Latency Analysis of Systems with Multiple Interfaces for Ultra-Reliable M2M Communication

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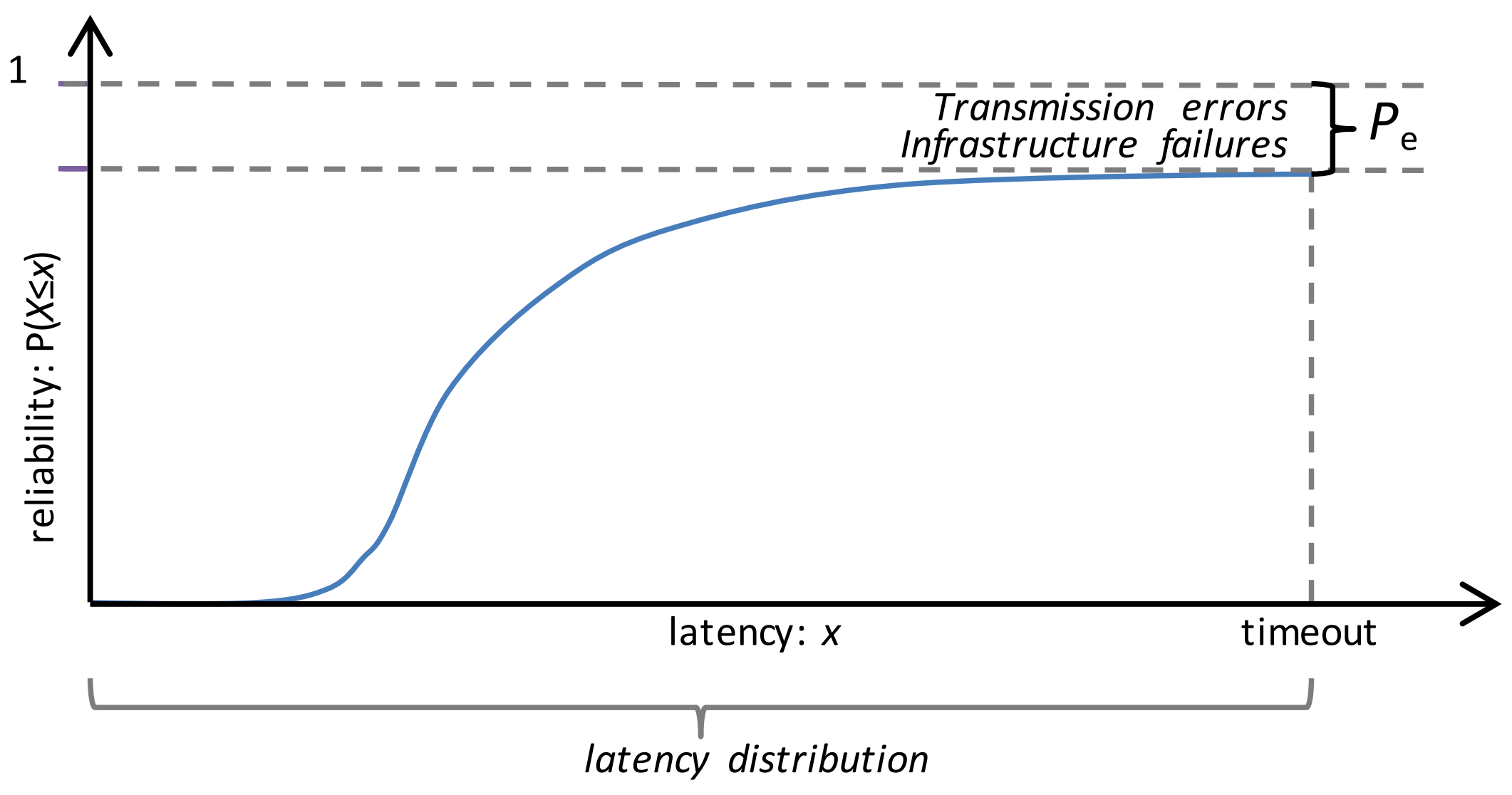
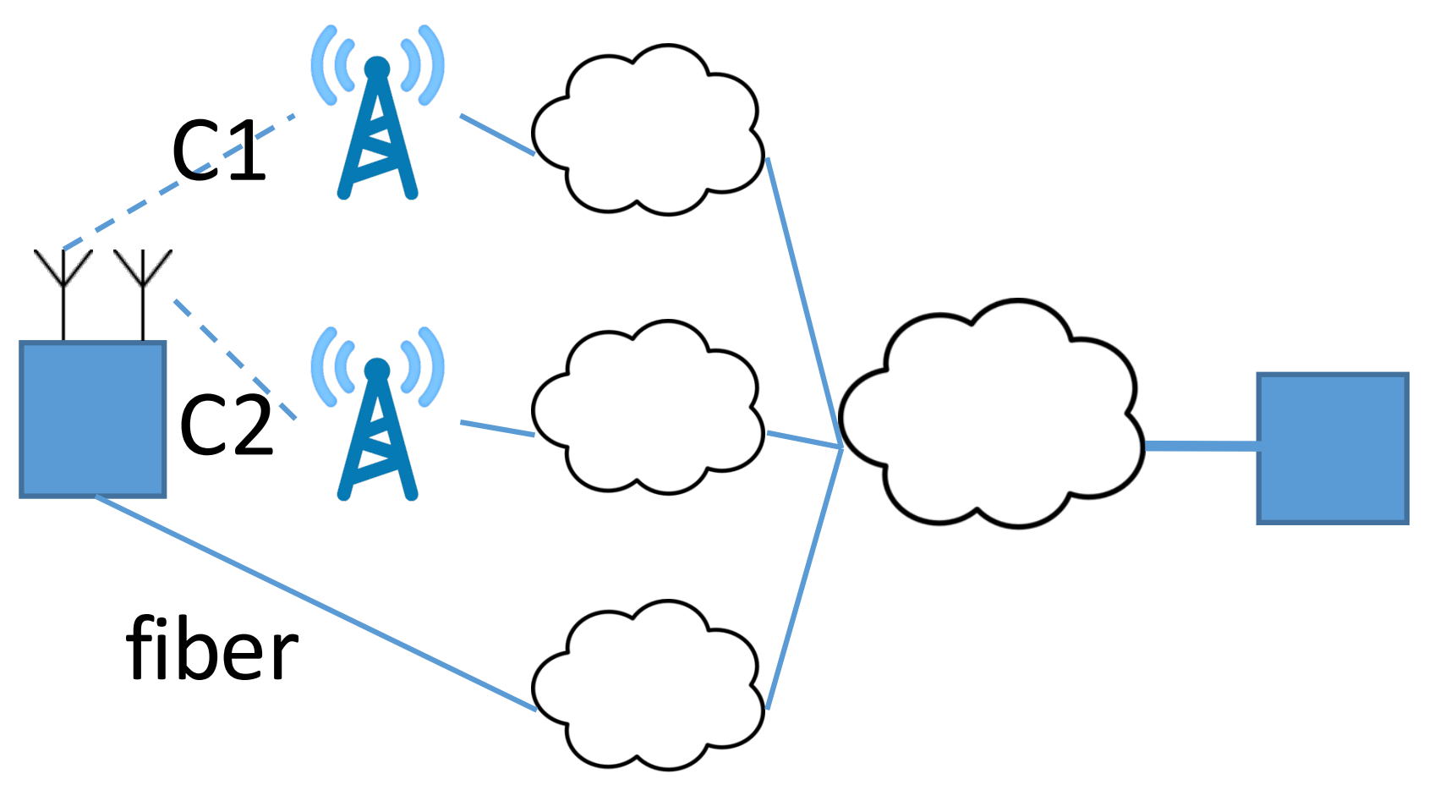
Introduction

