Intrusion Tolerance as a Two-Level Game

GameSec 2024, New York, USA
Conference on Decision and Game Theory for Security

Kim Hammar & Rolf Stadler

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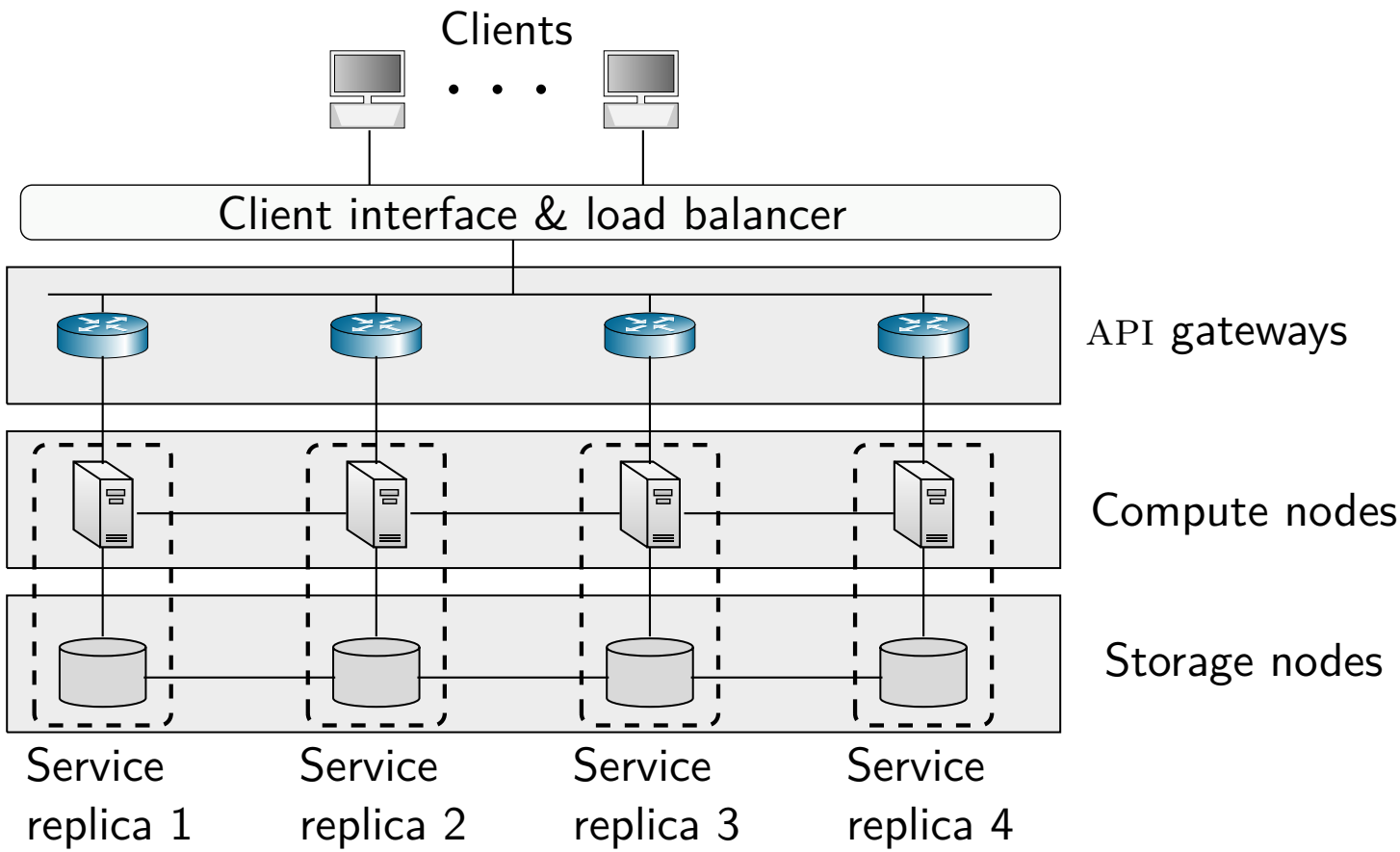
KTH Royal Institute of Technology

