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Distributed MILS (D-MILS) Specification, Analysis, Deployment, and Assurance of Distributed Critical Systems

Harald Rueß (fortiss, München)

Stefano Tonetta (FBK, Trento)

D-MILS Consortium

CONSORTIUM PARTNERS:
Fondazione Bruno Kessler (IT)
fortiss (DE)
Frequentis (AT)
LynuxWorks (FR)
RWTH Aachen University (DE)
The Open Group (UK) Lead
TTTech (AT)
Université Joseph Fourier (FR)
University of York (UK)

Overview

- Part 1: D-MILS project overview
  - Overview of the consortium
  - Objectives of the project and areas of work
  - Overview of the approach and the D-MILS platform
  - Specification language
  - Verification framework
  - Deployment on the D-MILS platform
  - Assurance case
- Part 2: Verification framework
  - Overview of the compositional approach
  - Target requirements
  - Annotation language
  - Verification algorithms
  - Tool support

Scientific and Technical Objectives Summary

- High-level specification in declarative languages
- Comprehensive: “Top-to-bottom” and “End-to-end”
- Pervasive automation support
- Compositional verification of desired properties
- Integrated assurance case for certification support
- Distributed platform configuration compilation
- Strong analytical environment
  - Security and dependability attributes of system computed from the properties of the components and the architecture

Scientific and Technical Objectives

"Top-to-bottom" coverage:

- High-level, graphical architectural design in AADL
- Behavior specification with AADL behavioral annex
- Property specifications in AADL annotations
- Integrated verification represented via graphical Goal Structuring Notation (GSN)
- Architectural-level verification
- Automated inventory of hardware platform resources
- Synthesis of low-level component configurations

Scientific and Technical Objectives

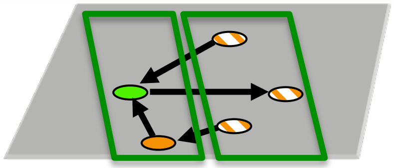
"End-to-end" coverage:

- Implementation-independent architectural specification
- High-level specification of dependability attributes
- Seamless realization of distributed architectures
- Verify that component composition supports dependability attributes
- Modular and scalable deterministic platform
- Incremental binding of architecture, implementation, integration, and deployment parameters

Technical Results Expected

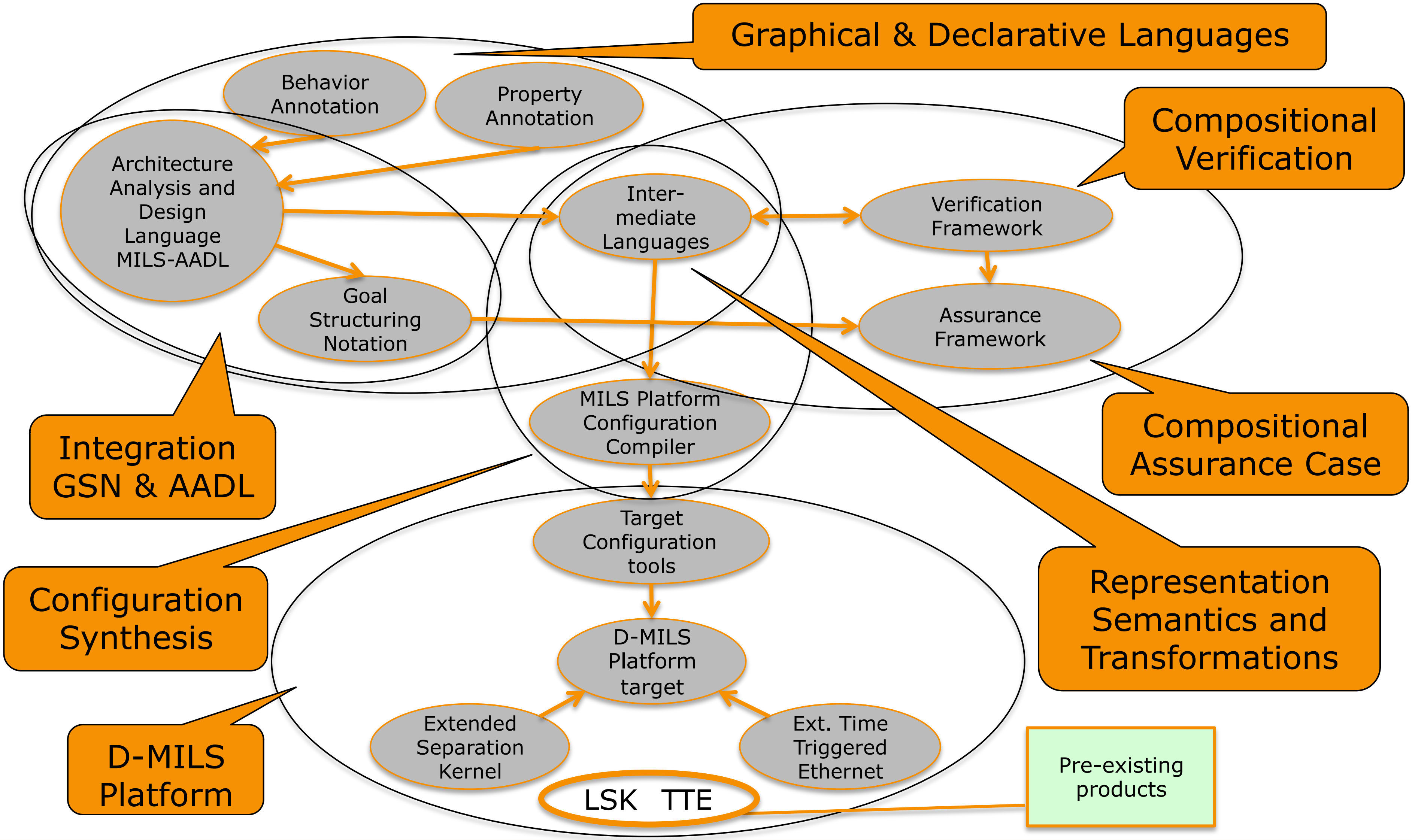
- Standardized, component-based high-assurance distributed platform
- Compositional assurance of systems from component assurance and composition analysis
- Framework for certification of systems built on the platform supported by extensive automation
- Enable application architectures to seamlessly span multiple nodes, for scalable determinism
- Industrial D-MILS Pilots / Technology Evaluation
    - Frequentis Voice Services
    - fortiss Smart Microgrid