- A communication link can be characterized by a latency-reliability function [1]:



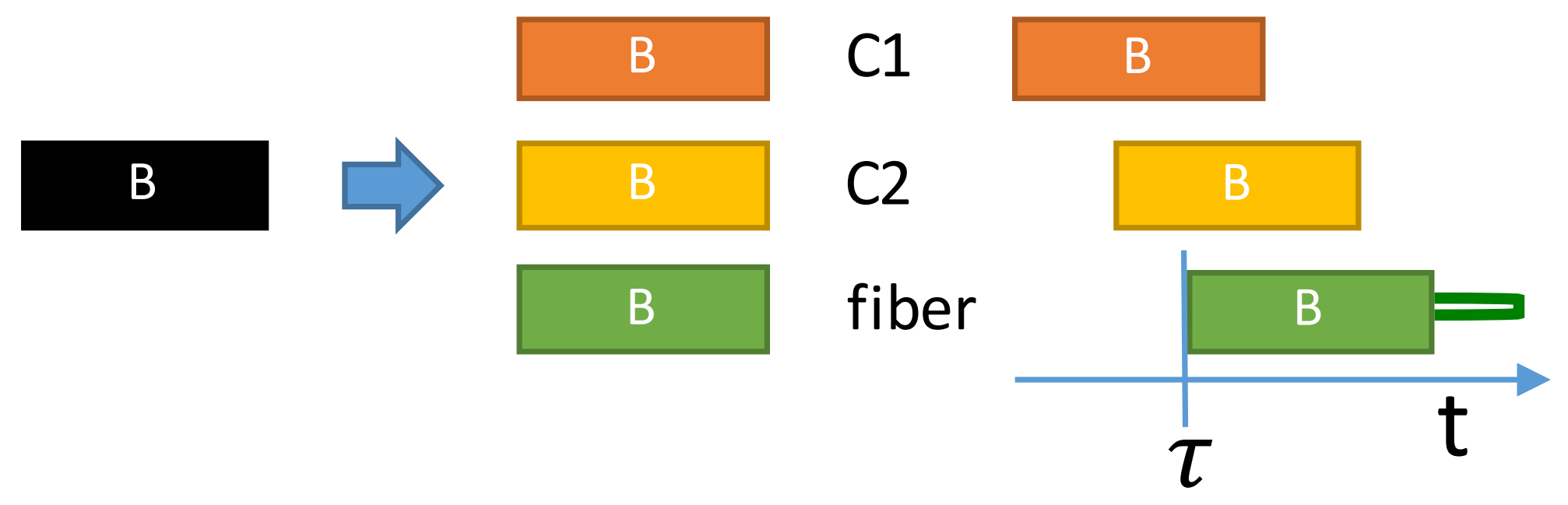
- Two factors determine shape:
  Latency variability: medium access, routing, queueing and processing, etc.
  Packet loss (x>timeout): Infrastructure failures, low SINR, access overload, queue overflow, etc. → P_e
- A periodically reporting M2M device (left) may have multiple connectivity options to reach the remote host (right):



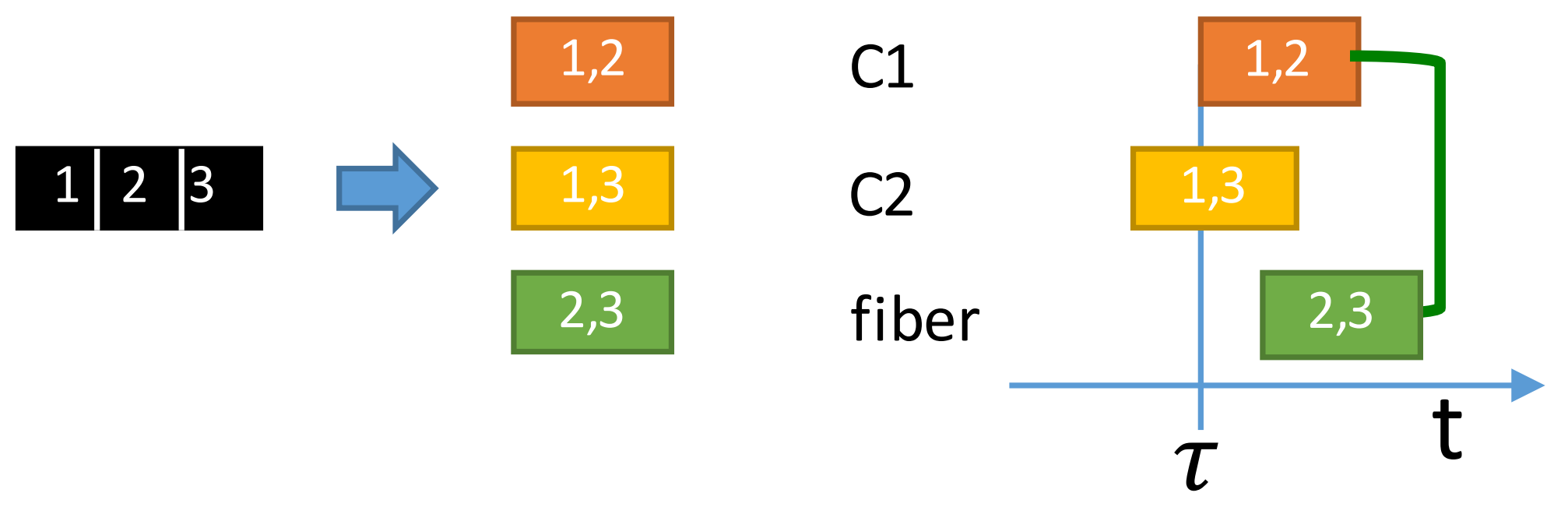
- For mission critical applications, the reliability of a single interface is insufficient.
- Reliability can be improved by using multiple interfaces simultaneously.

