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The design of safe automotive electronic systems

Some problems, solutions and open issues

Françoise Simonot-Lion

(Francoise.Simonot@loria.fr)

Nancy Université - LORIA (UMR 7503)

General Context

- **Automotive industry: the most important economic sector for the next 10 years**
  (Mercer Management Consulting)

- **Automotive electronics**
  (Strategy Analytics, McKinsey)

$$\text{Cost of Electronic Embedded systems / Cost of a car} = \begin{cases} 1\% & (1980) \\ 20\% & (2005) \\ 40\% & (2015) \end{cases}$$

- **In vehicle embedded systems**
  - Electronic components 50%
  - Software components 50% - 1,1 KBytes (1980) → 2MBytes (2000) → *10MBytes (2004)*

- **Software technology**
  - New services are easily developped
    - Customers requirements: cost, comfort, safety
    - Carmakers or suppliers requirements: cost, time to market

      Electronic systems = 90% innovation (Daimler Chrysler)
  - Mandatory for some functions (control of exhaust emission)

Problems

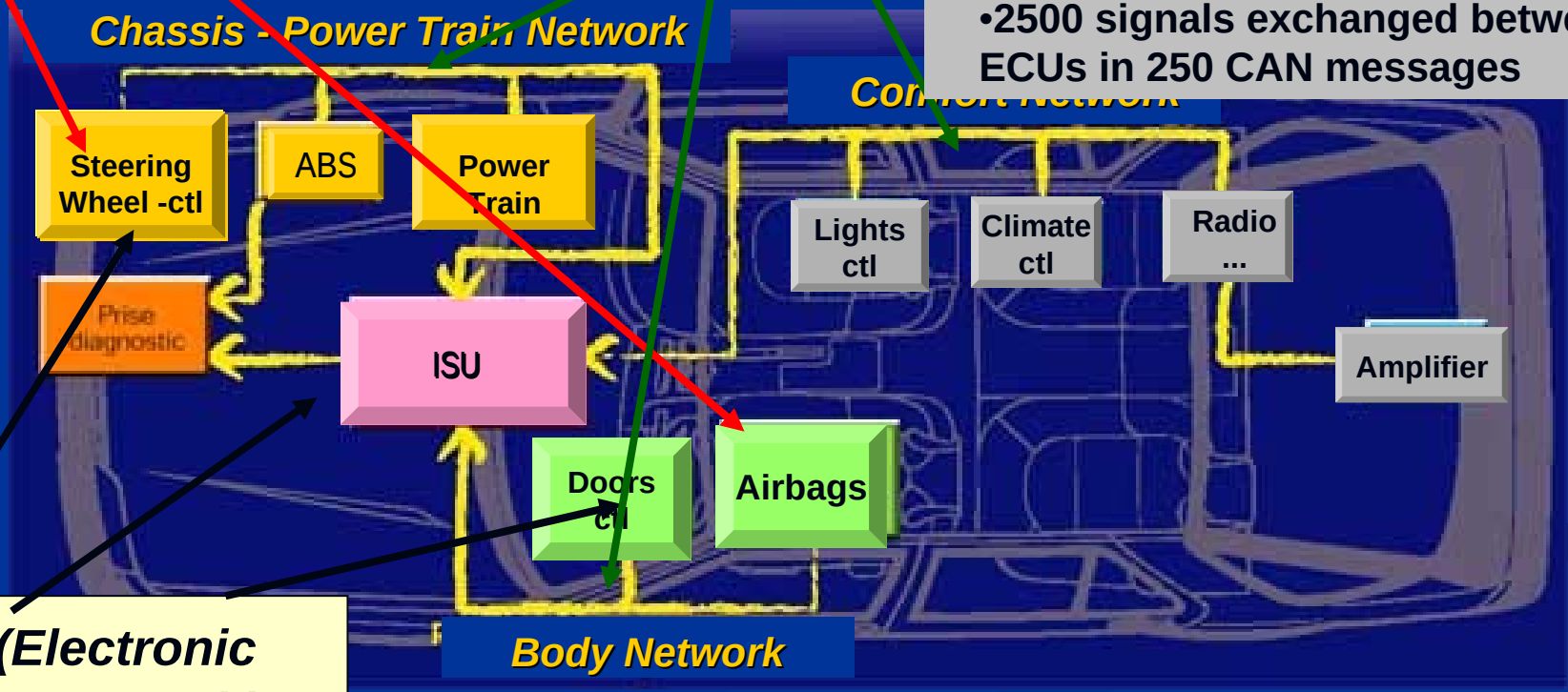
- Architectural complexity

Critical Functions

Complex Communic Architecture

VW Phaeton
Jürgen Leohold
IEEE WFCS 2004, Vienna, Austria

- 11 136 electrical devices
- 61 ECUs, 3 CAN networks, sub-networks, 1 bus multimedia
- 2500 signals exchanged between ECUs in 250 CAN messages



ECU ***(Electronic Component Unit)***

PSA communication service

Problems

- **Functional complexity**
  - Number of I/O signals - Size of the state vector (external/internal data)
  - Integration of critical and not critical functions
  - Interaction between functions - Functional modes
  - Safety requirements:
    - Values
    - Performances / time constraints
- **Development process**
  - Shared between several actors: Suppliers (subcontractors) / Car makers
  - Interaction between partners
    - Black boxes / White boxes / Grey boxes - Intellectual property
  - Process
    - Top – Down / Bottom - Up (reusability)
  - Standards

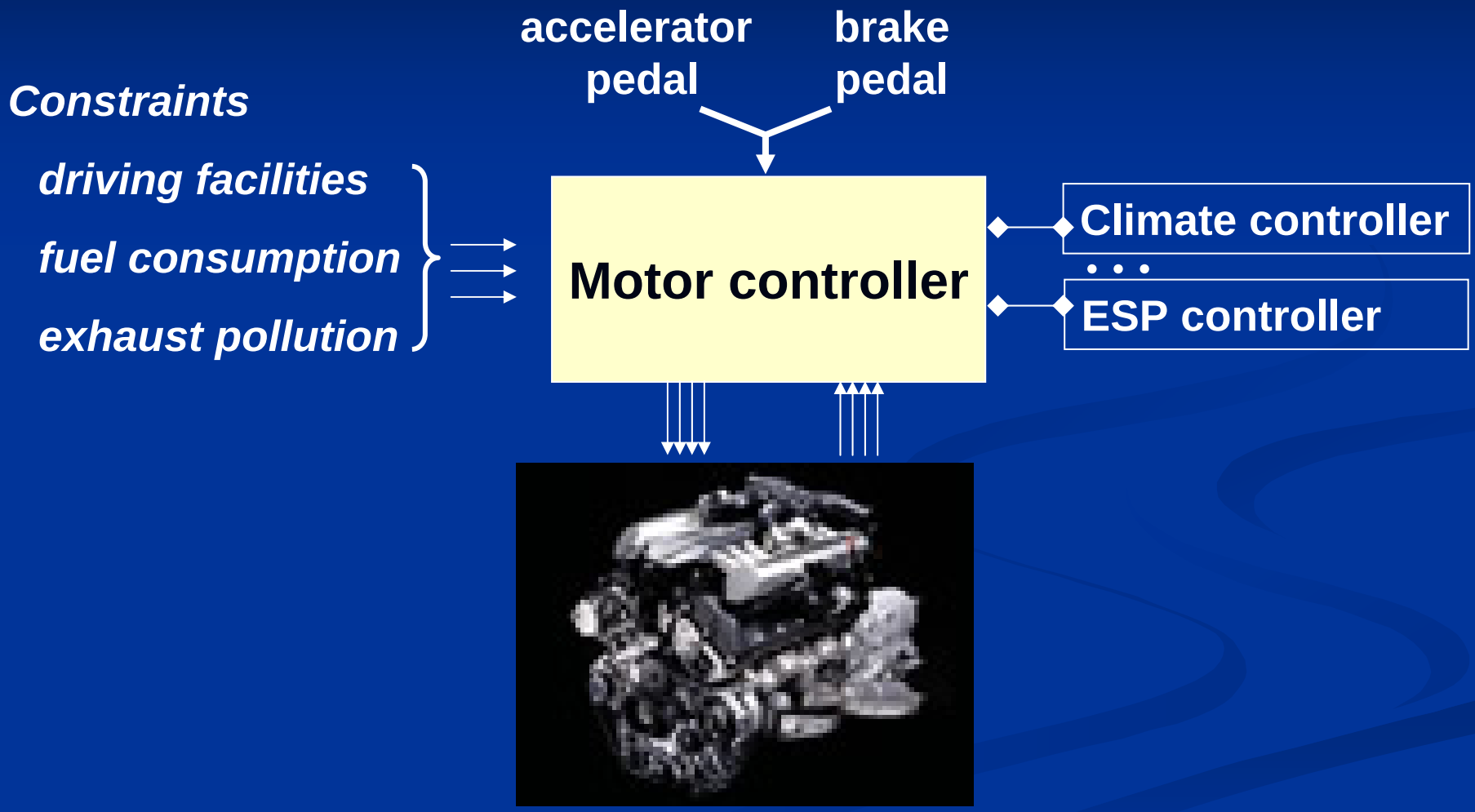
Under constraints:

Cost, Quality, Variants, Safety

Outline

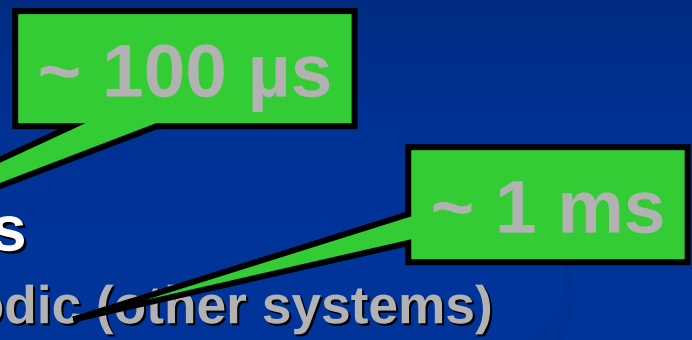
- Context and general problems
- Automotive domains
- An open issue: the safety assessment
  - Example: a steer-by-wire system
  - Impact of the communication system
    - Priority-based protocol
    - TDMA-based protocol
- Conclusions

Powertrain domain



Powertrain domain

- **Functional point of view**
  - Complex control laws
    - Multi-variables
    - Different sampling periods
      - Cyclic (motor times) - Periodic (other systems)
- **Operational point of view**
  - High computation power (*floating point coprocessors)*
  - Multi-tasks (different activation rules)
  - Compromise cost / resolution of sensors
  - Stringent time constraints (response time, freshness)



Chassis

Forces
ground, wind

Steering column

brake pedal

Constraints
comfort
safety

Wheel – suspension - …
controller
(ABS – ESP – ASC – 4WD - …)

Other systems

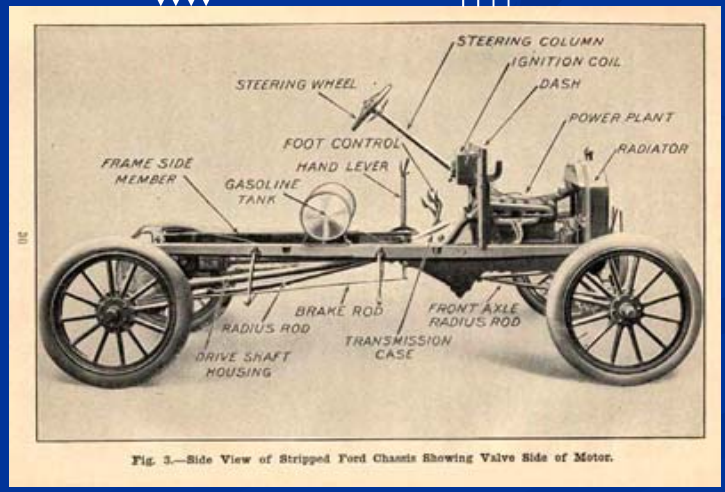


Fig. 3.—Side View of Stripped Ford Chassis Showing Valve Side of Motor.