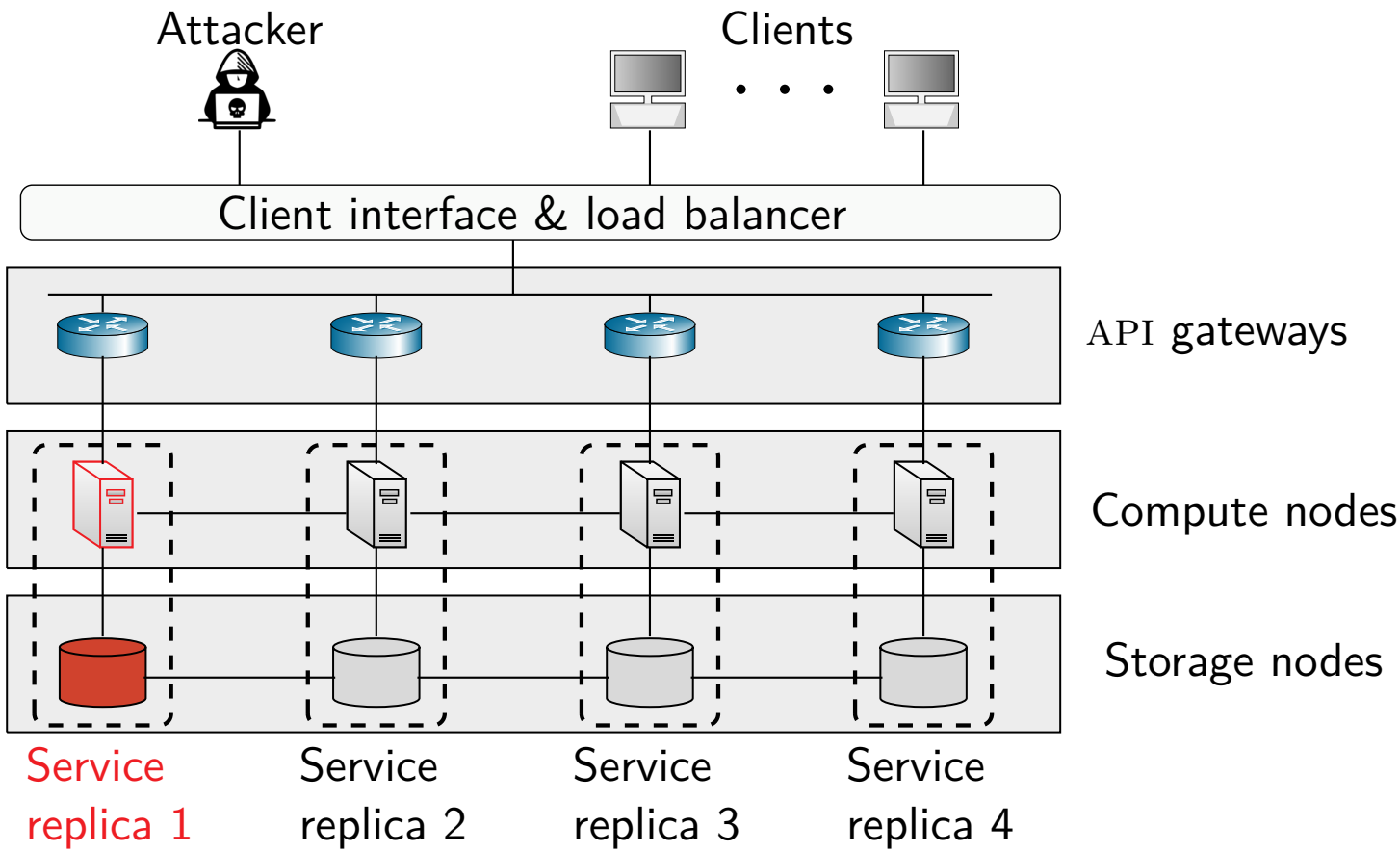
Oct 16, 2024

Use Case: Intrusion Tolerance



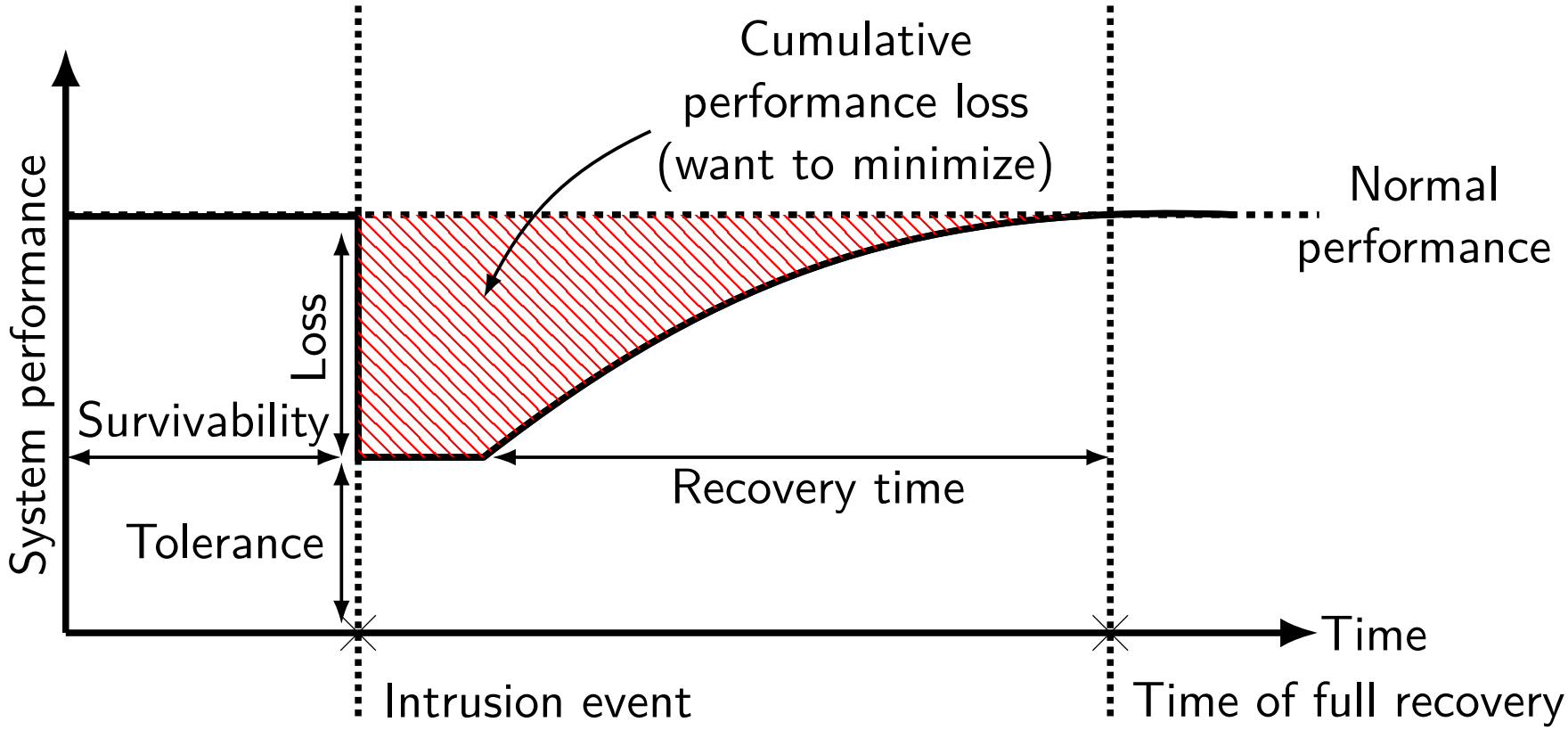
- A **replicated system** offers a service to a client population.
- The system should provide service without disruption.

Use Case: Intrusion Tolerance



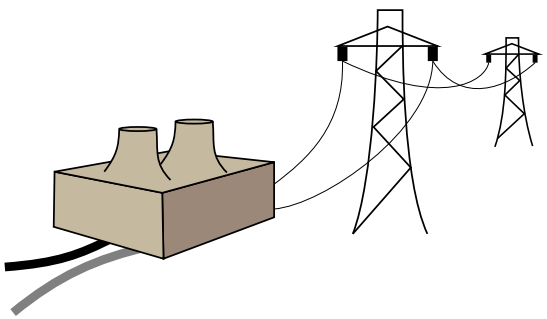
- An attacker seeks to intrude on the system and disrupt service.
- The system should **tolerate intrusions.**

Intrusion Tolerance (Simplified)

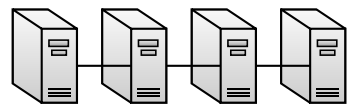


Increasing Demand for Intrusion-Tolerant Systems

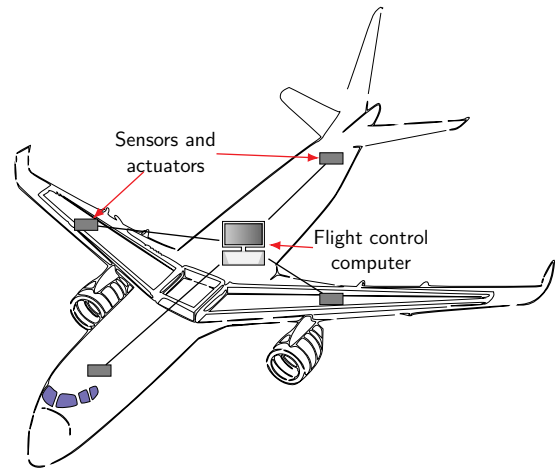
- As our **reliance on online services grows**, there is an increasing demand for intrusion-tolerant systems.
- Example applications:



Power grids
e.g., SCADA systems[1].



Safety-critical IT systems
e.g., banking systems, e-commerce applications[2], healthcare systems, etc.



Real-time control systems
e.g., flight control computer[3].

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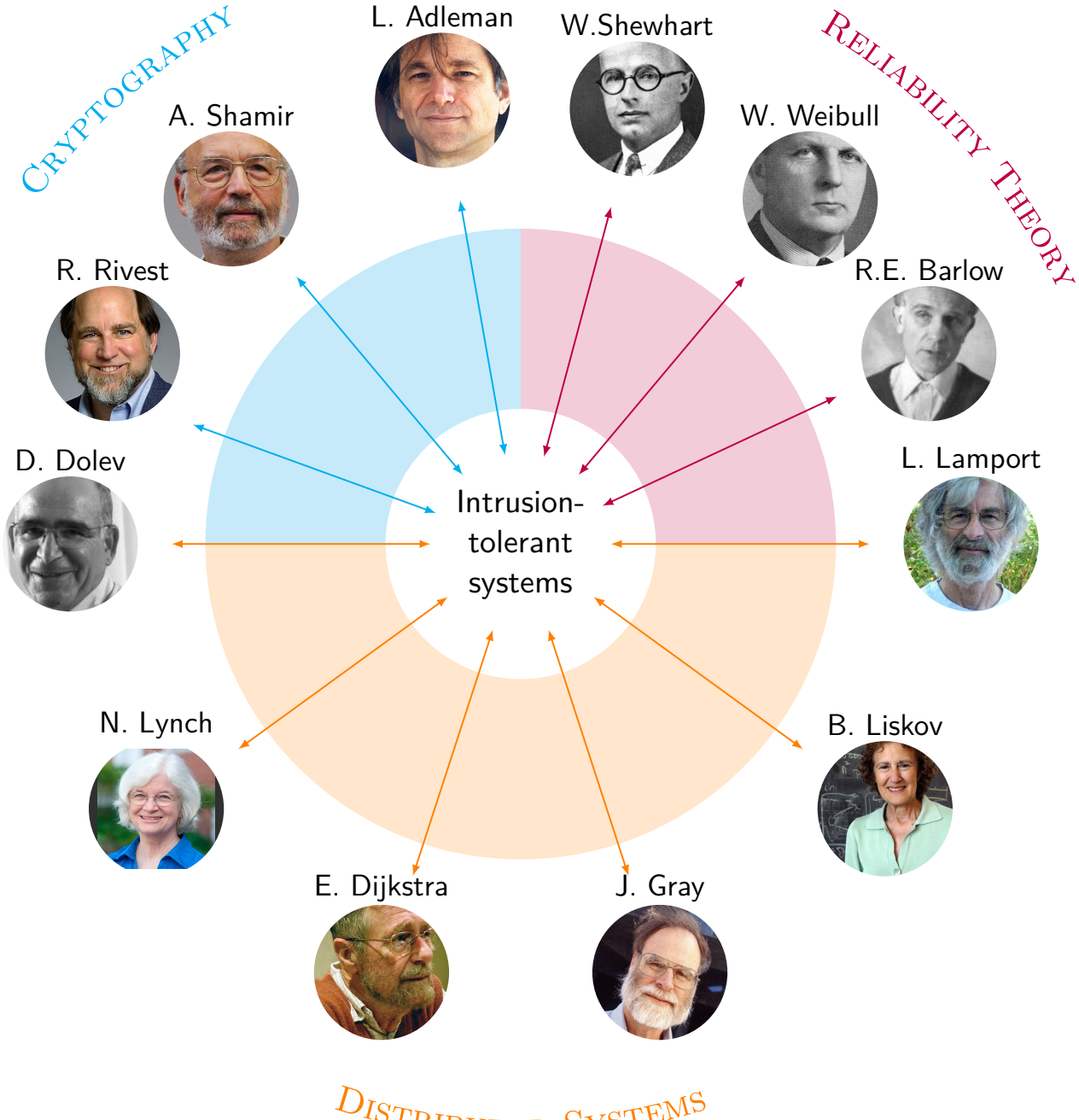
[1] Amy Babay et al. "Network-Attack-Resilient Intrusion-Tolerant SCADA for the Power Grid". In: *2018 48th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN)*. 2018, pp. 255–266. DOI: 10.1109/DSN.2018.00036.

