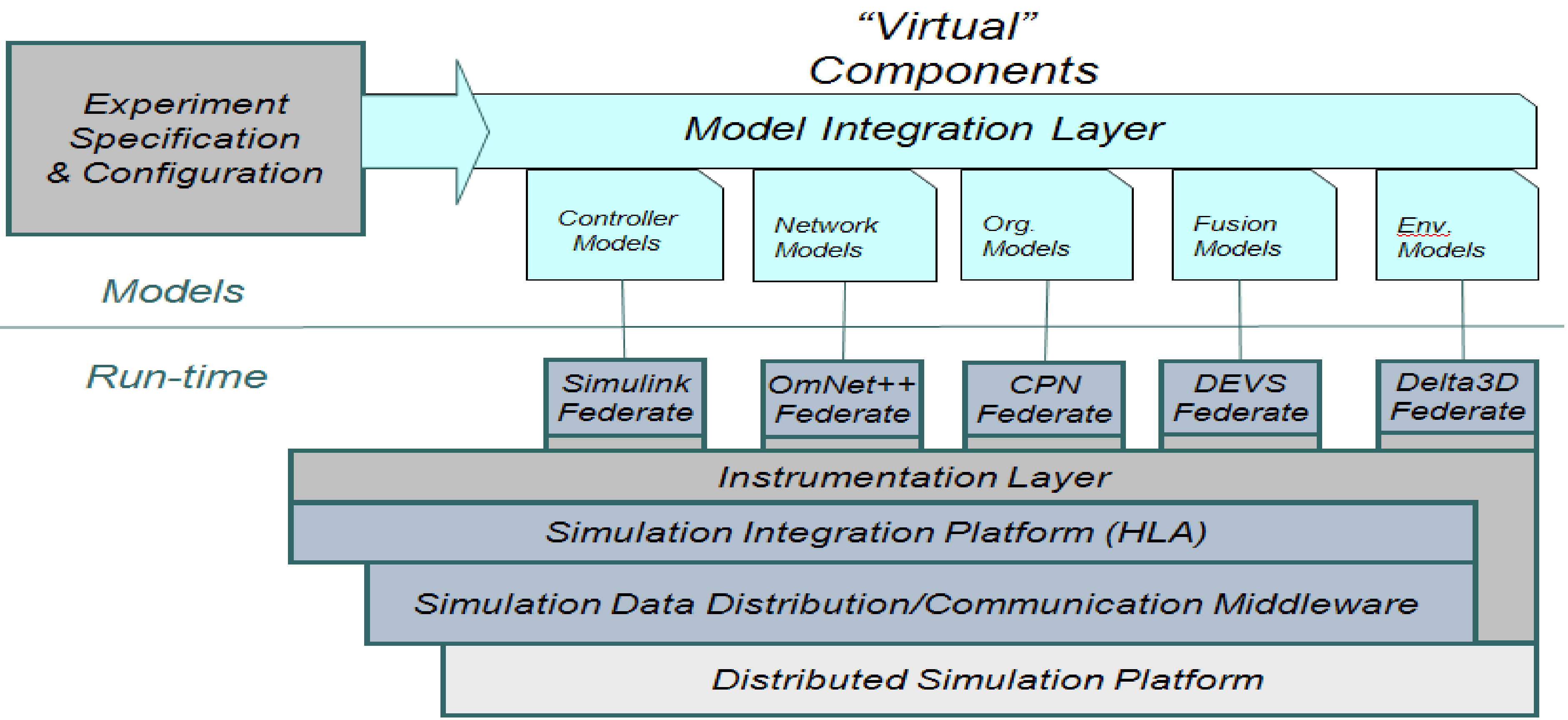
C2 Wind Tunnel

- Integration of multiple simulation tools
  - Matlab/Simulink, OMNeT++, DEVSJAVA, Delta3D, CPN, etc.
- Follow HLA standard
  - Coordinate execution of distributed simulations via RTI



C2 Wind Tunnel

- Model-integrated approach
  - Develop an overarching modeling environment based on GME
  - Integrate different platform-specific simulation models



Introducing Network Emulation Into C2WT

- Motivation to Introduce Network Emulation
- Design Consideration and Challenges
- Our Approach and Solution
  - Communication architecture
  - Time synchronization

In collaboration with Timothy Busch (AFRL/RISB)

From Simulation to Emulation

- Network components and policies are essential aspects of CPS
- The impact of network on CPS system need to be accurately characterized
  - Think about the network attacks…
- Limit of network simulator
  - Protocol implementation details are missing
  - Poor scalability

Network simulation is insufficient in providing the level of accuracy required by the evaluation of CPS.

From Simulation to Emulation

- Benefit of network emulation
  - Greater realism and accuracy with truthful protocol implementation and real network traffic delivery
  - Providing a computing platform where prototypes of software components can be deployed
- Network emulation platform
  - Emulab
  - DETERNet
    - Large number of tools available for emulate network attacks

Design Consideration

- Communication between simulated objects and real network objects
- Time synchronization between simulated objects and real network objects

Challenge in Data Communication

- Key Issue
  - There is potentially large volume of data communicated between the simulation and the emulation environment
  - Tradeoff between realism and performance
  - How to control the communication overhead
- Approaches
  - Identify the communication platform (e.g., RTI, pub/sub service, socket, etc.)
  - Control the application-level messages
  - Design efficient transport-level protocols (e.g., reliable multicast)

Challenge in Data Communication

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- Observation -- Different types of data
  - Command/Signal notification (E.g., Start to send, stop to send, change sending rate)
  - Application Data/Payload (E.g., Images, videos)
- Our approach
  - Identify the appropriate communication platform for different types of data
  - Define the appropriate granularity of communication data depending on the application semantics
  - Characterize the communication semantics in the modeling phase
    - Model integration

Challenge in Time Synchronization

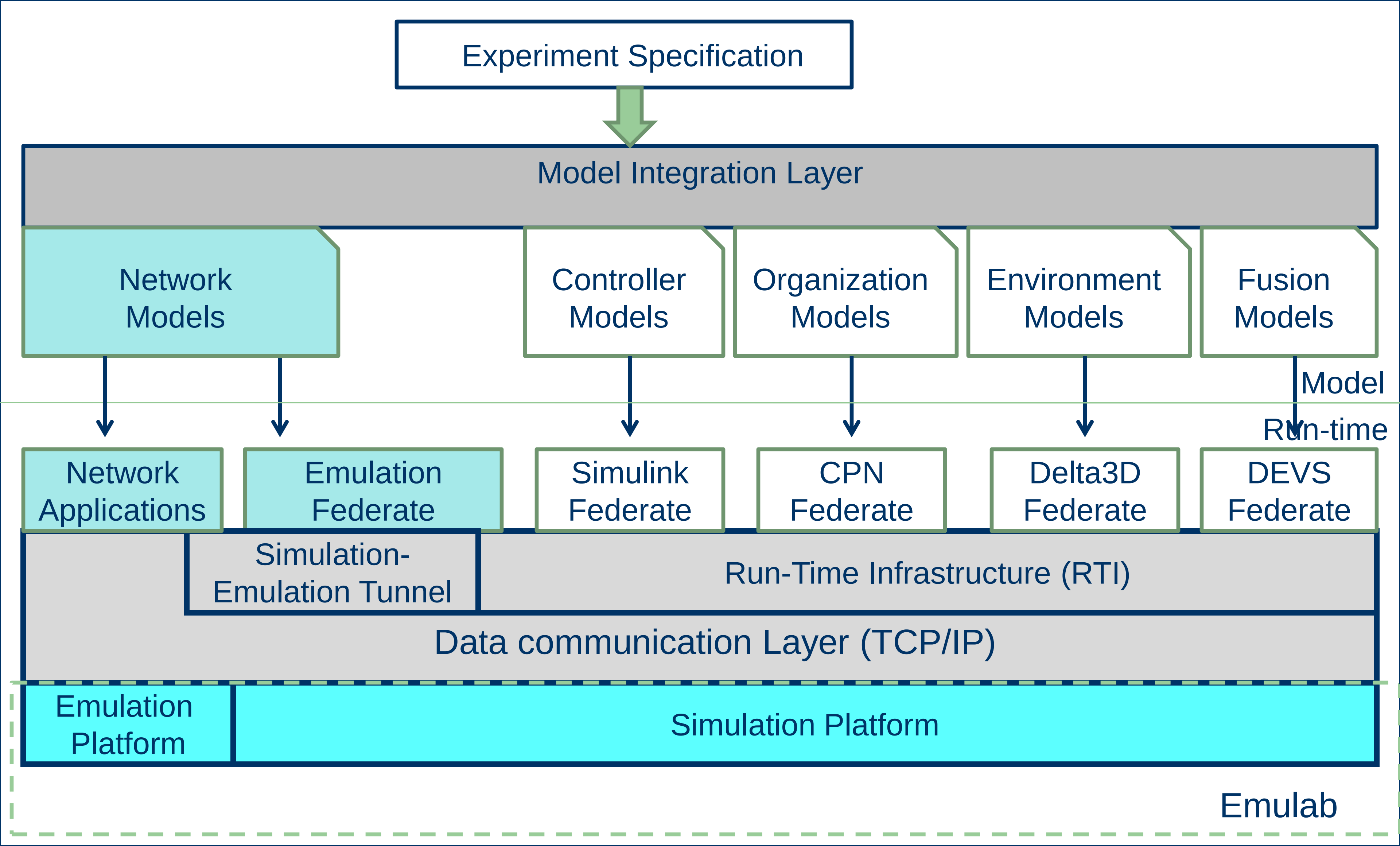
- Key Issue
  - Simulated objects run in simulation time which is coordinated by RTI time management
  - Network objects run in the user space of real operating systems and follow system time (usually real time)
  - How to reconcile these two time models
- Design consideration
  - Identify the appropriate time models for the integrated system
  - Design the time synchronization algorithms

Difference From Existing Works

- Similarity
  - Combining real network elements with simulated ones, each modeling different portions of a networked distributed system
- Fundamental Difference
  - In the existing work, the network is simulated, the application is real.
  - In our work, the network is real, the application is simulated.
  - Both require time synchronization. In our case, the network communication (e.g., packets in fly) can not be controlled.

Need new design for simulation-emulation communication and time synchronization

Architecture



Pros and Cons

- Pros
  - Limit the traffic load of RTI
    - The communication between simulated objects and real objects does not go through RTI
  - Few code changes to simulators
- Cons:
  - The node that hosts the Emulation Gateway Federate may be comes a bottleneck
    - All traffic goes through Emulation Gateway Federate
    - We may use multiple instances of Emulation Gateway Federate and perform parallel simulation to solve this bottleneck issue

Meta-Model and Models

- Network Topology Model
- Network Application Process Deployment and Communication Model
- Network Interaction Model