Chassis

- **Functional point of view**
  - Complex control laws
- **Operational point of view**
  - High computation power (*floating point coprocessors)*
  - Multi-tasks (different activation rules)
  - Compromise cost / resolution of sensors
  - Distribution
  - Stringent time constraints (response time, freshness, temporal consistency)

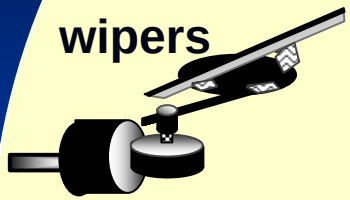
~1 ms

X-by-Wire

Critical domain for the safety

Body domain

wipers



Drivers
Passengers

Innovation

lights

controllers

Other systems

doors,

windows,

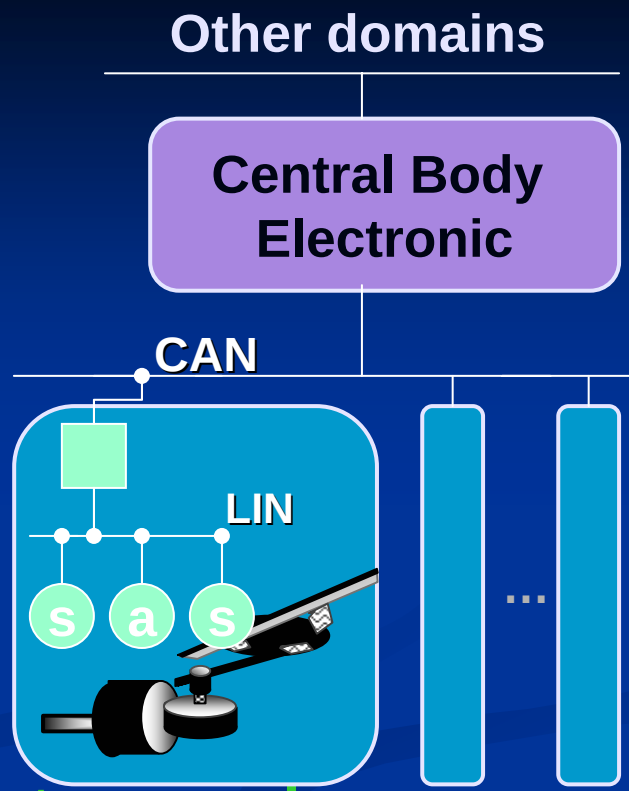
seats,

...

mirrors

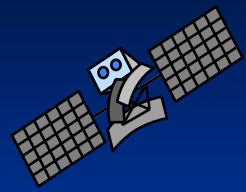
Body domain

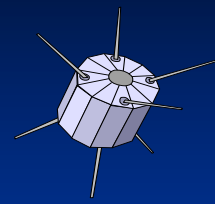
- **Functional point of view**
  - Numerous functions
  - Reactive systems
- **Operational point of view**
  - Highly distributed
  - Hierarchical distributed system
  - Time constraints (response time, temporal consistency)
  - Central Body Unit (critical entity)
    - Optimal scheduling of tasks
    - Optimal scheduling of messages



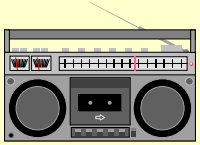
> 1 s

Telematic, multimedia domain





Driver
Passengers



Human Machine Interface
Multimedia applications
Communication

Other systems

Telediagnostic

…

Telematic, multimedia domain

- **Operational point of view**
  - **Upgradable devices, applications**
  - **« Plug and play »**
  - **Properties: security, multimedia QoS**
    - **Resource sharing**
    - **Fluid data streams**
    - **Bandwith**

Driver assistance → Active safety

- Night vision support
- Pedestrian object recognition

- ACC
- Lane keeping assistant

- Collision avoidance

Complexity of the closed loop

Domain characteristics

Deterministic guarantees *safety and performance*

Probabilistic guarantees

	Application type	*Constraints*	*Specification*
Power train	Hybrid systems	Hard real time	Matlab/Simulink
Chassis	Hybrid systems	Hard real time (safety)	Matlab/Simulink
Body	Discrete event systems	Real time	State machine (SDL, Statecharts)
Telematic - HMI	Multimedia data flow processing	Soft real time – Security – QoS	?

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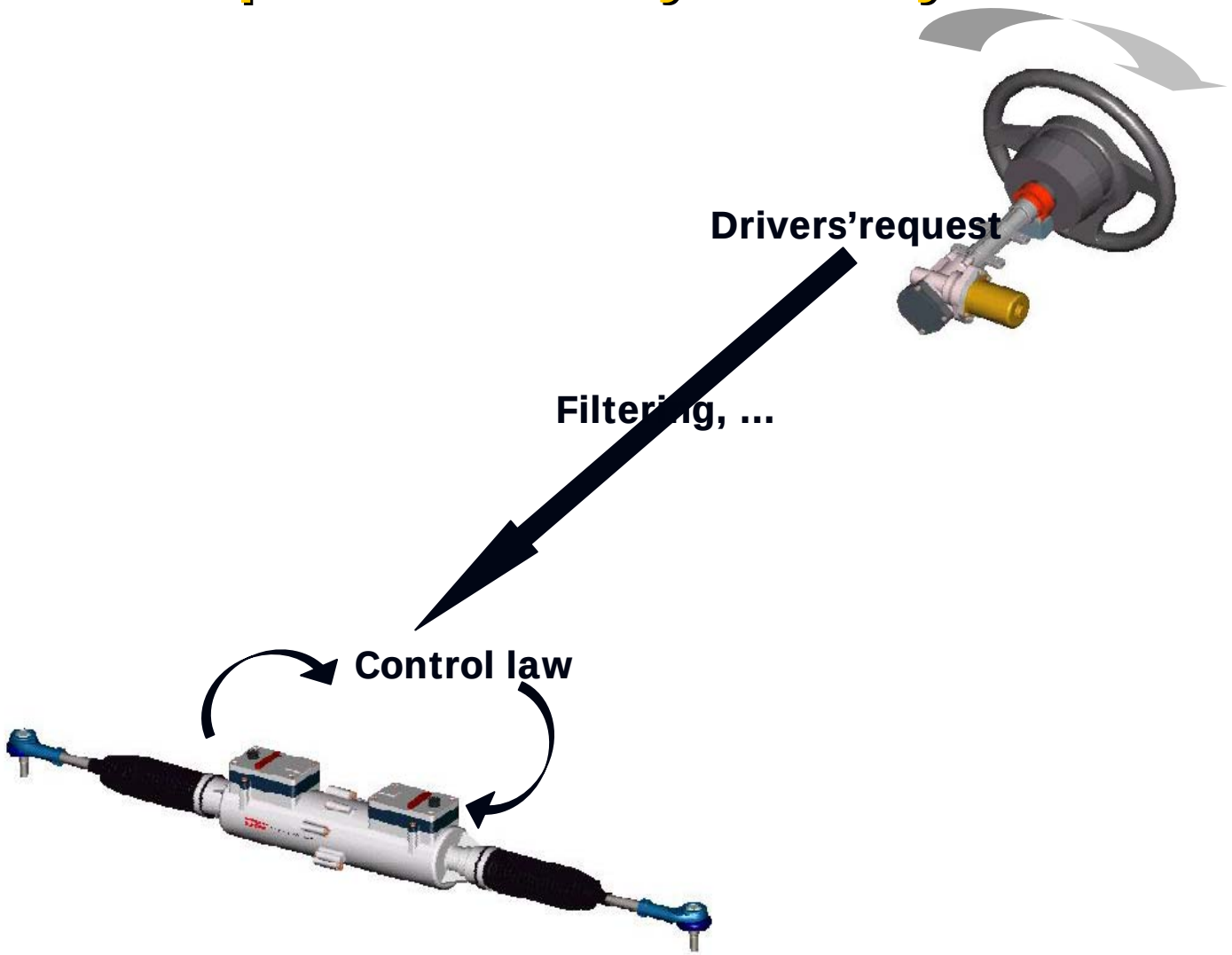
An open issue: safety assessment

- Design for cost, performance
  → Design for safety
- Reliability of electronic devices: difficult to evaluate formally
- Perturbation due to environment: not completly known
- Models for dependability evaluation: difficult to build, what level of accuracy, difficult to analyze
- Emergence of X-by-Wire systems (electronic technology): required stringent safety properties

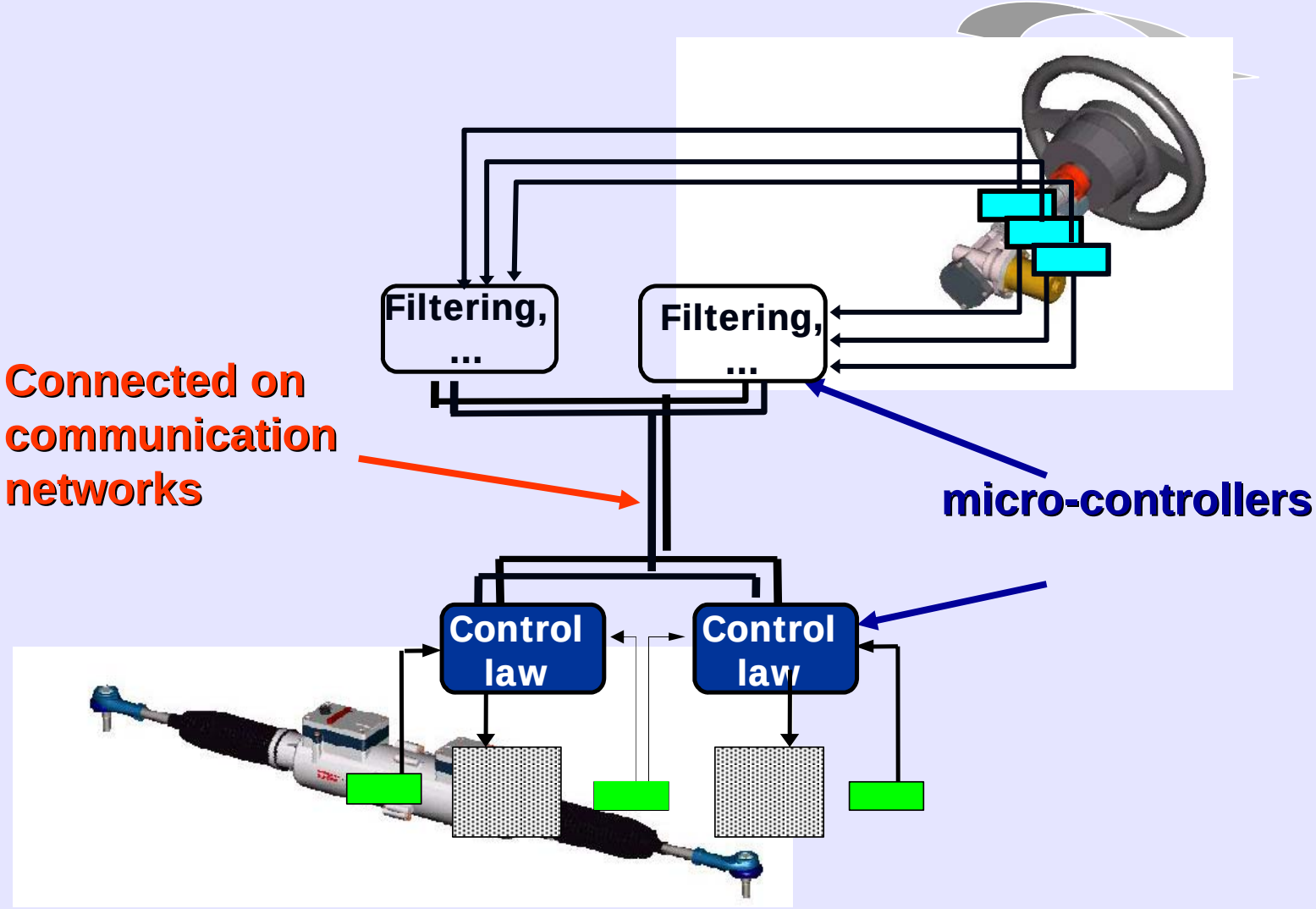
An open issue: safety assessment

Example: a Steer-by-Wire system



An open issue: safety assessment

Example: a Steer-by-Wire system



An open issue: safety assessment

- **Regulatory laws**
  - Internal recommendations, TüV
- **Standards**
  - DO 178B, C (avionic), EN 50128 (railway industry)
  - MISRA (Motor Industry Software Reliability Association)
  - IEC 61 508 (generic)
  - OSI 26 262 (draft 2005, forecasted publication 2007)

