High Integrity of Communications in Networks for Critical Control Systems

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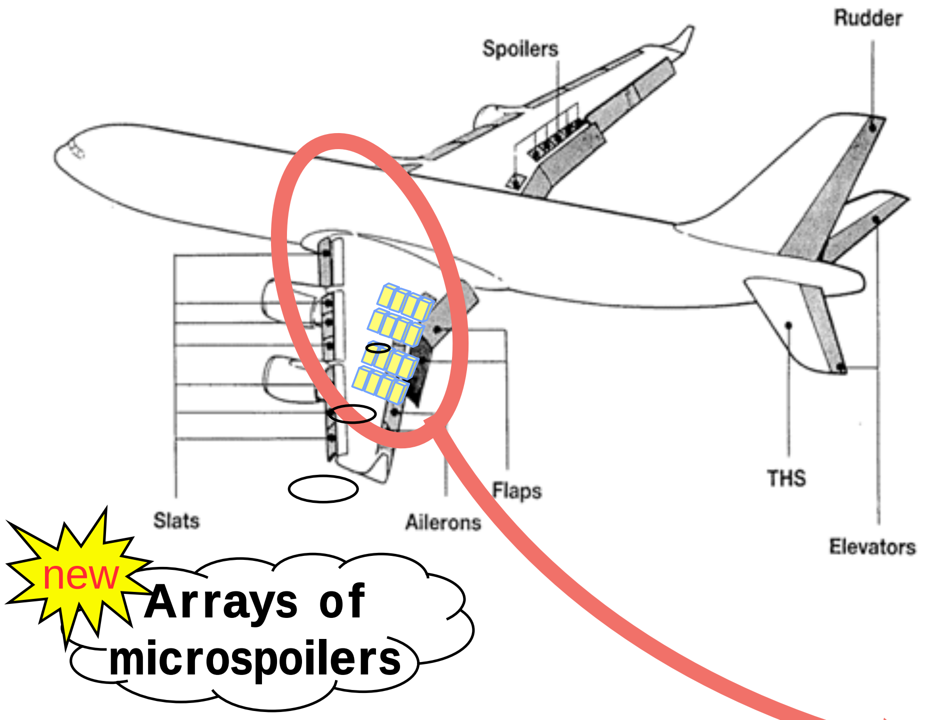
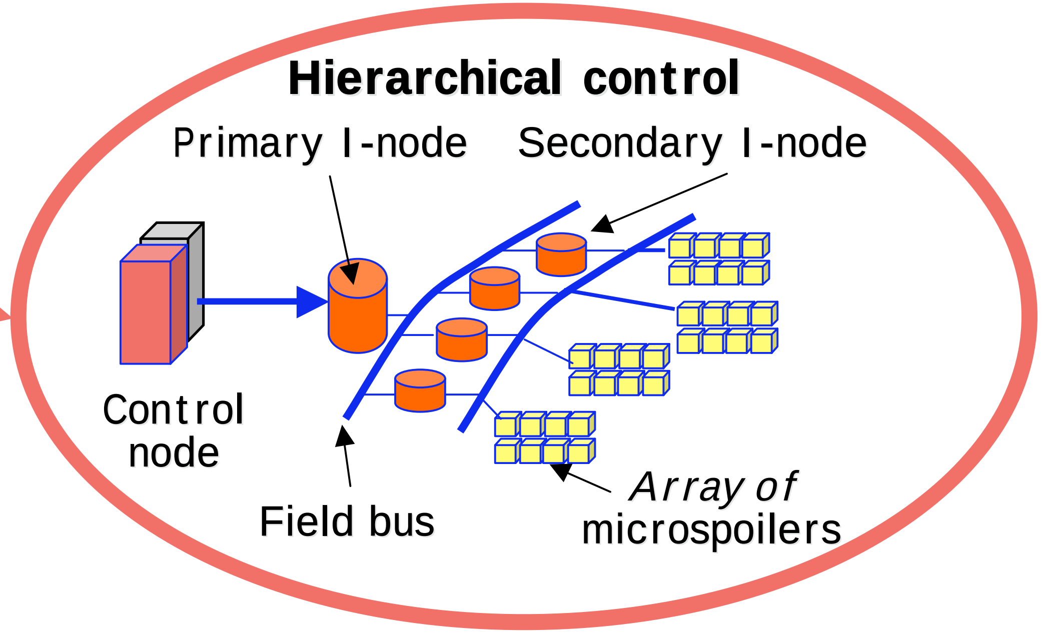
Context and Motivation