Transmission strategies

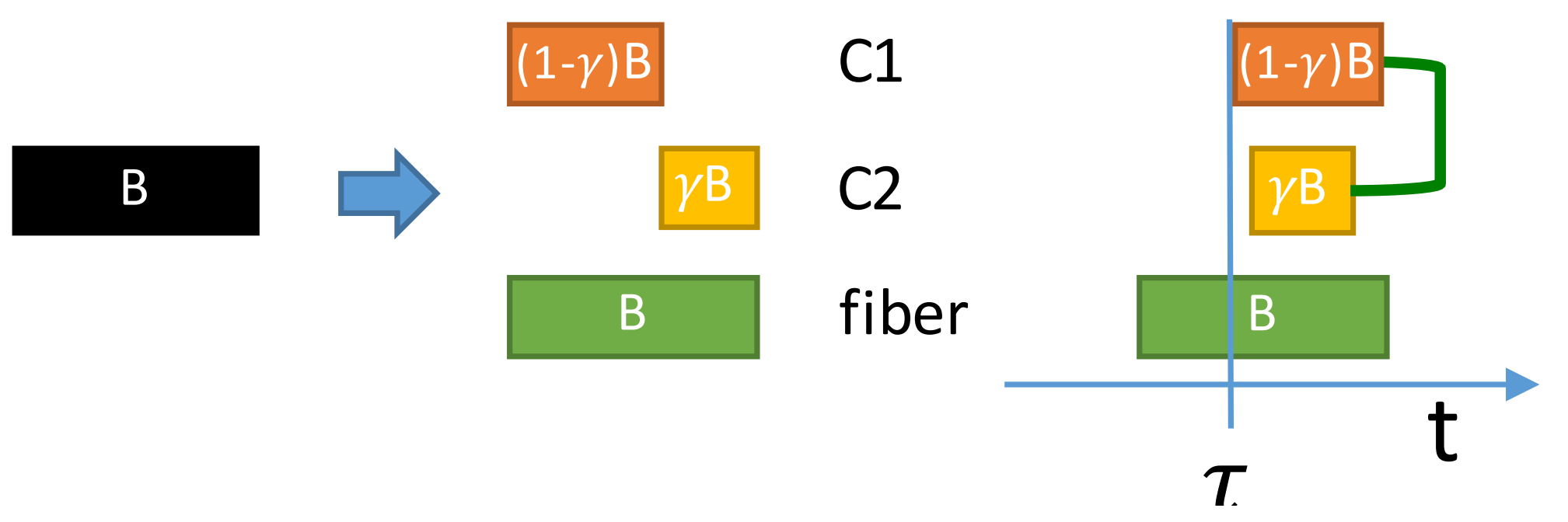
- **Cloning (parallel)**



- **2-of-3 (triple modular redundancy)**



- **Weighted (series + parallel)**



Reliability model intuition

- Calculation of reliability for strategies, is inspired by reliability engineering [2]:

$$R_{\text{cloning}} = 1-(1-R_{\text{fi}})(1-R_{\text{C1}})(1-R_{\text{C2}})$$

$$R_{\text{2-of-3}} = 3R^2(1-R)+R^3$$

$$R_{\text{weighted}} = 1-(1-R_{\text{fi}})(1-R_{\text{C1}}R_{\text{C2}})$$

- In the following, $F_i(x)$ instead of R.