(Automotive) Safety Integrity Level
SIL1 .. SIL4 / ASILx

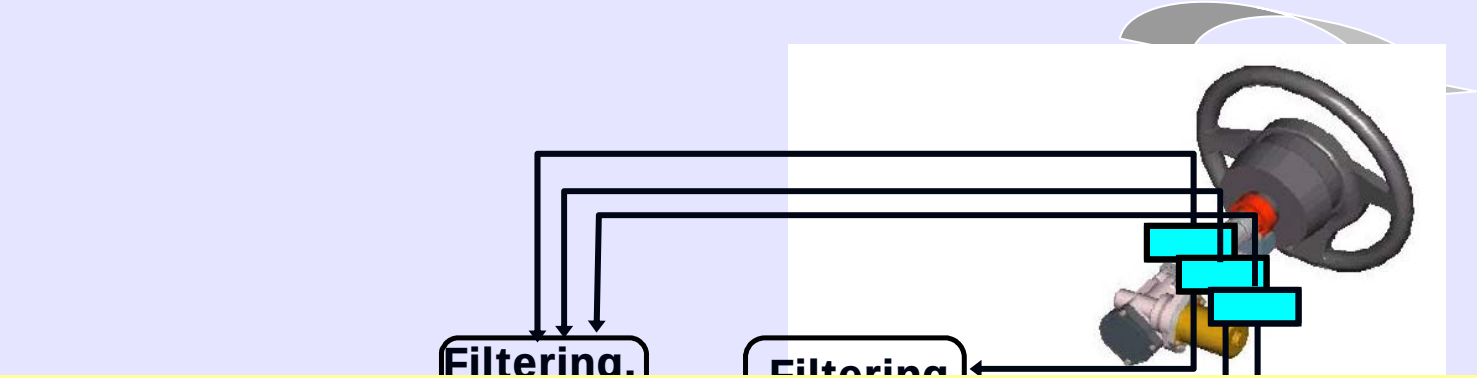
An open issue: safety assessment

- **OSI 26 262**
  - **Identification of scenario, situation**
    - **Frequency (often, quite often, sometimes, rare events)**
    - **Severity (death of persons, severe, light, no injuries)**
    - **Driver controllability (no, >1/100, >1/10)**
  - **Determination of function ASIL**
    - **ASIL A, …, ASIL D**
  - **ASILx corresponds to safety integrity attributes**
    - **Functional (no wrong signals)**
    - **Quantitative**

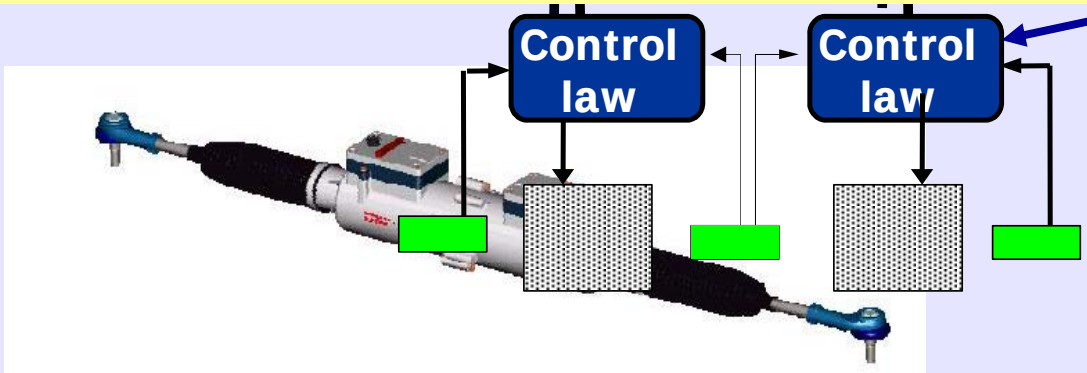
      Probability for a critical failure to occur in one hour < 10^{-n}

An open issue: safety assessment

Example: a Steer-by-Wire system



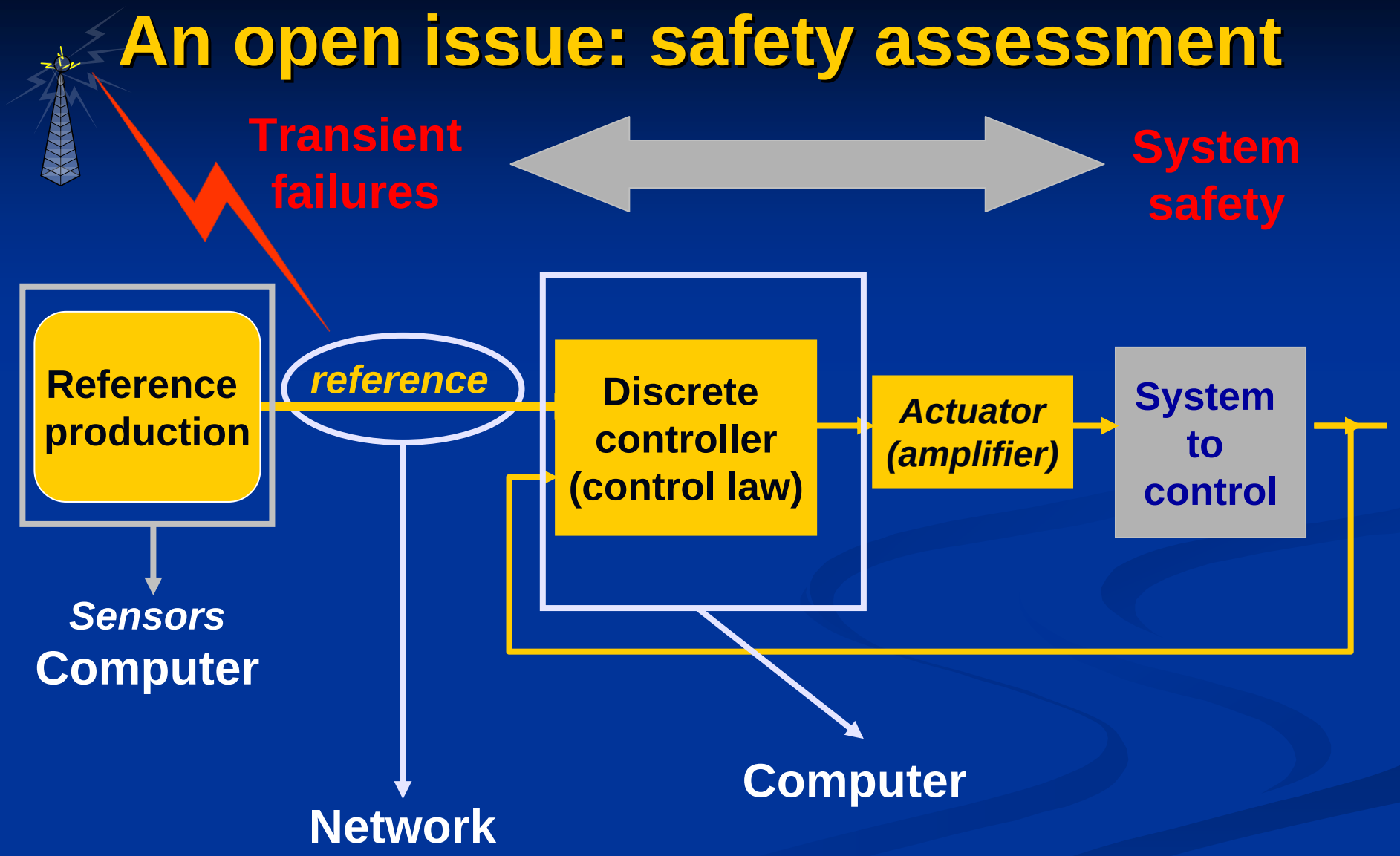
Probability of a critical failure occurrence < 10^{-9}



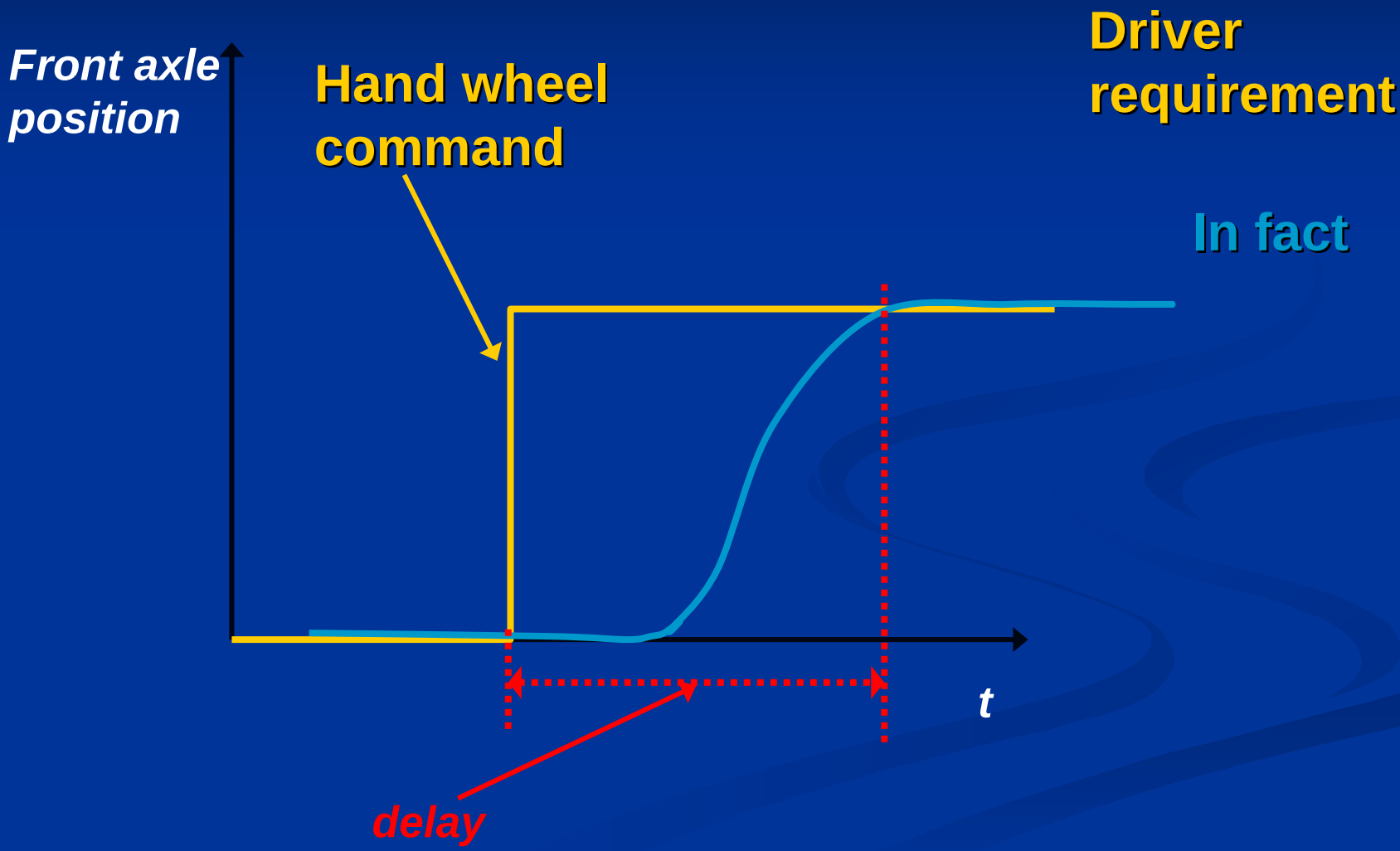
An open issue: safety assessment

- **A steer-by-wire: safety evaluation**
  - On hardware components/architecture
  - On software components (proof, code inspection, test cover, etc.)
  - On the operational architecture
    - Behavioral aspects (tasks, frames)
      - Vehicle response time
      - Embedded systems response time
    - Behavior *under transient faults* (EMI perturbations, overload situation, …)