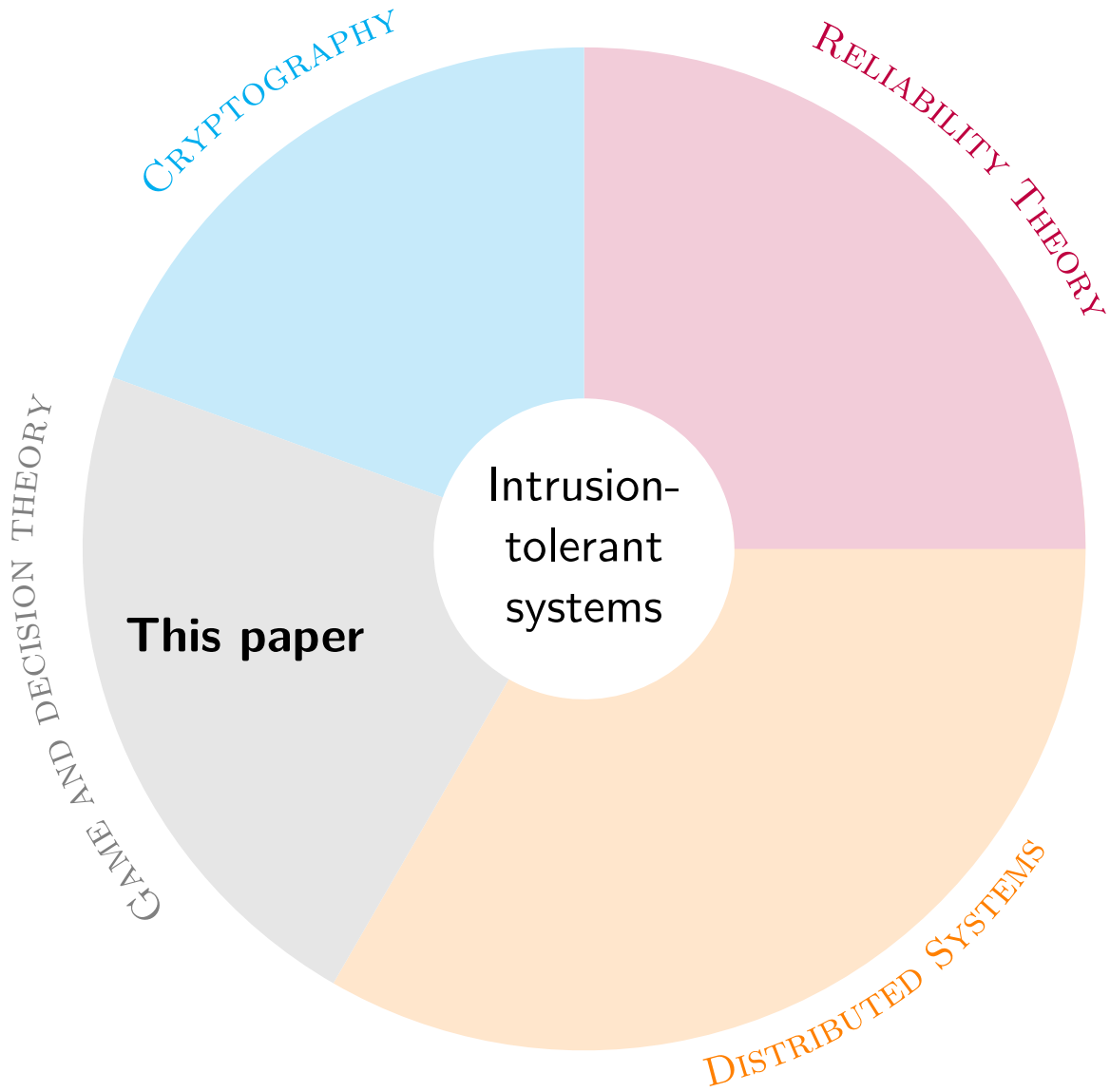
[2] Jukka Soikkeli et al. "Redundancy Planning for Cost Efficient Resilience to Cyber Attacks". In: *IEEE Transactions on Dependable and Secure Computing* 20.2 (2023), pp. 1154–1168. DOI: 10.1109/TDSC.2022.3151462.

[3] J.H. Wensley et al. "SIFT: Design and analysis of a fault-tolerant computer for aircraft control". In: *Proceedings of the IEEE* 66.10 (1978), pp. 1240–1255. DOI: 10.1109/PROC.1978.11114.

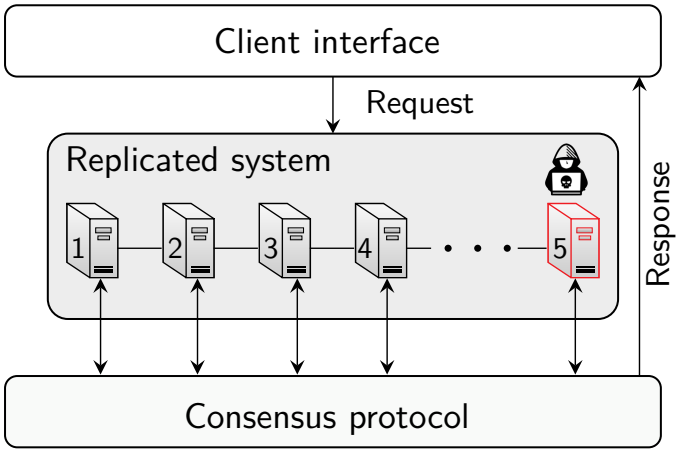
Theoretical Foundations of Intrusion Tolerance



Our Contribution

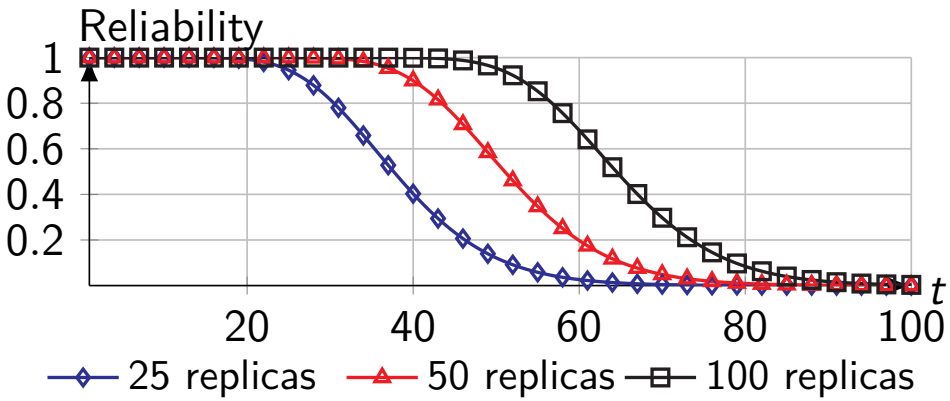


Building Blocks of An Intrusion-Tolerant System



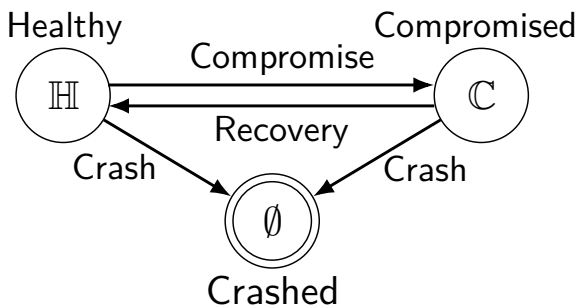
1. Intrusion-tolerant consensus protocol

A quorum needs to reach agreement to tolerate f compromised replicas.



