Contributions to the Engineering of Safety Critical Automotive Systems

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Credits:

Figure on slide 21 comes from a lecture by Phil Koopman (CMU, US). Several figures come from Cédric Wilwert's Phd defence (Loria, France)

Some words about me and my research group ..

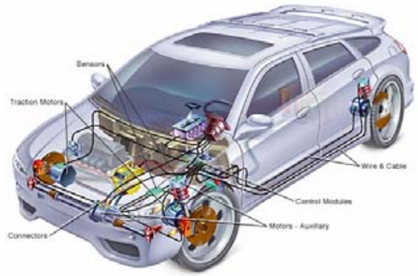
- TRIO : “Real-time and Interoperability”

- Around 18 people with 3 Prof., 1 Ass. Prof., 2 Researchers
- Belongs to the INRIA – located within the Loria Lab. in Nancy (France)
- Research objective : “Propose methods and tools for designing, validating, optimizing real-time systems”

- My research field : design of dependable systems

- Real-time scheduling
- Design of fault-tolerant communication protocols
- Probabilistic risk evaluation
- Software engineering for real-time systems
- *Optimization techniques*

Application to in-vehicle embedded systems



In-Vehicle Embedded Systems : functional domains

- Chassis domain : control the chassis components according to solicitations and driving conditions - ABS, ESP, ASC, 4WD, …
- Powertrain domain : control transmission and engine
- Body domain : dashboard, lights, windows, seats, ..
- Telematics and Human Man Interface (HMI)
- Active and passive safety domain : impact and rollover sensors, airbags deployment, …

In-Vehicle Embedded Systems

- Complexity : up to 80 ECUs - 5 networks - up to 2500 messages - distributed functions - several distinct functional domains

- Strong design constraints : cost, time-to-market, third part suppliers, …

- Safety Critical Functions : braking, steering, traction, suspension, engine control, active safety ..

- Increasing amount of software : most new functions mainly implemented in software … by 3rd part suppliers

Issue : how to ensure the system reliability with a high confidence level ? (e.g. 10^{-9} failure per functioning hour)

Threats to the correct functioning

- Types of faults :
  - faults caused by the user
  - faults during production / **implementation**
  - **Design flaws !**

- ‘worst-case’ situation not considered

- transient faults due to the environment : temperature, α-particles, electromagnetic interferences (EMI)

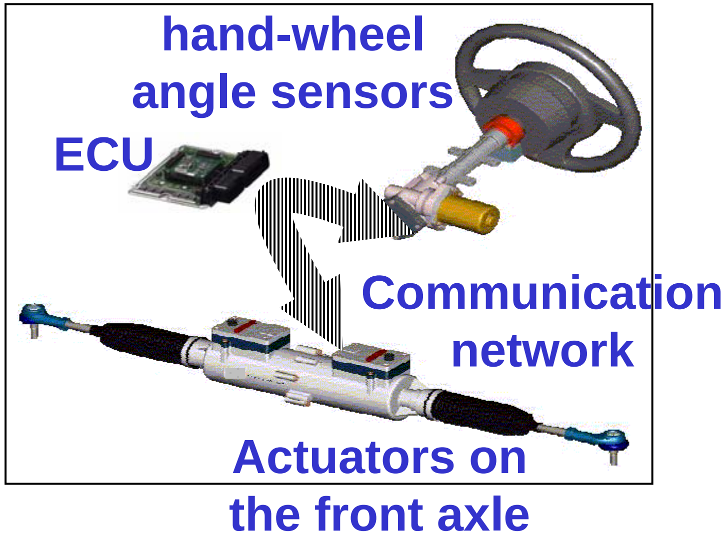
- EMI :
  - caused by radio FM, radars, powerlines, …
  - induce bit-flippings in RAM, ECU reboots, transmission errors, …
  - reported to be involved in numerous road accidents / breakdowns

Example : Steer-by-Wire (1/2)

- **X-by-Wire :** hydraulic and mechanical connections are replaced by networks and actuators

Mechanical Steering system

« Steer-by-Wire » system



Example : Steer-by-Wire (2/2)

- Why Steer-by-Wire ?
  - Decrease weight / increase space
  - Safety : intrusion of the steering column in the cockpit
  - Enable new functions : variable steer ratio, lane keeping, park assistance, crash avoidance, differentiated control of the wheels …

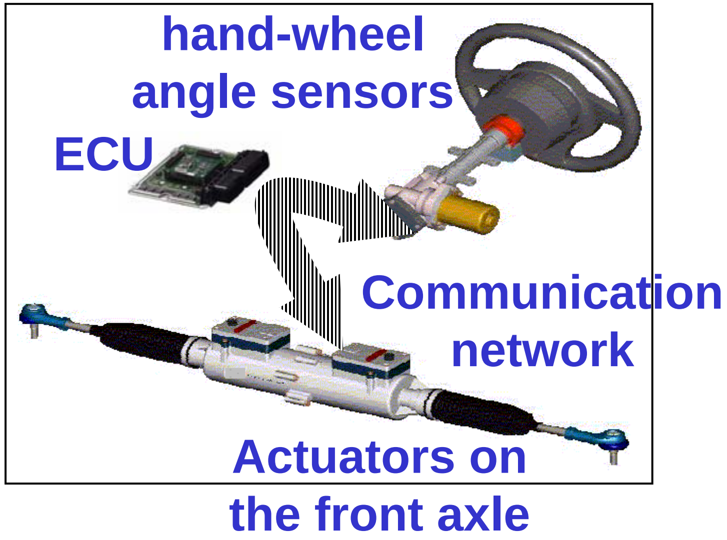
- Probably harder to implement than in airplanes because of costs, no maintenance and very high steering precision required

Example : Steer-by-Wire (1/2)

- X-by-Wire : hydraulic and mechanical connections are replaced by networks and actuators

Mechanical Steering system

« Steer-by-Wire » system



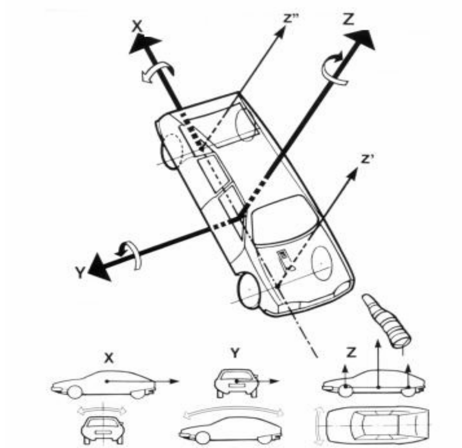
Basic issue with Steer-by-Wire : a delayed transmission of the hand-wheel angle to the front-wheel impacts QoS and Safety …

Steer-by-Wire : evaluation of the maximum tolerable delay

Road Tests

+

Matlab Simulink model

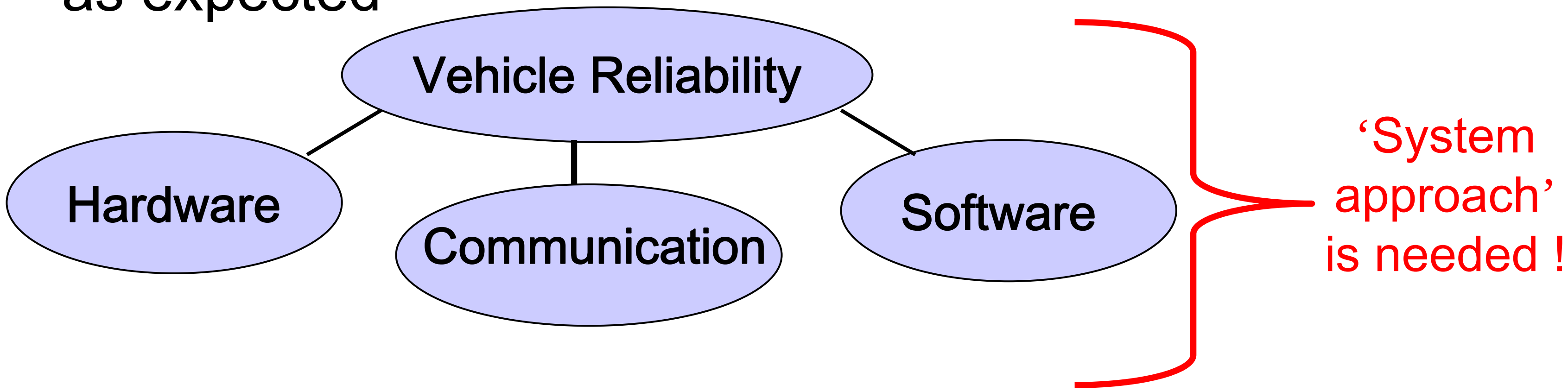


Crucial questions at design time :

- What is the probability to exceed the maximum delay ?
- How to optimize the configuration for more robustness ?
- Which transmission support / communication protocols / software layers are required ?
- How to detect dysfunctioning nodes at run-time ?