An open issue: safety assessment

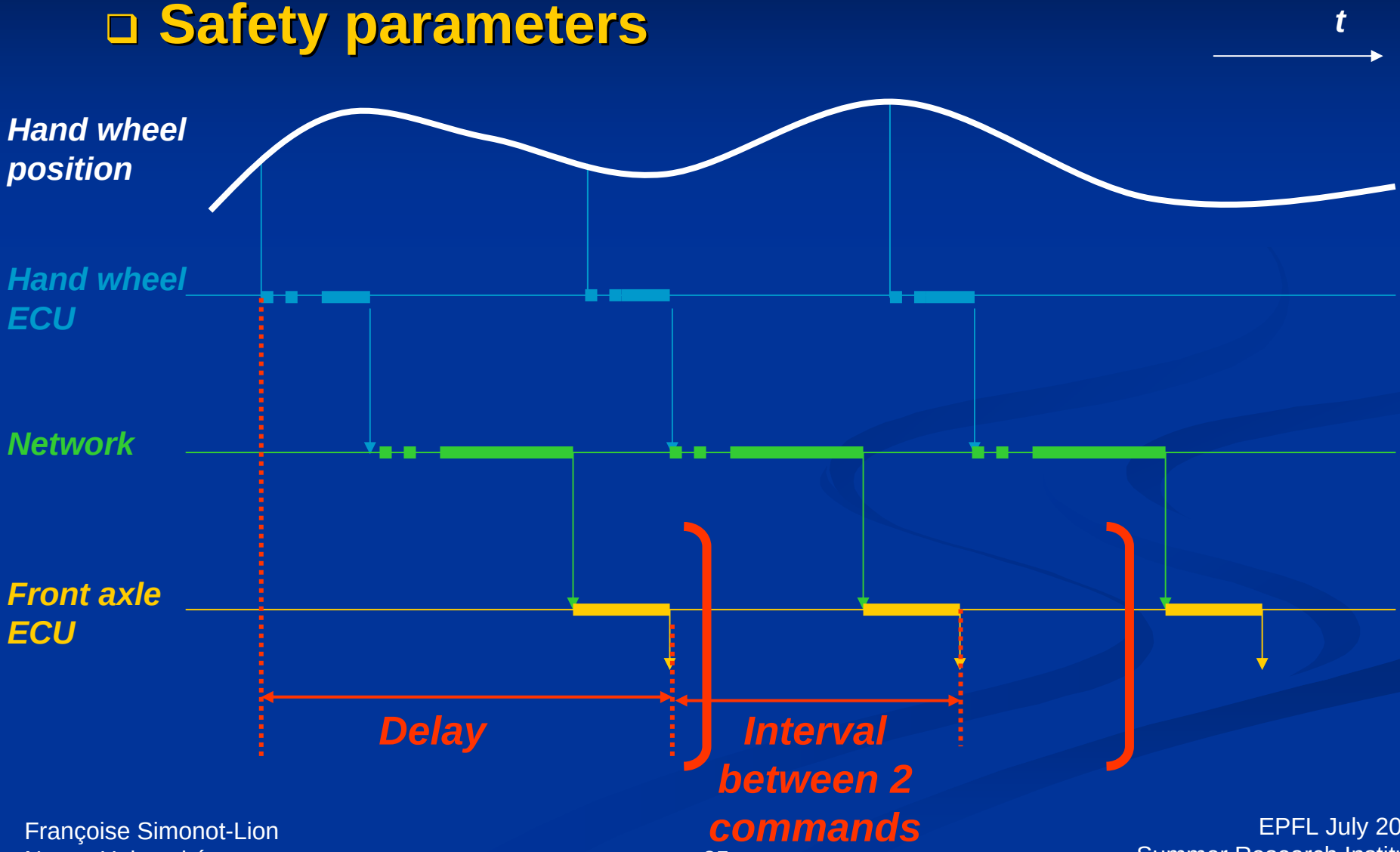


An open issue: safety assessment



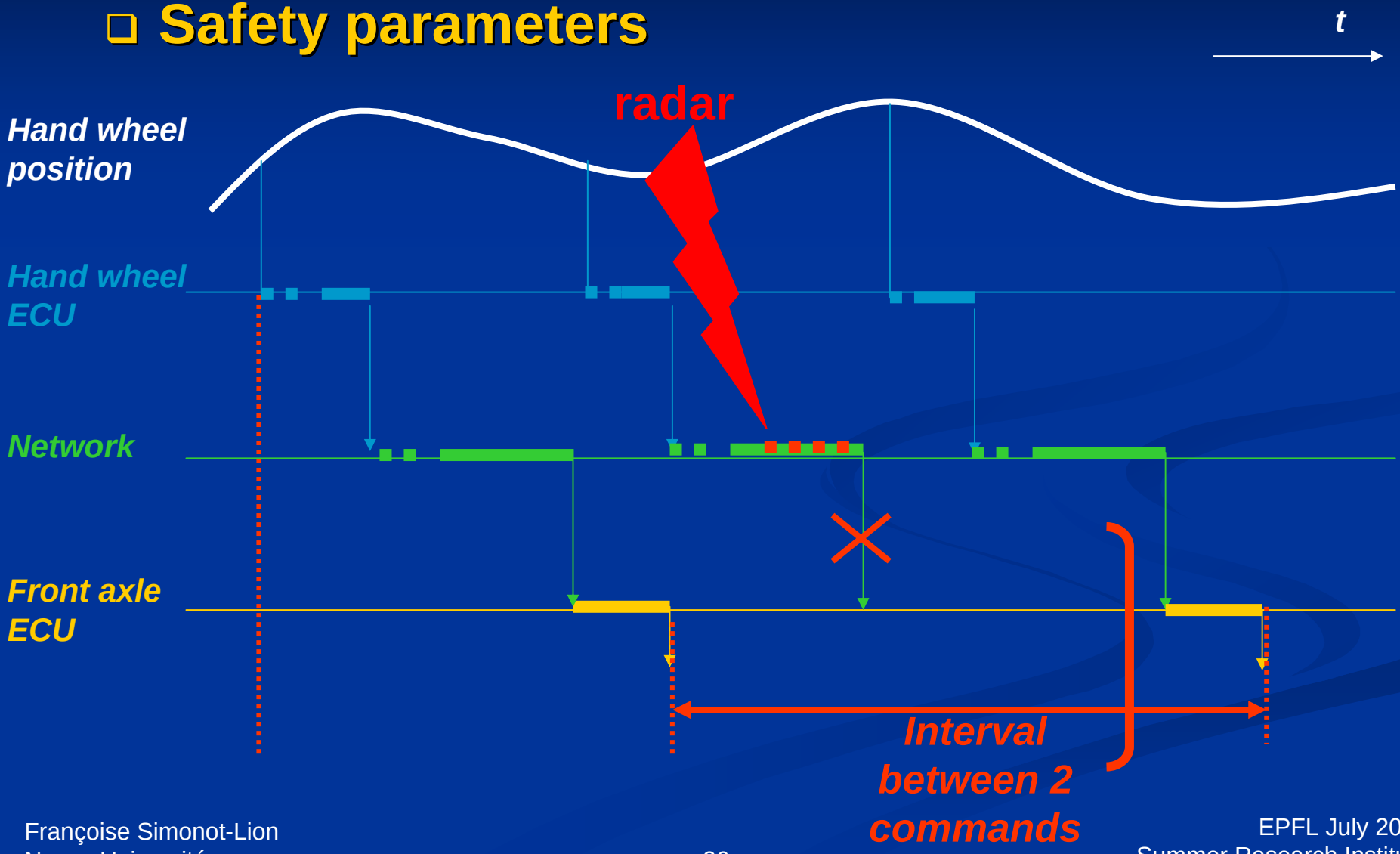
An open issue: safety assessment

- **Safety parameters**



An open issue: safety assessment

- **Safety parameters**



Technological standards

- **Networks and protocols - paradigms**
  - **Event-triggered**

    Transmission of messages only when an event occurs

CAN

+	-
minimisation of bandwith consumption incremental design	verification of temporal constraints detection of failed nodes

TTCAN
FTTCAN
FlexCAN
FlexRay

  - **Time-triggered**

    Transmission of message at predetermined points in time

TTP/C

+	-
predictability detection of failed nodes	network utilisation (aperiodic messages) flexibility

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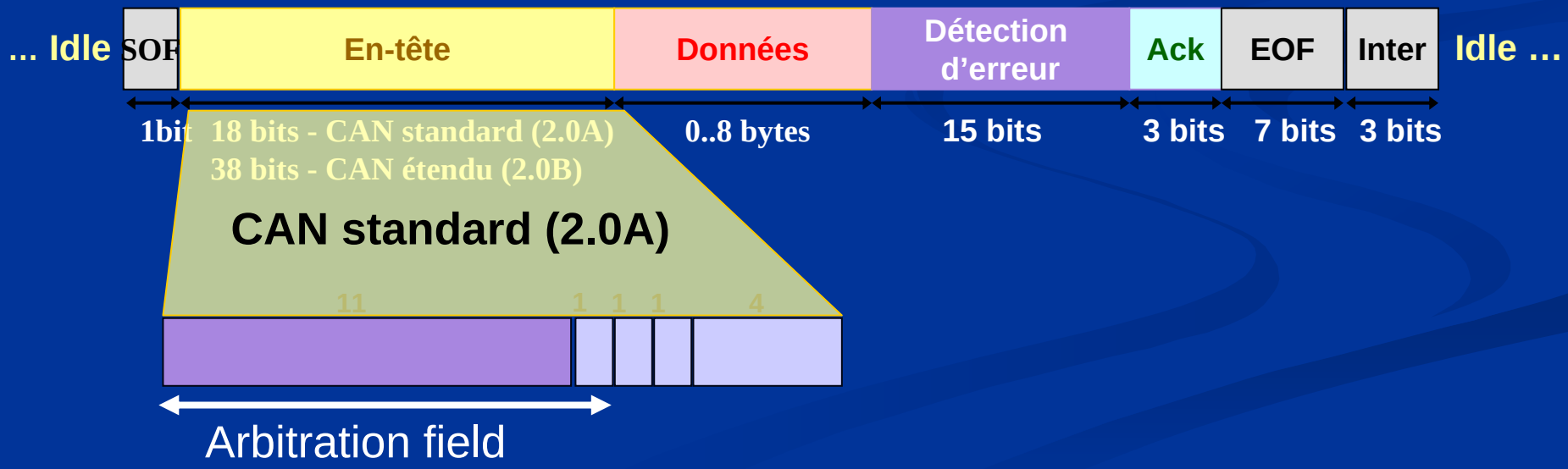
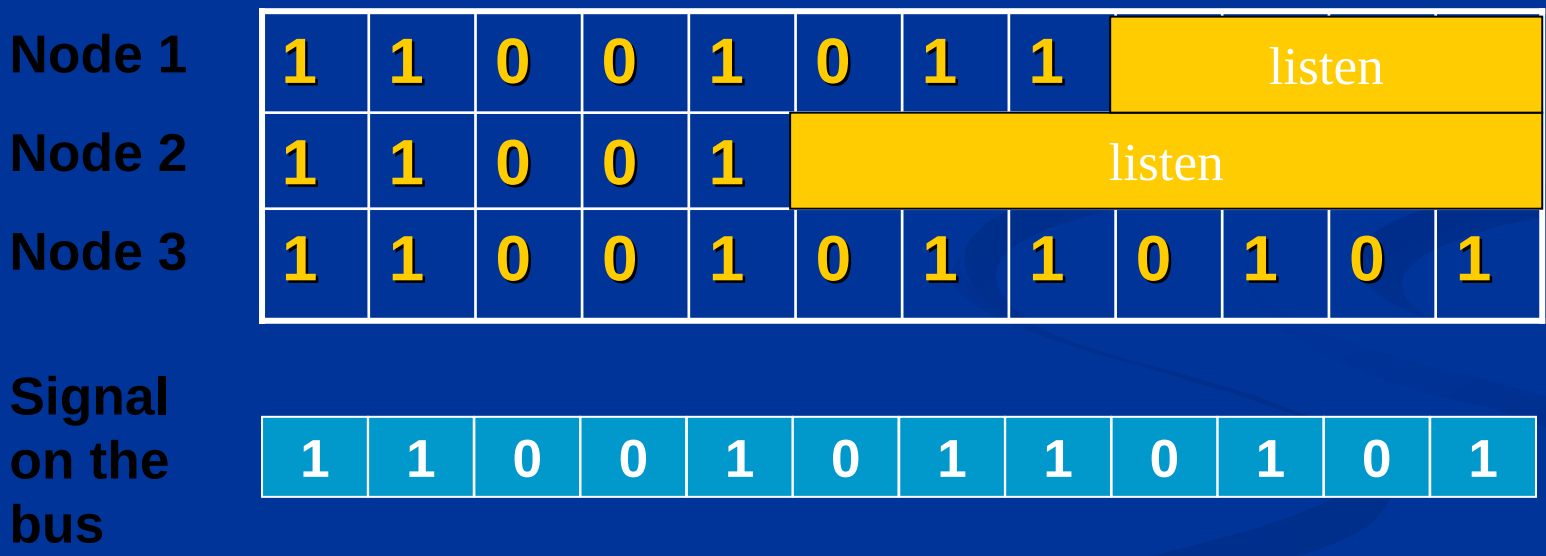
CAN – format of the frame

- Start of Frame (SOF) / synchronisation
- Header
- Application data
- CRC field
- Acknowledgement field
- End of frame (EOF), Intermission frame (Inter)



CAN – Priority-based arbitration

- Arbitration – bit dominant (0) / recessive (1)
- Frame identifier
- Example : 3 nodes try to emit at the same time



Node 3 gain access to the bus

CAN – response time evaluation

- **Without error**

- **Periodic / sporadic emission of frames**
  - Period T_m (seconds)
  - Length of application data s_m (bytes)
- **Bounded jitter on frame emission**
  - Jitter J_m (seconds)
- **Constraint**
  - Relative deadline D_m (seconds)

CAN – response time evaluation

- Frames are scheduled on the bus according to a Fixed Priority *Non Premptive*(FPNP) scheduling policy
- The worst case response time of a frame is given by (K. Tindell, 1994):

$$R_m = J_m + w_m + C_m$$

Emission jitter

Worst waiting time to gain access to the bus

Worst (physical) transmission time

$$R_m \leq D_m$$

CAN – response time evaluation

- Worst (physical) transmission time (11 bits identifier)

Overhead due to stuffing

$$C_m = \left(\left\lfloor \frac{34 + 8s_m}{4} \right\rfloor + 47 + 8s_m \right) \tau_{bit}$$

Length of applicative data (bytes)

Bit time duration (1μs for a 1Mbit/s. bus)

CAN – response time evaluation

Worst waiting time

Worst blocking time due to frames of lower priority (no preemption)