D-MILS Benefits



- A single policy architecture may span multiple D-MILS nodes expressed in declarative MILS-AADL
- Guarantees similar to a single MILS node: isolation, information flow control, determinism
- Determinism over network could be achieved in various ways – D-MILS uses Time-Triggered Ethernet
- Configure and schedule the network and the processors of the nodes coherently
- Verify architectural-based properties, develop GSN assurance case, synthesize platform configuration, using integrated tool chain leveraging existing verification technology (nuSMV, OCRA, BIP, AF3)

D-MILS Research and Technology Development Areas



Graphical & Declarative Languages

Compositional Verification

Integration GSN & AADL

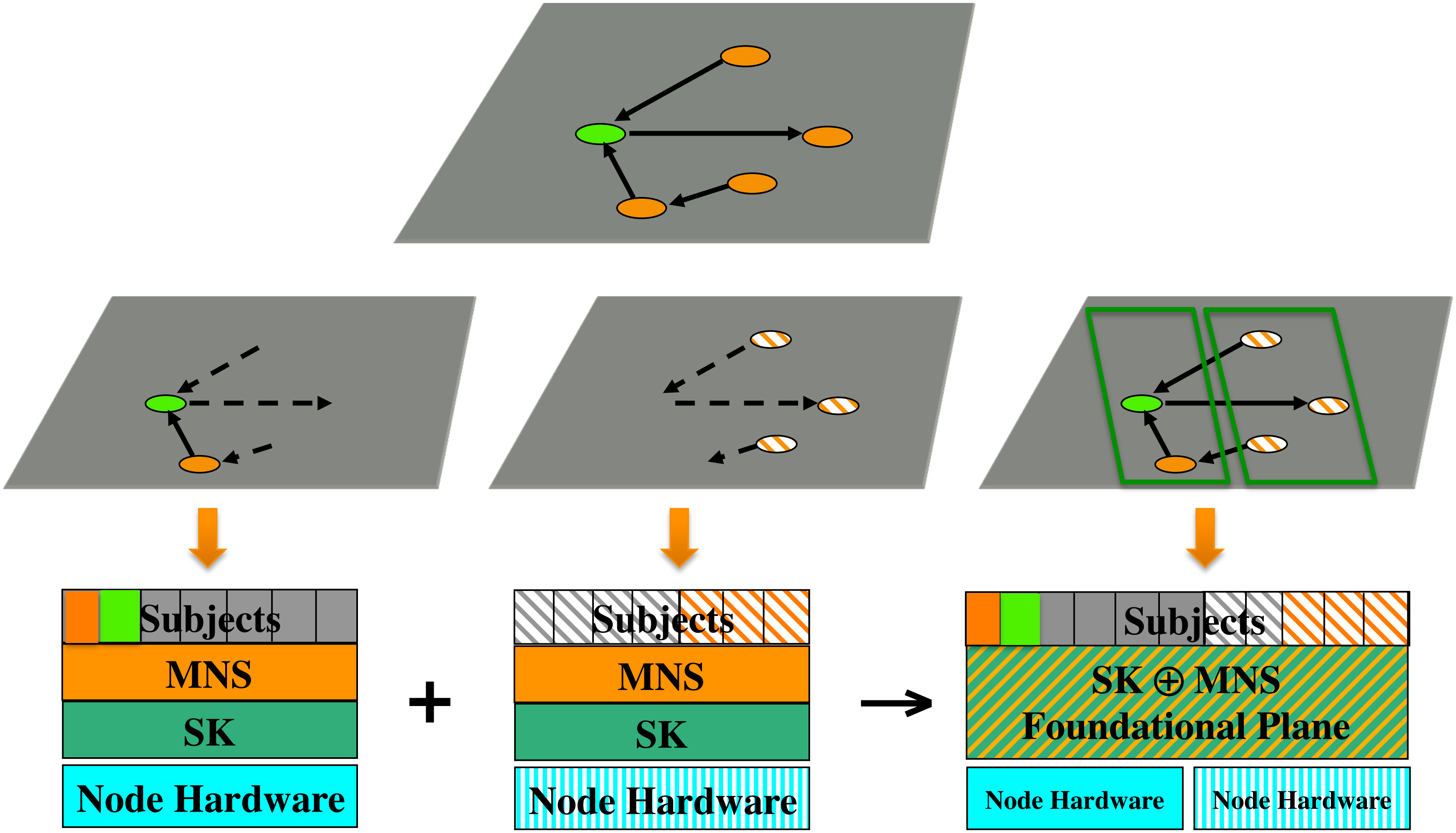
Compositional Assurance Case

Configuration Synthesis

Representation Semantics and Transformations