Dependable systems : systems in which the user can trust …

- Focus on reliability : probability that a system performs as expected

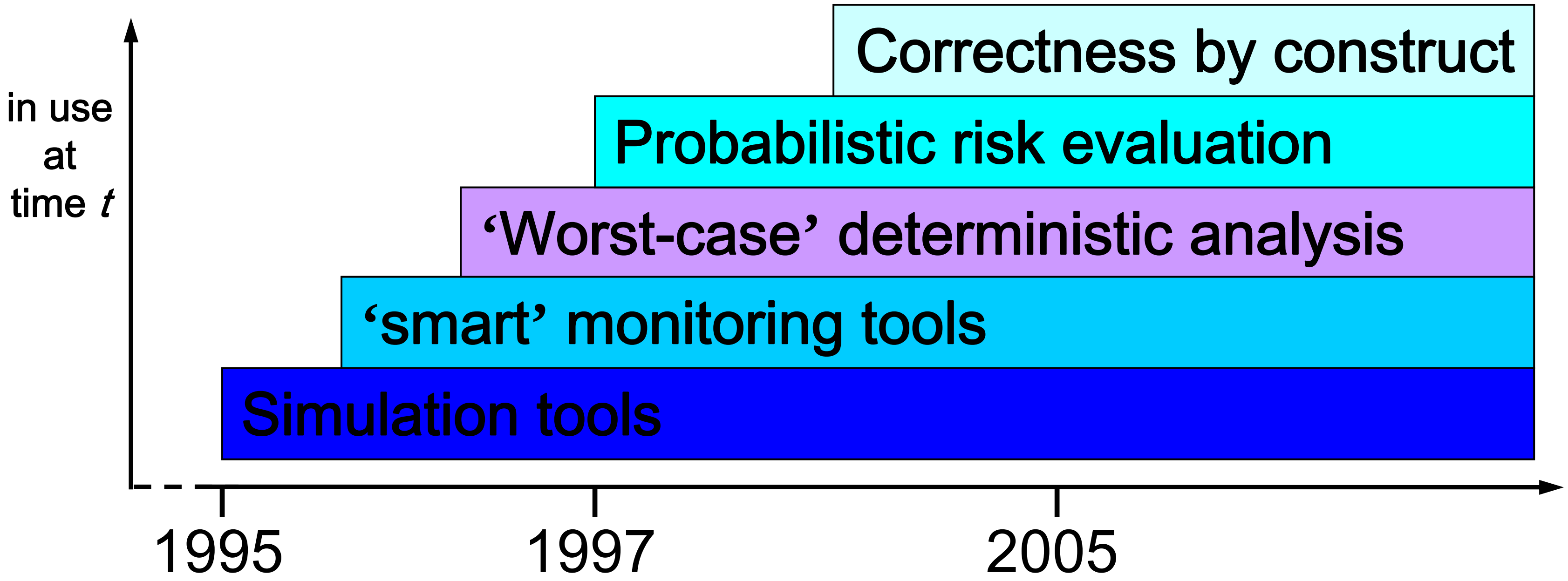


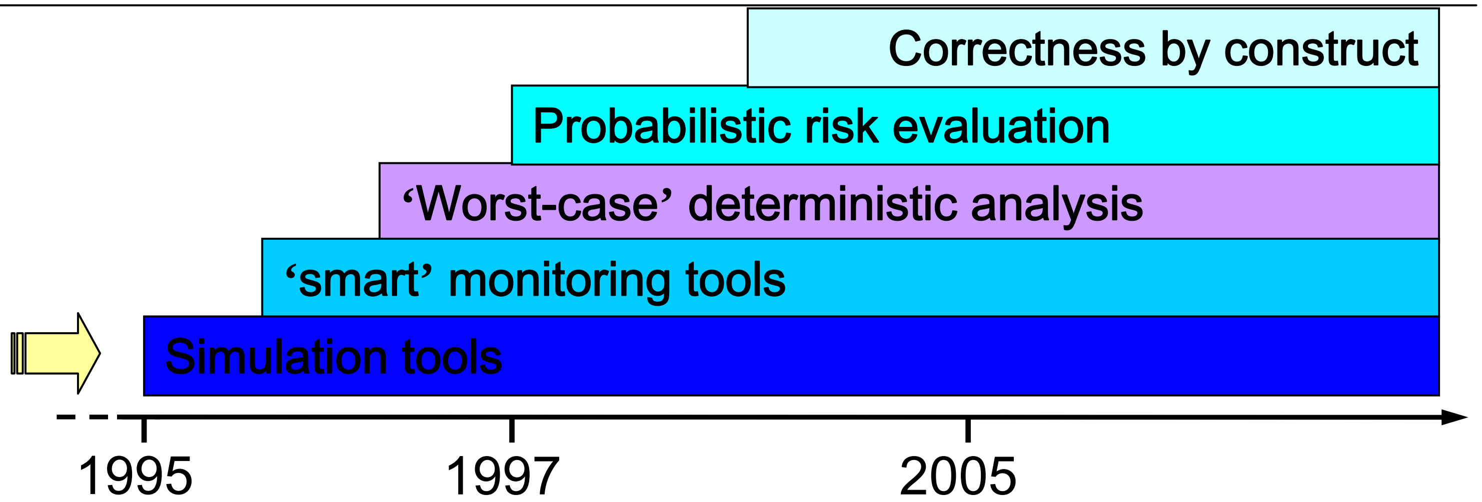
- Research issues :
  - Conceive new mechanisms : e.g. communication protocols, scheduling policies (not discussed today)
  - Propose models, methods and tools for validating dependability constraints

Validation = checking constraints fulfillment

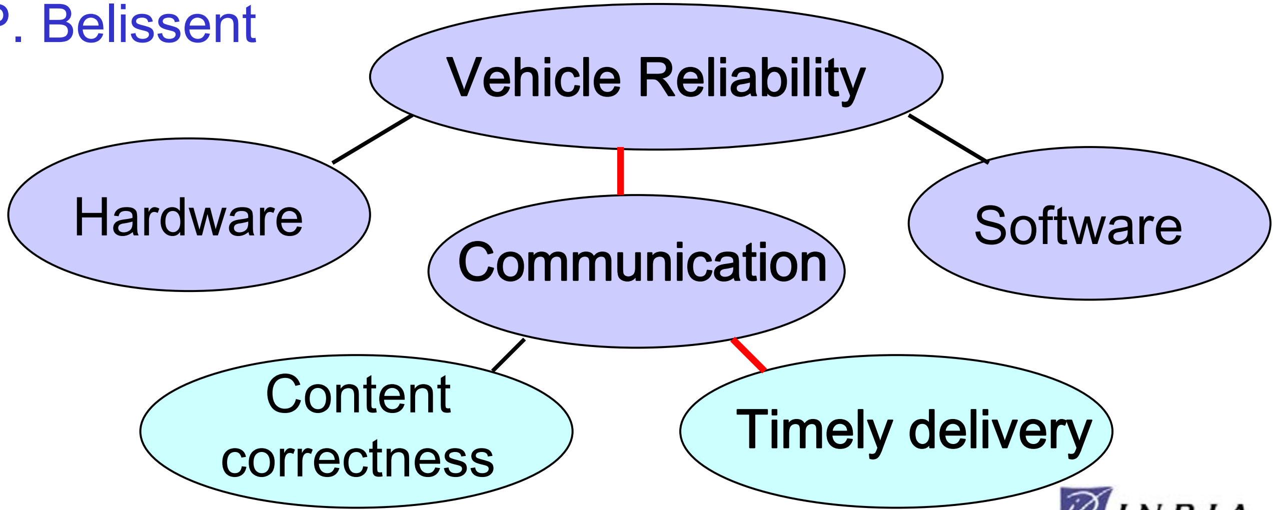
- ≠ **approaches** : model-based evaluation (simulation, analysis), prototype-based evaluation, hybrid techniques

Personal experience over the last 10 years :