Worst blocking time due to frames of higher priority

$$w_m = B_m + \sum_{\forall j \in hp(m)} \left\lceil \frac{w_m + J_j + \tau_{bit}}{T_j} \right\rceil C_j$$

Set of frames of higher priority than m

Emission period of frame j

$$B_m = \max_{\forall k \in lp(m)} (C_k)$$

Set of frames of lower priority than m

CAN – response time evaluation

- Recurrent algorithm

$$w_m^n = \max_{\forall k \in lp(m)} (C_k) + \sum_{\forall j \in hp(m)} \left\lceil \frac{w_m^{n-1} + J_j + \tau_{bit}}{T_j} \right\rceil C_j$$

$$w_m^0 = 0$$

CAN – response time evaluation

- **Under errors**

- **Periodic / sporadic emission of frames**
  - **Period T_m(seconds)**
  - **Length of application data s_m (bytes)**
- **Bounded jitter on frame emission**
  - **Jitter J_m(seconds)**

CAN – response time evaluation

- **Error model 1 (K. Tindell, 1994)**
  - ∀ t, in [0,t]
    - 0 or 1 burst of errors
    - Size of the burst: n_{errors}
    - Minimal interarrival of two consecutive errors: T_{errors}

Worst case – maximum number of errors in [0,t]:

$$\left(n_{error} + \left\lceil \frac{t}{T_{error}} \right\rceil - 1\right)$$

CAN – response time evaluation

- **Overhead due to one error**
  - **Error frame emission**

    23 τbits (worst case)

  - **Retransmission of the erroneous frame**

    occurrence of all the errors at the last bit of the longuest frame that is able to be transmitted (worst case)

CAN – response time evaluation

Overhead due to the errors occurring in $\left[0 \quad w_m^{n-1} + C_m\right]$

Worst waiting time to gain access to the bus (without errors)

$$w_m^n = E_m(w_m^{n-1} + C_m) + \max_{\forall k \in lp(m)}(C_k) + \sum_{\forall j \in hp(m)} \left\lceil \frac{w_m^{n-1} + J_j + \tau_{bit}}{T_j} \right\rceil C_j$$

$$w_m^0 = 0$$

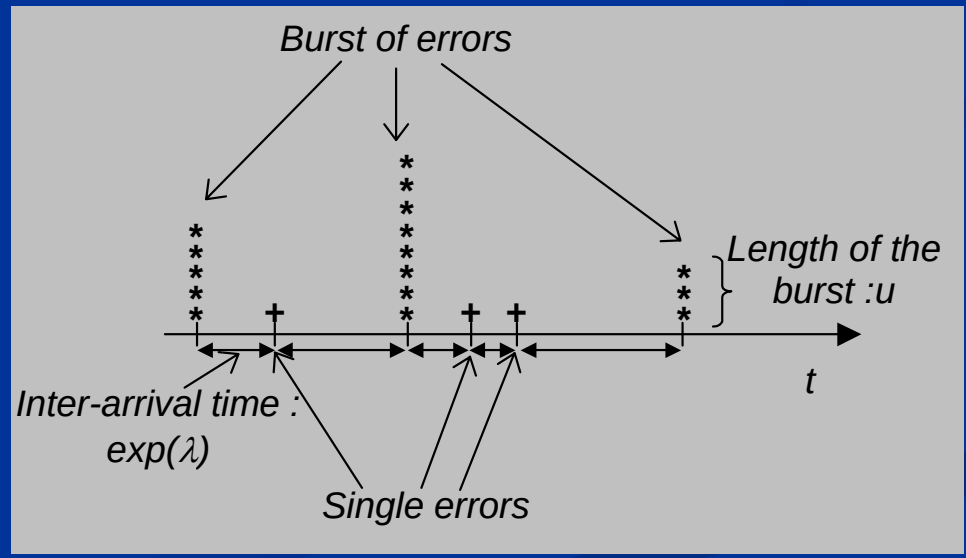
$$E_m(t) = (n_{error} + \left\lceil \frac{t}{T_{error}} \right\rceil - 1).(23\tau_{bit} + \max_{j \in hp(m)}(C_j))$$

CAN – response time evaluation

- **Error model 2 (N. Navet, 1999)**

The number of errors in [0 t] is a random variable *X(t)*

- the inter-arrival of errors is given by ***exp(λ)***,
- the length of a burst (number of errors) is given by ***u***,
- when an error occurs, ***a*** is the probability that this error is a burst and ***1-a*** that it is a single error



CAN – response time evaluation

Overhead due to i errors

Worst waiting time to gain access to the bus

$$w_m^n(i) = \varepsilon_m(i) + \max_{\forall k \in lp(m)}(C_k) + \sum_{\forall j \in hp(m)} \left\lceil \frac{w_m^{n-1}(i) + J_j + \tau_{bit}}{T_j} \right\rceil C_j$$

$$w_m^0(i) = 0$$

$$\varepsilon_m(t) = i.(23\tau_{bit} + \max_{j \in hp(m)}(C_j))$$

$$\eta_m = \max\{n \in N \mid R_m(n) \leq D_m\}$$

worst-case deadline failure probability

$$P[X(R_m(\eta_m)) > \eta_m]$$

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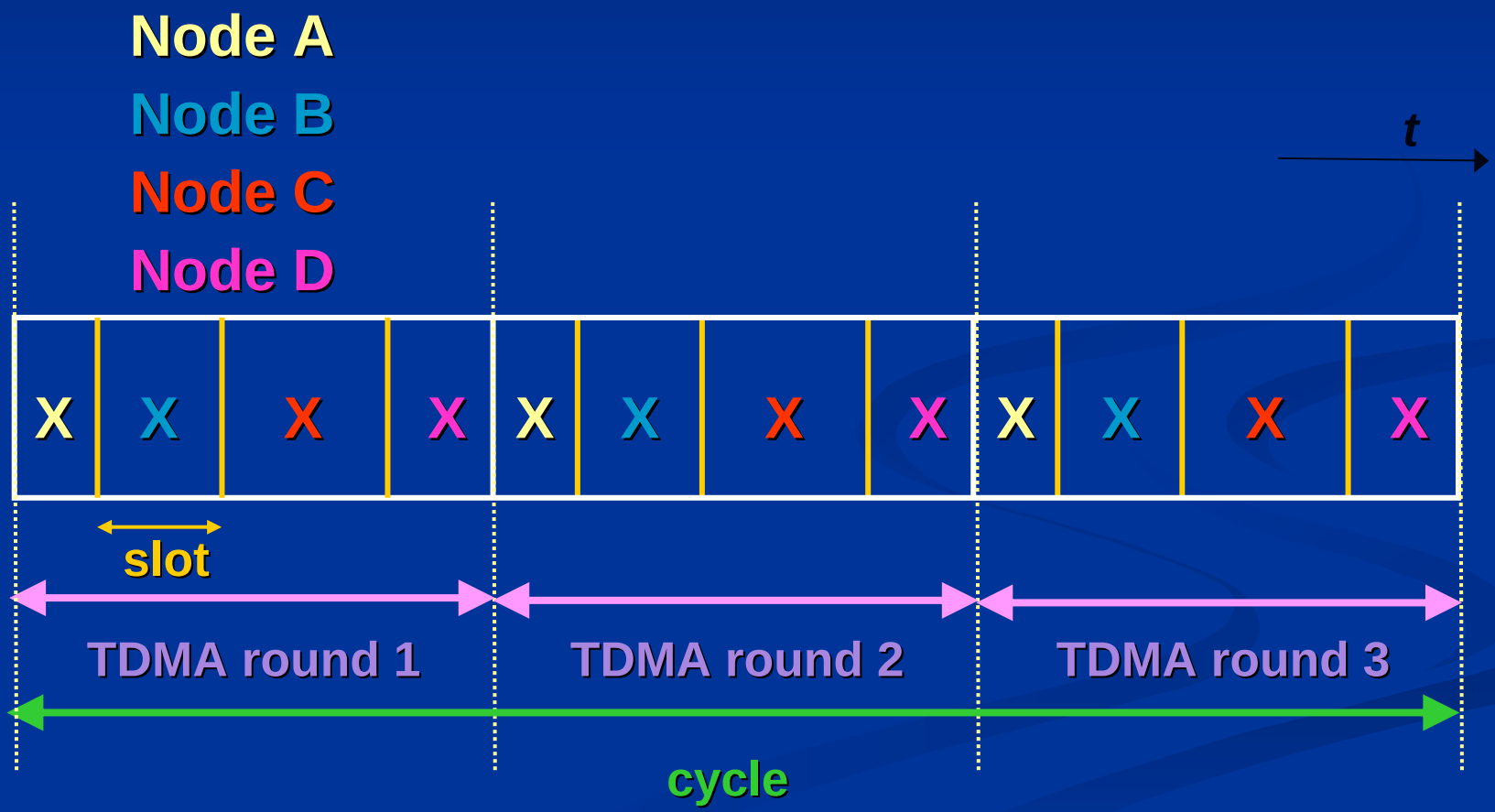
TDMA-based protocol

- Principles



TDMA-based protocol

- **Probability for the system to reach a critical failure mode (Wilwert, 2005)**

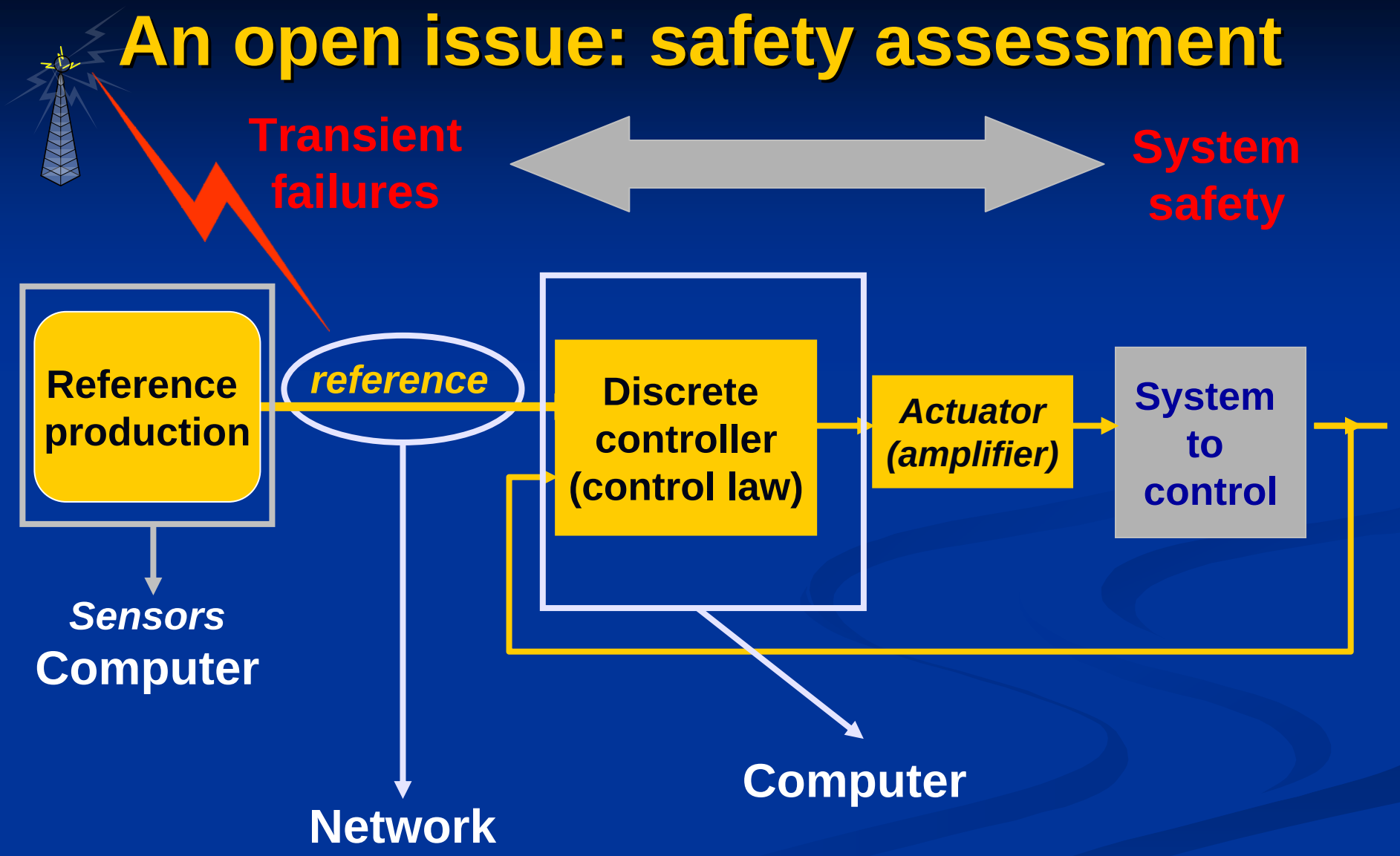
External fault (EMI perturbation)

Failure at communication system level (erroneous frame)

Fault at the controller level (loss of a reference)

Failure at system level (the system is no more safe)

An open issue: safety assessment



TDMA-based protocol

- Models

Parameters (cycle length, etc.)