Meta-Model for Network Topology

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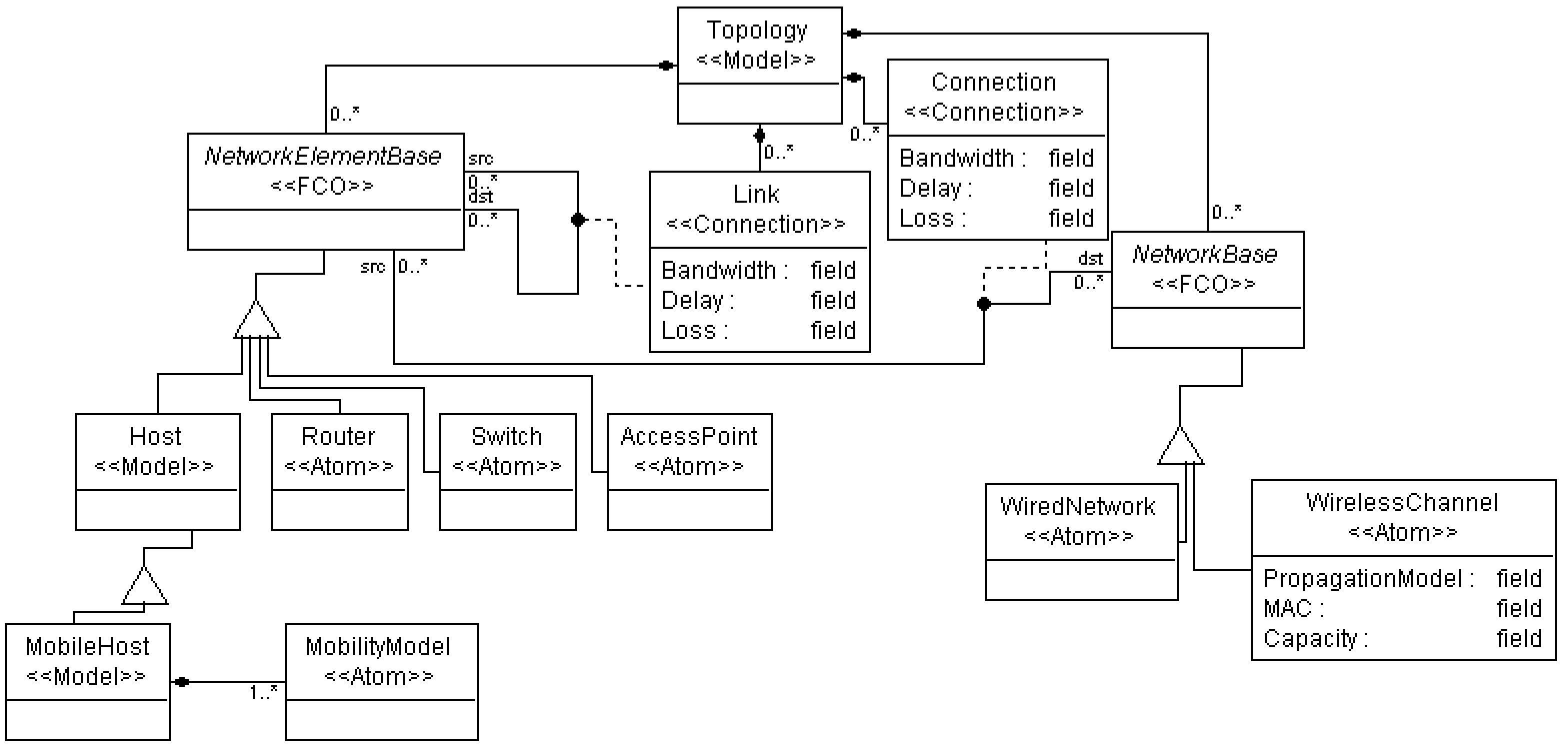
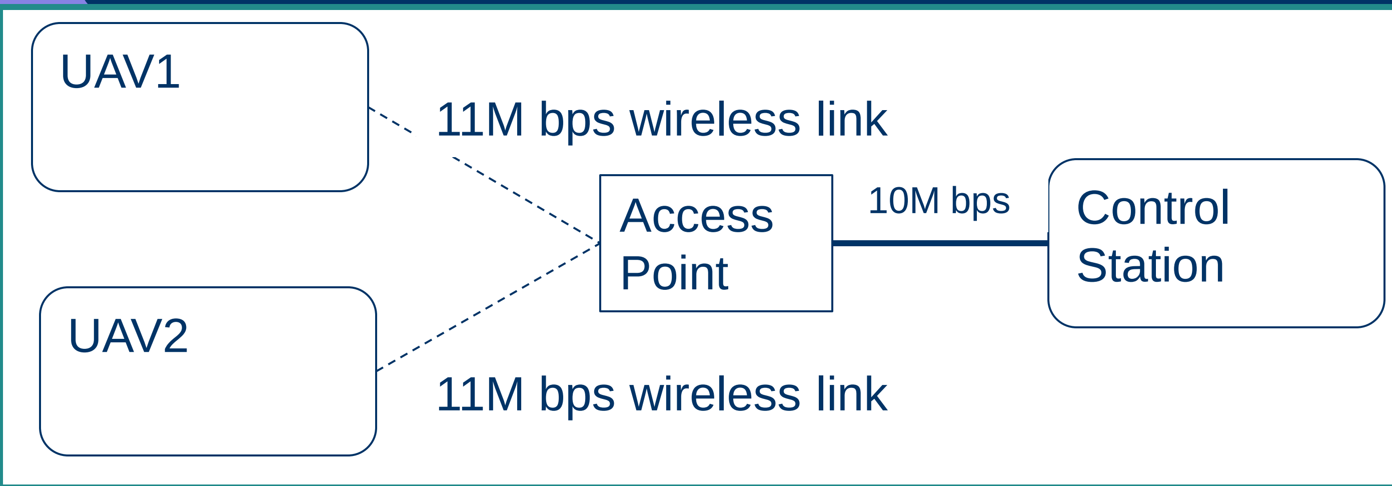
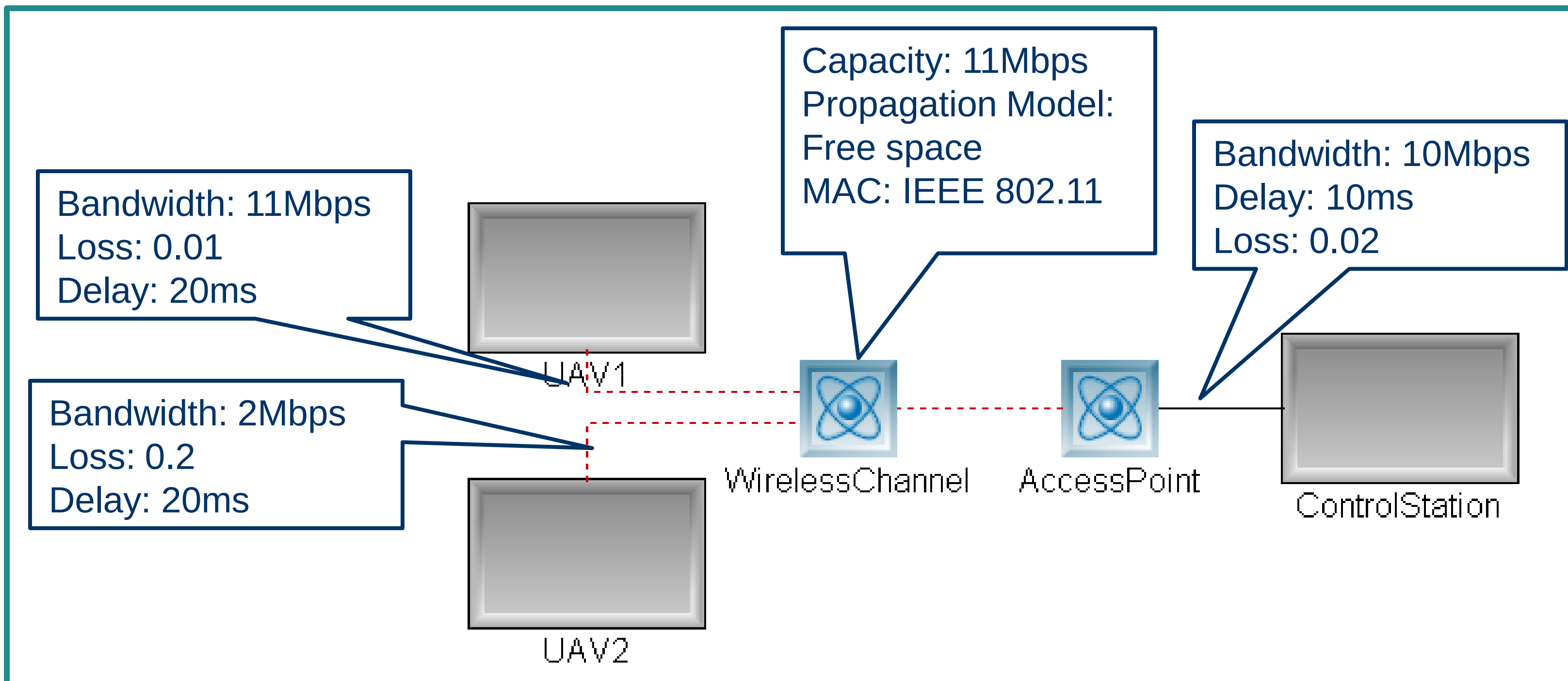
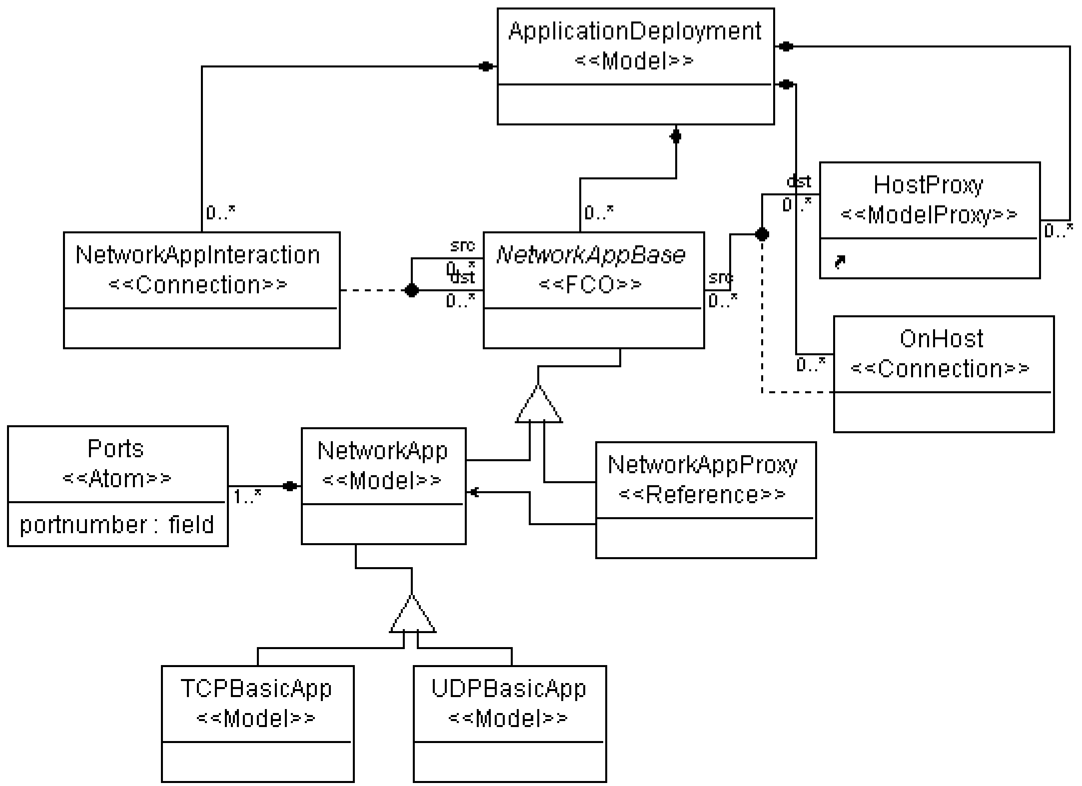