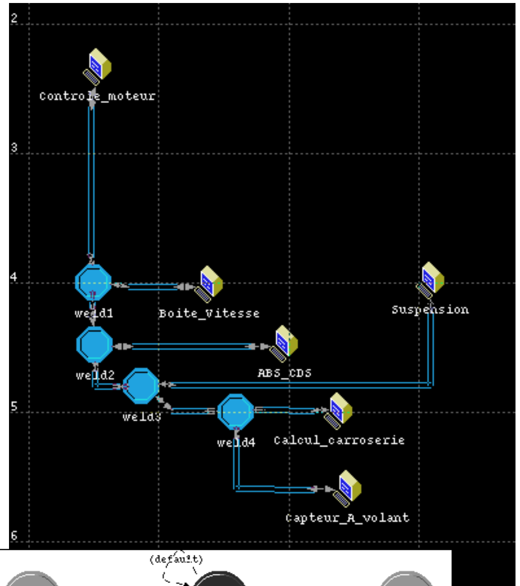


- **1995 :** Qnap2 Controller Area Network (CAN) model developed for Renault
- **1996-97 :** the VACANS tool (Validation of CAN based systems) - Initial developer: P. Belissent



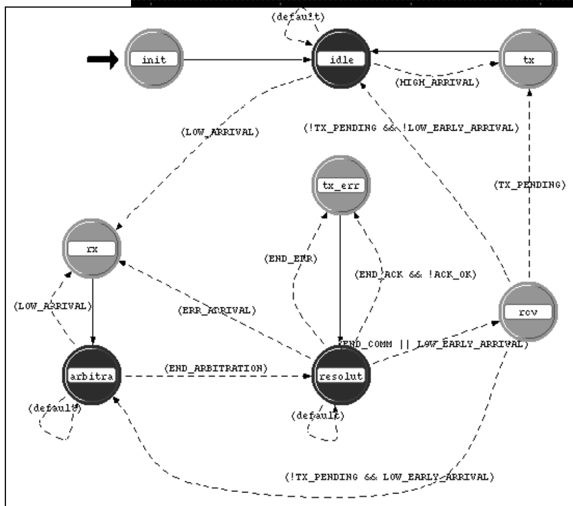
VACANS : Validation of CAN based systems discrete event simulator based on OPNET

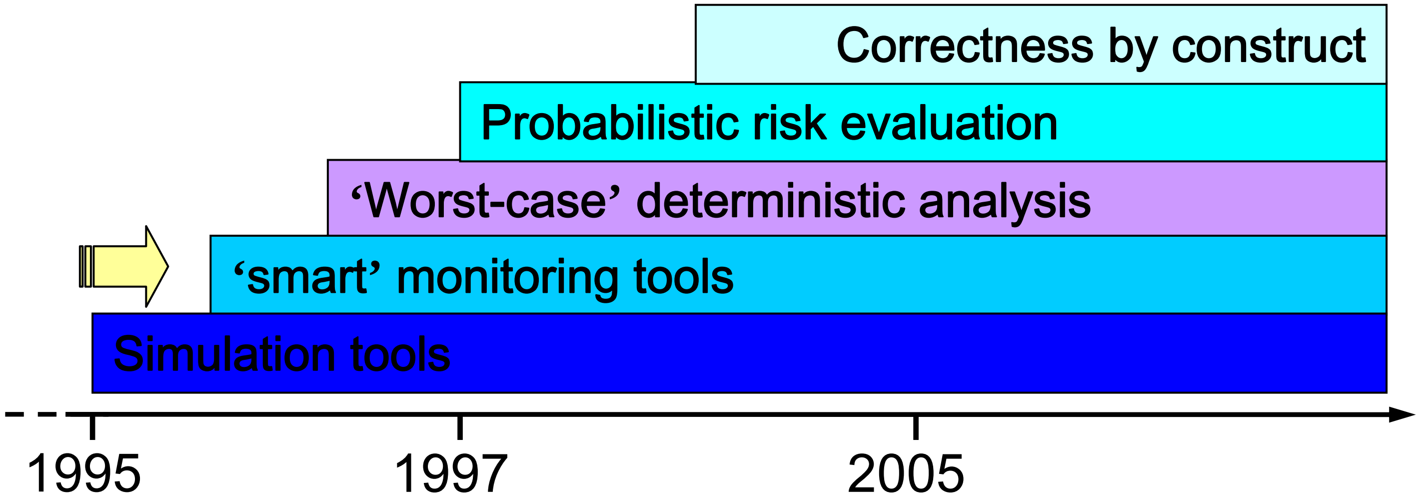
Network level



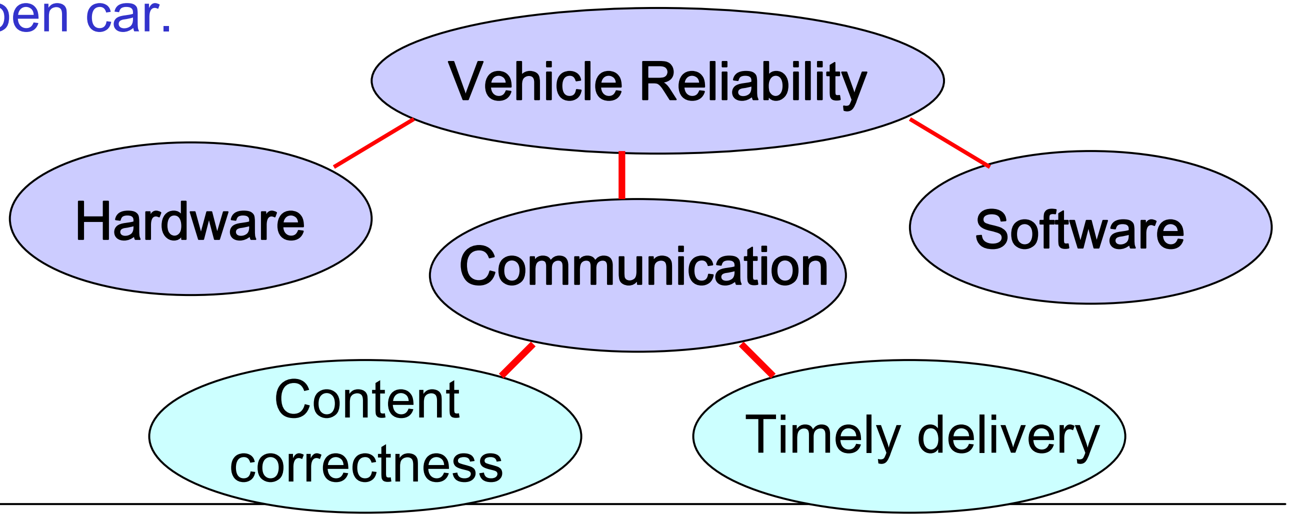
- Specification through an Architecture Description Language
- Automatic generation of the models from ADL spec.
- Provides both simulation and analytic results
- Distributed by Delta-Partners in 1997-98

Node level modelling
with
Finite State Machine
embedding C code

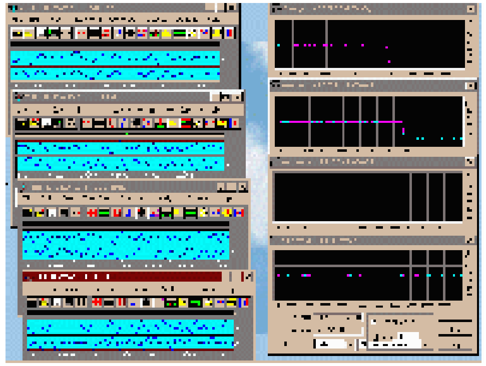




1996-97 : ‘Observer’ - a ‘smart’ network analyzer for Controller Area Network (CAN) - industrial contract with PSA - used for a Citroën car.



Observer : Analyzing CAN-based applications



Network monitoring is mandatory !