Fault injection

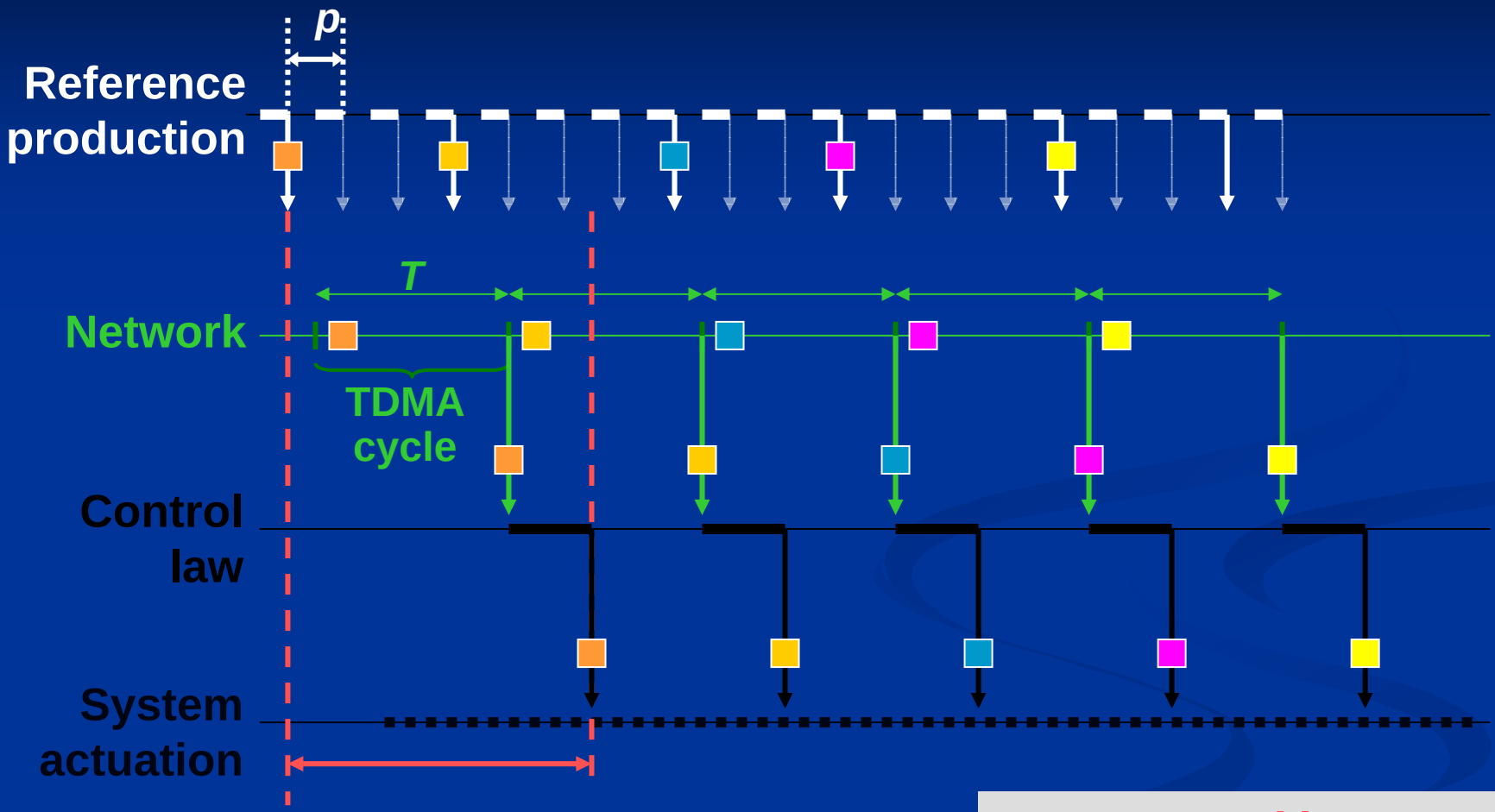
Indicators

Control law
+
implementation model

Matlab / Simulink model

SimulinkCar model

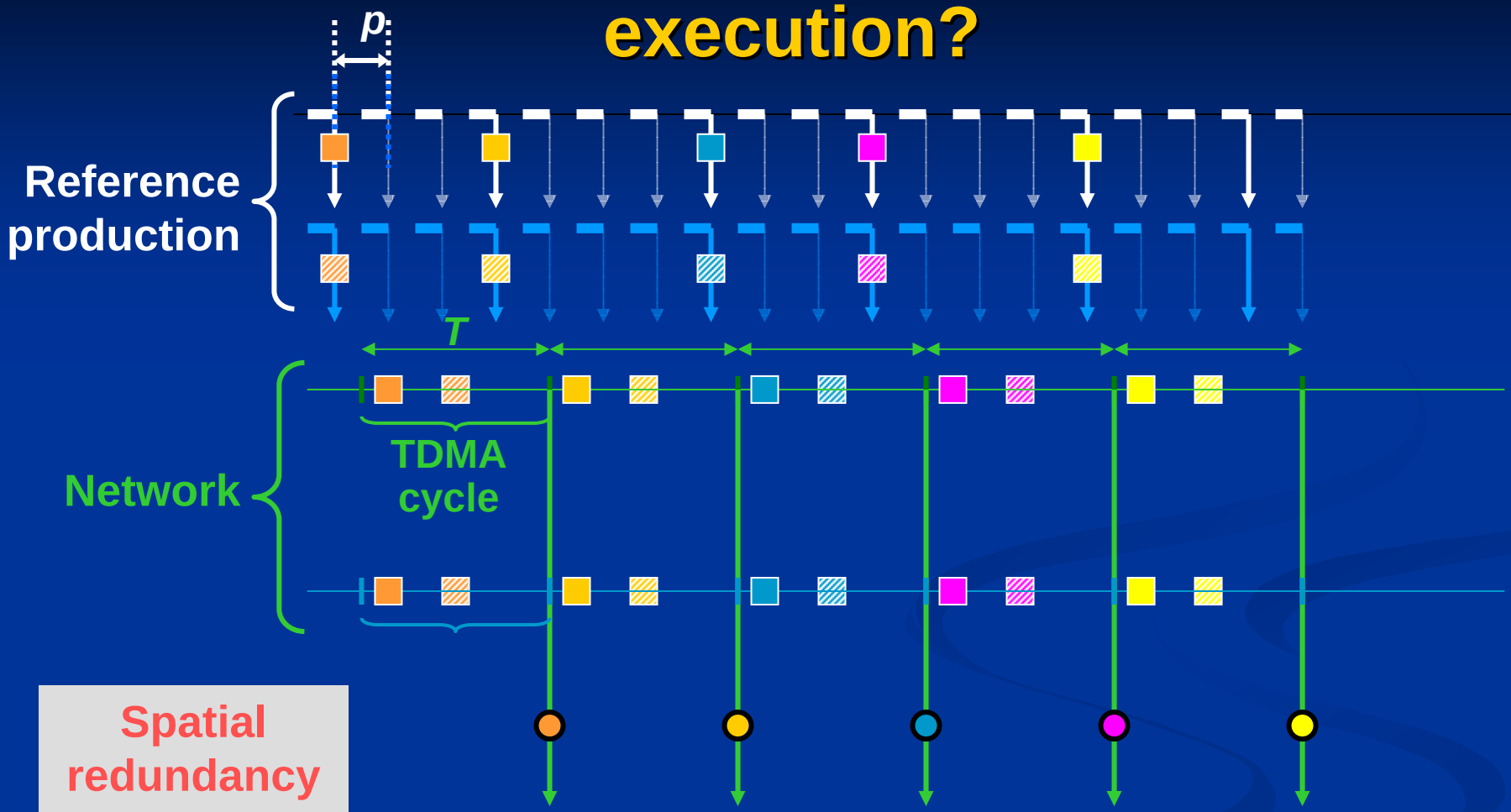
Which reference for each control law execution?



Bounded delay

Control law synchronized with the TDMA cycle

Which reference for each control law execution?

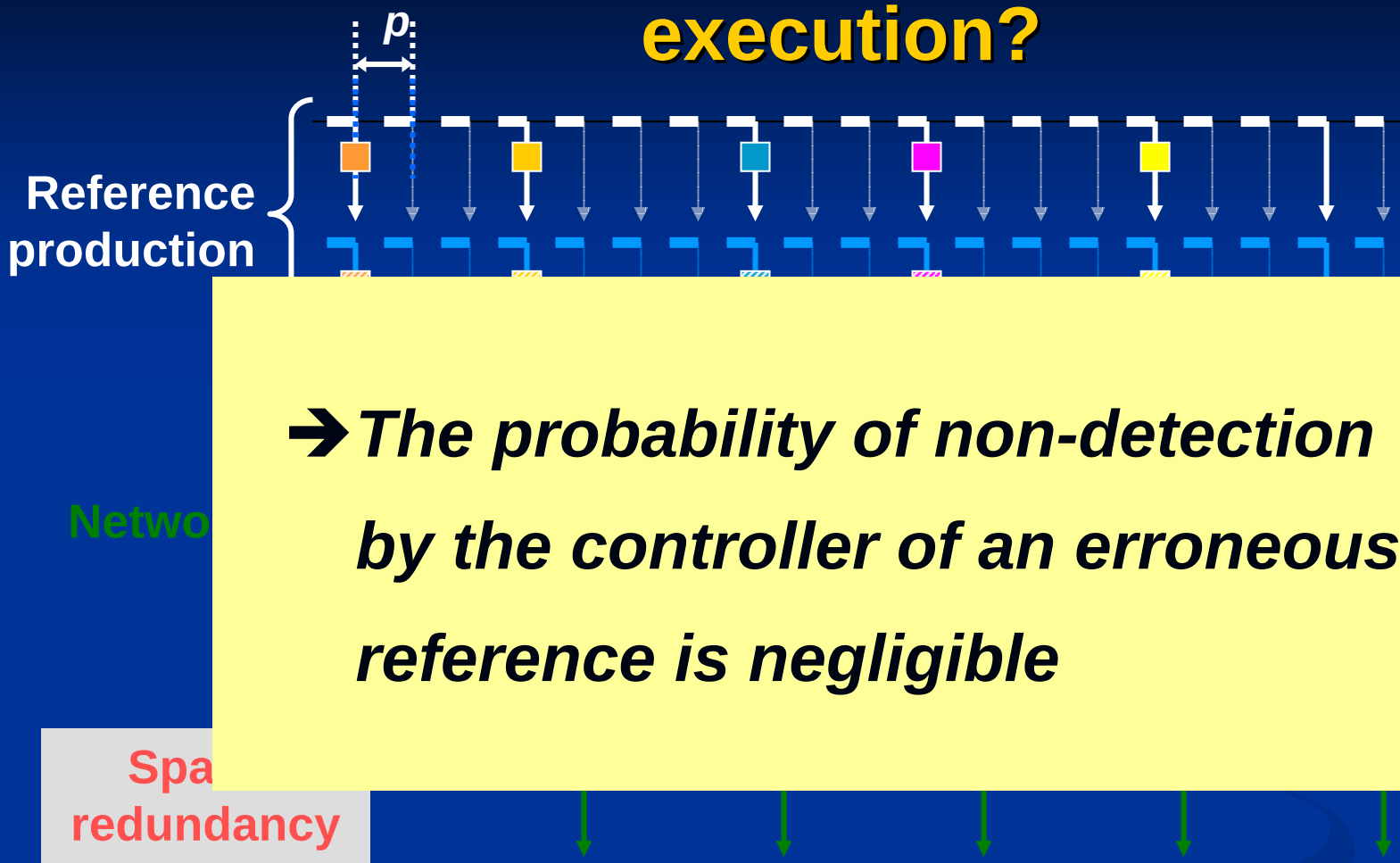


Spatial redundancy (two buses)

Temporal redundancy (FTU = 2 producer nodes)

Fail silence of the producers

What reference for each control law execution?