2. Replication strategy

Cost-reliability trade-off.



3. Recovery strategy

Compromises will occur as $t \to \infty$.

Prior Work on Intrusion-Tolerant Systems

The Rampart Toolkit for Building High-Integrity Services

Michael K. Reiter

AT&T Bell Laboratories, Holmdel, New Jersey, USA
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Abstract. Rampart is a toolkit of protocols to facilitate
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Published 1995

- Fixed number of replicas
- No recoveries

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The SecureRing Protocols for Securing Group Communication*

Kim Potter Kihlstrom, L. E. Moser, P. M. Melliar-Smith
Department of Electrical and Computer Engineering
University of California, Santa Barbara, CA 93106
kimk@alpha.ece.ucsb.edu, moser@ece.ucsb.edu, pmms@ece.ucsb.edu

Abstract

The SecureRing group communication protocols prov… reliable ordered message delivery and group members… services despite Byzantine faults such as might be caused… modifications to the programs of a group member follow… illicit access to, or capture of, a group member.

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Practical Byzantine Fault Tolerance and Proactive Recovery

MIGUEL CASTRO
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Published 2002

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- **Periodic** recoveries

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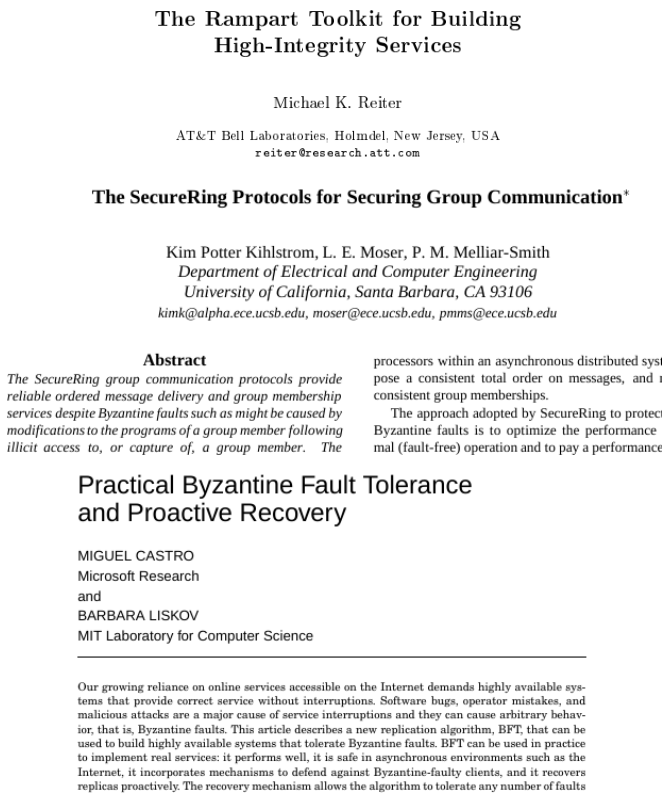

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Our growing reliance on online services accessible on the Internet demands highly available systems that provide correct service without interruptions. Software bugs, operator mistakes, and malicious attacks are a major cause of service interruptions and they can cause arbitrary behavior, that is, Byzantine faults. This article describes a new replication algorithm, BFT, that can be used to build highly available systems that tolerate Byzantine faults. BFT can be used in practice to implement real services: it performs well, it is safe in asynchronous environments such as the Internet, it incorporates mechanisms to defend against Byzantine-faulty clients, and it recovers replicas proactively. The recovery mechanism allows the algorithm to tolerate any number of faults

A Qualitative Analysis of the Intrusion-Tolerance Capabilities of the MAFTIA Architecture

Robert Stroud, Ian Welch[1], John Warne, Peter Ryan,
School of Computing Science, University of Newcastle upon Tyne, UK
{R.J.Stroud, J.P.Warne, Peter.Ryan}@ncl.ac.uk
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Published 2004

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- Periodic recoveries

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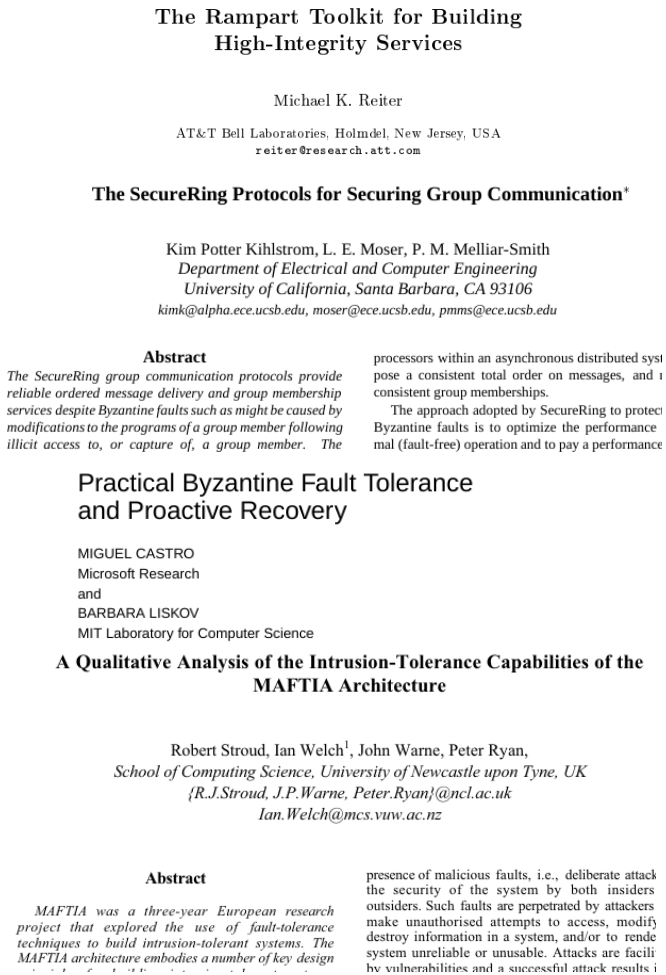

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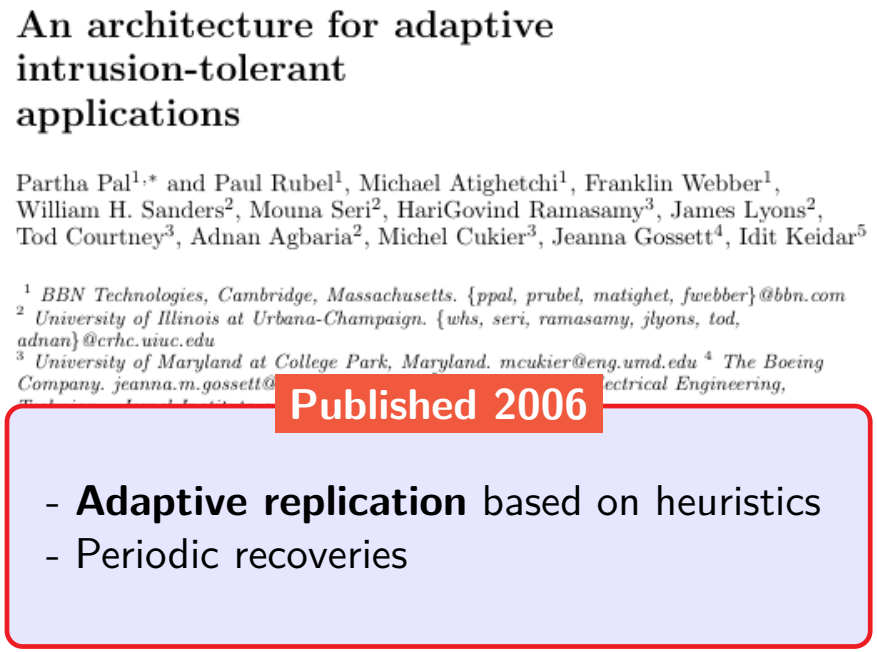

An architecture for adaptive intrusion-tolerant applications

Partha Pal[1,*] and Paul Rubel[1], Michael Atighetchi[1], Franklin Webber[1], William H. Sanders[2], Mouna Seri[2], HariGovind Ramasamy[3], James Lyons[2], Tod Courtney[3], Adnan Agbaria[2], Michel Cukier[3], Jeanna Gossett[4], Idit Keidar[5]