Failure model

- Continuous Time Markov Chain is used to model failure, restoration and correlation:

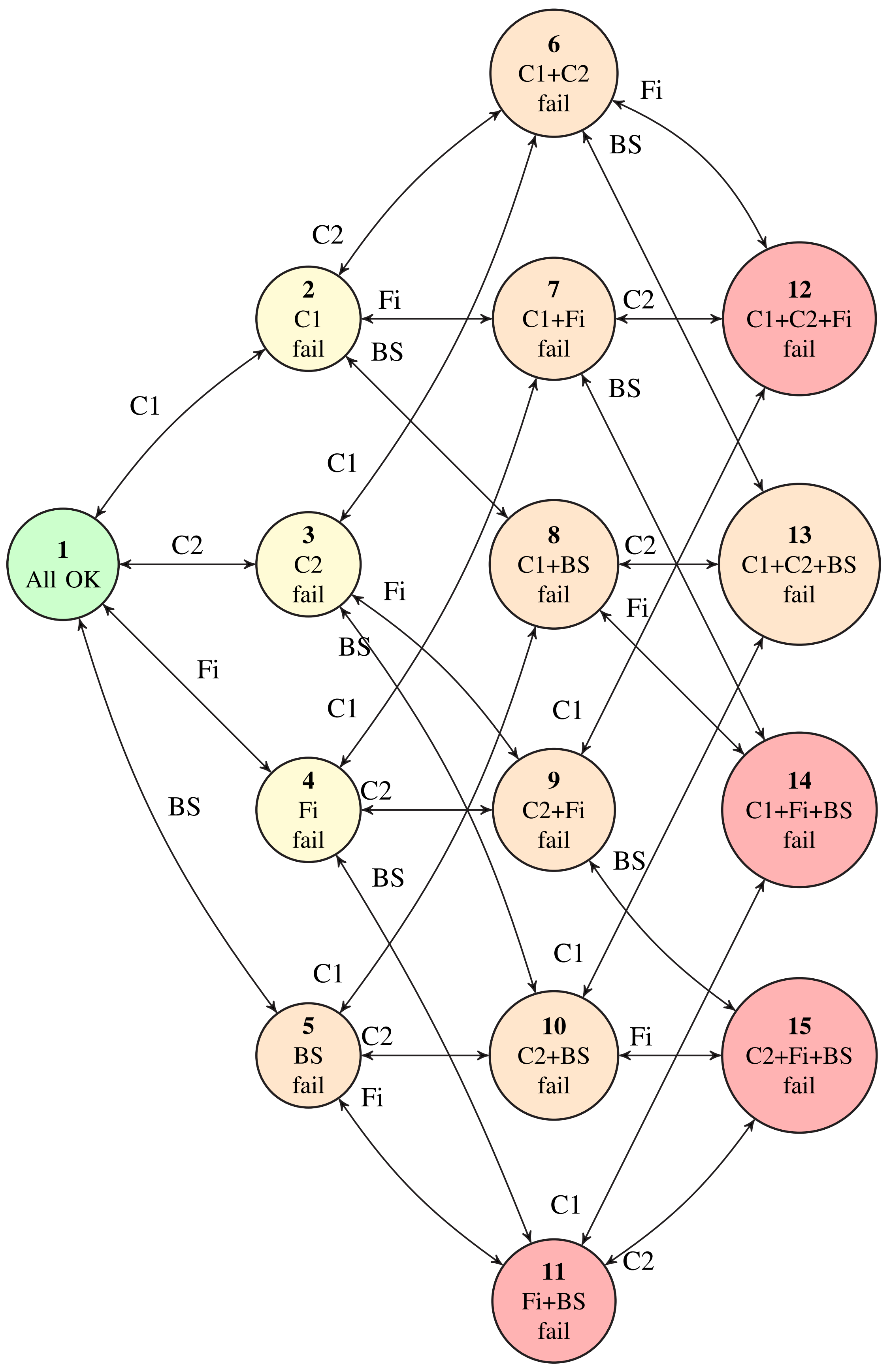


Fig. 1: A two-way arrow represents a failure rate in the right direction and restoration rate in the left direction, e.g. λ_{C1} and μ_{C1} between states 1 and 2.