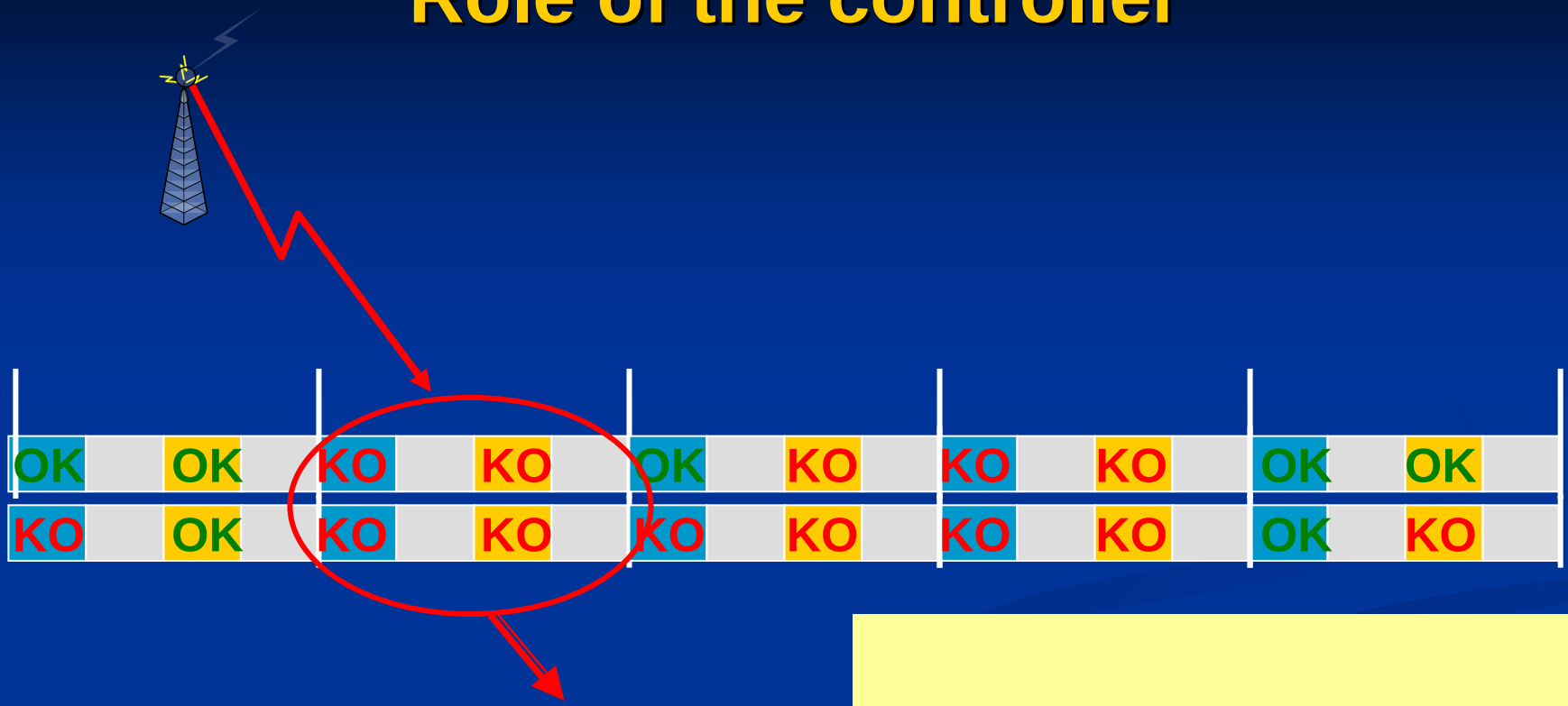
➔ *The probability of non-detection by the controller of an erroneous reference is negligible*

Role of the controller

External fault

Failure at the « slot » level

Role of the controller



Failure at the TDMA-cycle level = Fault for the controller

➔ ***Fault tolerance of the controller:***

recovery mechanism

(compensation)

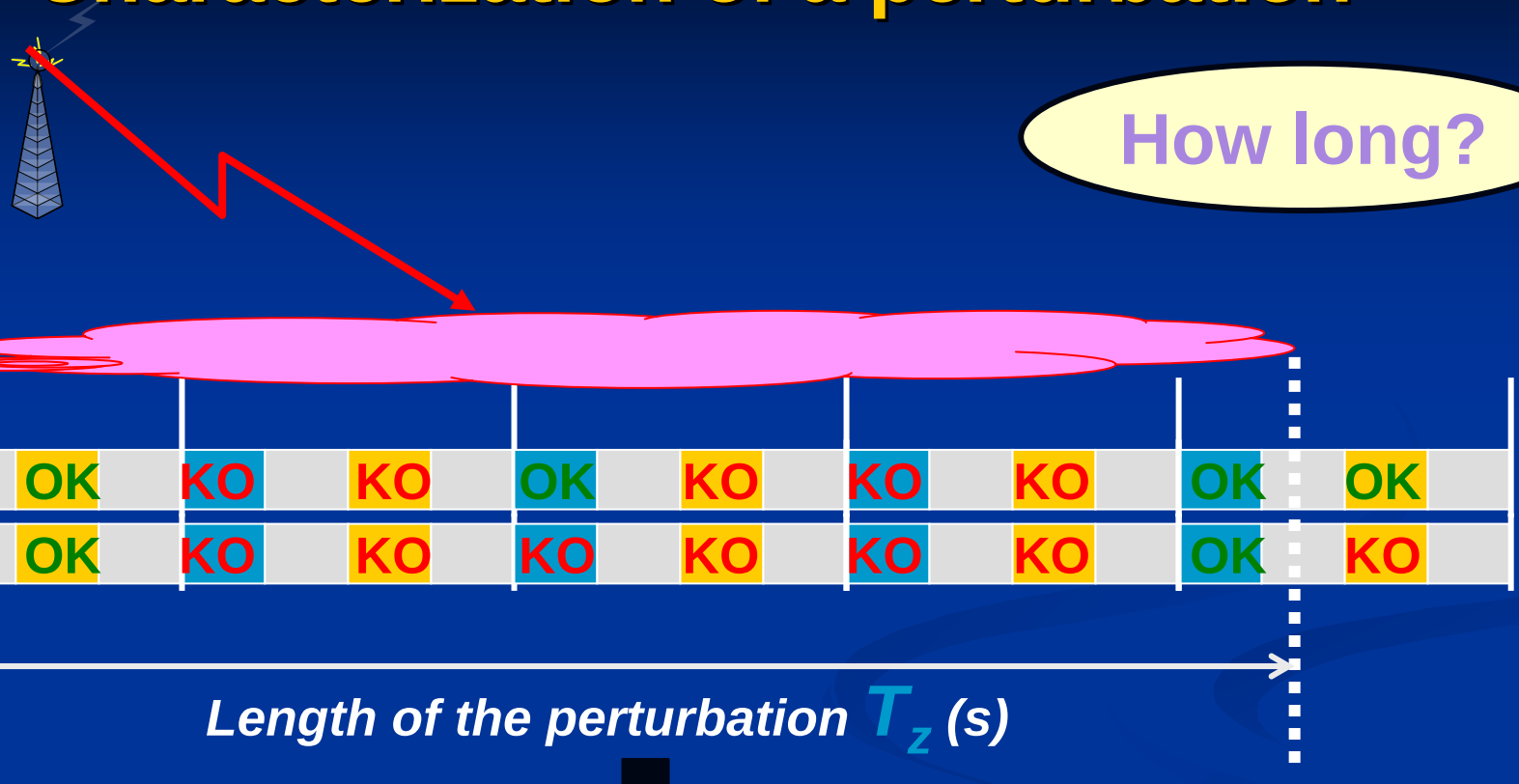
Role of the controller

➔ ***Failure of the controller:***

the controller is able to control the system in a safe mode if and only if there are less than k consecutive faults

The system is therefore no more safe!

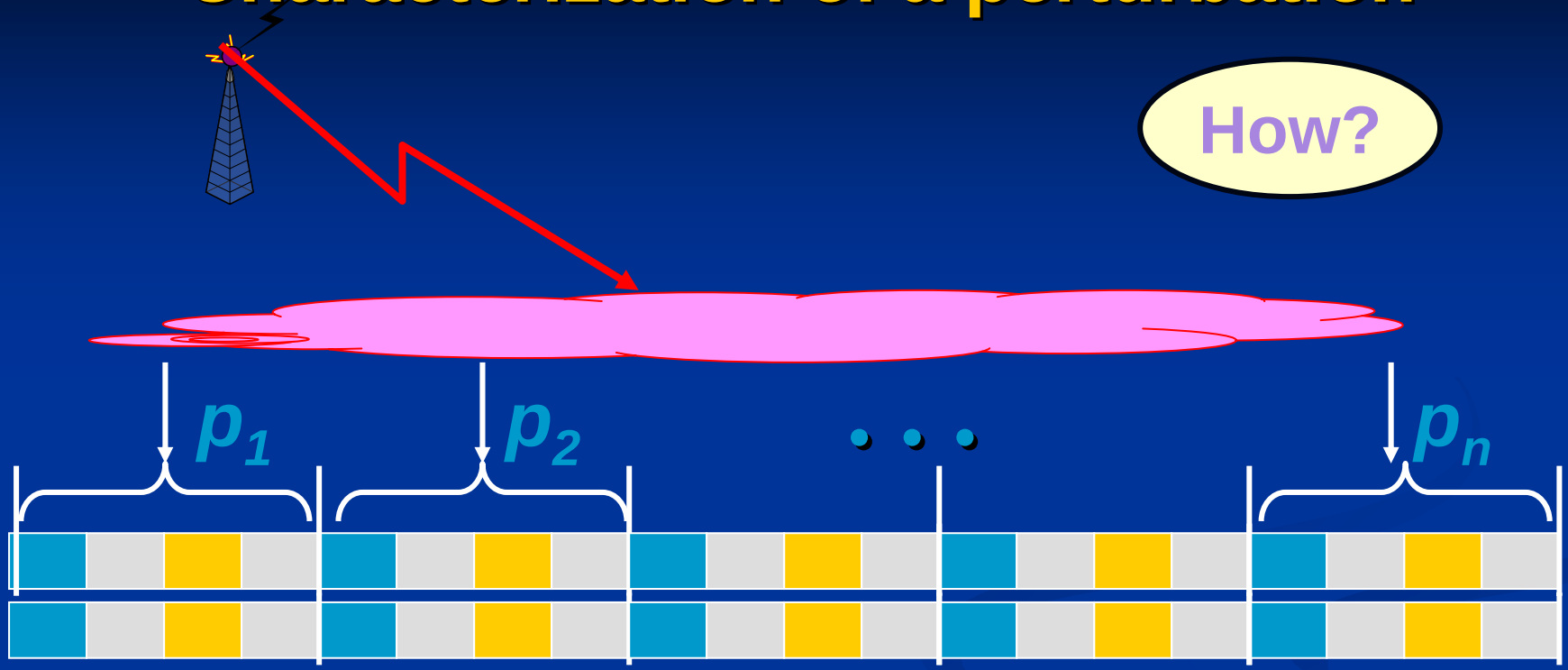
Characterization of a perturbation



Length of the perturbation n *(TDMA cycles) – worst case*

$$n = \left\lceil \frac{T_z}{T} \right\rceil + 2$$

Characterization of a perturbation



p_i **probability for the i^{th} TDMA cycle in a sequence of n cycles to be fully corrupted**

Problem

To determine the probability to have more than k consecutive corrupted cycles when the system is under a perturbation whose duration is T_z and whose effect is given by the function $P(p_1, p_2, \ldots, p_n)$

$$P_{fail}(k, T_z, P)$$

Technical solutions

- **Similar to « consecutive-k-out-of-n:F » systems - C(k,n:F)**
  - System = ordered sequence of n components
  - The system fails if and only if more than k consecutive components fail
  - *L_n: number of consecutive failed components*

$$P(L_n < k) = R(k, n; p)$$

[Burr,1961], [Lambridis,1985], [Hwang,1986]

$p_1 = p_2 = \ldots = p_n = p$

$$R(n,k;p) = \sum_{m=0}^{\lfloor (n+1)/(k+1) \rfloor} (-1)^m \, p^{mk} q^{m-1} \left(\binom{n - mk}{m-1} + q \binom{n-mk}{m} \right)$$

with $q = 1 - p$

Efficient algorithm (ETFA05)

Technical solution for *P* variable?