D-MILS Platform

Distributed MILS (D-MILS): Policy architecture deployment spanning nodes



Subjects
MNS
SK
Node Hardware

+

Subjects
MNS
SK
Node Hardware

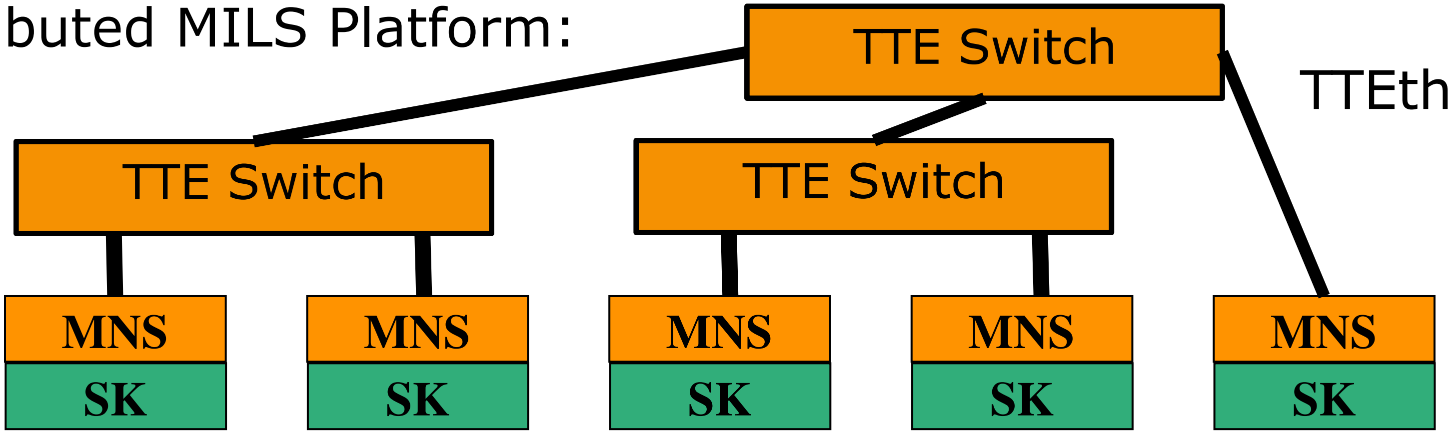
→

Subjects
SK ⊕ MNS
Foundational Plane
Node Hardware
Node Hardware

MNS – MILS Networking System SK – Separation Kernel

Distributed MILS Platform – MILS nodes with deterministic communication

A Distributed MILS Platform:



TTE Switch

TTEthernet

TTE Switch

TTE Switch

MNS **SK**

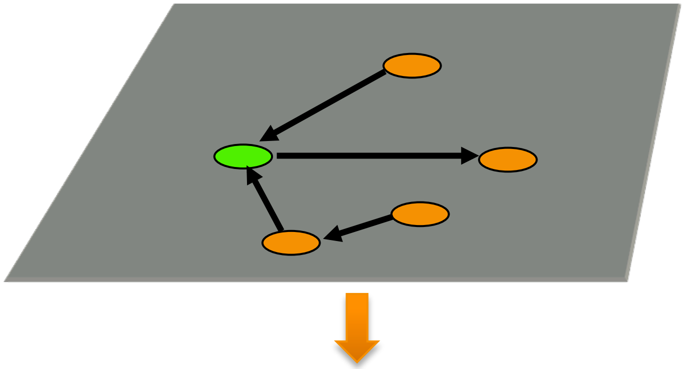
MNS **SK**

MNS **SK**

MNS **SK**

MNS **SK**

Enables:



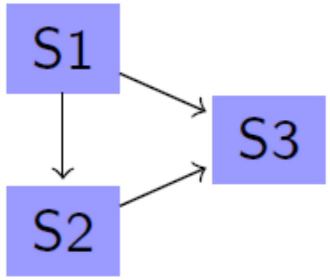
Realization of deterministic distributed MILS architectures

SK ⊕ MNS
Foundational Plane

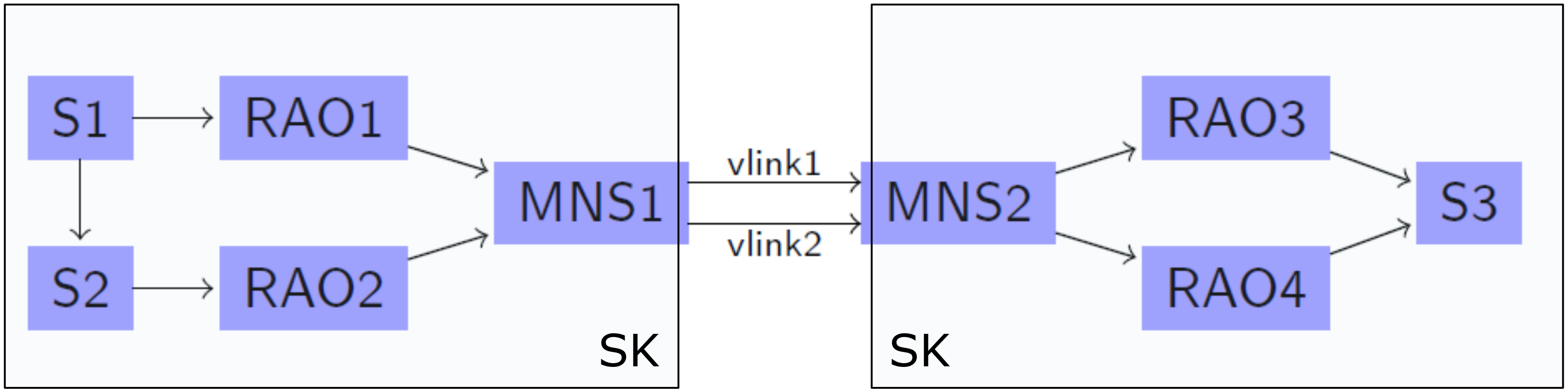
Node Hardware **Node Hardware** **Node Hardware** **Node Hardware** **Node Hardware**