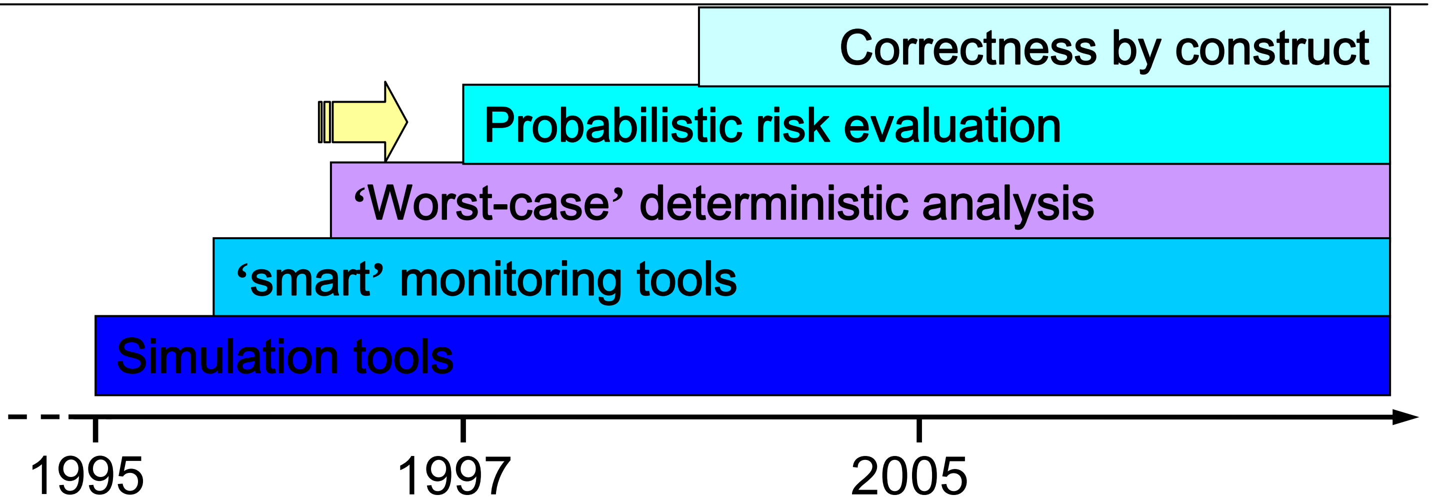
- check ECUs from suppliers meet their specification !
- gather statistics on transmission errors ⇒ error models
- inject ‘faults’ and see what happens …
- verify the respect of high-level applicative constraints

Typical high-level constraint : delay between a gear change and the torque reduction

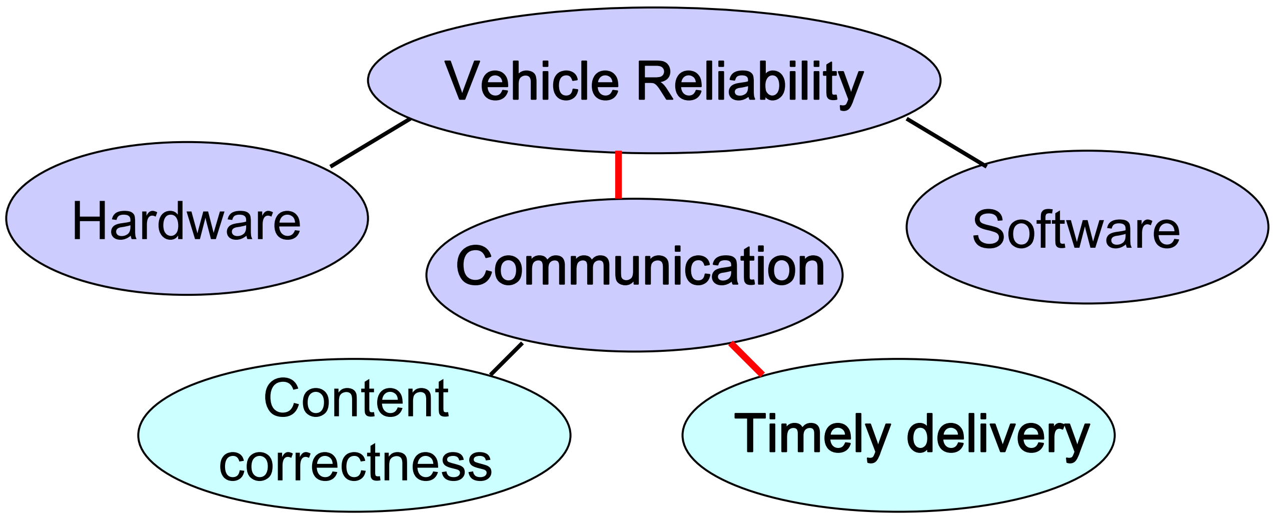
```
frames
{       0x349
        {
        name Automatic_Gear_Box
        dlc  5
        field 0 0x03 gearChange
        field 3 0x0f poslevier
        field 3 0xf0 rapport
        }
        0x208
        {
        name Engine_Controller
        dlc  7
        field 6 0xff torque
        }
}
```

```
rules
{       0x349
        {
                gearChange equal 1
                wait 0x208
                with torque in 0 255
                maxDelay 20000
        }
}
```

The delay observed on the bus is not the actual delay but it helps to determine a tight bound



- 1997 : Frame Deadline Failure Probability on CAN
- 2004 : Optimal configuration for TDMA networks

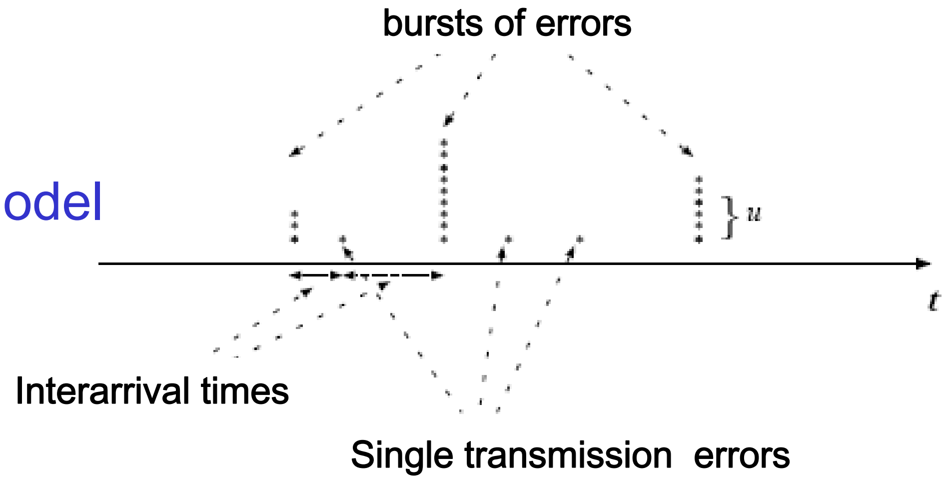


Frame Deadline Failure Probability Analysis

Question : what is the probability a given information arrives on time ?

Approach :

1) propose a 'realistic' error model



2) compute the maximum error threshold $\eta_k = \max\{n \in \mathbb{N} \mid R_k(n) \leq D_k\}$

3) compute the probability to exceed the threshold

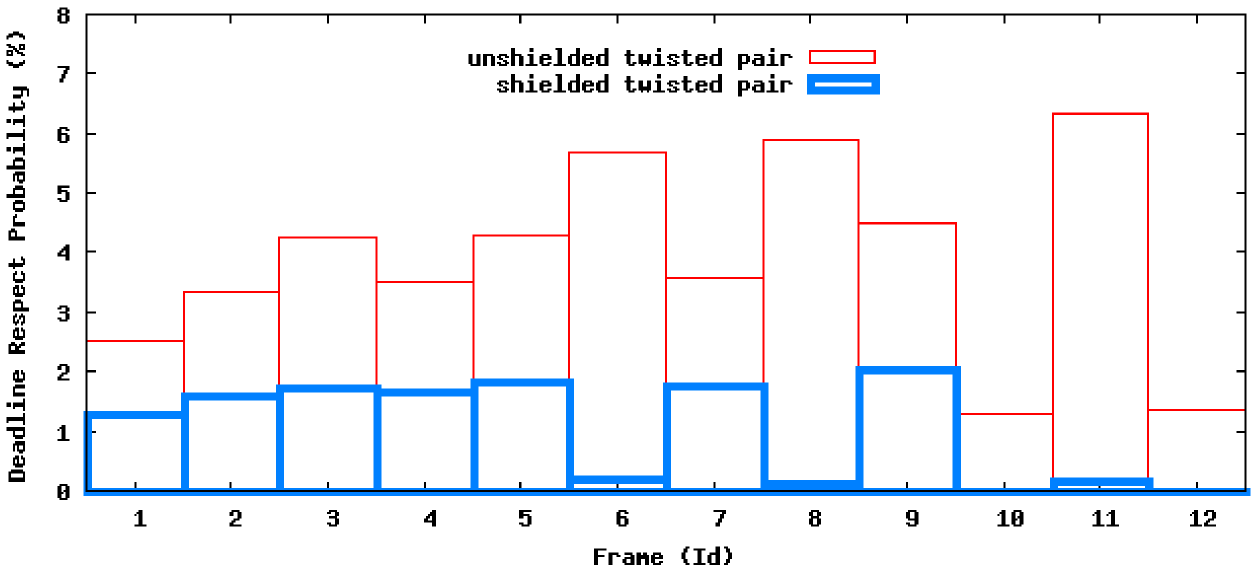
$$P[X(R_k(\eta_k)) > \eta_k] = 1 - \sum_{i=0}^{\eta_k} P[X(R_k(\eta_k)) = i]$$