- **Recurrent relation:**

Given a probability profile P = (p_1, p_2, …, p_n)

$$u_m(k) = u_{m-1}(k) - \lambda_m(k) u_{m-k-1}(k) \quad \text{for} \quad k+1 \le m \le n$$

$$u_m(k) = 1 \quad \text{for} \quad 0 \le m \le k-1$$

$$u_k(k) = 1 - \lambda_k(k)$$

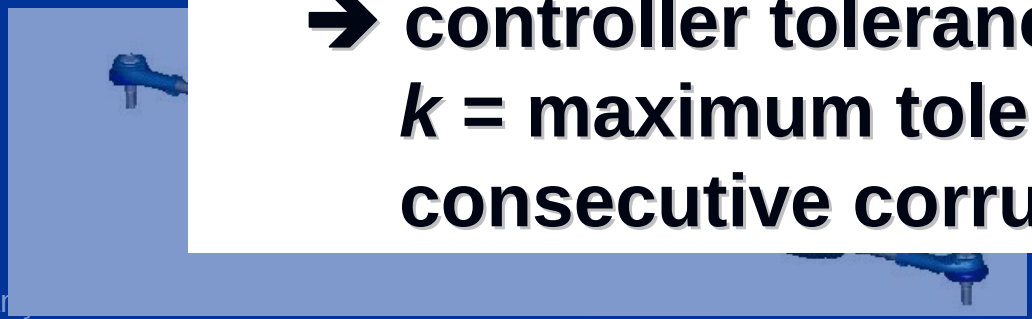
$$\lambda_m(k) = q_{m-k} p_{m-k+1} p_{m-k+2} \cdots p_m$$

$$\text{for} \quad m \ge k \quad \text{with} \quad q_0 = 1 \quad \text{and} \quad q_m = 1 - p_m$$

$$P_{fail}(k, T_z, P) = 1 - u_n(k), \text{ with } n = \left\lceil \frac{T_z}{T} \right\rceil + 2$$

Case study: a Steer-by-Wire system

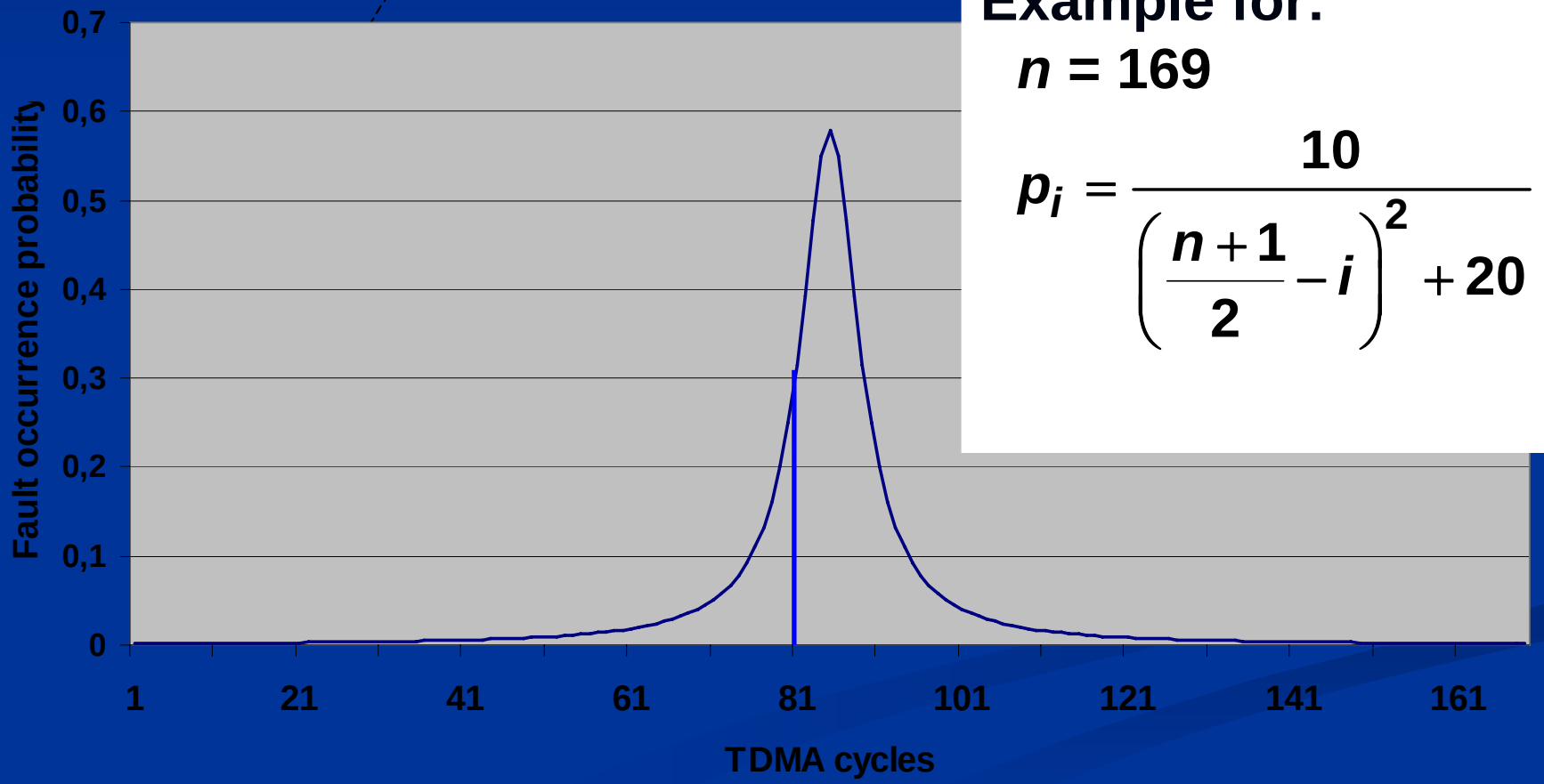
- **Extreme situation**
  - vehicle speed (90 km/h)
  - sharp turning
- **Perturbated area Tz = 1.5 s**
- **Matlab/Simulink model**
  - Controller + Vehicle
  - Fault injection / simulation



➔ **controller tolerance**
k **= maximum tolerated number of consecutive corrupted TDMA-cycles**

Case study: a Steer-by-Wire system

- Perturbation profile: radio transmitter



Example for:

$n = 169$

$$p_i = \frac{10}{\left(\frac{n+1}{2} - i\right)^2 + 20}$$

Case study: a Steer-by-Wire system

$$p_i = \frac{10}{\left(\frac{n+1}{2} - i\right)^2 + 20}$$

TDMA cycle *T* (ms)	Perturbation duration *n* (TDMA cycles)	Tolerance of the controller *k* (TDMA cycles)	System failure probability *Pfail*
4	377	10	$2.2\ 10^{-8}$
7	217	5	$1.6\ 10^{-3}$
10	152	4	$0.8\ 10^{-2}$

Conclusions

- **Automotive industry is dependent of software-based embedded systems**
  - **Emergence of X-by-Wire systems**
  - **Technological standards – communication networks**
- **Safety assessments**
  - **Standard ISO 26 262**
  - **Integration of several points of view**

Timing, dependability annotations

Certification, verification

Muli-competencies experts

References

- K. Tindell, H. Hanssmon, A. J. Wellings, *Analysing Real-Time Communications: Controller Area Network (CAN)*, IEEE Real-Time Systems Symposium 1994: 259-263
- K. Tindell, A. Burns, A. J. Wellings, *An Extendible Approach for Analyzing Fixed Priority Hard Real-Time Tasks*, Real-Time Systems 6(2): 133-151 (1994)
- K. Tindell, J. Clark, *Holistic schedulability analysis for distributed hard real-time systems*, Microprocessors and Microprogramming, vol. 40, pp. 117–134, 1994.
- A. Burns, K. Tindell, A. J. Wellings, *Effective Analysis for Engineering Real-Time Fixed Priority Schedulers*, IEEE Trans. Software Eng. 21(5): 475-480 (1995)
- K. Tindell, A. Burns, A.J. Wellings, Calculating controller area network (CAN) message response times, Control Engineering Practice, vol. 3, no. 8, pp. 1163–1169, 1995.
- N. C. Audsley, Alan Burns, R. I. Davis, K. Tindell, A.y J. Wellings, *Fixed Priority Pre-emptive Scheduling: An Historical Perspective*, Real-Time Systems 8(2-3): 173-198 (1995)
- K. Tindell, A. Burns, A. J. Wellings, *Analysis of Hard Real-Time Communications*, Real-Time Systems 9(2): 147-171 (1995)
- S. Poledna, *Fault-Tolerant Real-Time Systems: The Problem of Replica Determinism*, Kluwer Academic Publishers, 1996.
- H. Kopetz, *Real-Time Systems: Design Principles for Distributed Embedded Applications*, Kluwer Academic Publishers, 1997.
- M. Krug, A. V. Schedl, *New demands for in-vehicle networks*, in Proceedings of the 23rd EUROMICRO Conference'97, Budapest, Hungary, July 1997, pp. 601–605.
- X-by-Wire Project, Brite-EuRam 111 Program, *X-By-Wire - safety related fault tolerant systems in vehicles, final Report*, 1998.
- S. Poledna, W. Ettlmayr, M. Novak, *Communication bus for automotive applications*, in Proceedings of the 27th European Solid-State Circuits Conference, Villach, Austria, September 2001.
- N. Navet , Y.-Q. Song, *Validation of real-time in-vehicle applications*, Computers in Industry, vol. 46, no. 2, pp. 107–122, November 2001.

References

- H. Pfeifer, F.W. von Henke, *Formal Analysis for Dependability Properties: the Time-Triggered Architecture Example*, in Proceedings of the 8th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA 2001), October 2001, pp. 343–352.
- G. Leen, D. Heffernan, *Expanding automotive electronic systems*, *IEEE Computer*, vol. 35, no. 1, January 2002.
- P. Koopman, *Critical embedded automotive networks*, IEEE Micro, Special Issue on Critical Embedded Automotive Networks, vol. 22, no. 4, pp. 14–18, July-August 2002.
- L.-B. Fredriksson, *CAN for critical embedded automotive networks*, *IEEE Micro*, vol. 22, no. 4, July-August 2002.
- G. Lima, A. Burns, *Timing-independent safety on top of CAN*, in Proceedings of the 1st International Workshop on Real-Time LANs in the Internet Age, Vienna, Austria, 2002.
- G. Lima A. Burns, *A consensus protocol for CAN-based systems*, in Proceedings of the 24th Real-time Systems Symposium, 2003, pp. 420–429.
- G. Rodriguez-Navas, M. Barranco, and J. Proenza, *Harmonizing dependability and real time in CAN networks*, in 2nd International Workshop on Real-Time LANs in the internet Age, Porto, Portugal, 2003.
- L.M. Pinho, F. Vasques, *Reliable real-time communication in CAN networks*, IEEE Transactions on Computers, vol. 52, no. 12, pp. 1594–1607, 2003.
- J. Rushby, *A comparison of bus architecture for safety-critical embedded systems*, Technical Report NASA/CR-2003-212161, NASA, March 2003.
- A. Albert, *Comparison of event-triggered and time-triggered concepts with regards to distributed control systems*, in Proceedings of Embedded World 2004, Nürnberg, February 2004.
- M. Ayoubi, T. Demmeler, H. Leffler, P. Köhn, *X-by-Wire functionality, performance and infrastructure*, in *Proceedings of Convergence 2004*, Detroit, Michigan, 2004.
- P. Bühring, *Safe-by-Wire Plus: Bus communication for the occupant safety system*, in *Proceedings of Convergence 2004*, Detroit, Michigan, 2004.

References

- R. Santos Marques, F. Simonot-Lion, N. Navet, Development of an in-vehicle communication middleware, Object Oriented Modeling of Embedded Real-Time Systems, Post-proceedings of OMER 3, Heinz-Nixdorf Institute publisher, 2005.
- N. Navet, F. Simonot-Lion, Fault Tolerant Services for Safe In-Car Embedded Systems, in The Embedded Systems Handbook, CRC Press, 2005.
- C. Wilwert, N. Navet, Y.-Q. Song, F. Simonot-Lion, *Design of Automotive X-by-Wire Systems*, in The Industrial Communication Technology Handbook, CRC Press, 2005.
- B. Gaujal, N. Navet, *Maximizing the Robustness of TDMA Networks with Applications to TTP/C*, Real-Time Systems, Kluwer Academic Publishers, vol 31, n°1-3, pp5-31, December 2005.
- N. Navet, Y.-Q. Song, F. Simonot-Lion, C. Wilwert, *Trends in Automotive Communication Systems*, Proceedings of the IEEE, special issue on Industrial Communications Systems, invited paper, vol 96, n°6, pp1204-1223, 2005.
- N. Navet, Y-Q. Song, F. Simonot, *Worst-Case Deadline Failure Probability in Real-Time Applications Distributed over CAN (Controller Area Network)*, Journal of Systems Architecture, Elsevier Science, vol. 46, n°7, 2000.
- F. Simonot-Lion, Y.-Q. Song, *Design and validation process of in-vehicle embedded electronic systems* in The Embedded Systems Handbook, CRC Press - Taylor&Francis (Ed.) (2005)
- F.Simonot, F. Simonot-Lion, Y.-Q. Song, *Dependability Evaluation of Real-Time Applications Distributed on TDMA-Based Networks,* in 6th IFAC International Conference on Fieldbus Systems and their Applications - FeT'2005 (2005)
- F. Simonot-Lion, F.Simonot, Y.-Q. Song, C. Wilwert, *Quantitative Evaluation of the Safety of X-by-Wire Architecture subject to EMI Perturbations,* in 10th IEEE International Conference on Emerging Technologies and Factory Automation - ETFA'2005 1 (2005) 755-762
- R. I. Davis, A. Burns, R. J. Bril, J. J. Lukkien, *Controller Area Network (CAN) schedulability analysis: Refuted, revisited and revised*, Real-Time Systems 35(3): 239-272 (2007)

Thank you