Full reliability model

- Latency-reliability function is calculated per state s and payload size B as $F_s^{\mathsf{st}}(x,B)$:

cloning

$$\begin{bmatrix} 1-(1-\hat{F}_1)(1-\hat{F}_2)(1-\hat{F}_3) \\ 1-(1-\hat{F}_2)(1-\hat{F}_1) \\ 1-(1-\hat{F}_2)(1-\hat{F}_1) \\ 1-(1-\hat{F}_3)(1-\hat{F}_2) \\ \hat{F}_1 \\ \hat{F}_1 \\ \hat{F}_3 \\ \hat{F}_1 \\ \hat{F}_2 \\ \hat{F}_1 \\ 0 \\ 0 \\ \hat{F}_1 \\ 0 \\ 0 \end{bmatrix}$$

weighted

$$\begin{bmatrix} 1-(1-\hat{F}_1)(1-(\hat{F}_2\hat{F}_3)) \\ \hat{F}_1 \\ \hat{F}_1 \\ \hat{F}_2\hat{F}_3 \\ \hat{F}_1 \\ \hat{F}_1 \\ 0 \\ \hat{F}_1 \\ 0 \\ \hat{F}_1 \\ 0 \\ 0 \\ \hat{F}_1 \\ 0 \\ 0 \end{bmatrix}$$

2-of-3

$$\begin{bmatrix} F_{\mathsf{A}}+F_{\mathsf{B}}+F_{\mathsf{C}}+F_{\mathsf{D}} \\ \hat{F}_1\hat{F}_3 \\ \hat{F}_1\hat{F}_2 \\ \hat{F}_2\hat{F}_3 \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$

- Thereafter, state-reliabilities $F_s^{\mathsf{st}}(x,B)$ are weighted by the steady-state probabilities π_s (i.e. fraction of time in each state):

$$F_{k\text{-dep}}(x,B) = \sum_{s=1}^{L} \pi_s \cdot F_s^{\mathsf{st}}(x,B)$$

Assumptions

- Reliability parameters:

	Availability	λ (f/week)	μ (r/week)
Cellular	0.98	1.0013	50.4 (200 min/r)
Fiber	0.998	0.0561	28 (6 hrs/r)
Base station	0.9995	0.0267	50.4 (200 min/r)