Frame Deadline Failure Probability Analysis

Benefits :

- evaluate the « robustness » of the application to transmission errors
- basic block for functional-level safety analysis
- optimize the configuration - minimize $E[C] = \sum_{m_k \in \mathcal{M}} c_k \cdot P[R_k > D_k]$

choice of the transmission support



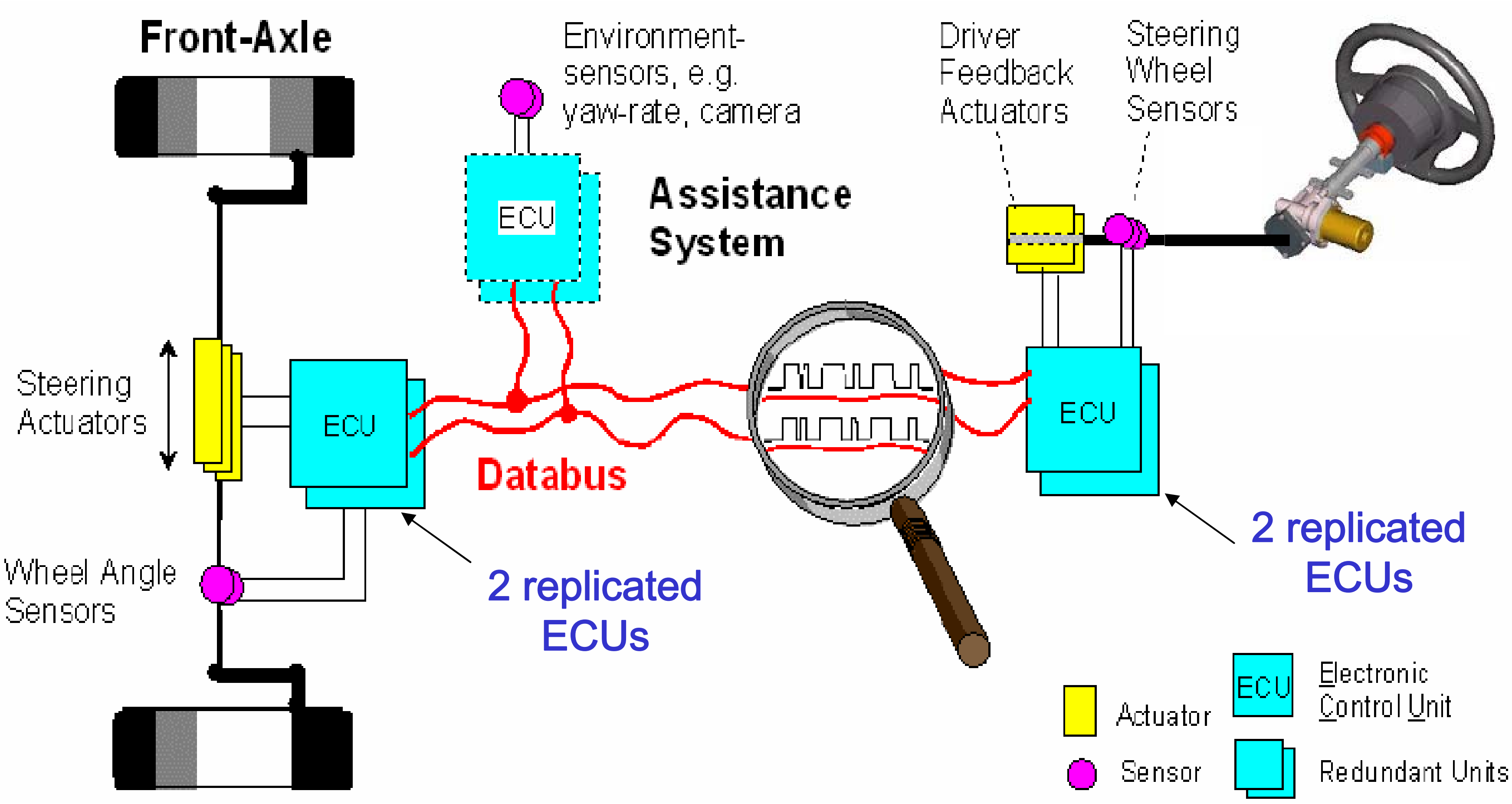
Frame Deadline Failure Probability Analysis

In the literature :

- improvements for particular cases (e.g. RTSS'01)
- optimization technique using this analysis (e.g. ICC'98)
- configuration tools implementing the analysis (e.g. ICC'99)
- same error model and approach re-used for other networks (e.g. wireless communication)

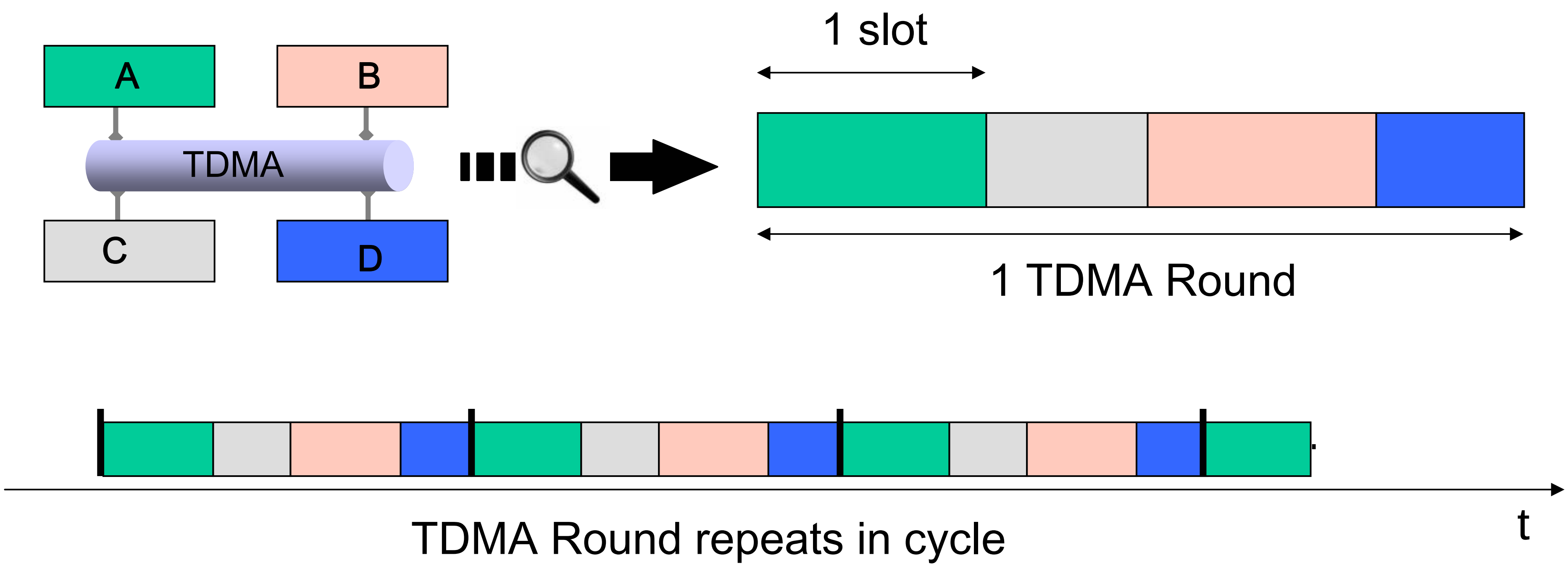
Optimal Configuration of TDMA networks

Question : how to best configure the communication for maximal safety?