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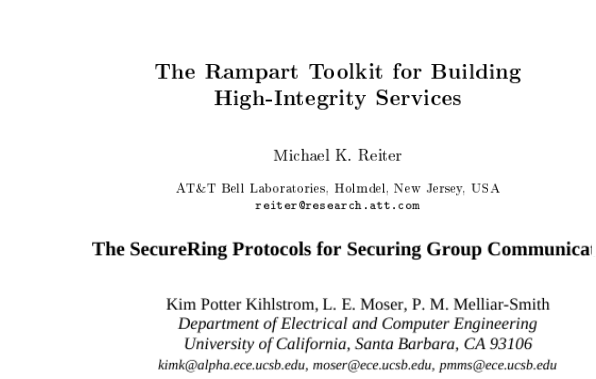
[3] *University of Maryland at College Park, Maryland. mcukier@eng.umd.edu* [4] *The Boeing Company. jeanna.m.gossett@* ectrical Engineering,

Published 2006

- **Adaptive replication** based on heuristics
- Periodic recoveries

Prior Work on Intrusion-Tolerant Systems



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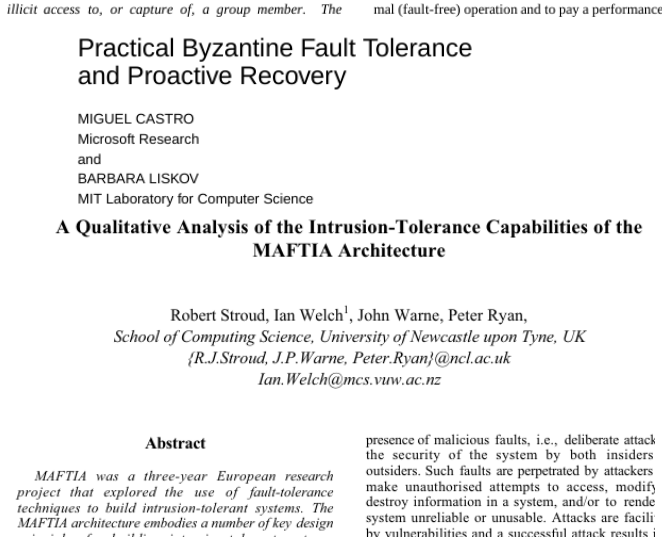

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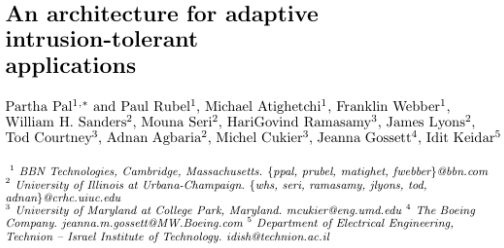

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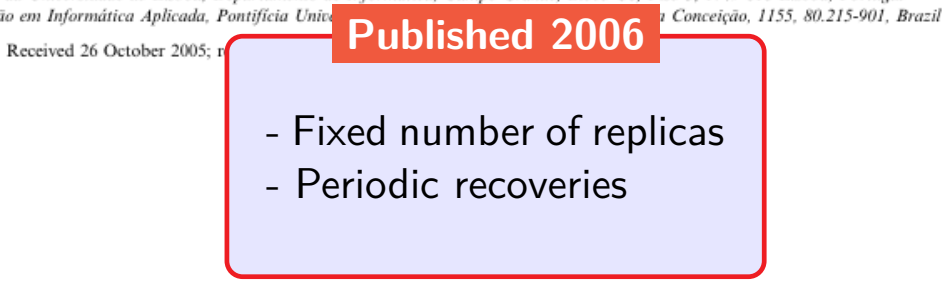

Worm-IT – A wormhole-based intrusion-tolerant group communication system

Miguel Correia [a,*], Nuno Ferreira Neves [a], Lau Cheuk Lung [b], Paulo Veríssimo [a]

[a] *Faculdade de Ciências da Universidade de Lisboa, Departamento de Informática, Campo Grande, Bloco C6, Piso 3, 1749-016 Lisboa, Portugal*
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Received 26 October 2005; r…

Published 2006

- Fixed number of replicas
- Periodic recoveries

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Received 26 October 2005; received in revised form 28 March 2006; accepted 30 March 2006

Resilient Intrusion Tolerance through Proactive and Reactive Recovery*

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Published 2007

- Fixed number of replicas
- **Supports both periodic and reactive recoveries**
- Does not provide reactive recovery strategies

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Worm-IT – A wormhole-based intrusion-tolerant group communication system

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State Transfer for Hypervisor-Based Proactive Recovery of Heterogeneous Replicated Services

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Published 2011

- Fixed number of replicas
- Periodic recoveries

Prior Work on Intrusion-Tolerant Systems

The Rampart Toolkit for Building High-Integrity Services

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The SecureRing Protocols for Securing Group Communica

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Abstract

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Resilient Intrusion Tolerance through Proactive and Reactive Recovery*

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Practical Byzantine Fault Tolerance and Proactive Recovery

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A Qualitative Analysis of the Intrusion-Tolerance Capabilities of the MAFTIA Architecture

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Network-Attack-Resilient Intrusion-Tolerant SCADA for the Power Grid

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Skynet: a Cyber-Aware Intrusion Tolerant Overseer

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Can we do better by leveraging game-theoretic strategies?

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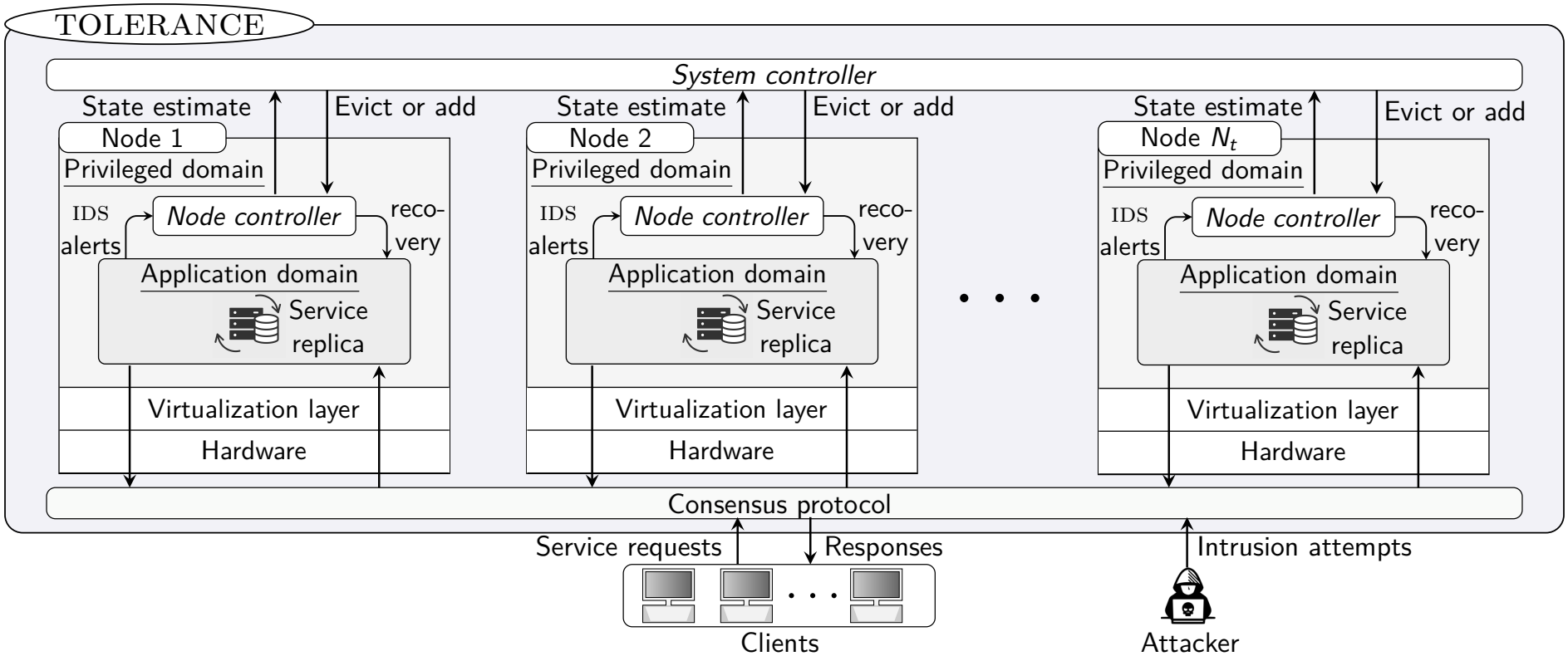
The TOLERANCE Architecture

Tw**o**-**le**vel **r**ecovery **an**d replication **c**ontrol with f**e**edback.