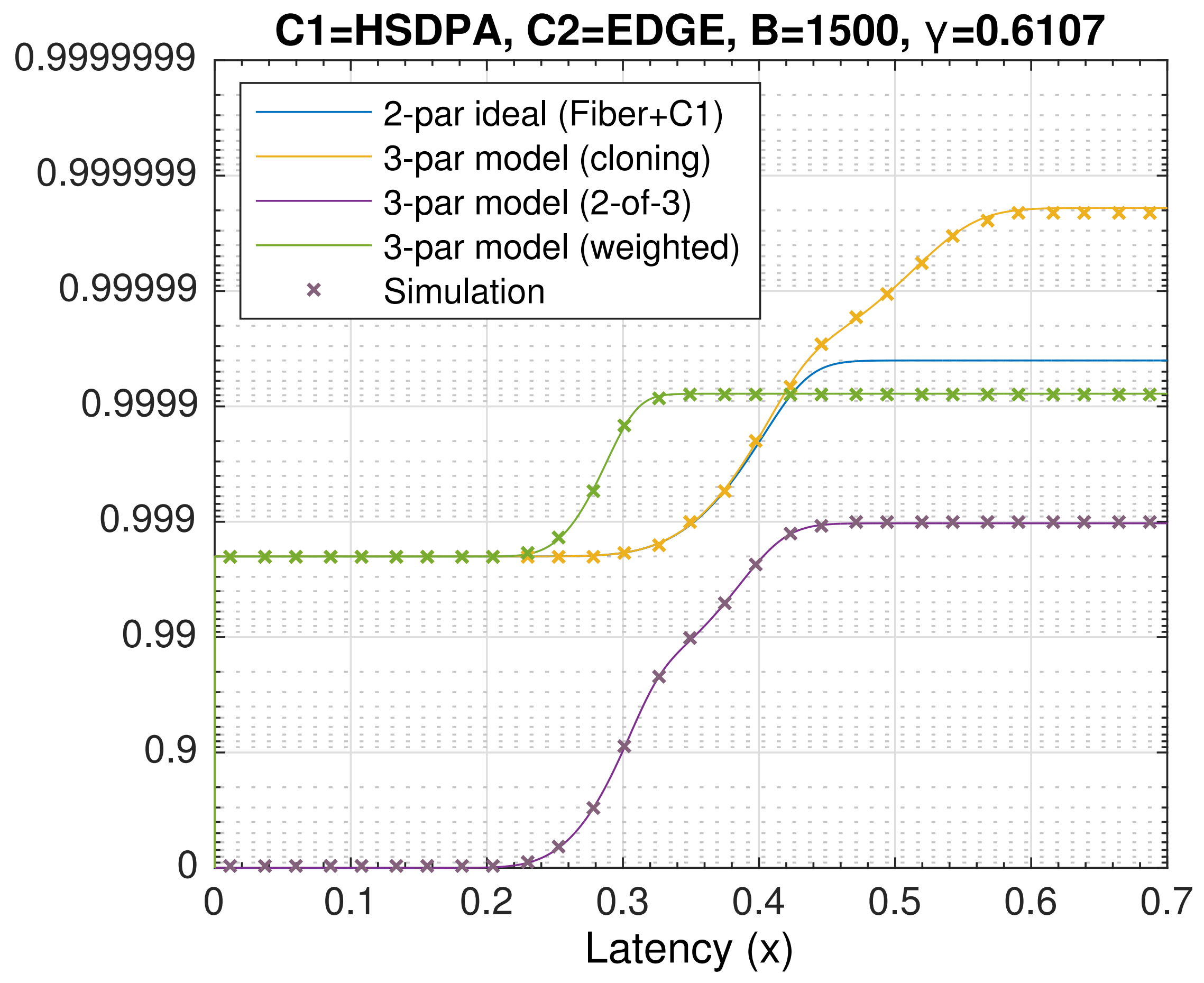
- Latency is assumed to follow Gaussian distribution with parameters:

$$\mu = \frac{\alpha \cdot B + \beta}{2},\ \sigma = \frac{\mu}{10}\ \text{[ms]}$$

  - B is payload size in bytes.
  - Linear regression parameters based on field measurements from Telekom Slovenije.

	GPRS	EDGE	UMTS	HSDPA	LTE
α	0.70	0.46	0.43	0.35	0.0067
β	400	230	200	178	41

Results and discussion



- **Cloning** on three interfaces boosts reliability from 1-2 nines with single interfaces to 5 (almost 6) nines.
- **2-of-3** is unreliable and not recommended.
- **Weighted** reduces latency at 4 nines by 25 % by splitting of payload. (Larger payload gives larger gain.)

Conclusion and outlook

- The model is fast to implement and evaluate and has been verified by simulation.
- **Recommendations from analysis**:
  - For low latency and good reliability, use *weighted* packet splitting strategy.
  - For highest reliability use *cloning* over all available interfaces.
- In practice, latency distributions are heavy-tailed. Follow-up work has shown similar results as above for heavy-tailed latency, however with slightly less latency reduction.

References

[1] E. G. Ström, P. Popovski, and J. Sachs, "5g ultra-reliable vehicular communication," *arXiv preprint arXiv:1510.01288*, 2015.

[2] M. Rausand and A. Høyland, *System reliability theory: models, statistical methods, and applications*. John Wiley & Sons, 2004, vol. 396.

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