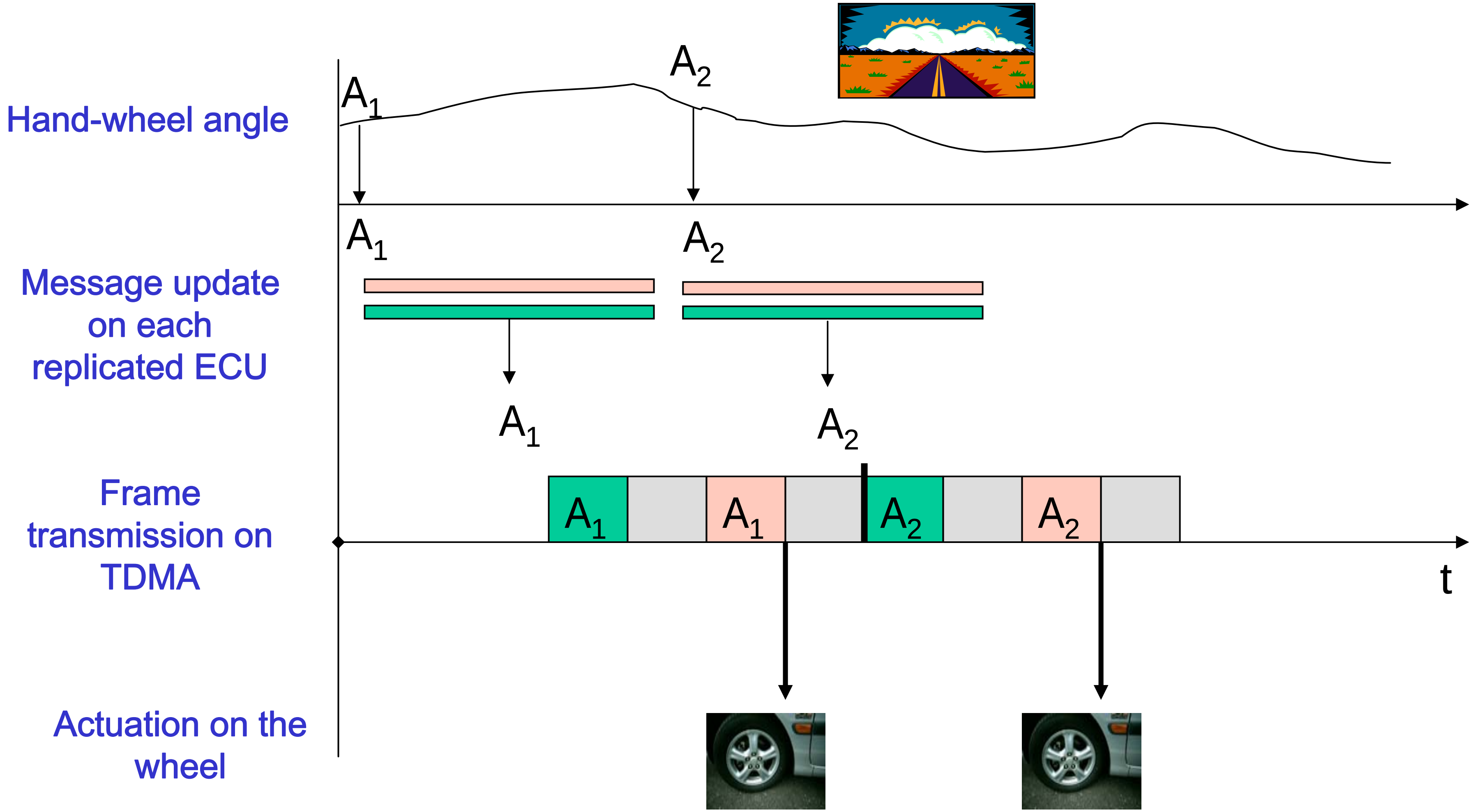


Basics of TDMA networks

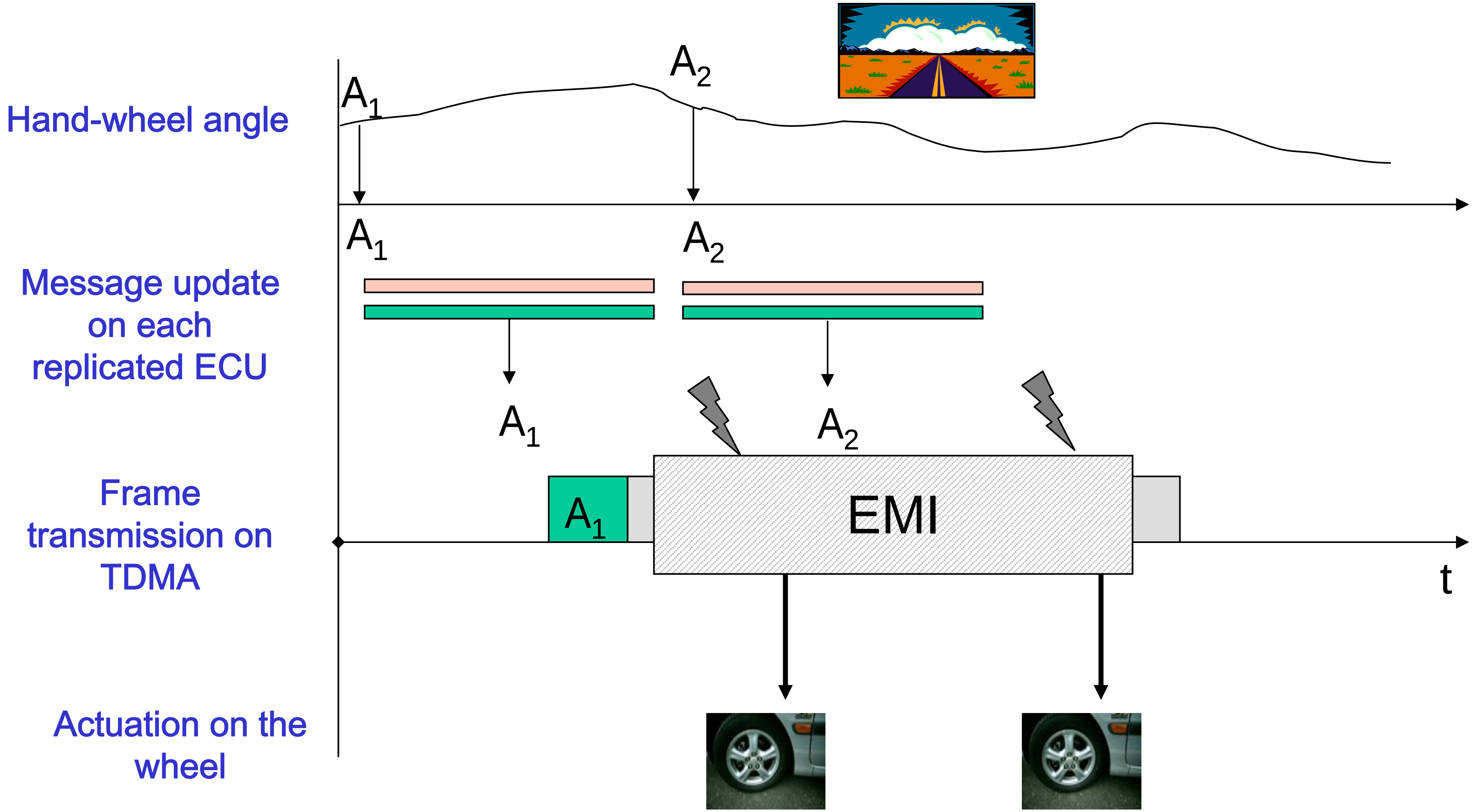
TDMA : well suited for dependability - in use in avionics - in production cars within the next few years (FlexRay)



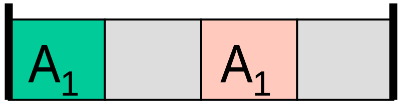
Function : turn the wheels according to the driver's request

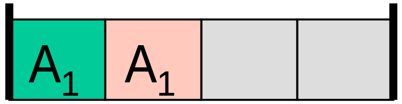


Function : turn the wheels according to the driver's request



Maximizing the robustness of TDMA

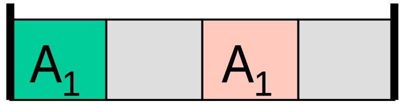
Question: 

or 

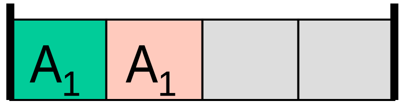
??