D-MILS Implementation

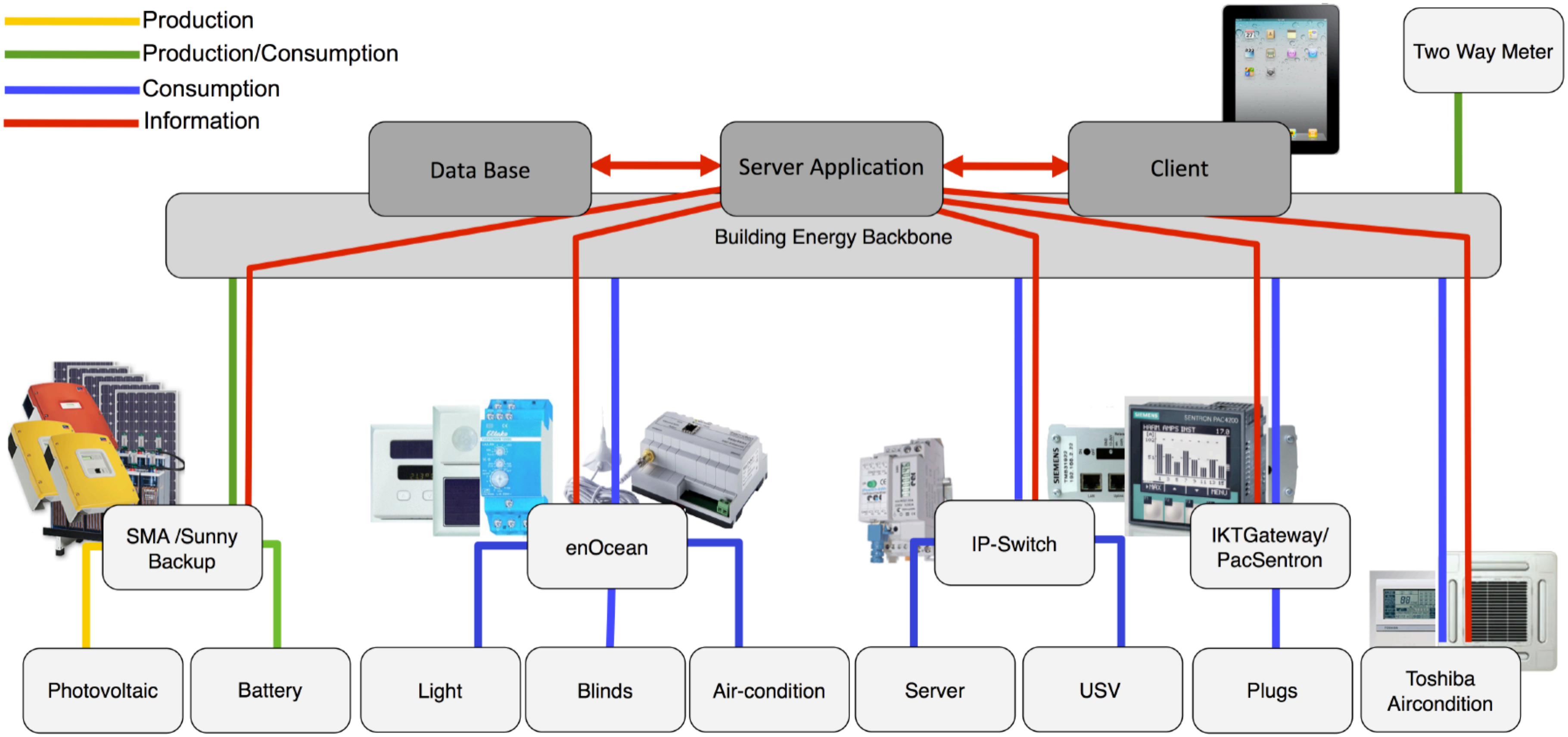
- The policy architecture:



- …may be deployed on a ***distributed MILS separation kernel*** with two nodes, MNS and TTEthernet as follows:



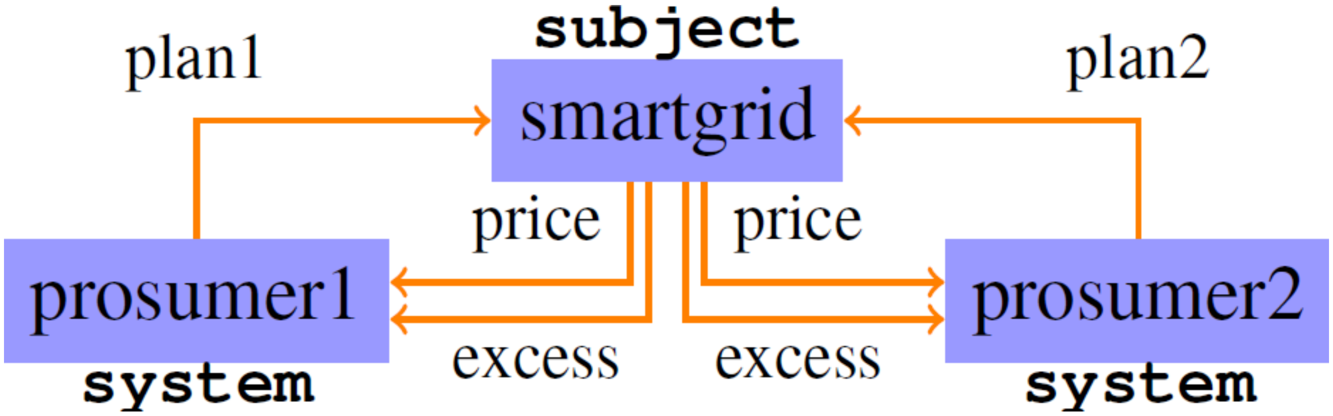
Demonstrator: fortiss Smart Microgrid



🟨 Production
🟩 Production/Consumption
🟦 Consumption
🟥 Information

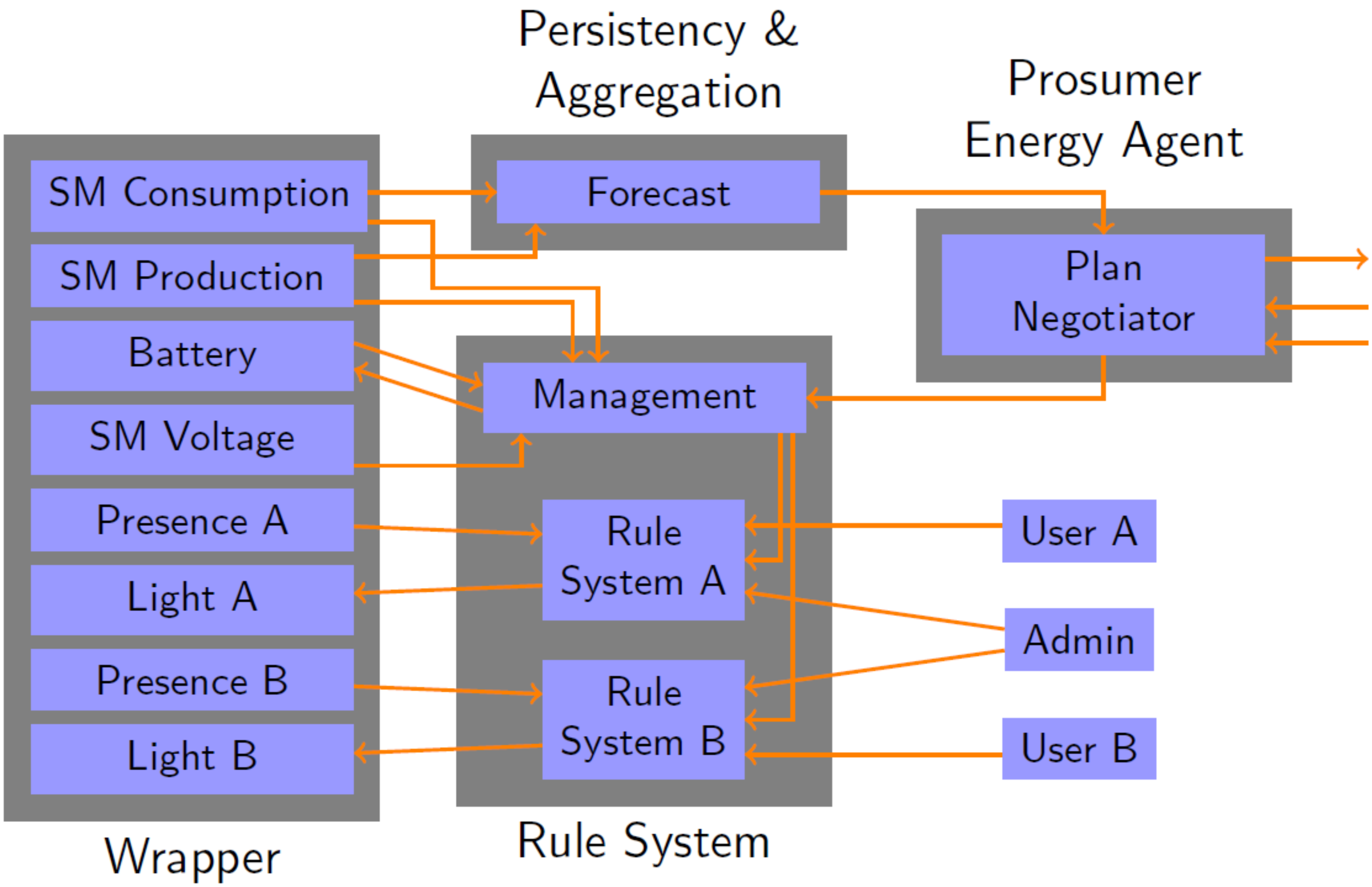
Data Base
Server Application
Client
Two Way Meter
Building Energy Backbone
SMA /Sunny Backup
enOcean
IP-Switch
IKTGateway/ PacSentron
Photovoltaic
Battery
Light
Blinds
Air-condition
Server
USV
Plugs
Toshiba Aircondition