- Usage of fully-digital communication networks into critical embedded systems (commercial aircraft architecture)



- **Flexible control**
  - accommodate distinct commands on different actuators
  - -> all devices cannot be connected to the same bus
  - Need for intermediate functional nodes "I-nodes"(not simple repeaters)

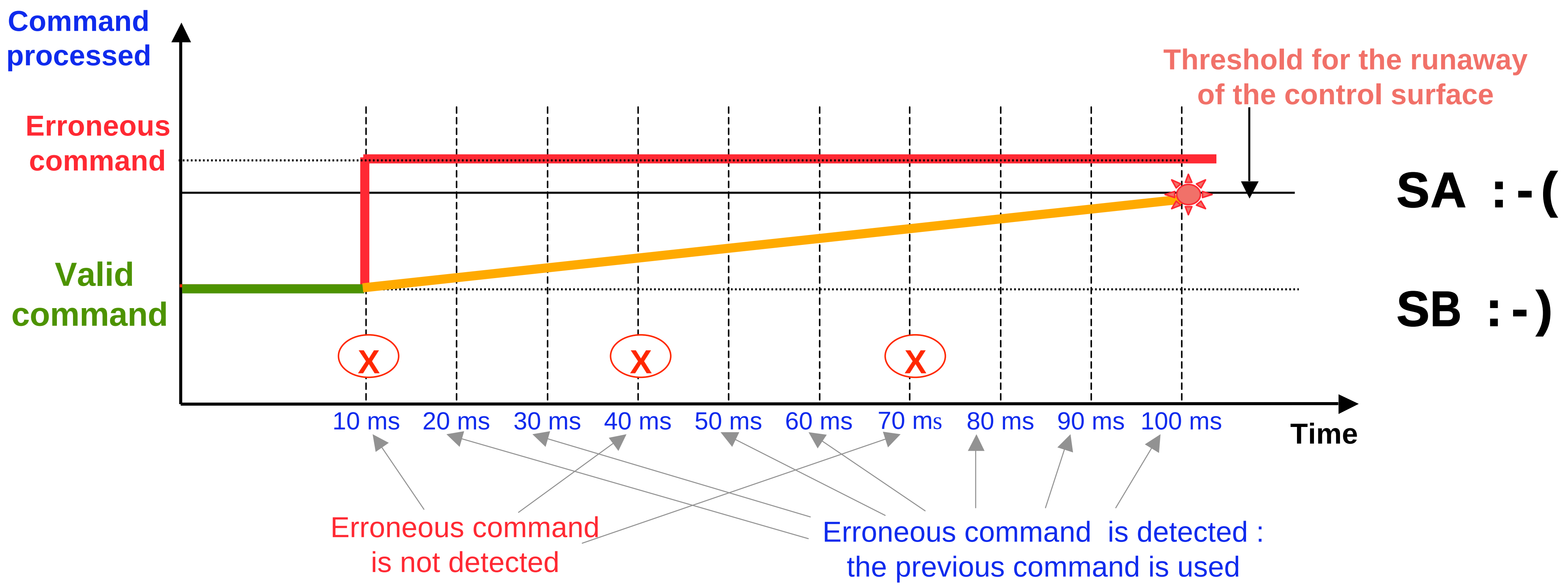


Baseline

- **Slow dynamics of the process** (more than one erroneous command sustained before leading to an undesired event)
  -> Option to (re-)use previous command (even erroneous
- **Undesired Event (UE) = "Runaway" of the controlled surface**
  -> Discrepancy wrt nominal reference value ≥ 5°
  [servomechanisms with max. speed movement of 50°/s]
  Erroneous reference value applied for ≥ 100ms (10 cycles) => **UE**
- **Safety requirement "risk of undesired event ≤ 10^{-9}/h"**
  -> Constraint on communication system integrity
  "Number of undetected erroneous messages < threshold *t*"
- **Recovery (mitigate issues) -> back-up actions**
  - **Ensure the correct updating of the reference value to the servomechanism**
  - **Do not discard too quickly the communication system**
  - **Do not impair the required safety level**