Topology Model

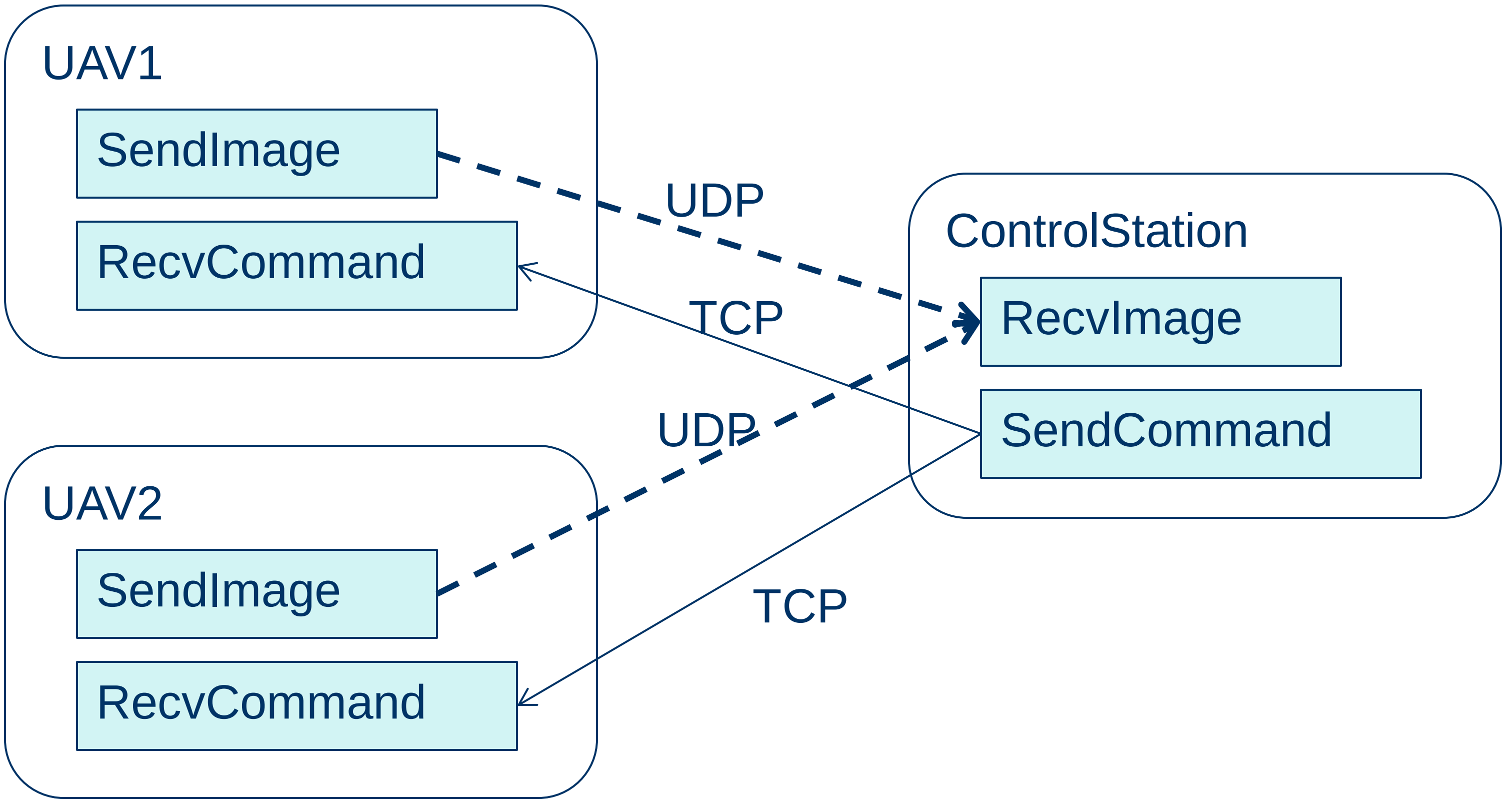




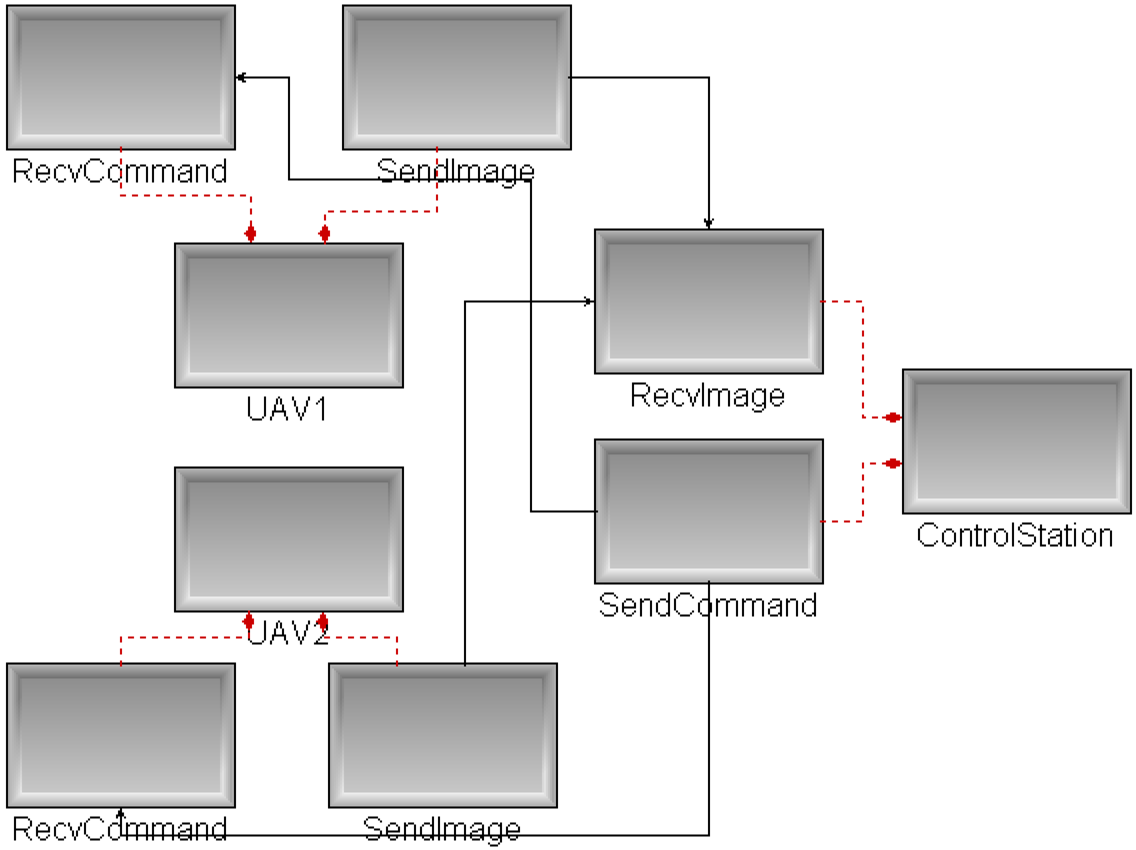
Deployment MetaModel



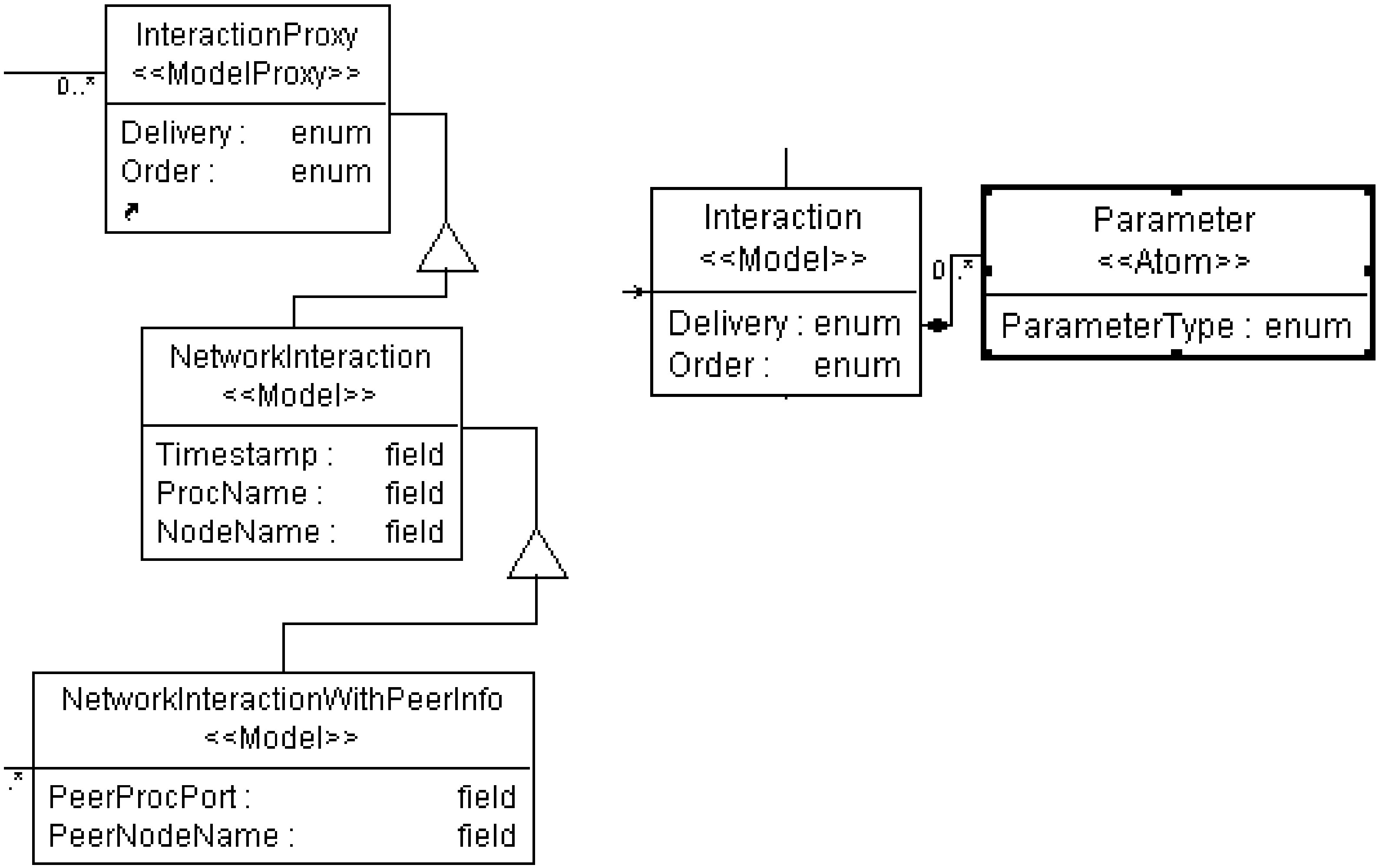
Deployment Model Example



Deployment Model Example

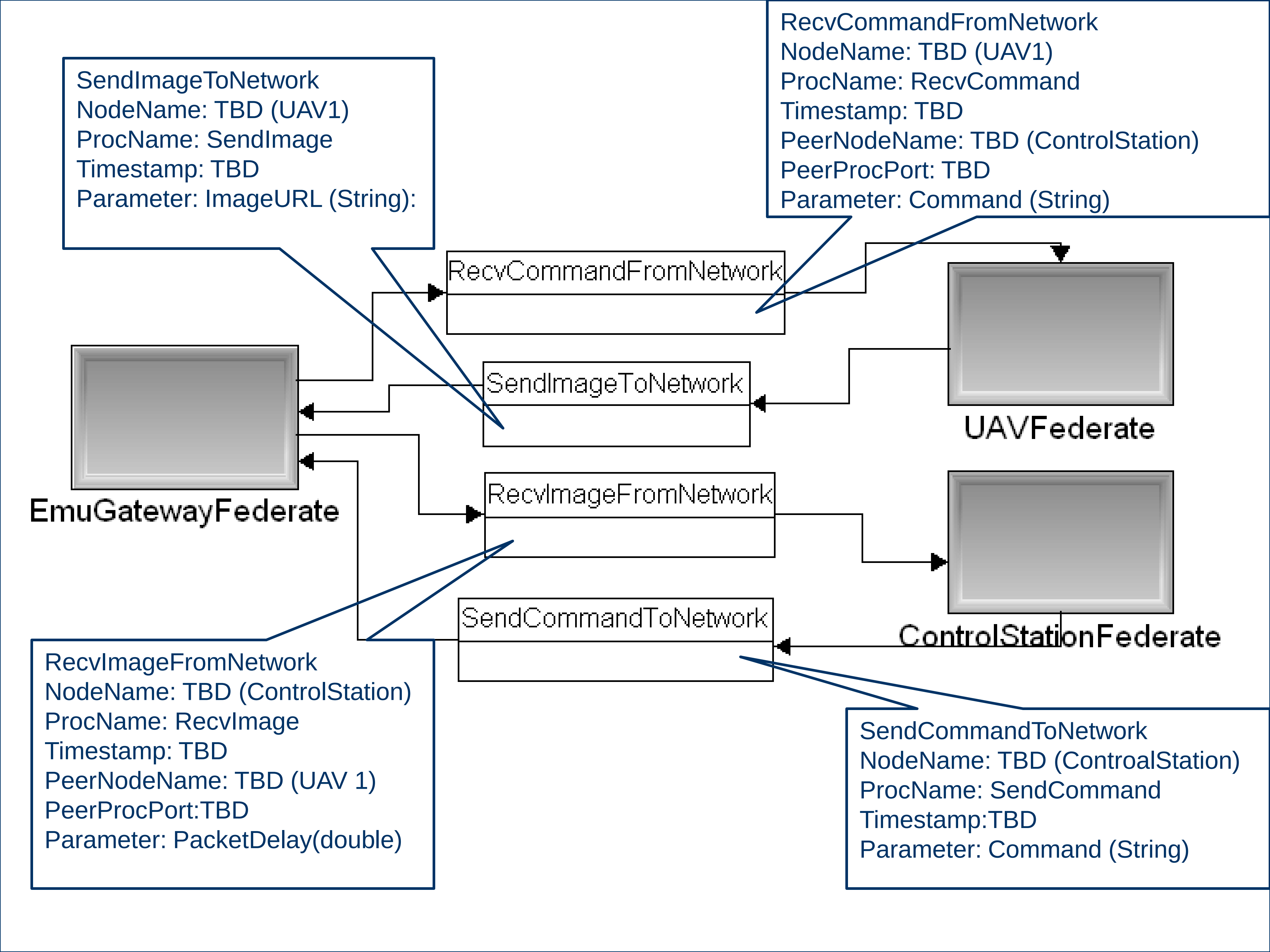


Network Interaction MetaModel



Network Interaction Model Example

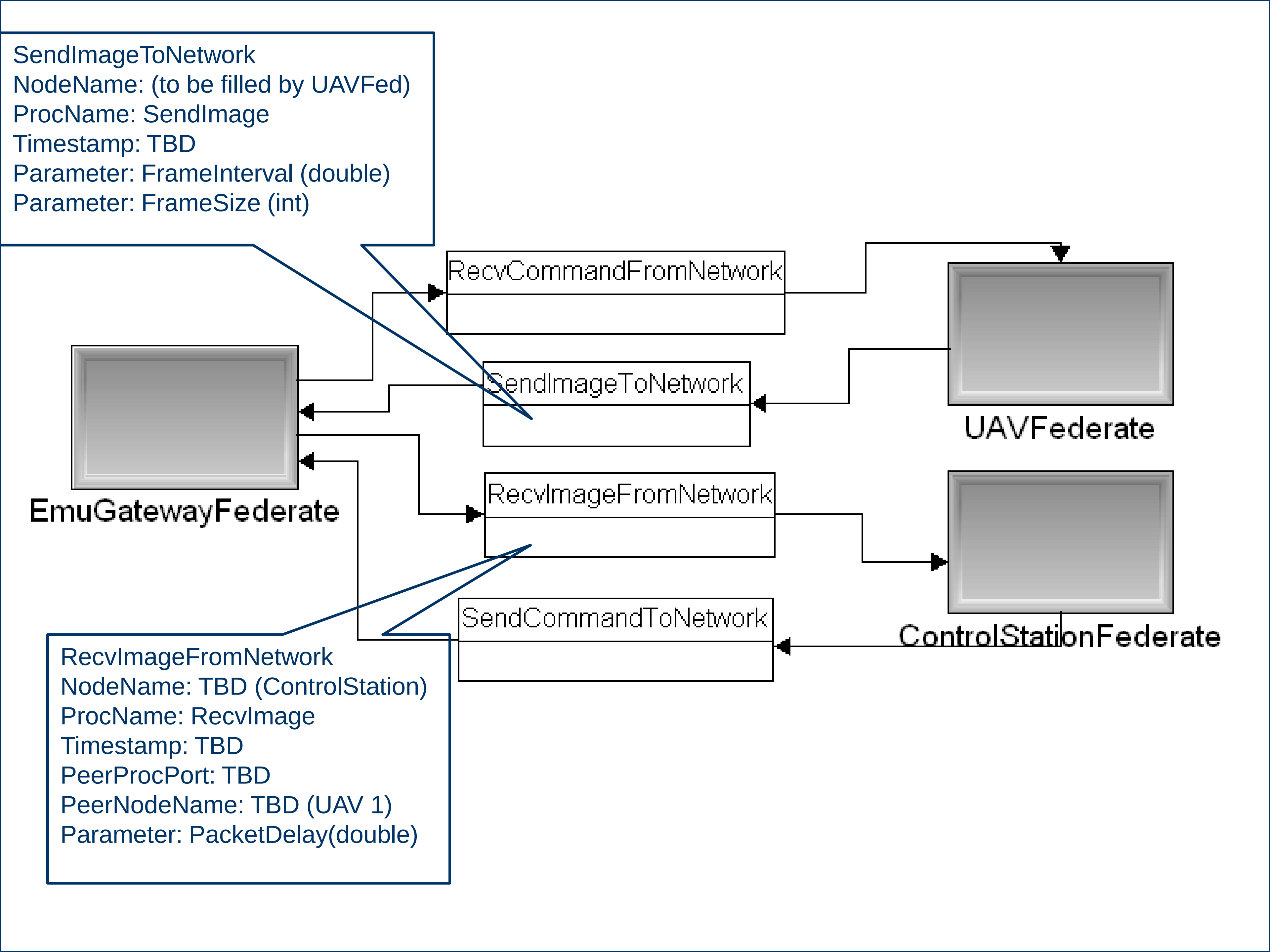
- Connection-oriented UDP
  - Message driven → no fixed packet size, interval, starting time
    - Command: String
    - Image: URL/real data

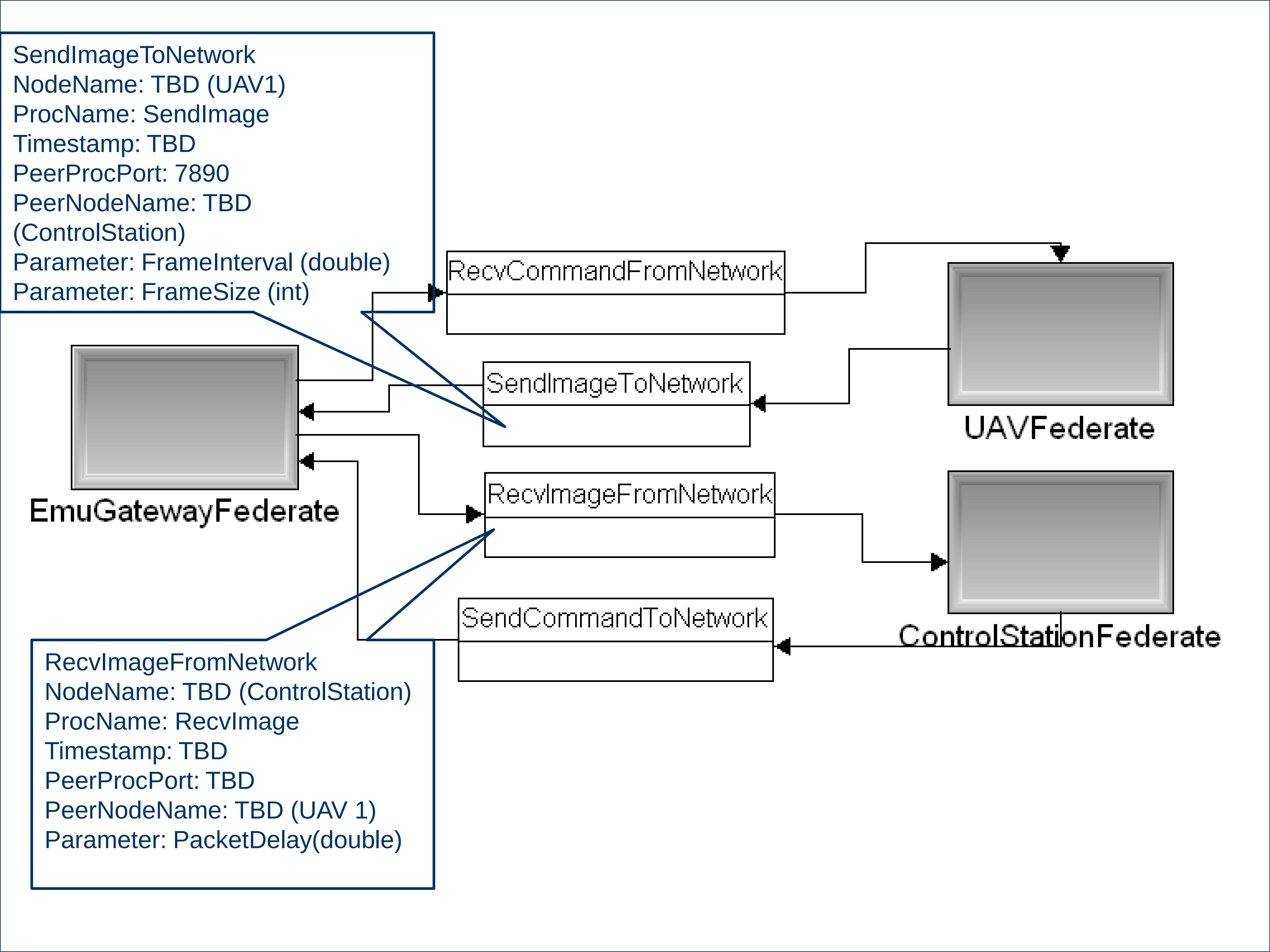


SendImageToNetwork
NodeName: TBD (UAV1)
ProcName: SendImage
Timestamp: TBD
Parameter: ImageURL (String):
RecvCommandFromNetwork
NodeName: TBD (UAV1)
ProcName: RecvCommand
Timestamp: TBD
PeerNodeName: TBD (ControlStation)
PeerProcPort: TBD
Parameter: Command (String)
RecvCommandFromNetwork
SendImageToNetwork
RecvImageFromNetwork
SendCommandToNetwork
EmuGatewayFederate
UAVFederate
ControlStationFederate
RecvImageFromNetwork
NodeName: TBD (ControlStation)
ProcName: RecvImage
Timestamp: TBD
PeerNodeName: TBD (UAV 1)
PeerProcPort:TBD
Parameter: PacketDelay(double)
SendCommandToNetwork
NodeName: TBD (ControalStation)
ProcName: SendCommand
Timestamp:TBD
Parameter: Command (String)

Network Interaction Model More Examples

- Case II -- Connection-oriented UDP
  - Parameterized UDP
    - Parameter: frame size, frame interval
- Case III – Connectionless UDP


SendImageToNetwork