Smart Microgrid Architectural View

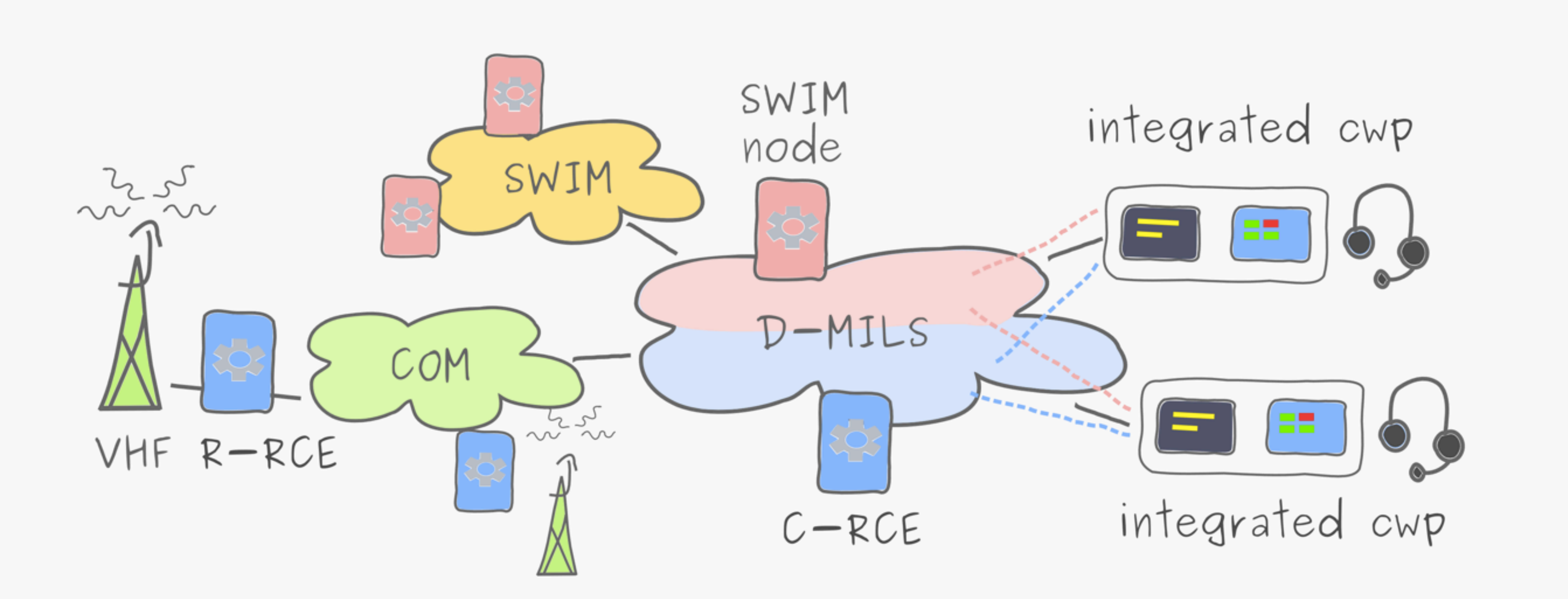


- Smart grid sends the current price of energy.
- Each prosumer sends a plan indicating how much energy it intends to consume and provide during the day.
- Smart grid checks whether the grid can support the resulting consumption or production.
- If the overall plan is not feasible, the prosumers need to modify their plans and resend them.
- The negotiation continues until the plans are accepted.

Smart Microgrid Prosumers



Demonstrator: Frequentis Voice Services



cwp... controller working position
rce...radio control equipment
r-rce...remote rce
c-rce...center rce
swim...system wide information management

Summary of Accomplishments to Date

- Defined syntax and formal semantics of MILS-AADL dialect
- Parser for MILS-AADL
- Transformations of MILS-AADL for verification and configuration
- Compositional verification framework for MILS-AADL models
- Foundations and tool support for compositional GSN assurance cases
- Synthesis of MILS component configuration data for target components
- Operational D-MILS Platform (distributed LynxSecure separation kernel running over TTEthernet)
- MILS Platform Configuration Compiler providing synthesis of configuration data for target platform components
- Two industrial demonstrators in progress: fortiss smart micro grid and Frequentis Voice Services

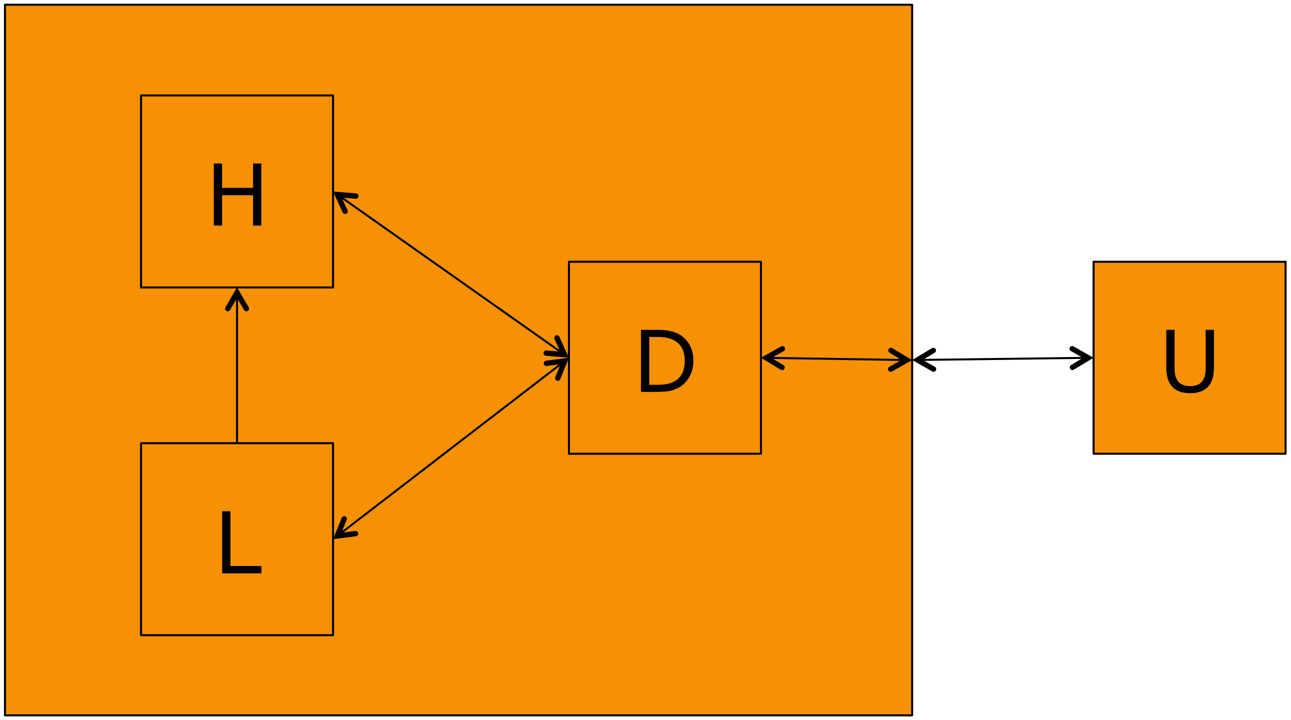
Verification Framework

- The framework consists of a collection of tools integrated to support modeling, validation and verification
- Modeling language: MILS-AADL
  - With a formal semantics
- Validation with
  - Simulation
  - Deadlock checking
  - Timelock checking
  - Reachability and other queries in temporal logic
- Verification of
  - Functional requirements
  - Real-time requirements
  - Security requirements
  - Safety requirements