Fail-silent producer node : if a frame is received, the content is correct

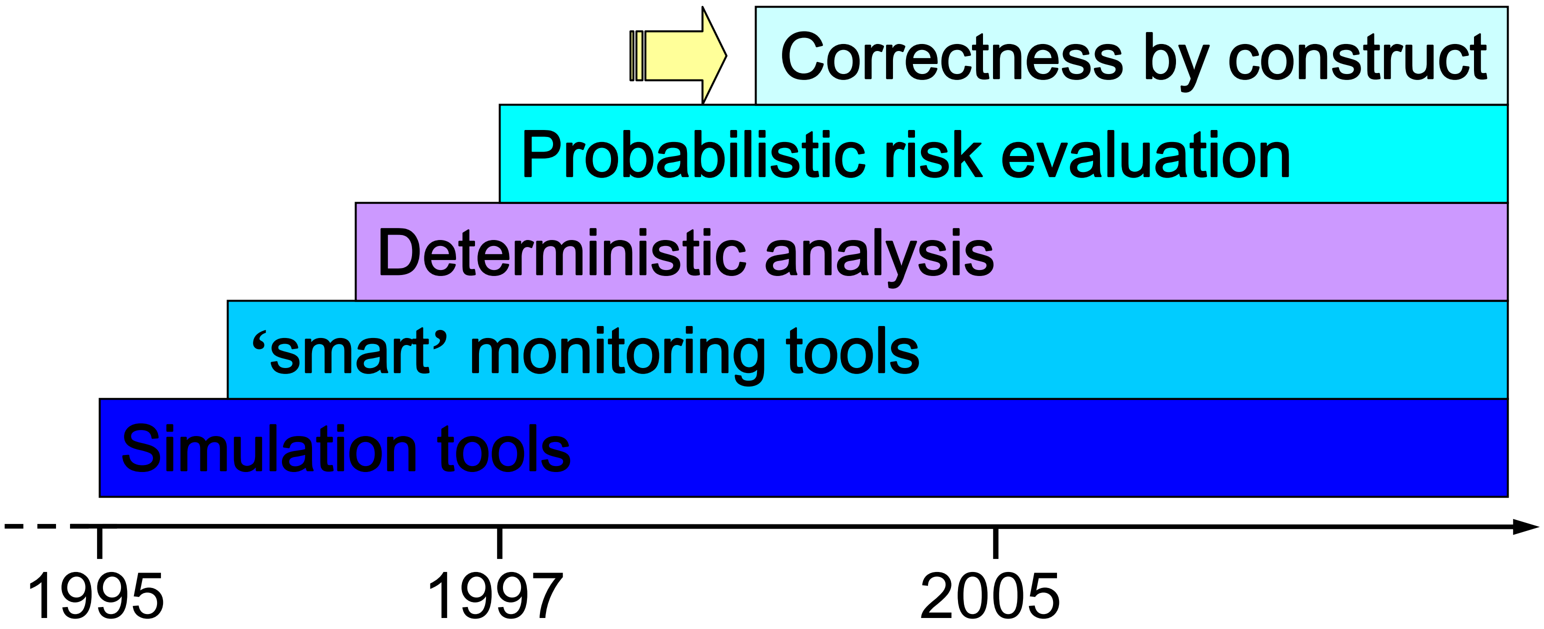
- Fail-silent nodes : one frame is enough



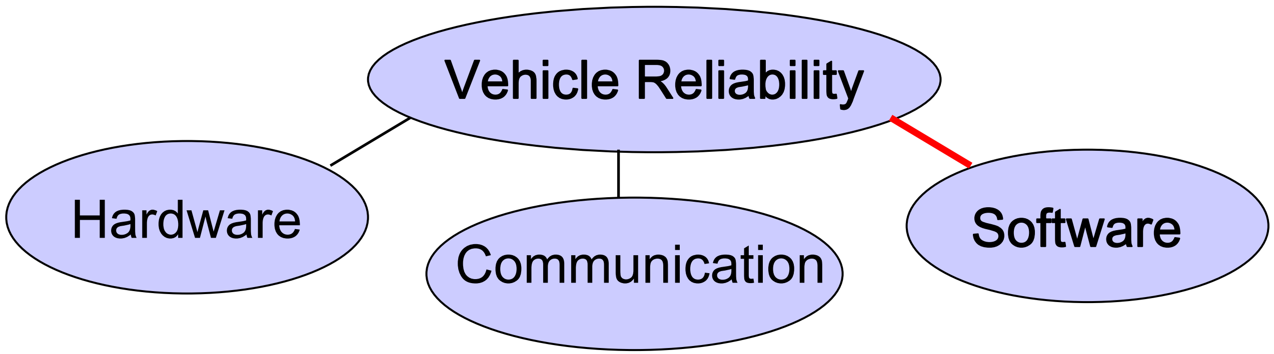
- Non fail-silent nodes : all frames are needed



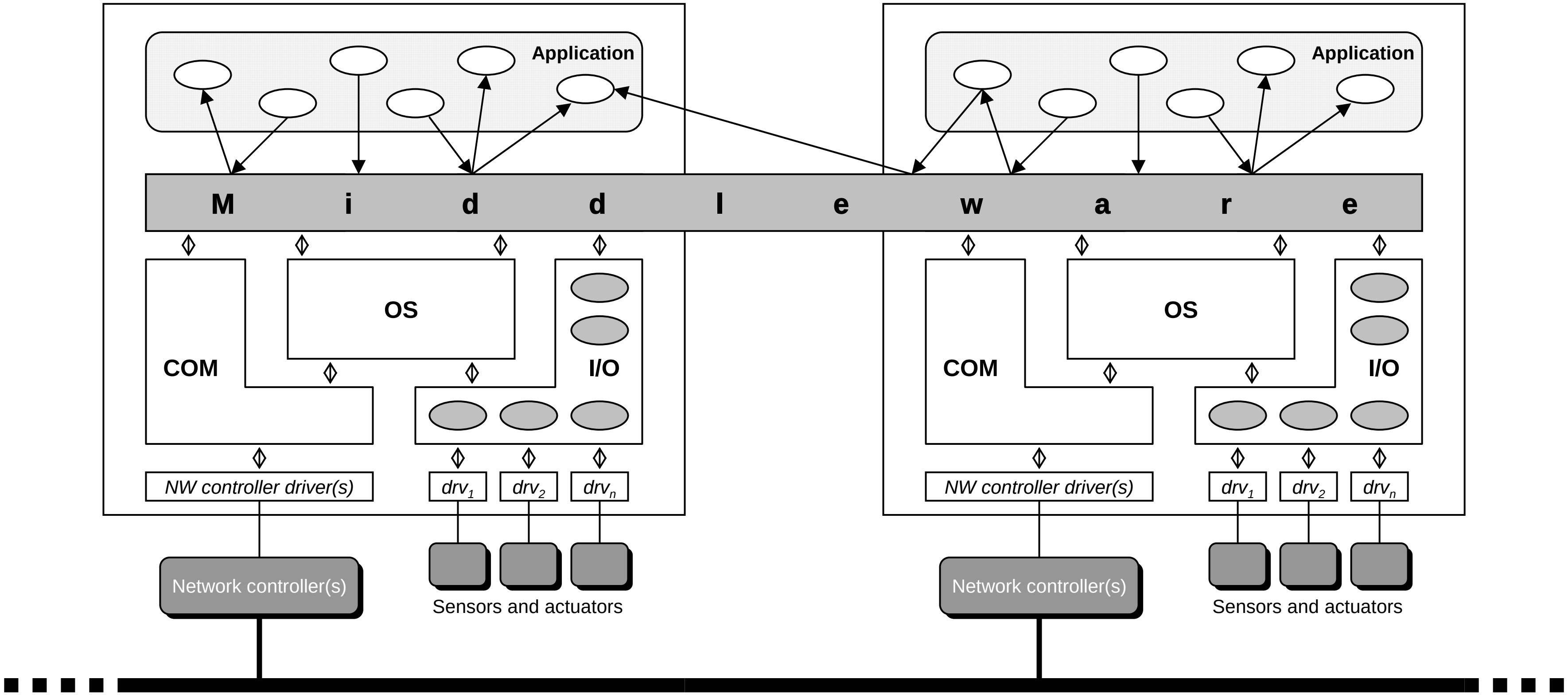
➢ Simple design guidelines providing large robustness improvements …



1998 - 2005 : Design of automotive middleware

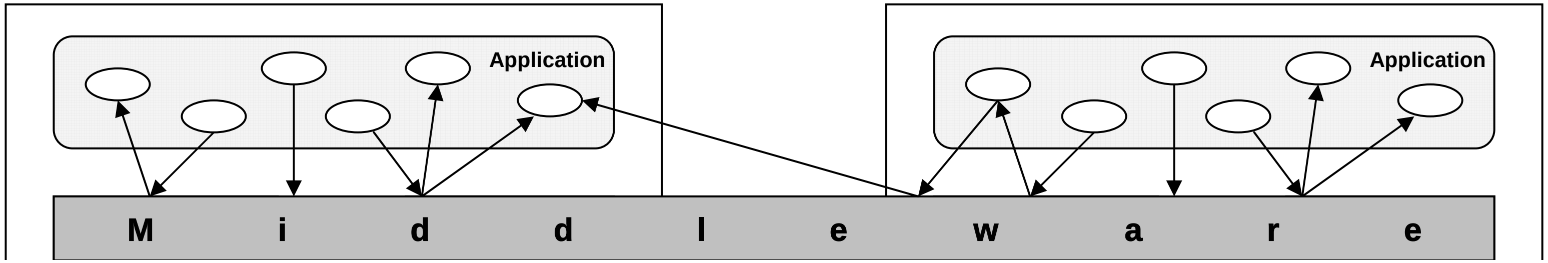


Automotive Middleware Design



Middleware : software layer between platform and application

Automotive Middleware Design



Aims :