NodeName: (to be filled by UAVFed)
ProcName: SendImage
Timestamp: TBD
Parameter: FrameInterval (double)
Parameter: FrameSize (int)
RecvCommandFromNetwork
SendImageToNetwork
RecvImageFromNetwork
SendCommandToNetwork
EmuGatewayFederate
UAVFederate
ControlStationFederate
RecvImageFromNetwork
NodeName: TBD (ControlStation)
ProcName: RecvImage
Timestamp: TBD
PeerProcPort: TBD
PeerNodeName: TBD (UAV 1)
Parameter: PacketDelay(double)


SendImageToNetwork
NodeName: TBD (UAV1)
ProcName: SendImage
Timestamp: TBD
PeerProcPort: 7890
PeerNodeName: TBD (ControlStation)
Parameter: FrameInterval (double)
Parameter: FrameSize (int)
RecvCommandFromNetwork
SendImageToNetwork
UAVFederate
EmuGatewayFederate
RecvImageFromNetwork
SendCommandToNetwork
ControlStationFederate
RecvImageFromNetwork
NodeName: TBD (ControlStation)
ProcName: RecvImage
Timestamp: TBD
PeerProcPort: TBD
PeerNodeName: TBD (UAV 1)
Parameter: PacketDelay(double)

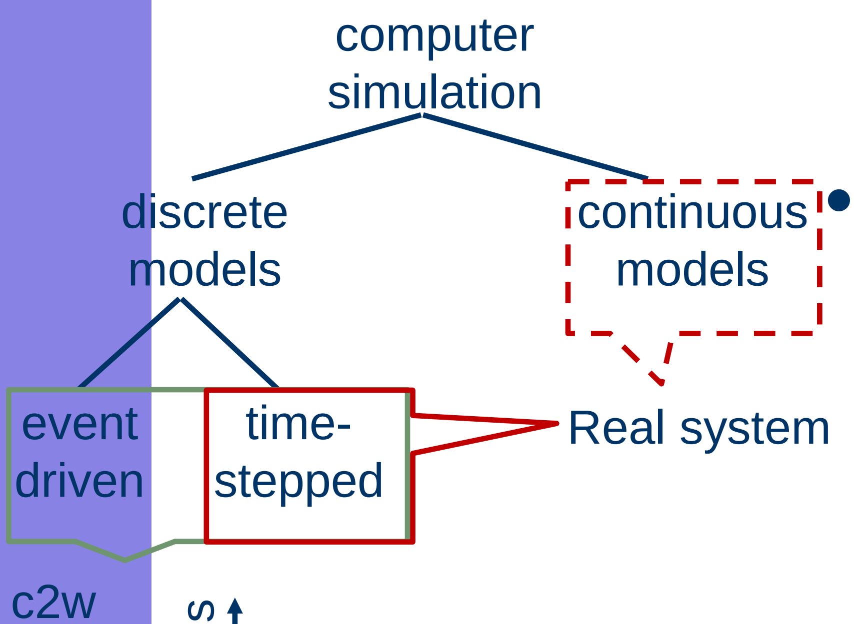
Time Synchronization Overview

- Time Synchronization
  - Simulated objects run in simulation time which is coordinated by RTI time management
  - Network objects run in the user space of real operating systems and follow system time (usually real time)
  - How to reconcile these two time models
- Roadmap
  - Review basic concepts
  - Identify the appropriate time models for the integrated system
    - Real time
    - As fast as possible
  - Design the time synchronization algorithms