Compositional approach

- Framework based on a compositional approach
- System properties are inferred by component properties
- Advantages:
  - Efficient reasoning
  - Delegate proof of application components to the provider
  - Focus on the verification of the architecture
- Formalized assumptions: components' expectations on their environment
  - Assumptions must be satisfied by the environment

Starlight example (architecture)



Starlight example (verification)

- The system provides some service to the user
  - The user issues commands that are processed by H or L
- Functional requirement: the system returns the correct result
- Commands labeled with high and low security levels
  - The user must switch the system to high before issuing a high command
- Security requirement: the low component must not receive high commands
- Safety requirement: the system satisfy functional and security requirements even if some subcomponents fail
- System requirements guaranteed by the properties of the subcomponents

Requirements and properties

- Functional requirements:
  - Invariants
  - Temporal logic
- Real-time and hybrid requirements
  - Functional requirements with timing constraints and taking into account models of physical components
- Security requirements
  - Requirements implementing security functions
  - Non-interference
- Safety requirements
  - Requirements related to safety
  - Modeled and verified taking into account failures

Annotation language

- Used to formalize requirements and specify verification tasks
- Annotations are interpreted by the specific tool
    - Tool's specification syntax with references to the MILS-AADL model
    - Example:

```
{OCRA: CONTRACT st
    assume: always ({secret(cmd)} implies
        ((not {switch_to_low} since{switch_to_high})));
    guarantee: never {secret(low_cmd)};
}
```

- Possibility to connect to other tools (e.g., crypto protocol verification)

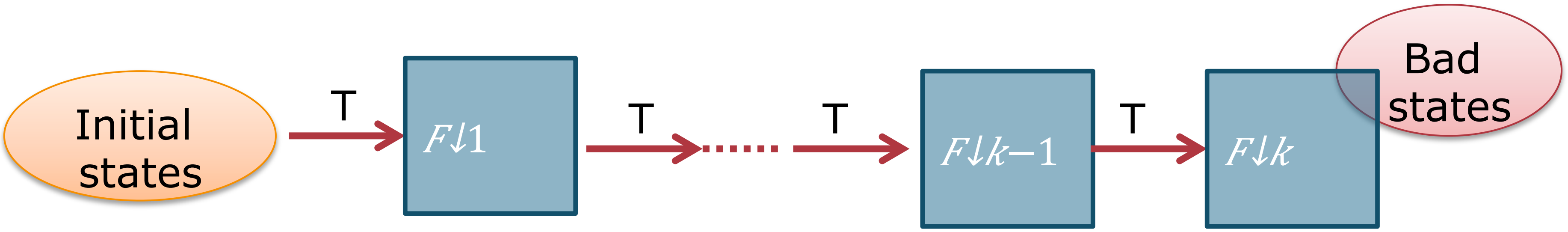
Verification issues

- MILS-AADL models have infinite-domain data variables, continuous-time semantics, with safety and security concerns
- Model checking of reachability for infinite-state systems is a hard problem
- Temporal logic even harder
- Safety and security properties harder and harder
- Major problem of model checking in general: scalability

Infinite states of MILS-AADL

- Semantics of MILS-AADL models is a transition system
- States given by component modes and assignment to data variables
- Data types include integer and real
- Parameters may include undefined functions (e.g., “computation(data)” or “is_secret(data)”)
- Standard approaches:
  - Abstraction
    - Requires refinement in case of false positive
  - Automatic abstraction refinement
    - Typically does not scale
  - Induction, k-induction, theorem proving
    - Requires to provide manually lemmas

IC3



- New technique (Bradley 2012) to prove invariants automatically finding a suitable inductive invariant.
- Currently recognized as the most effective model checking algorithm.
- Build an inductive invariant F such that $F \vDash P$
- Trace of formulas $F_0 = I, F_1, \ldots, F_k$ such that:
  - $F_{i+1} \subseteq F_i \; (F_i \vDash F_{i+1})$
  - $F_i \wedge T \vDash F_{i+1}$
  - $F_i \vDash P$
- Eventually either counterexample is found or $F_i \equiv F_{i+1}$ proving P
- Mixture of inductive reasoning and search-based techniques

IC3 + implicit abstraction

- Integrated with predicate abstraction
- Only the evolution of a set of predicates is tracked in the abstraction, the rest is abstracted away
- Implicit abstraction does not compute the abstract state space
- Definition of predicates embedded in the transition relation
- Abstraction refinement is fully incremental
  - Can keep previous trace $F_1, \dots, F_k$
  - Abstract transition relation strengthened by additional predicates
- Implemented in nuXmv

Temporal logic

- Many requirements formalized into temporal logic (e.g. LTL)
- No effective procedure to verify LTL over infinite-state systems
- Standard automata-based approach to $M \vDash \phi$:
  - Reduction to check that a certain condition f can be visited finitely many times
- K-Liveness (Classen & Sorensson 2012):
  - Key idea: check if f can be visited at most k times for increasing value of k
  - Reduced to invariant checking
  - Very efficient for finite-state systems
  - Integrated with IC3 for an incremental check of different k
- Implemented in nuXmv
  - Combined with IC3IA for verification of infinite-state systems

K-liveness for timed/hybrid models

- Problem for parametric and real-time/hybrid systems
  - The number of visits of f can depend on parameters
  - f can be visited an arbitrary number of times in a finite amount of time (related to Zeno paths)
- K-Zeno: check if there is a bound on the number of times the fairness is visited along a diverging sequence of time points
- Essential point: use an additional transition system $Z{\downarrow}\beta$ to force a minimum distance β between two fair time points
- Note: β is a symbolic expression over parameters and variables.
- Key contribution: define β so that, if $M \models \phi$, then there exists k such that f can be visited at most k times.
- Implemented in nuXmv and integrated in HyCOMP for the verification of hybrid systems