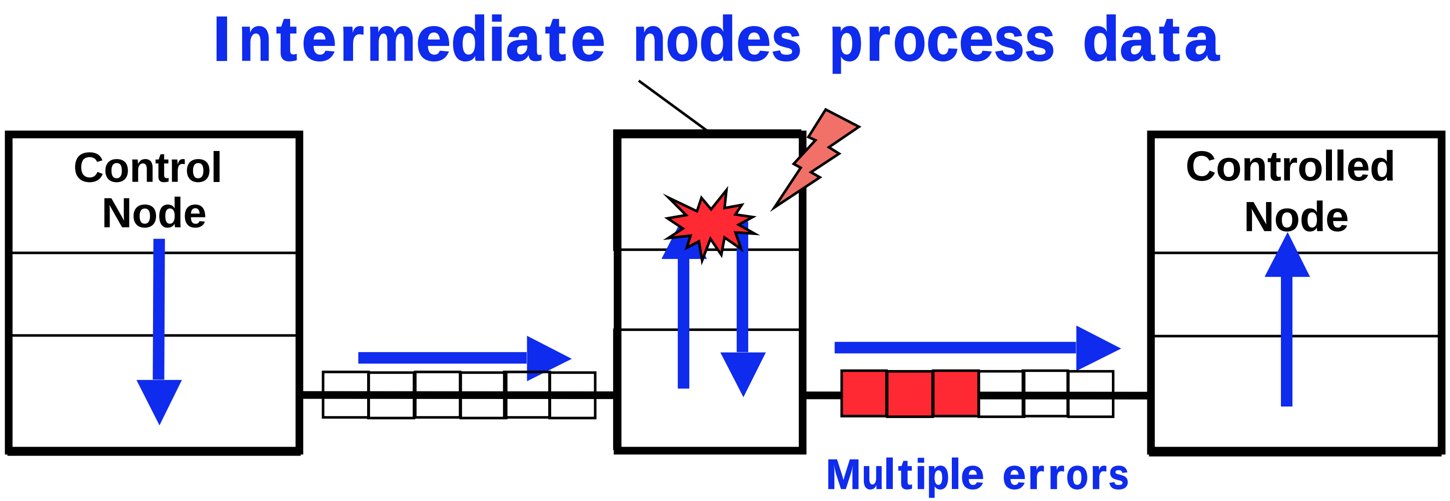
About Recovery and Undesired Event

- Re-use of the previous ("correct") command and "filtering":
  - SA) launch the recovery after *r* consecutive processing cycles for which an error has been signaled;
  - SB) launch the recovery after *r* processing cycles for which an error has been signaled out of a window of *w* successive cycles
- Example (*w* = 10 and *r* = 3)



Target UE = Reception of 3 erroneous message in set of 10 cycles

Impact of Intermediate Nodes



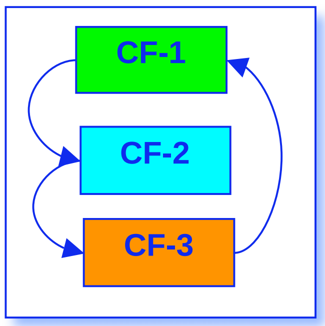
- **Classical approaches: -> Inefficient and/or improper**
  - Basic coding techniques (CRCs)
  - End-to-end detection mechanims (HEDC, Keyed CRC, Safety Layer)