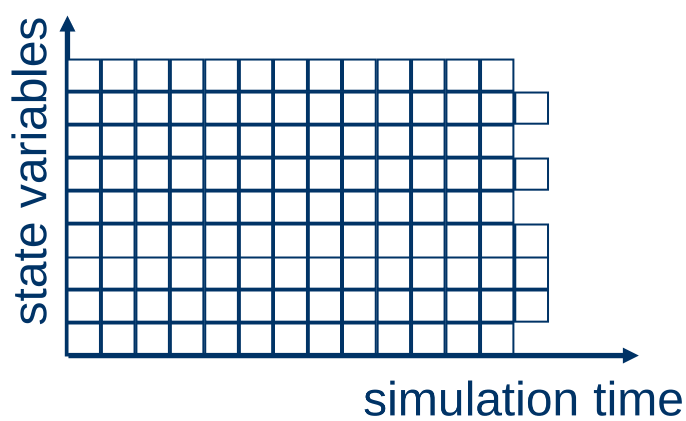
Let's first review the basics…

Slides are adapted from Dr. Fujimoto's lecture notes

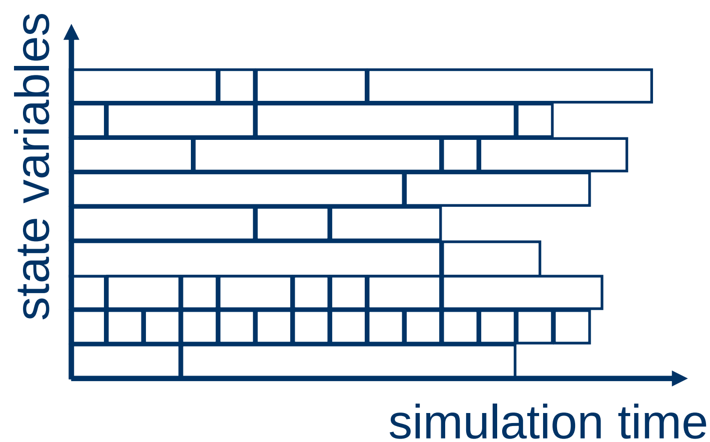
Time Models in Simulation



- Continuous time simulation
  - State changes occur continuously across time
  - Typically, behavior described by differential equations
- Discrete time simulation
  - State changes only occur at discrete time instants
  - Time stepped: time advances by fixed time increments
  - Event stepped: time advances occur with irregular increments



time stepped execution



event driven execution

Modes of Execution

- *As-fast-as-possible* execution (unpaced): no fixed relationship necessarily exists between advances in simulation time and advances in wallclock time
- *Real-time* execution (paced): each advance in simulation time is paced to occur in synchrony with an equivalent advance in wallclock time
- *Scaled real-time* execution (paced): each advance in simulation time is paced to occur in synchrony with S * an equivalent advance in wallclock time

  Simulation Time = W2S(W) = $T_0 + S * (W - W_0)$

  W = wallclock time; S = scale factor

  W_0 (T_0) = wallclock (simulation) time at start of simulation

Discrete Event Simulation System

dependent on the system model

Simulation Application

models system behavior

- compute event and its time stamp
- event can modify state variables or schedule new events

calls to schedule events

calls to event handlers

Simulation Executive

processes events in time stamp order

- manage event list
- manage advances in simulation time

independent of the system model

Discrete event simulation:

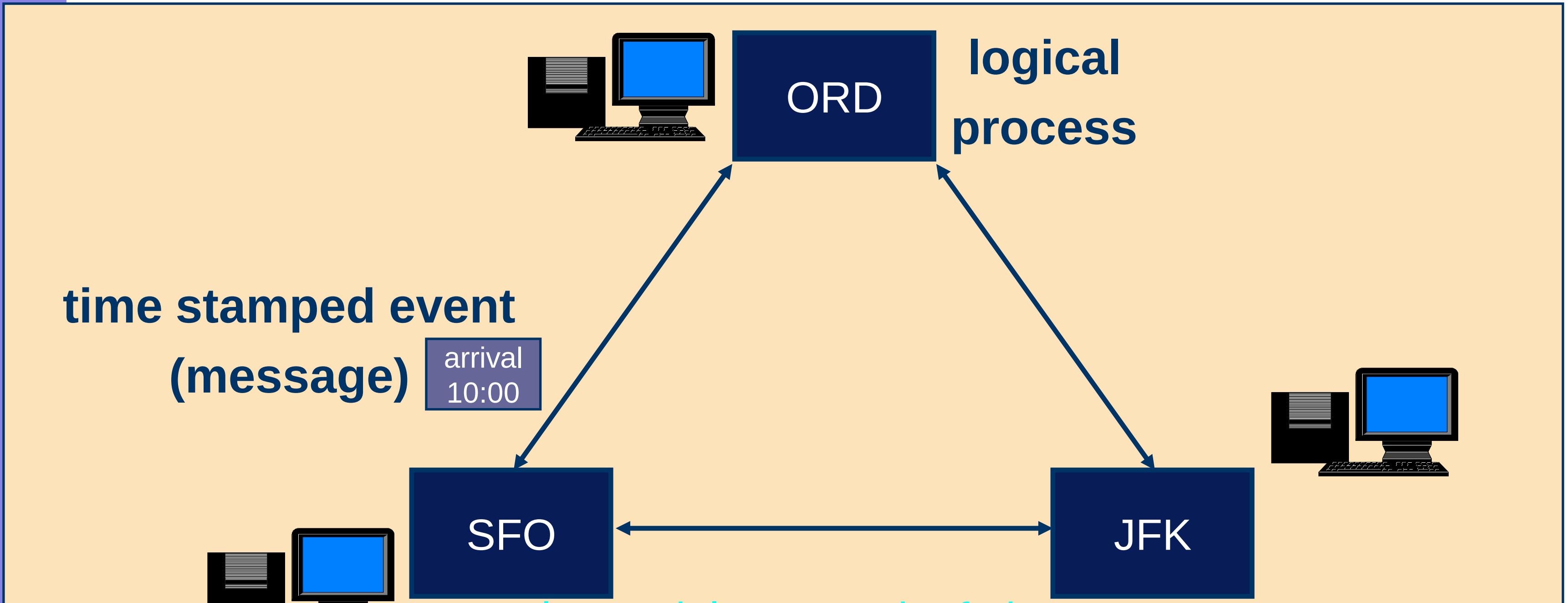
- computer model for a system where changes in the state of the system occur at *discrete* points in simulation time.

Fundamental concepts:

- system state (state variables)
- state transitions (events)

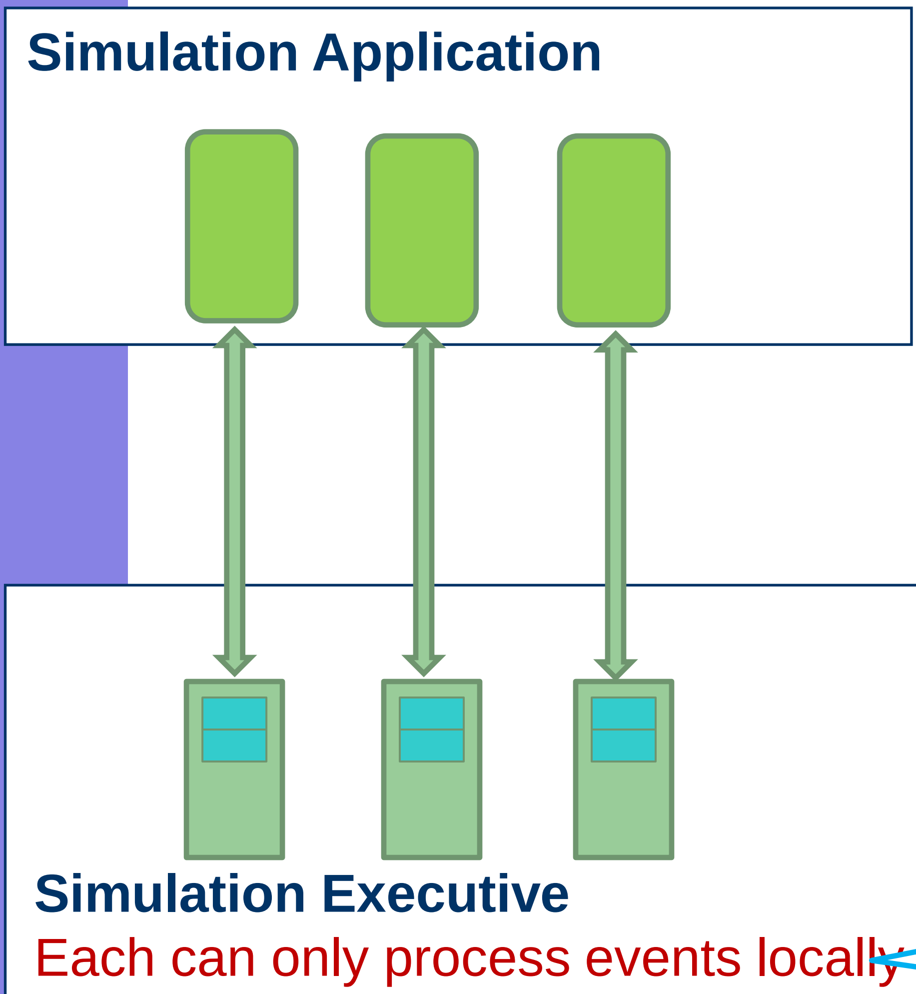
Parallel/Distributed Discrete Event Simulation

- Encapsulate each simulator in a logical process (LP)
- LP is capable of concurrent execution
- Logical processes can schedule events for other logical processes
  - Interactions via message passing
  - No shared state variables



Example: model a network of airports

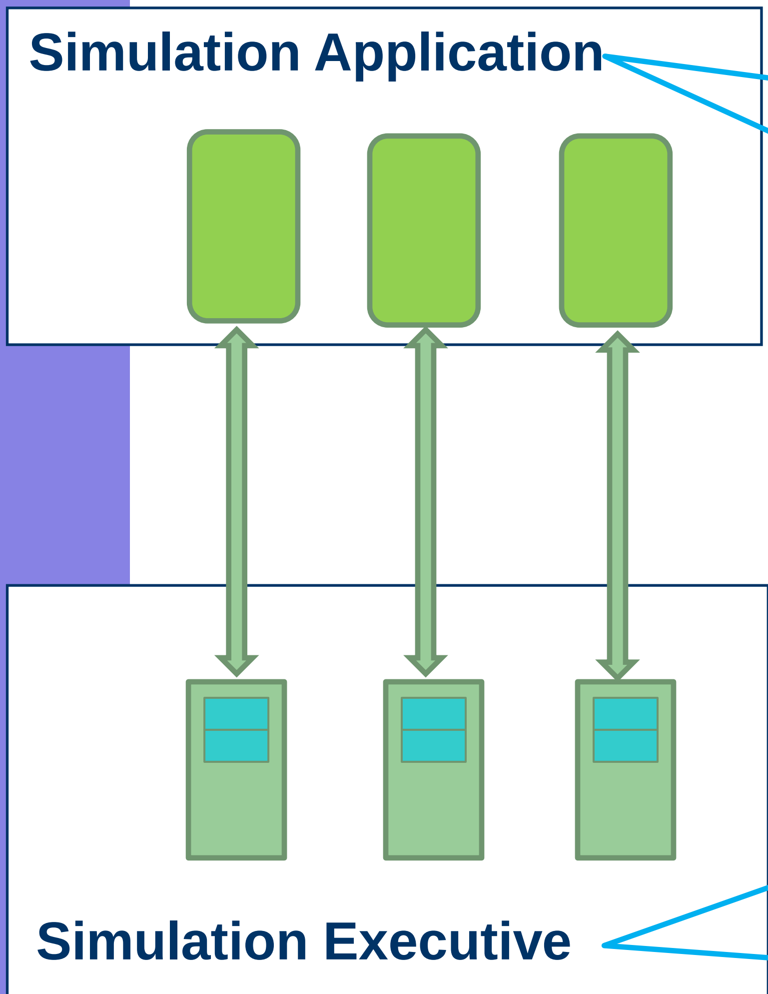
Time Synchronization



- Synchronization Problem
  - ensure each LP processes events in time stamp order
- Observation
  - Adherence to the local causality constraint is sufficient to ensure that the parallel simulation will produce exactly the same results as a sequential execution where all events across all LPs are processed in time stamp order.