Contract-based reasoning

- Assumptions and guarantees expressed in temporal logic
- Refinement proved generating a set of proof obligations in temporal logic
- Proof obligations discharged with k-liveness/k-zeno
- Implemented in OCRA

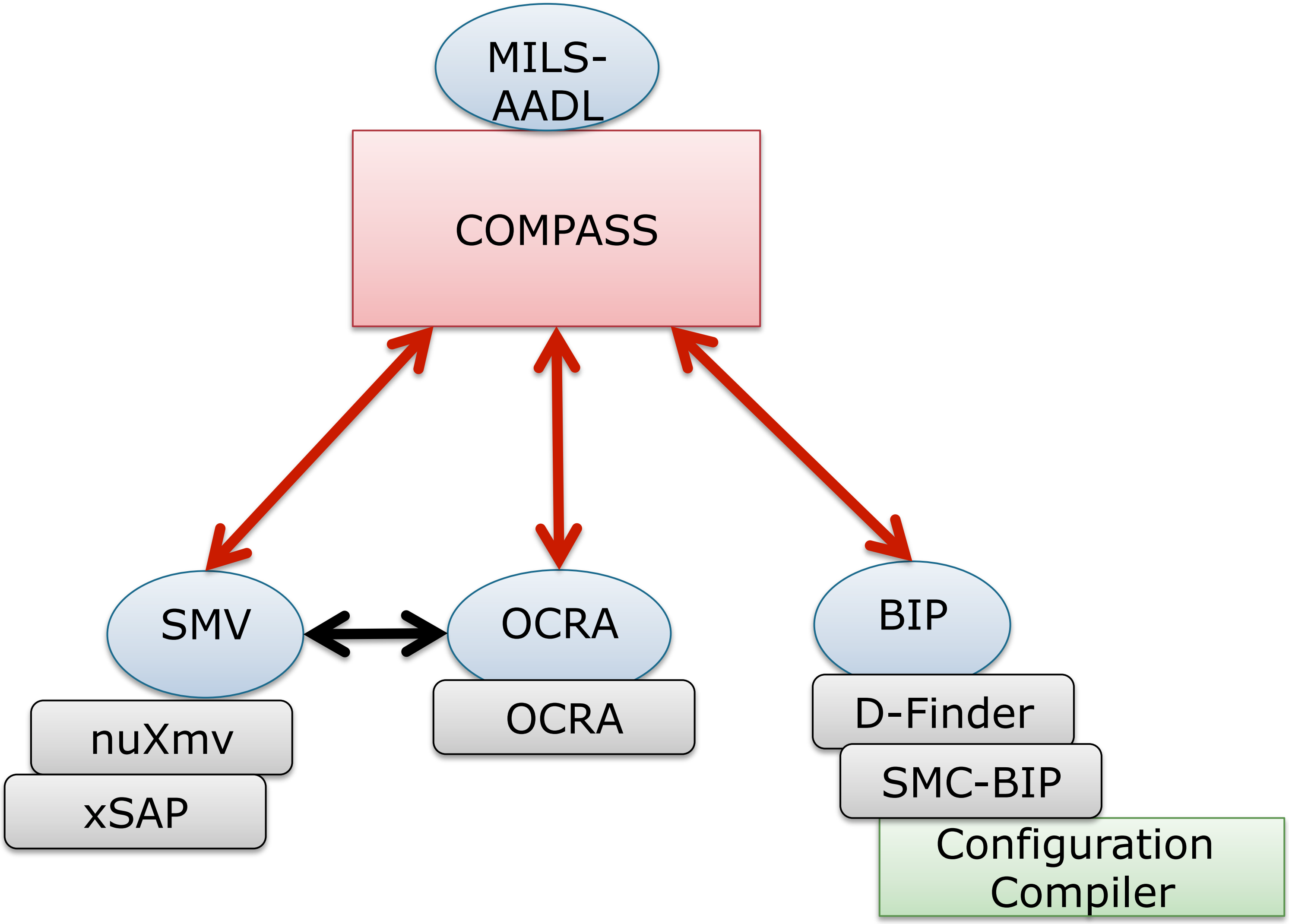
Automatic generation of invariants

- Previous method requires a manual definition of the decomposition
- Other methods generate components' properties automatically
- Application for timed systems and timed properties
- Observation:
  - invariant generation methods ignore time synchronization
  - invariants generated on timed models are too weak
- New approach
  - strengthening the invariants by exploiting time properties
  - augment atomic components with additional history clocks
  - generate local invariants for extended components
  - infer additional history clock constraints from interactions
- Method implemented and experimented on classical benchmarks
  - D-Finder prototype for Real-Time BIP
  - additional heuristics to improve scalability

Secure-BIP

- An extension of the BIP component framework with Information Flow Security
- Secure-BIP = BIP + security annotations
    - security labels on ports and variables
    - track information flow of interactions and data
- Two notions of non-interference studied:
    - event non-interference wrt interaction flow
    - data non-interference wrt data flow
- Static verification of non-interference
    - based on sufficient syntactic conditions
    - implemented in the Secure-BIP tool

D-MILS Toolset



Tool support for algorithms

- OCRA/nuXmv covers:
  - Invariants
  - LTL
  - LTL with real-time constraints
  - LTL for hybrid systems
- BIP covers
  - Deadlock
  - Transitive Non-interference
- Intransitive non-interference will be structurally guaranteed by the MILS-AADL model.
- Safety addressed with
  - COMPASS by model extension and applying above compositional methods on the extended models
  - XSAP for fault tree analysis

Conclusions

- Verification framework based on formal methods
- Focused on analysis of architecture
- Main concerns: automation, efficiency, representation of requirements
- Compositional approach formalizing assumptions and guarantees of components
- Model-based approach, i.e. same model for analysis, for platform configuration, for assurance case
- Evidence of architecture correctness combined with arguments on the platform in the assurance case