—> Introduce some degree of diversification

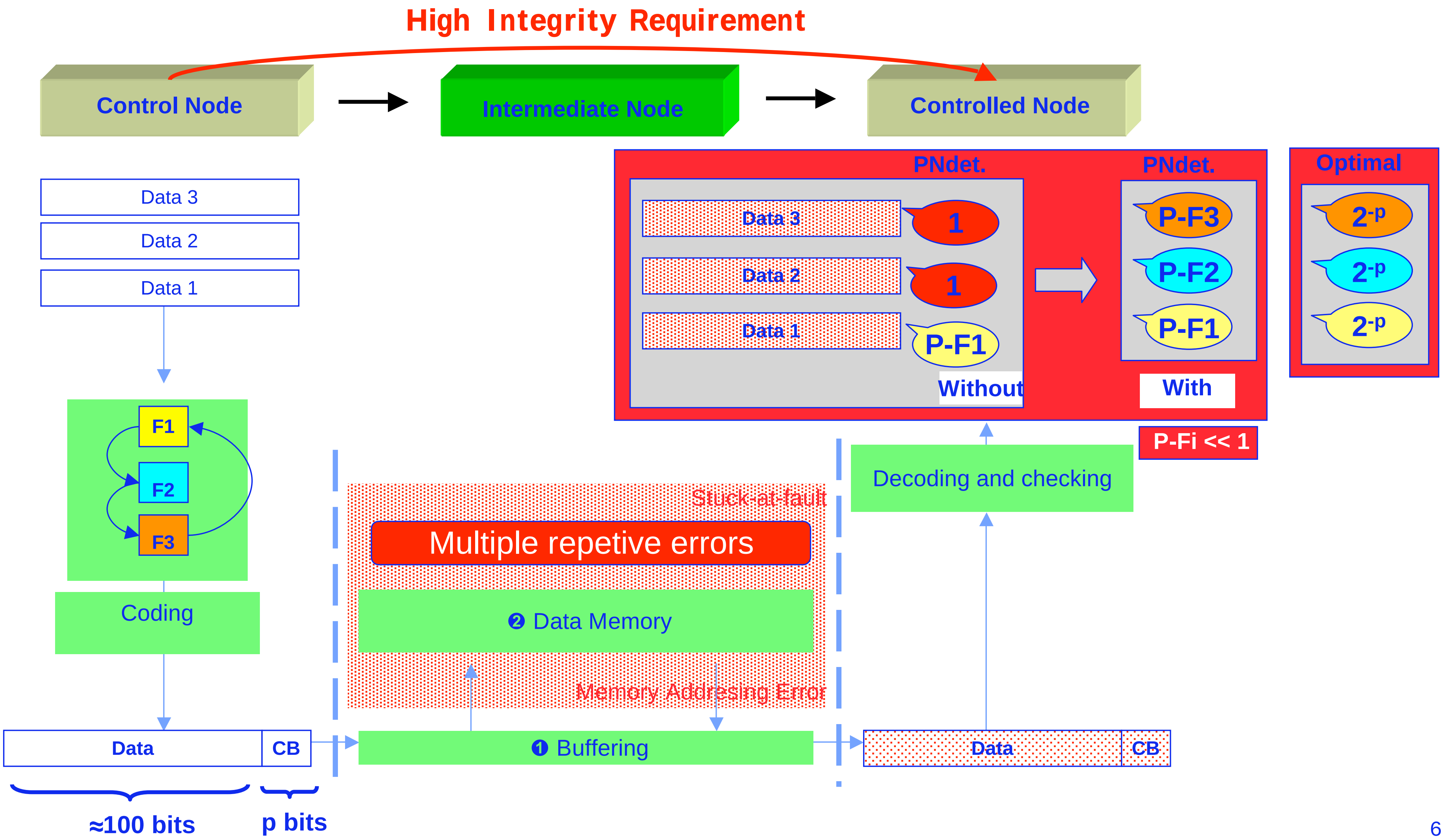
- data and redundancy (e.g., TMR)
- data and coding (Turbo Codes)
- coding function (e.g., rotation of the coding function)