How to ensure that the events are processed in time stamp order globally? -> Many algorithms

Synchronization Implementation



Two models
- Event oriented views
- Process oriented views

- Implement the time synchronization algorithm.
- Support the event scheduling/process advancing

Event vs. Process Oriented Views

Event oriented view

State variables

Integer: InTheAir;
Integer: OnTheGround;
Boolean: RunwayFree;

```
Arrival Event:
    In_The_Air := In_The_Air + 1;
    /* compute time al'rcraft landed and done uSlng runway */
    If (Runway_Free)
        RunwaY_Free := FALSE;
        Schedule Landed Event at time Now+R;
```

```
Landed Event:
    /* update state for the aircraft that has landed */
    In_The_Air := In_The_Air - 1;
    On_The_Ground := On_The_Ground + 1;
    Schedule Departure Event at time Now+G

    /* land next aircraft if there is one */
    if (In_The_Air > 0)
        Schedule Landed Event at time Now + R;
    else
        Runway_Free .- TRUE;
```

```
Departure Event:
    On_The_Ground := On_The_Ground _ 1;
```

Entities modeled by event handlers

Process oriented view

State variables

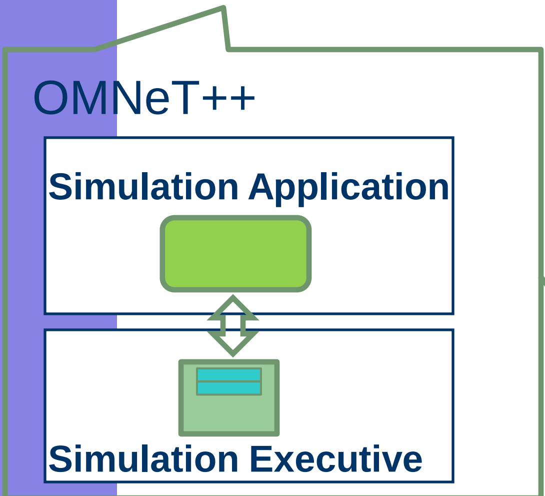
Integer: InTheAir;
Integer: OnTheGround;
Boolean: RunwayFree;

```
1   InTheAir := InTheAir + 1;
2   WaitUntil (RunwayFree); /* circle */
3   RunwayFree := FALSE;        /* land */
4   AdvanceTime(R);
5   RunwayFree := TRUE;
    /* simulate aircraft on the ground */
6   InTheAir := InTheAir - 1;
7   OnTheGround := OnTheGround + 1;
8   AdvanceTime(G);
    /* simulate aircraft departure */
9   OnTheGround := OnTheGround – 1;
```

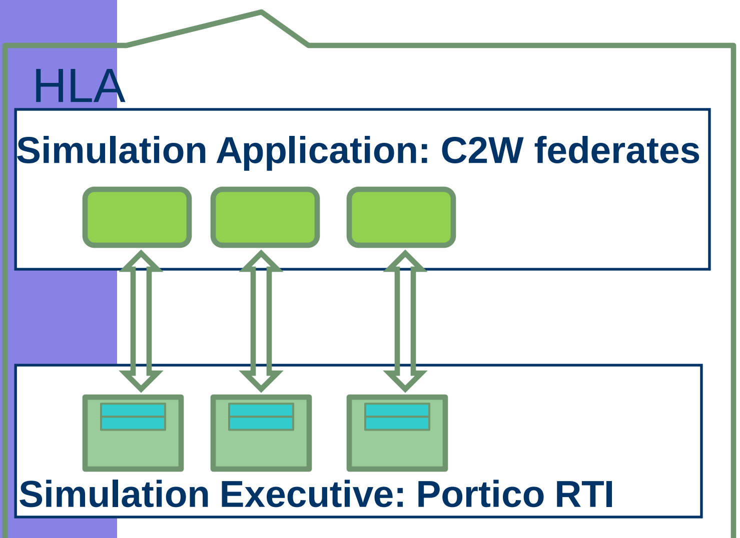
Entities modeled by processes

In C2 Wind Tunnel

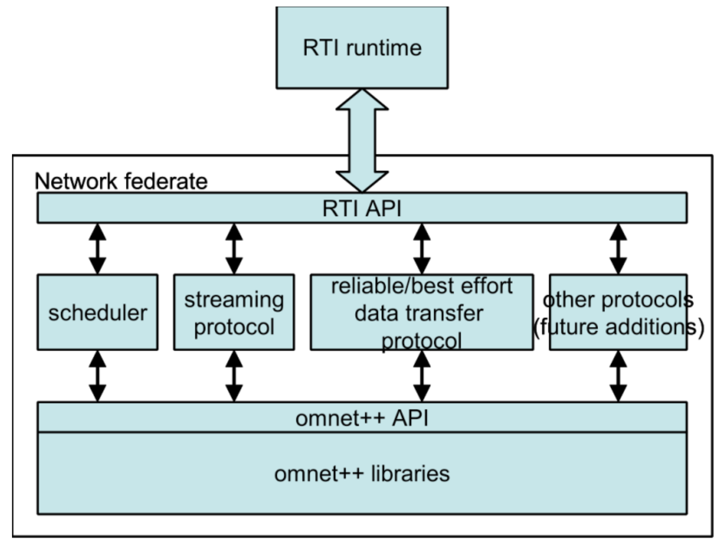
Event oriented view



Process oriented view



OMNeT++ becomes a federate
OMNeT++ scheduler communicates with RTI

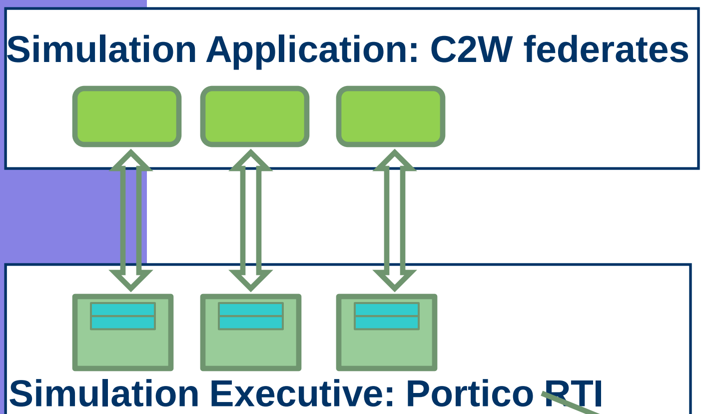



```
cMessage *HLAScheduler::getNextEvent()
{
    cMessage *msg = sim->msgQueue.peekFirst();
    if (!msg)
        throw new cTerminationException(eENDEDOK);

    while( msg->arrivalTime() > rti->getTime() )
    {
        rti->advanceTime();
        msg = sim->msgQueue.peekFirst();
    }

    return msg;
}
```

Time Management in C2 Wind Tunnel



HLA Time management

•Time AdvanceRequest
(time-stepped mechanism)

•NextEvent Request
•(event-driven federate)

•AdvanceGrant

Two Modes:
• real time
• as fast as possible

In Federation Manager:

```
sleep_time = time_diff
if (sleep_time >0)
        sleep(sleep_time);

next_time = time.getTime() + 0.1;
timeAdvanceRequest (next_time);
```

Get back to our problem

- Time synchronization issue in the distributed simulation should be handled by simulation executive.
- C2W system follows the HLA standard (process-oriented view), where RTI handles the time synchronization. The "simulation application" calls the time management primitives.

We do not deal with the time sync issue directly in C2W. Do we need to worry about it once the emulated network brings in?

Get back to our problem

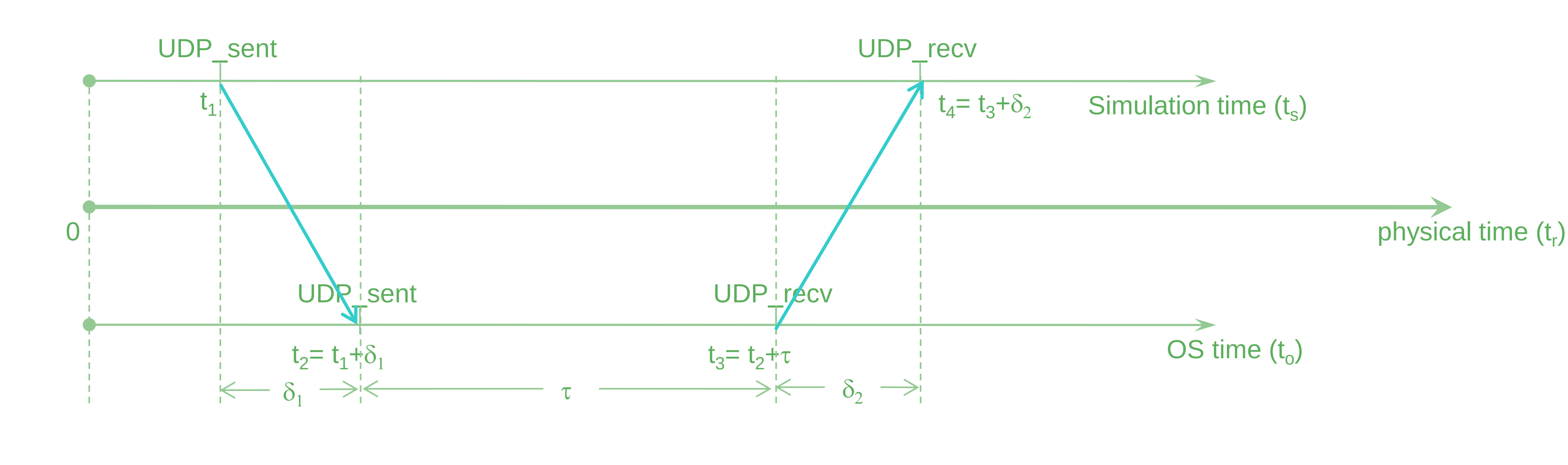
- Questions to answer
  - What mode
    - Real time mode -- each synchronizes to real-time
    - As fast as possible mode – see next question
  - Who is handles the time synchronization

In emulated systems, its system clock (not just the network object) needs to be synchronized.

- RTI does the job, each emulated system becomes a federate.

Time Synchronization
Real Time Mode

- The simulation (t_s) and operation system (t_o) time are synchronized with real time (t_r) : $t_s=t_o=t_r$
- Currently available in C2 Wind Tunnel
- Synchronization is done separately by simulation/real system – no need for coordination
- Issue (see the example below)
  - The propagation delay between the simulation/emulation environment introduces errors into the measurement
  - Such error will accumulate



Synchronize To Real Time -- Challenge

- Since simulation will receive events from emulation, simulation time should lag behind or equal to emulation time so that the events from emulation will not arrive at simulation in its past time
- Since emulation will receive events from simulation, simulation time should lead or equal to emulation, so that the events from simulation will not arrive at emulation in its past time
- Without delay, simulation and emulation should be synchronized to the same time
- With delay in both directions, this is a non-trial issue.