- hide the distribution of the application: intra-ECU, inter-ECU, interdomains communication
- provide a standard API hiding the heterogeneity of the platforms : networks, CPU, OSs, …
- provide high-level services for reducing development time : mode management, redundancy management, download, …
- ensure required QoS : correct protocol flaws, enhanced CRC, …

Benefits :

- improve interoperability, portability and reuse
- cut development time - increase application correctness

Automotive Middleware Design : context

- AEE project (1998-2001) - partners : PSA, Renault, Sagem, Siemens, Valeo, Inria, …

Architecture Electronique Embarquée

- ITEA EAST-EEA project (2000-2004) - partners : Audi, Volvo, DC, BMW, Fiat, Bosch, PSA, Renault, Etas, ZF, INRIA,T.U. Darmstadt, …

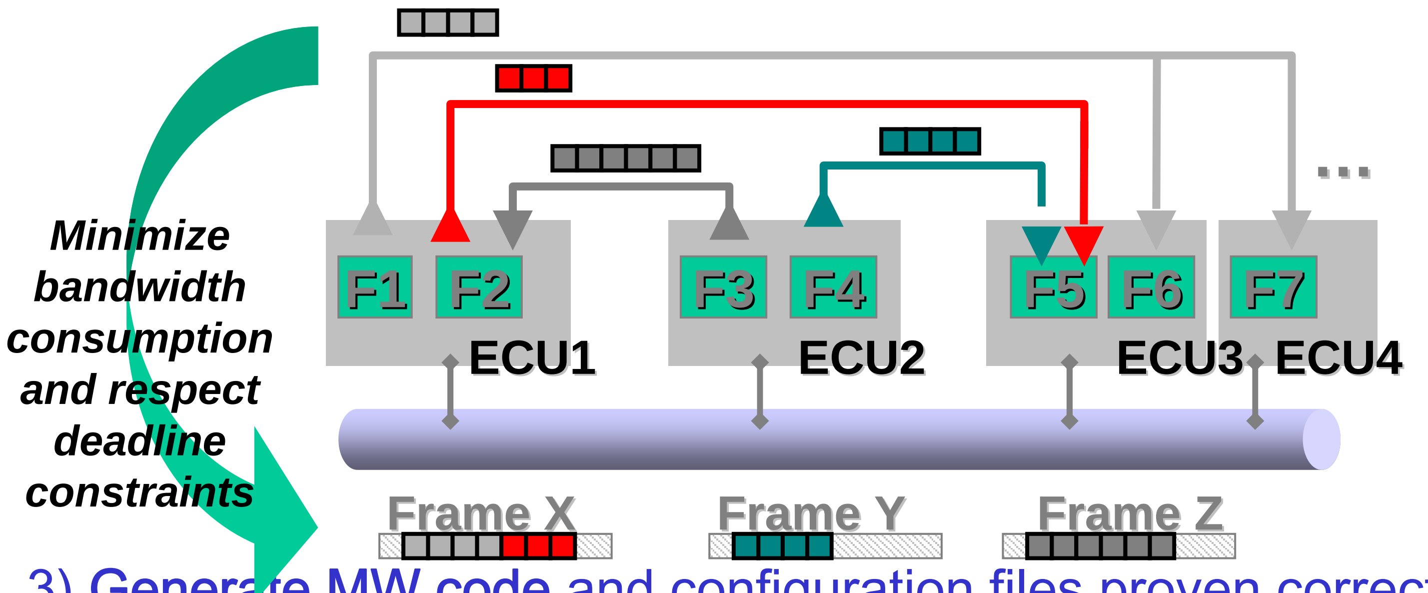
Specification of the MW for the **Powertrain domain** - implemented in demonstrator

MW : Ongoing research since 2001

1) Specification of the MW with Design Patterns

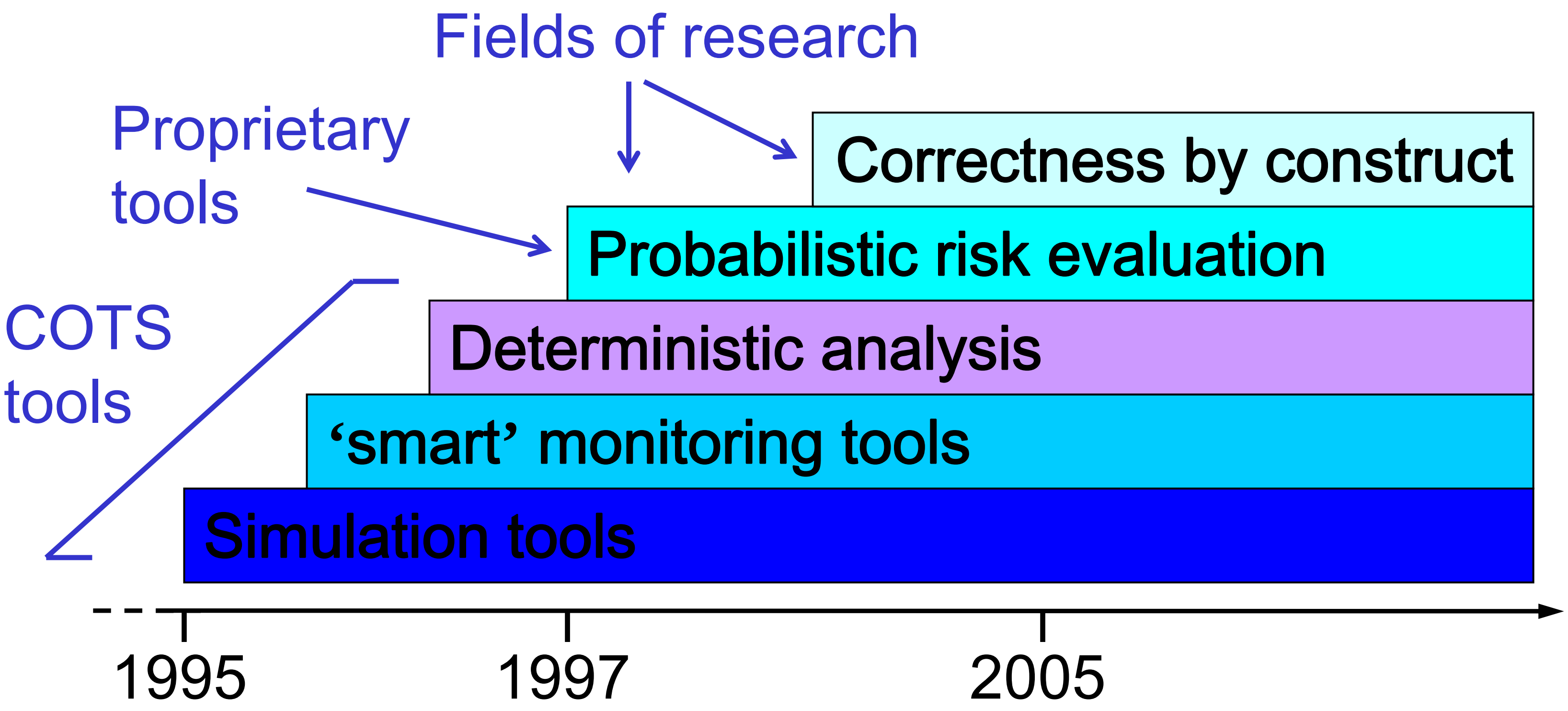
2) Optimize MW implementation wrt dependability constraints

- Create set of MW tasks and configure scheduling
- Configure the set of frames (frame packing)



3) **Generate MW code** and configuration files proven correct wrt dependability

Current practice and future work in the design of dependable automotive systems



Future work (1/2)

- Fine-grained analytic models
  - needed both for
    - dependability evaluation
    - being embedded in adaptive mechanisms
  - guiding principles :
    - consider hardware / software / communication
    - no independency assumption between failures !!

Future work (2/2)

- Component based engineering with correctness by construction
  - current practice in formal methods:
    1. deterministic fault-hypothesis (e.g. TTP/C: at most 1 error every 2 TDMA rounds)
    2. proof under this assumption (e.g. a faulty node will be detected within 2 rounds)
  - Step 1 : cooperation with researchers in formal methods
    - propose ‘realistic’ fault-hypothesis
    - probabilistic guarantees ?
  - Step 2 : composition of components with guaranteed dependability expressed in a probabilistic way

Some references : available at http://www.loria.fr/~nnavet

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Thanks for your attention !