  Multiple Error Coding Function ->

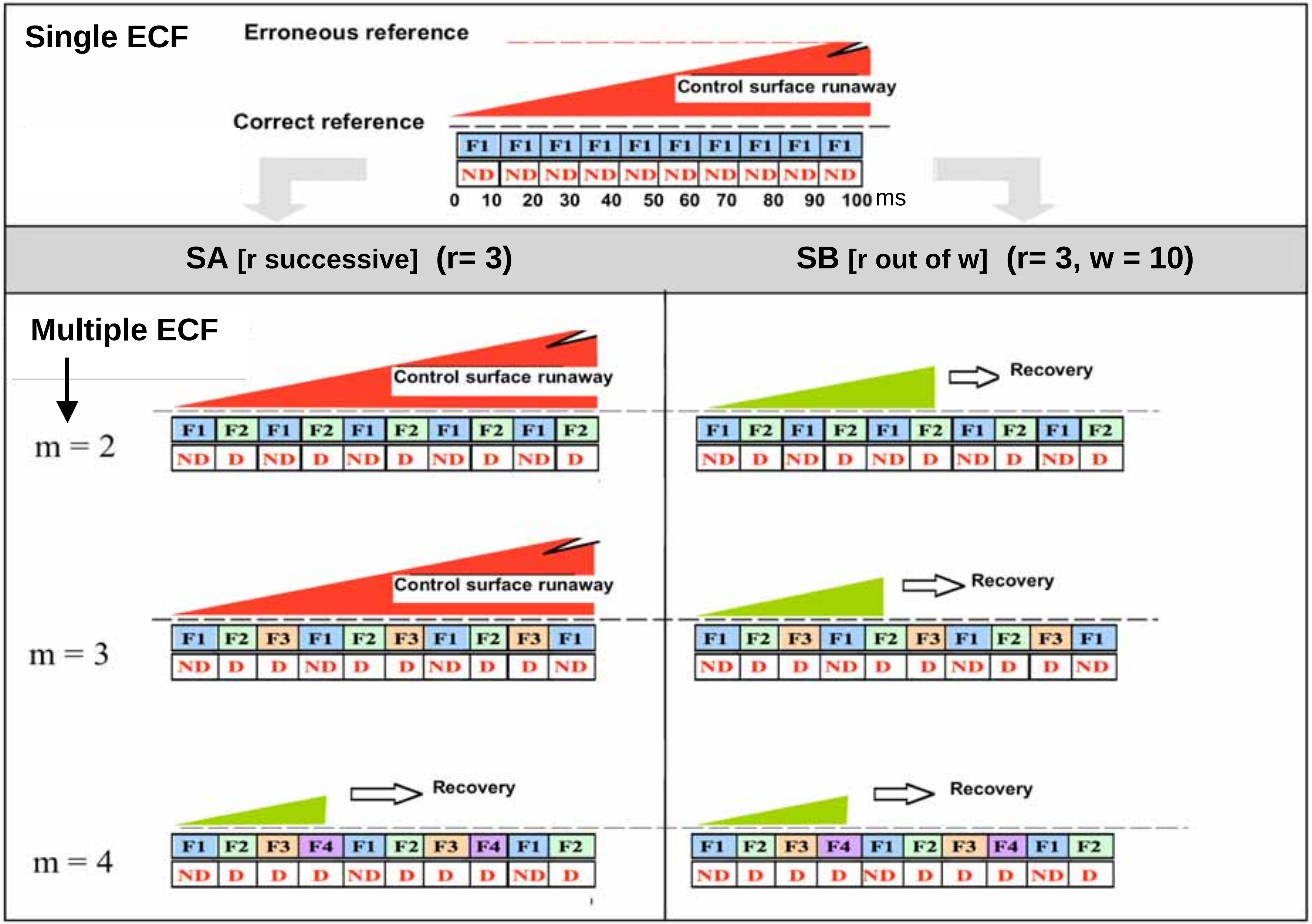
  (m = 3)