Synchronize To Real Time Basic Idea

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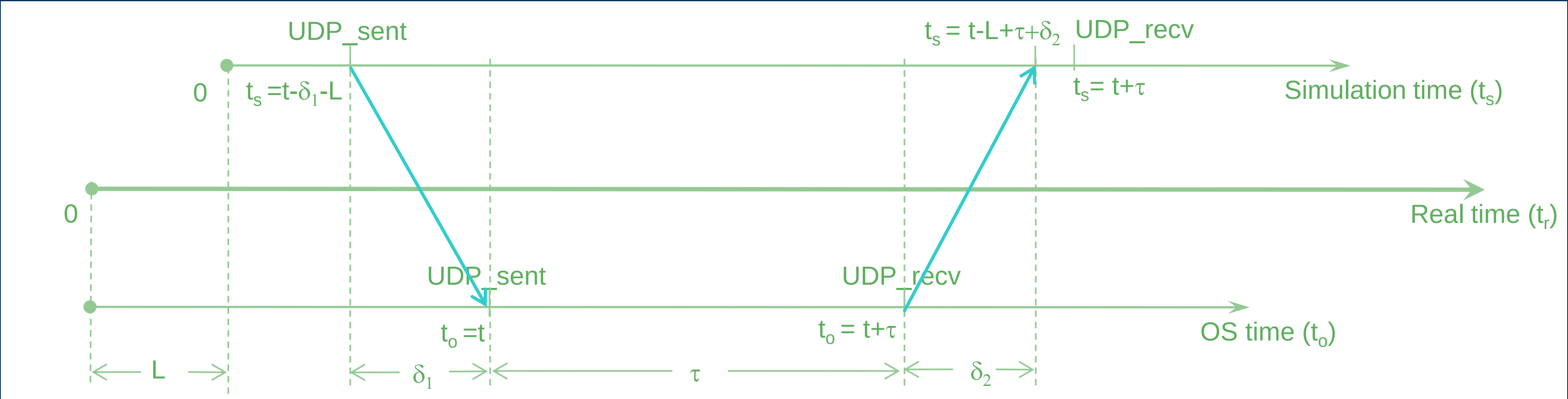
- Synchronize only OS time with real time ($t_o = t_r$)
- Separate simulation time from real time
- The simulation environment should have at least a lag of ($L >= \delta_2$) from real time to accommodate the communication delay emulation to simulation environment, if any incoming traffic is expected. ($t_s = t_r - L$)
- Simulation clock advances at the same pace as real physical clock
- All the outgoing traffic event with time stamp t will be actually scheduled/tunneled to emulation environment at simulation time $t - \delta_1 - L$ to compensate the delay from simulation to emulation and the lag between simulation and emulation so that it could arrive at emulation at real time t.
- For incoming traffic with time stamp ($t+\tau$), it will arrive at the simulation at simulation time $t_s = t - L + \tau + \delta_2$. Since $L \geq \delta_2$, the event can be scheduled at $t_s = t + \tau$



Synchronize To Real Time Limitation and Application

- The packet does not arrive at the emulated network on its timestamp time (t), only the measured delay information (τ) from the emulation environment is correctly .
  - Can not be used if the packet interacts with other existing traffic → this is a serious constraint.
- If the simulation is slower than real time, then there is no easy fix.

So it seems that synchronizing to real time has limited usage…
Not really. Depending on the value of L (δ), the system may tolerate some inaccuracy.

- **Using a model-based approach, the simulator could adjust its time management strategy based on the communication context**

Time Synchronization
As Fast As Possible Mode

- The simulation (t_s) and operation system (t_o) time are synchronized using a virtual clock(t_v) : $t_s=t_o=t_v$
- Currently in C2 Wind Tunnel simulation AFAP mode runs in virtual time
- Challenge-- Reconcile two time models
  - Real time, which flows naturally (not forced by a progression of events)
  - Virtual time is adjusted by the progression of discrete events in the simulation system

Synchronize To Virtual Time System Virtualization

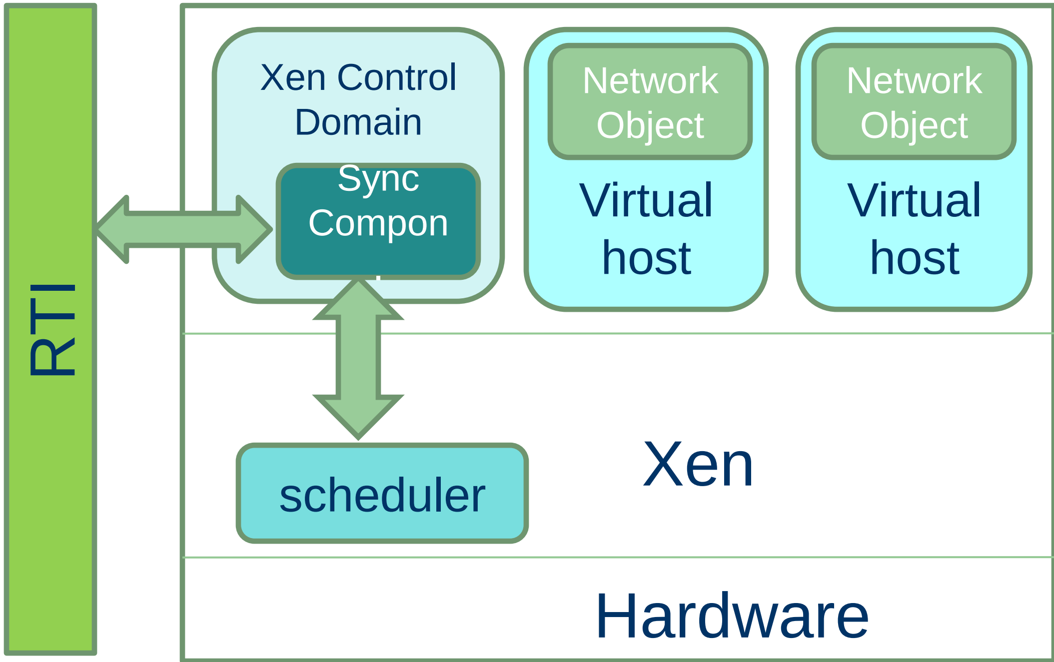
- Need virtualization of the real systems/networks to control over their run-time behavior
  - The execution of a virtual system/network needs to be stalled until the virtual clock proceeds
  - As the system execution is interrupted due to the synchronization process, the internal clocks need to be manipulated to provide the virtual system/network a consistent and continuous time.
- Use Xen Hypervisor
  - Thin layer between system hardware and the operating system
  - Facilitate the parallel execution
  - Control the running behavior of OS on top of it

Synchronize To Virtual Time Using RTI

- Synchronization component is implemented in the privileged Xen Control domain as a federate
- Use a conservative approach
  - Define small slices to be target barrier of execution
  - Request RTI to advance time towards the barrier
  - Once granted, release the scheduler to process the jobs with time stamp larger than the barrier

Size of the slice determines the accuracy of the synchronization

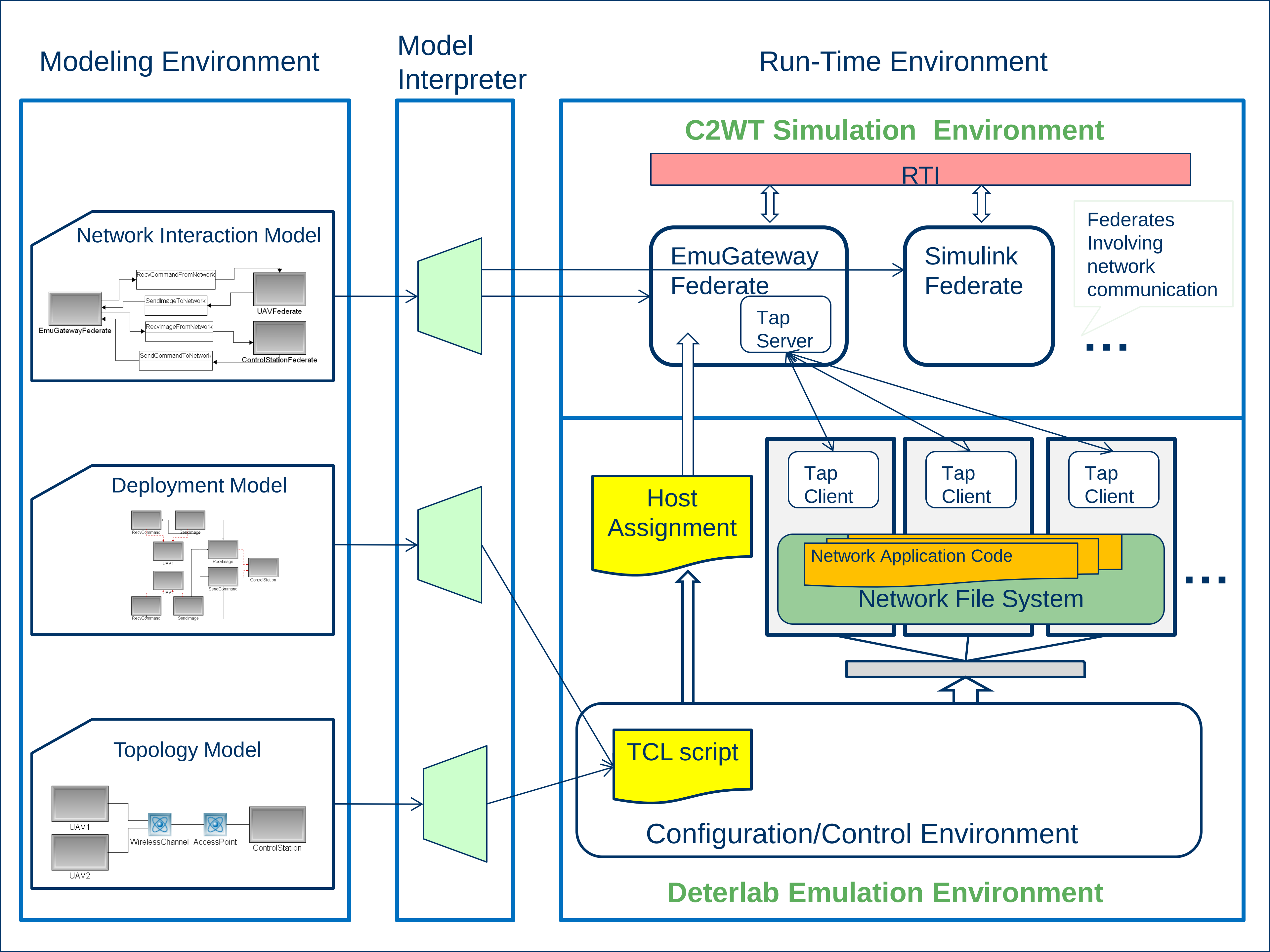
If the arrival pattern of the events/jobs
Is known, we can pick the time slice based on the statistical requirement of the experiment accuracy