Definition 1 (Correct service)

The system provides **correct service** if the healthy replicas satisfy the following properties:

Each request is eventually executed. (Liveness)

Each executed request was sent by a client. (Validity)

Each replica executes the same request sequence. (Safety)

Proposition 1 (Correctness of TOLERANCE)

A system that implements the TOLERANCE *architecture* ***provides correct service*** *if*

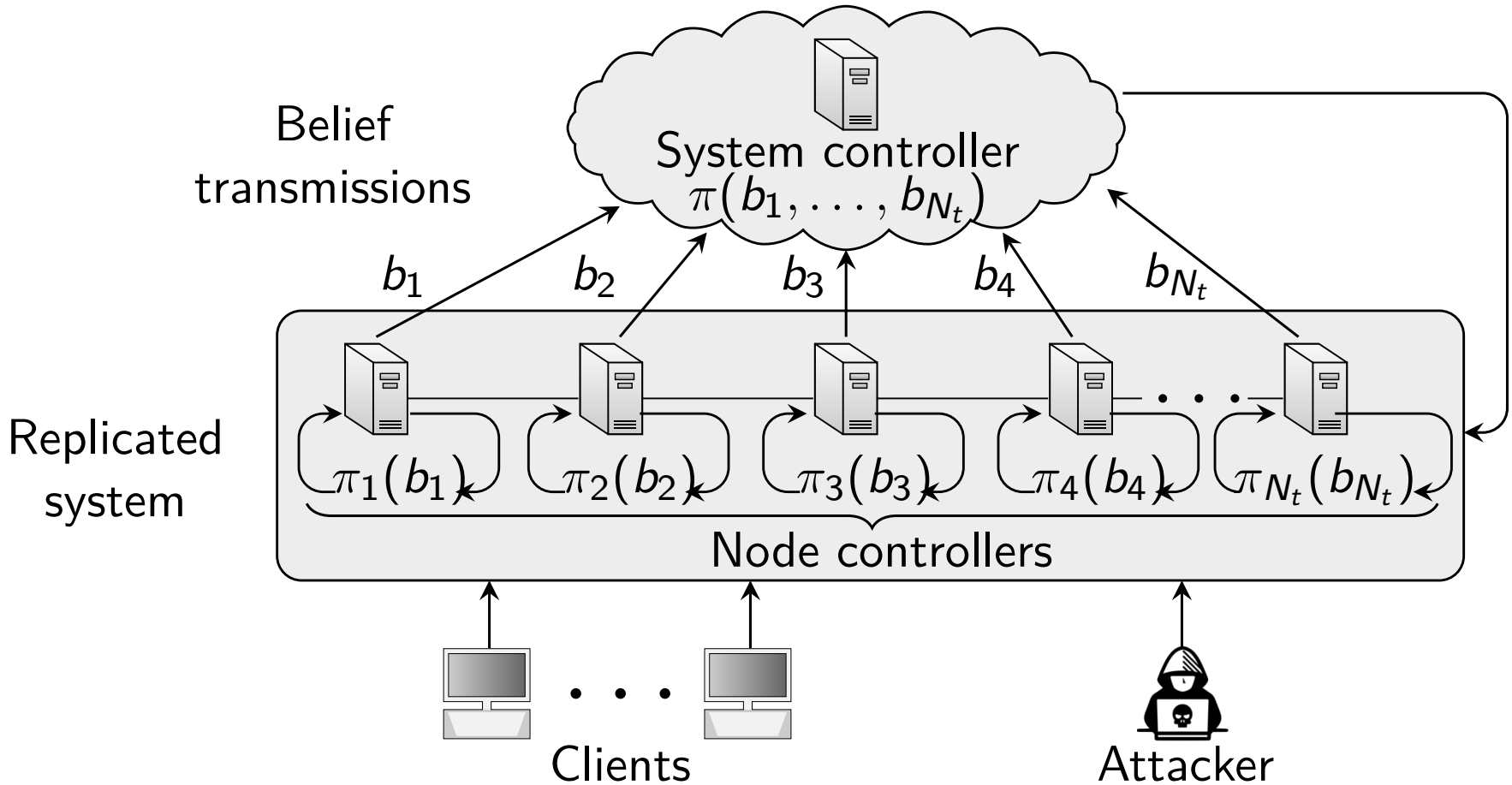
Network links are authenticated.

At most f nodes are compromised or crashed simultaneously.

$N_t \geq 2f + 1$.

The system is partially synchronous.

Intrusion Tolerance as a Two-Level Game



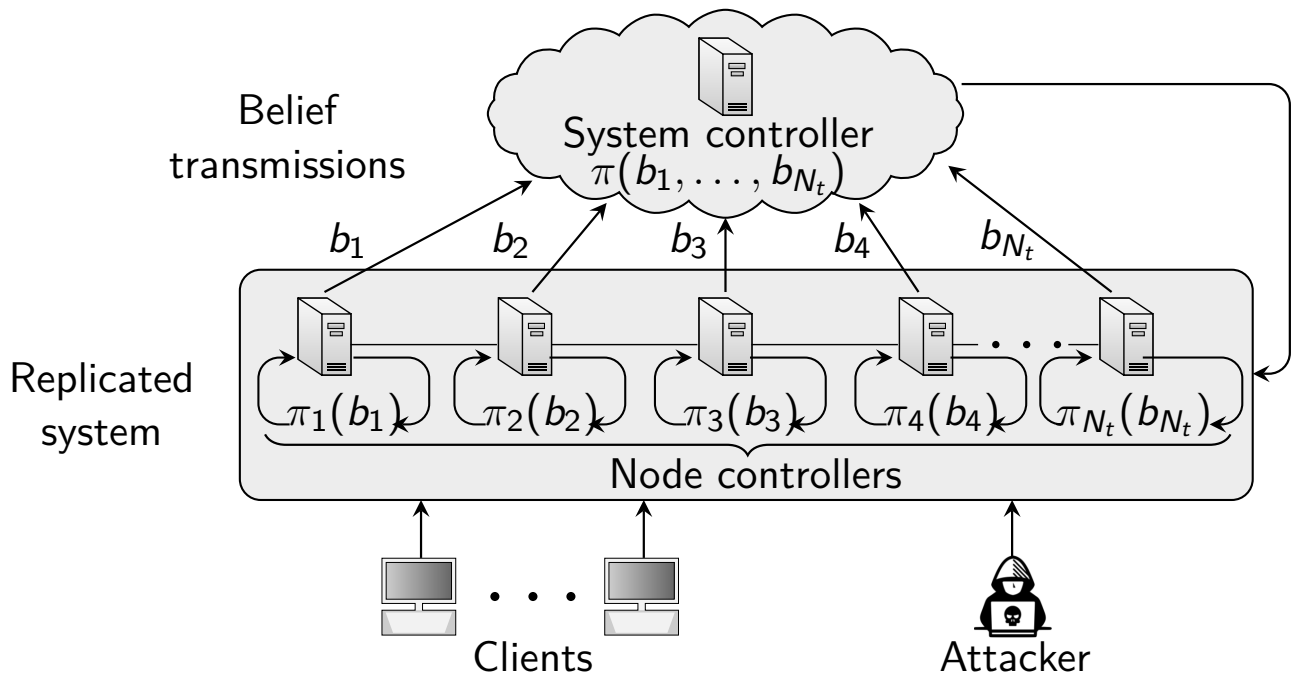
- We formulate intrusion tolerance as a two-level game.
- The local game models intrusion recovery.
- The global game models replication control.

Assumption 1

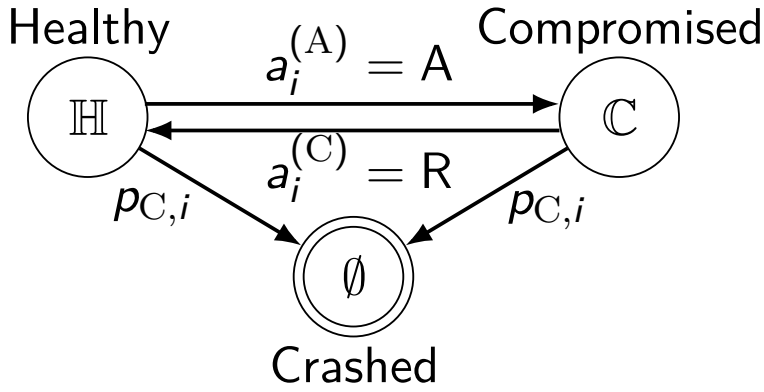
The probability that the system controller fails is negligible.