Principle and Benefit

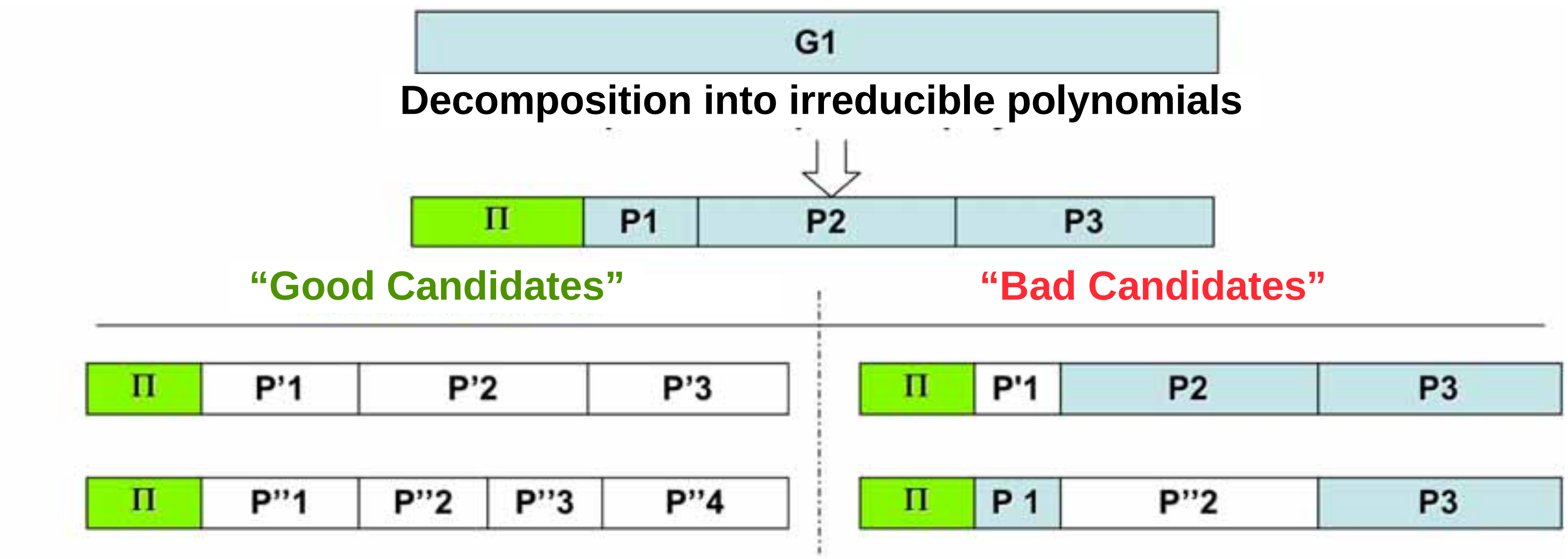


Impact on Detection and Recovery



Implementation Using CRCs

Generator Polynomial



- Π = small degree polynomial featuring "standard" error detection properties (e.g., [1+x])
- P'i and P''i ≠ Pi ∀i

Generator Polynomial Selection

$G_1(x) = \underline{(1+x)} \cdot \underline{(1+x+x^7)} \cdot (1+x^2+x^3+x^4+x^8) = 1+x^3+x^5+x^6+x^7+x^9+x^{10}+x^{12}+x^{15}+x^{16}$		
Examples of Potentially Good Candidates		
$G_*(x) = (1+x)$. 7-degree irreducible polynomial . 8-degree irreducible polynomial		
Identifier	Polynomial representation	Decomposition into irreducible polynomials
$G_2(x)$	$1+x+x^6+x^7+x^8+x^9+x^{10}+x^{13}+x^{15}+x^{16}$	$\underline{(1+x)} \cdot (1+x+x^3+x^5+x^7) \cdot (1+x+x^2+x^4+x^5+x^6+x^8)$
$G_3(x)$	$1+x+x^6+x^{10}+x^{12}+x^{16}$	$\underline{(1+x)} \cdot (1+x+x^2+x^3+x^7) \cdot (1+x+x^4+x^5+x^6+x^7+x^8)$
$G_4(x)$	$1+x^5+x^6+x^7+x^8+x^9+x^{10}+x^{16}$	$\underline{(1+x)} \cdot (1+x^3+x^7) \cdot (1+x+x^2+x^5+x^6+x^7+x^8)$
Examples of Potentially Bad Candidates		
$G_*(x) = (1+x) \cdot (1+x+x^7)$. 8-degree irreducible polynomial		
$G_5(x)$	$1+x+x^2+x^3+x^5+x^6+x^9+x^{10}+x^{12}+x^{14}+x^{15}+x^{16}$	$\underline{(1+x)} \cdot \underline{(1+x+x^7)} \cdot (1+x+x^5+x^6+x^8)$
$G_6(x)$	$1+x^3+x^6+x^7+x^{10}+x^{13}+x^{14}+x^{16}$	$\underline{(1+x)} \cdot \underline{(1+x+x^7)} \cdot (1+x^2+x^3+x^4+x^5+x^7+x^8)$