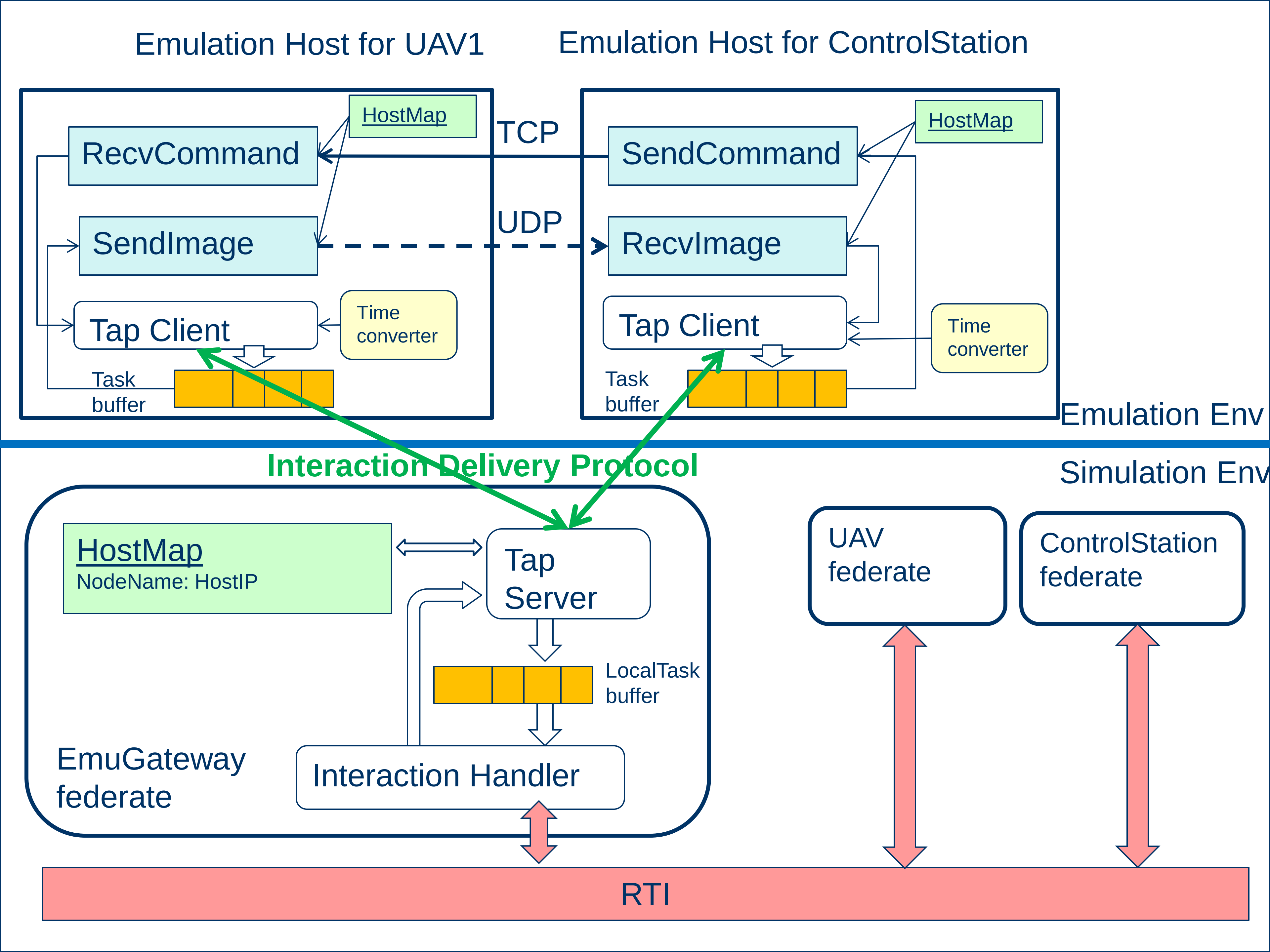


Handling Packet in Transmission

- Key Issue: Packet can not be stopped in the middle of the transmission or accelerated to meet the synchronized time
- A closer look of the problem – what does it mean by “in the middle”
  - Packet queued at a router. In Emulab, the routers are emulated by host. Queued packets are synchronized to virtual clock → not a problem
  - Packet transmitted along the link .The link delay of a packet is determined by its size and the bandwidth of the link → this is a true problem
    - If arrive ahead of time, the real time propagation delay needs to be converted to virtual time and the packet reception will be scheduled later → need a time keeping mechanism
    - If arrive behind the time, then there will be an issue. We need to adjust the bandwidth of the link (in Emulab) to avoid this problem

Implementation Details


Modeling Environment
Model Interpreter
Run-Time Environment
Network Interaction Model
RecvCommandFromNetwork
SendImageToNetwork
RecvImageFromNetwork
SendCommandToNetwork
UAVFederate
EmuGatewayFederate
ControlStationFederate
Deployment Model
Topology Model
UAV1
UAV2
WirelessChannel
AccessPoint
ControlStation
C2WT Simulation Environment
RTI
EmuGateway Federate
Tap Server
Simulink Federate
Federates Involving network communication
...
Host Assignment
Tap Client
Tap Client
Tap Client
Network Application Code
Network File System
...
TCL script
Configuration/Control Environment
Deterlab Emulation Environment


Emulation Host for UAV1
Emulation Host for ControlStation
HostMap
RecvCommand
TCP
SendCommand
HostMap
SendImage
UDP
RecvImage
Tap Client
Time converter
Tap Client
Time converter
Task buffer
Task buffer
Emulation Env
Interaction Delivery Protocol
Simulation Env
HostMap
NodeName: HostIP
Tap Server
UAV federate
ControlStation federate
LocalTask buffer
EmuGateway federate
Interaction Handler
RTI

Interaction Delivery Protocol

- Initialization
  - Tap client has the socket address of server (IP address + port)
  - Tap client registers itself to server
    - What is NodeName it emulates (UAV1)
  - Tap server builds the HostMap table
    - NodeName to HostIP
  - Tap server provides the information to Tap cients which require the HostMap, tap client will put it in /etc/hosts.

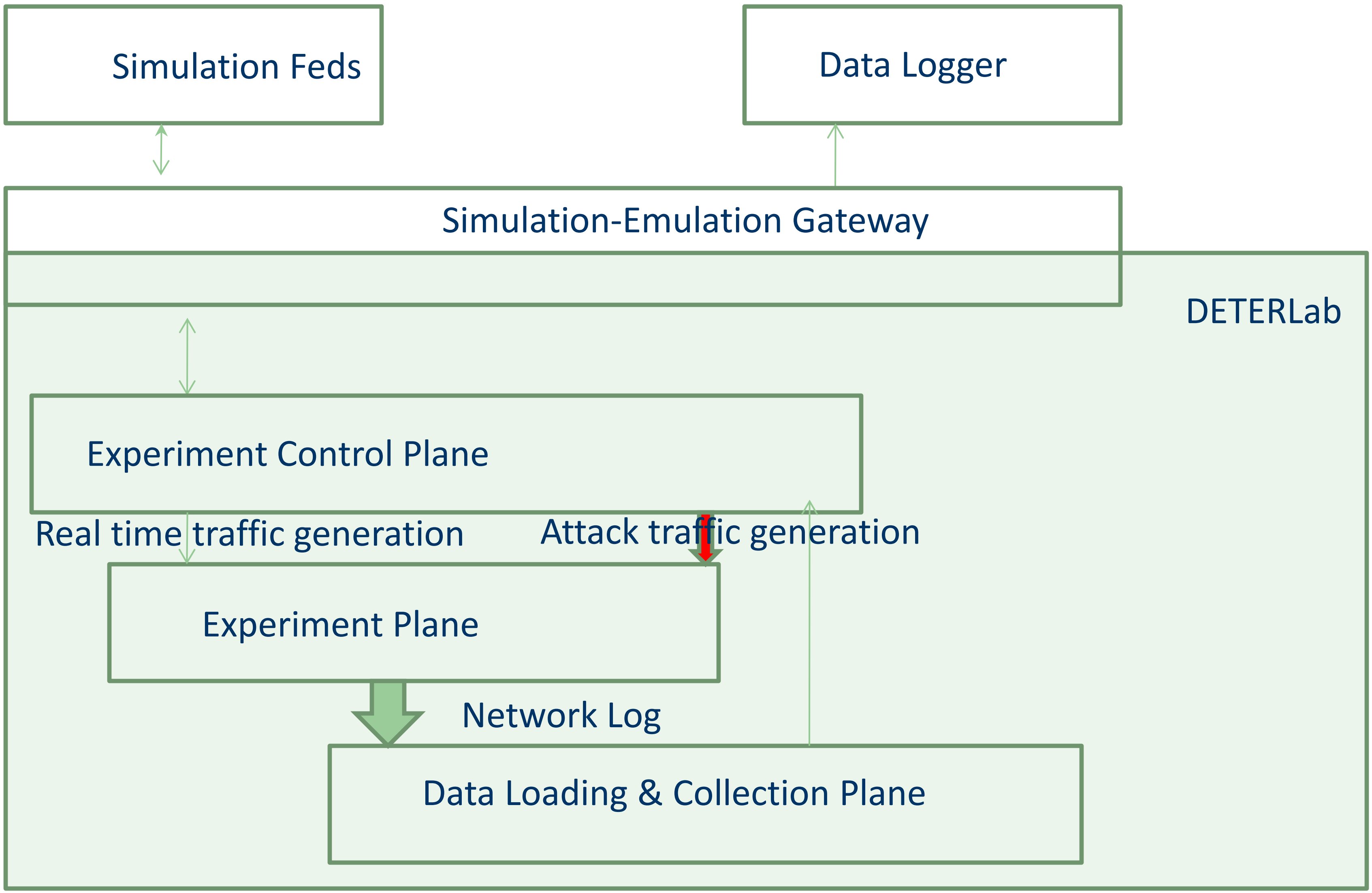
- Data communication
  - message format

repeat

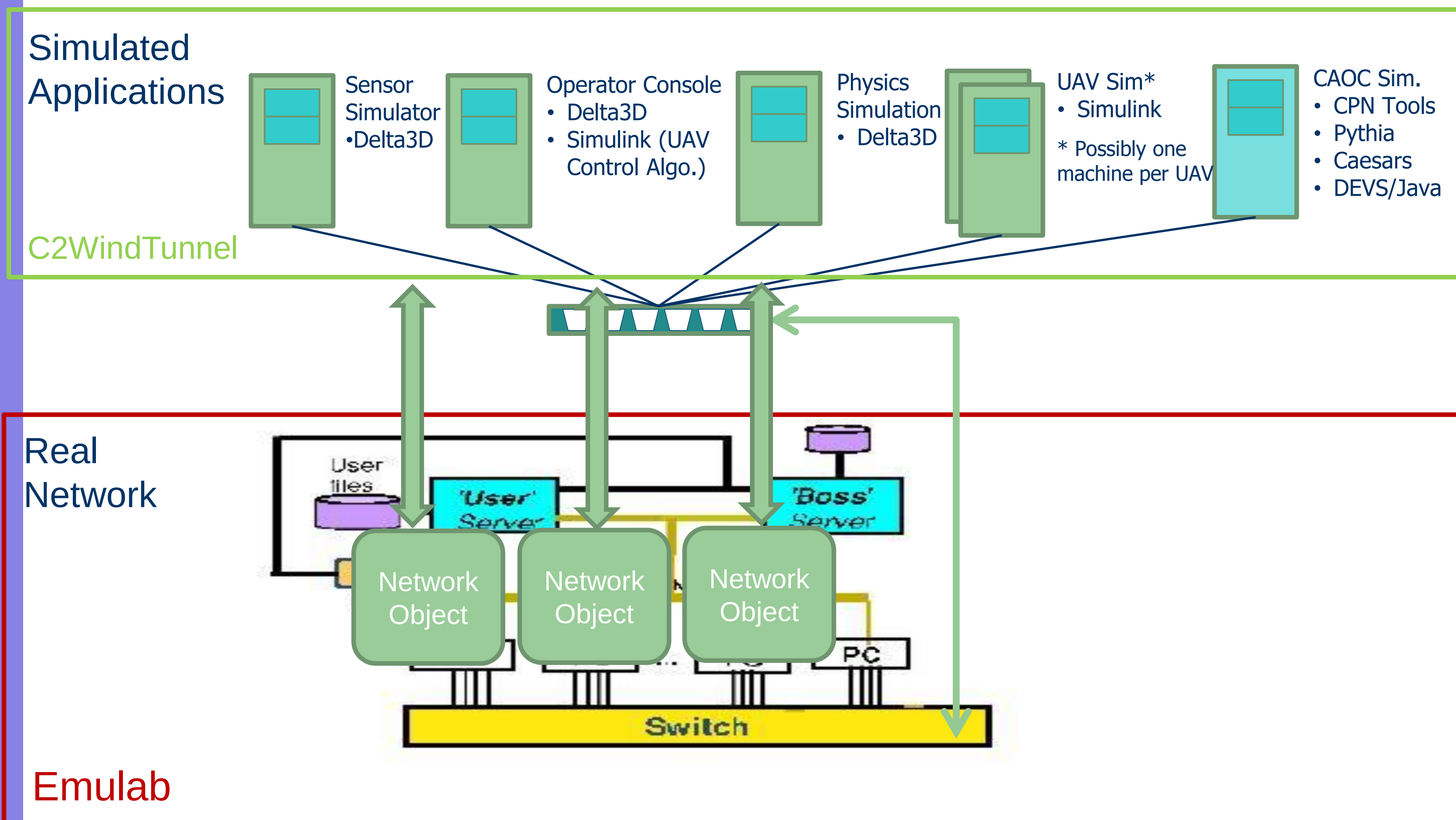
ProcName	TimeStamp	ParemeterName	ParemeterLength	ParemeterValue	….	END

SendImage	10s	ImageURL	18	10.0.0.2/imagefile	END

Integration With DeterLab



Our Experiment Setup



Future Work

- Step II: Integration with DeterLab
  - Enable system virtualization, migrate the virtual clock into Xen Hypervisor
  - Component allocation
  - Time keeping at the emulated routers
- Step III: Integration with Experiment Testbed
  - Evaluation of security policy on C2 systems

Summary

- Security of CPS is an essential concern
- Building a tool and environment for assessing the security impacts on CPS is a critical step
- Three-step effort at Vanderbilt
  - Simulation integration
  - Emulation integration
  - Real network integration