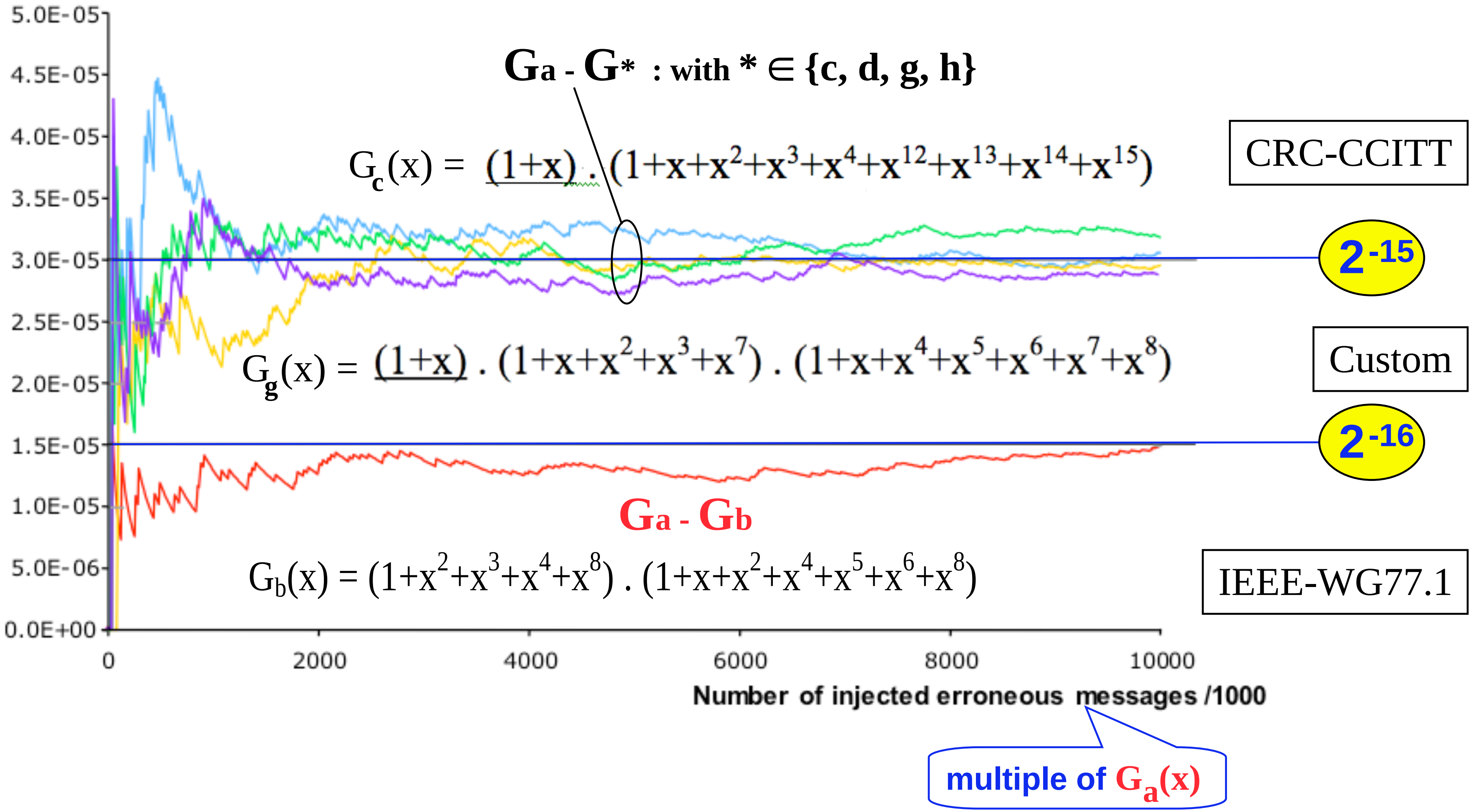
This was analyzed and confirmed via extensive simulation runs

Example of Analysis: Target Codes

$G_a(x) = \underline{(1+x)} \cdot (1+x+x^{15}) = 1+x^2+x^{15}+x^{16}$ — **Standard generator polynomial : CRC-16**		
Standard generator polynomials		
$G_*(x) = (1+x) \cdot$ 15-degree polynomial		
Identifier	Polynomial representation	Decomposition into irreducible polynomials
$G_b(x)$: IEEE-WG77.1	$1+x+x^5+x^6+x^8+x^9+x^{10}+x^{11}+x^{13}+x^{14}+x^{16}$	$(1+x^2+x^3+x^4+x^8) \cdot (1+x+x^2+x^4+x^5+x^6+x^8)$
$G_c(x)$: CRC-CCIT T	$1+x^5+x^{12}+x^{16}$	$\underline{(1+x)} \cdot (1+x+x^2+x^3+x^4+x^{12}+x^{13}+x^{14}+x^{15})$
$G_d(x)$: IBM-SDLC	$1+x+x^2+x^4+x^7+x^{13}+x^{15}+x^{16}$	$\underline{(1+x)}^2 \cdot (1+x+x^3+x^4+x^5+x^6+x^8+x^{10}+x^{12}+x^{13}+x^{14})$
$G_e(x)$: CRC-16Q*	$1+x+x^3+x^4+x^5+x^6+x^8+x^{11}+x^{15}+x^{16}$	$\underline{(1+x)} \cdot (1+x^3+x^5+x^8+x^9+x^{10}+x^{15})$
$G_f(x)$: IEC-TC57	$1+x+x^4+x^7+x^8+x^9+x^{11}+x^{12}+x^{14}+x^{16}$	$\underline{(1+x)}^2 \cdot (1+x+x^3+x^6+x^7) \cdot (1+x^2+x^3+x^4+x^5+x^6+x^7)$
Custom generator polynomials		
$G_*(x) = (1+x) \cdot$ 7-degree irreducible polynomial . 8-degree irreducible polynomial		
$G_g(x) = G_3(x)$	$1+x+x^6+x^{10}+x^{12}+x^{16}$	$\underline{(1+x)} \cdot (1+x+x^2+x^3+x^7) \cdot (1+x+x^4+x^5+x^6+x^7+x^8)$
$G_h(x) = G_4(x)$	$1+x^5+x^6+x^7+x^8+x^9+x^{10}+x^{16}$	$\underline{(1+x)} \cdot (1+x^3+x^7) \cdot (1+x+x^2+x^5+x^6+x^7+x^8)$

Examples of Simulation Runs

$G_a(x) = \underline{(1+x)} \cdot (1+x+x^{15}) \cdot (1+x^3+x^{15}+x^{16})$ CRC-16



Concluding Remarks

- **Pragmatic Approach for Mitigating High Integrity Requirements in Critical Communications Systems**

- **CRC-based Implementation:**
  - Theoretical issues associated to properties of generator polynomials provide a sound basis for identifying criteria for selecting suitable coding functions
  - Criteria validated via extensive simulation runs

- **Generalization: investigation of alternative policies for mixing distinct coding functions (CF)**

- **Formalization: derivation of closed-form expressions**
  - Probability of undetected errors (PUE)
  - (Min) Latency for system recovery action after an error is undetected (LRA)
    [# of message cycles]

  Example: $m>1$ # of distinct CF; r # of reported error detections,
  w size of window (for SB, only)

  LRA(SA) = r+1 for $r < m$; LRA(SB) = $\lceil m \times r / (m-1) \rceil$ for $LRA < w$