Assumption 2

Compromise and crash events are statistically independent across nodes.



The Local Recovery Game



- **Partially observed stochastic game** Γ_i.
- Players: (C)ontroller and (A)ttacker.

- Controller actions: (R)ecover and (W)ait.
- Attacker actions: (A)ttack and (F)alse alarm.

- **States**: $\mathcal{S}_{\mathrm{N}} = \{\mathbb{H}, \mathbb{C}, \emptyset\}$.
- $p_{\mathrm{C},i}$: crash probability, $p_{\mathrm{A},i}$: attack success probability.
- Observation $o_{i,t} \sim z_i(\cdot|a^{(\mathrm{A})})$: IDS alerts at time t.

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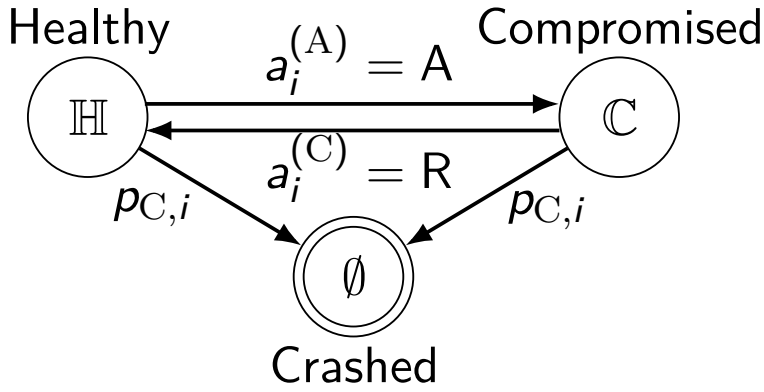

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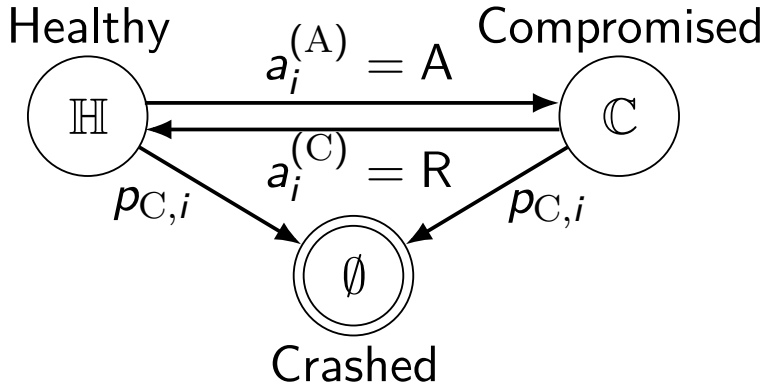

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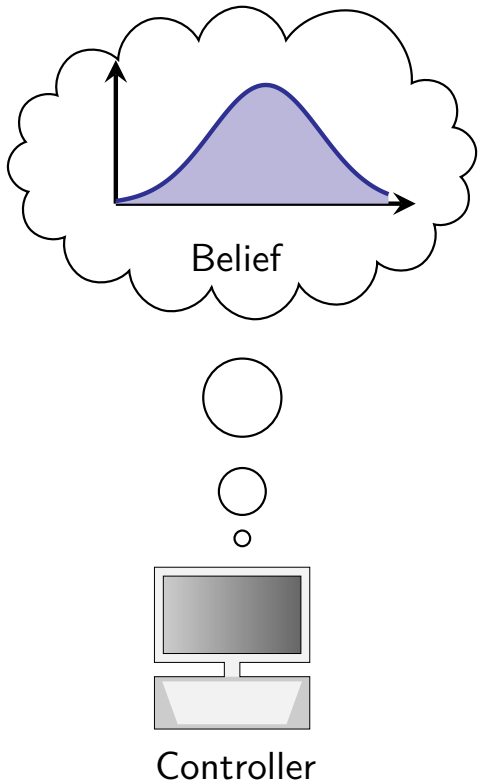
Node Controller Strategy

- The controller computes the **belief**

$$b_{i,t}(s) \triangleq \mathbb{P}[S_{i,t} = \mathbb{C} | \mathbf{h}_t^{(\mathrm{C})}].$$

$$\mathbf{h}_t^{(\mathrm{C})} \triangleq (b_{i,1}, a_{i,1}^{(\mathrm{C})}, o_{i,2}, a_{i,2}^{(\mathrm{C})}, o_{i,3}, \ldots, a_{i,t-1}^{(\mathrm{C})}, o_{i,t}).$$



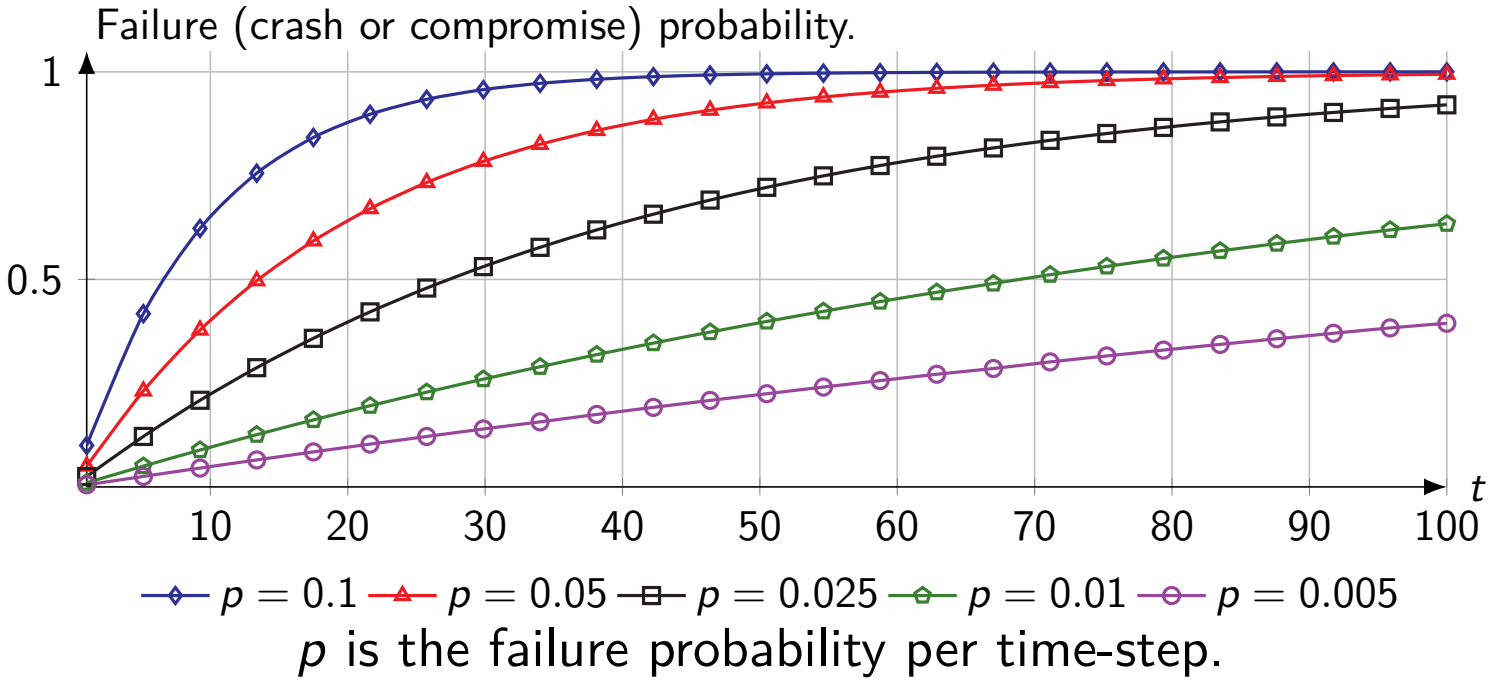
- Controller strategy:

$$\pi^{(\mathrm{C})} : [0, 1] \to \Delta(\{\mathsf{W}, \mathsf{R}\}).$$

Node Controller Objective

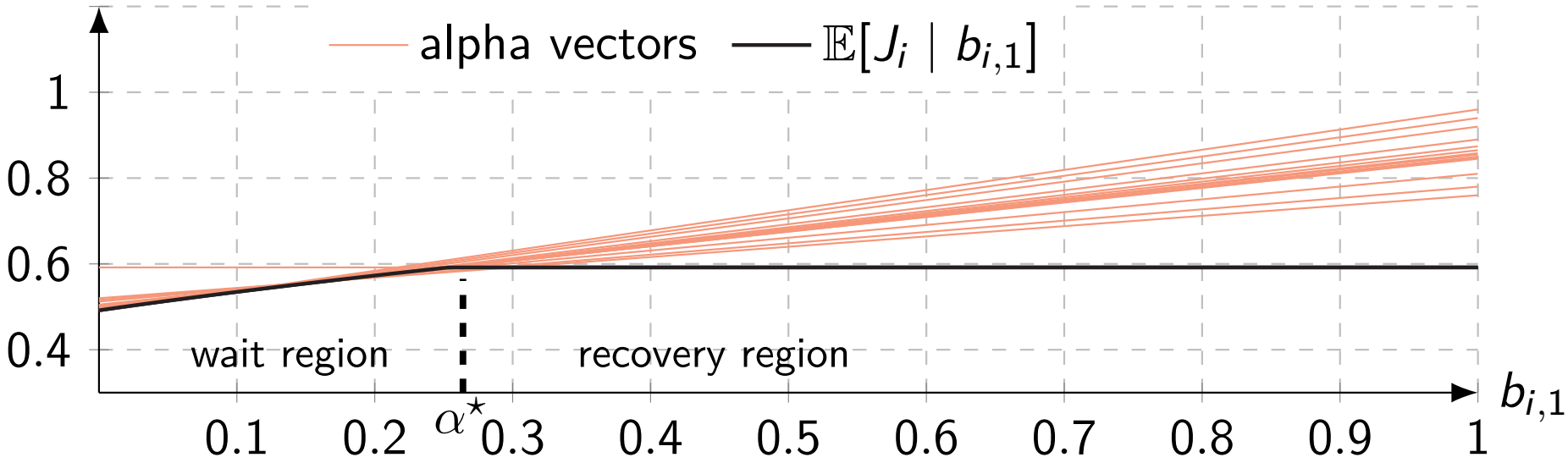
- **Cost:** $J_i \triangleq \eta T_i^{(\mathrm{R})} + F_i^{(\mathrm{R})}$. (Zero-sum game)
  - $T_i^{(\mathrm{R})}$ is the average *time-to-recovery*.
  - $F_i^{(\mathrm{R})}$ is the *recovery frequency*.
  - $\eta > 1$ is a scaling factor.

- Bounded-time-to-recovery constraint: The time between two recoveries can be at most Δ_{R}.



p is the failure probability per time-step.

Threshold Structure of the Controller's Best Response



The controller's best response value.

Theorem 2

There exists a best response strategy that satisfies

$$\tilde{\pi}_{i,t}^{(\mathrm{C})}(b_{i,t}) = \mathsf{R} \iff b_{i,t} \geq \alpha_{i,t}^\star \qquad \forall t,$$

where $\alpha_{i,t}^\star \in [0,1]$ *is a threshold.*

Efficient Computation of Best Responses

Algorithm 1: Threshold Optimization

Input: Objective function J_i, parametric optimizer po.

Output: A approximate best response strategy $\hat{\pi}^{(\mathrm{C})}_{i,\theta}$.

Algorithm

$\Theta \leftarrow [0, 1]$.

For each $\theta \in \Theta$, define $\pi^{(\mathrm{C})}_{i,\theta}(b_{i,t})$ as

$$\pi^{(\mathrm{C})}_{i,\theta}(b_{i,t}) \triangleq \begin{cases} \mathrm{R} & \text{if } b_{i,t} \geq \theta \\ \mathrm{W} & \text{otherwise.} \end{cases}$$

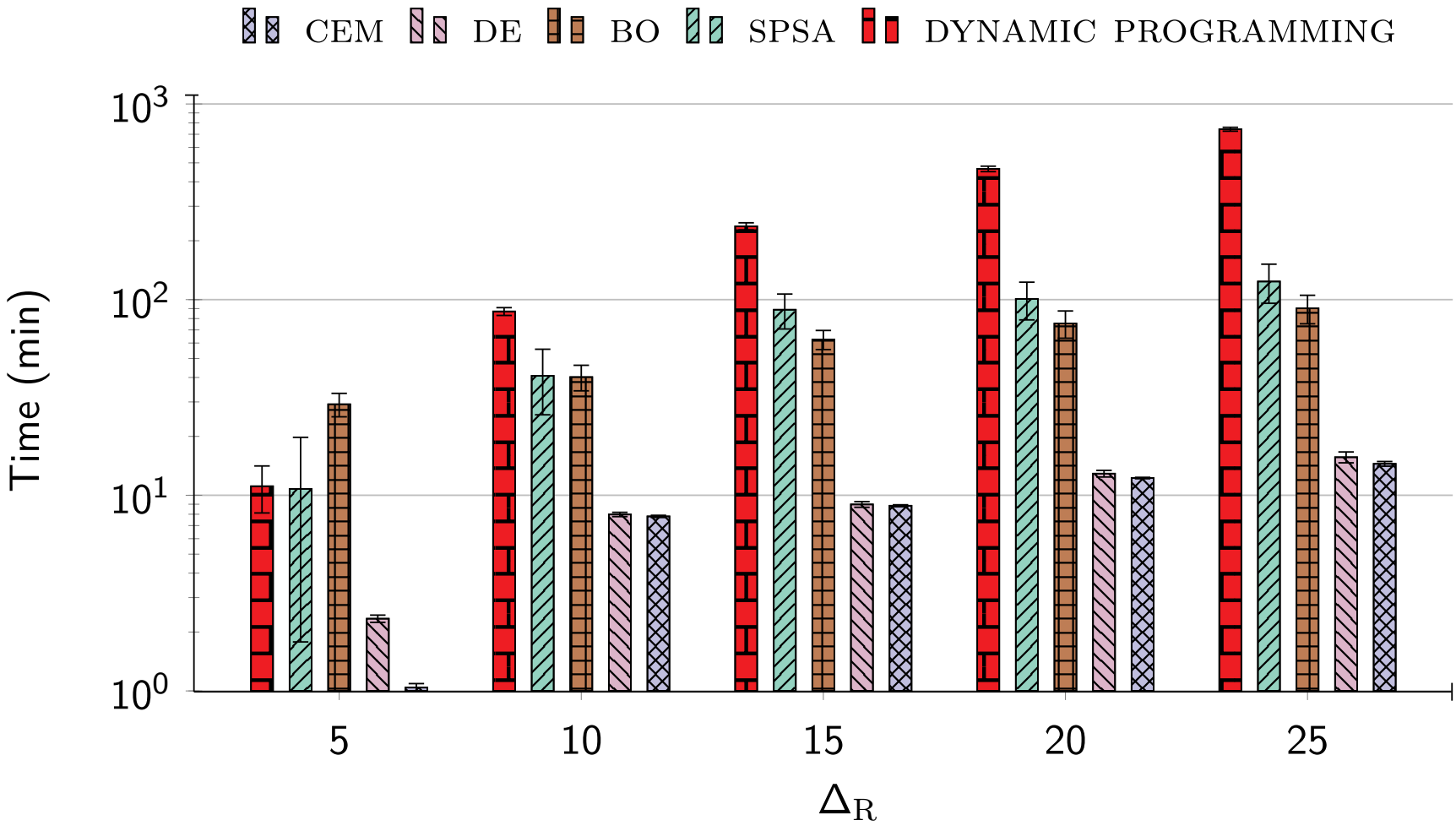
$J_\theta \leftarrow \mathbb{E}_{\pi^{(\mathrm{C})}_{i,\theta}}[J_i]$.

$\hat{\pi}^{(\mathrm{C})}_{i,\theta} \leftarrow \mathrm{po}(\Theta, J_\theta)$.

return $\hat{\pi}^{(\mathrm{C})}_{i,\theta}$.

- Examples of parameteric optimization algorithmns: CEM, BO, CMA-ES, DE, SPSA, etc.

Efficient Computation of Best Responses



Mean compute time to obtain a best reponse for different values of the bounded-time-to-recovery constraint Δ_{R}.

Definition 3 (Perfect Bayesian equilibrium (PBE))

Let $\mathbb{B}$ denote the Bayesian belief operator. Then $(\boldsymbol{\pi}^\star, \mathbb{B})$ is a PBE iff

1. **Optimality:**
   $\boldsymbol{\pi}^\star$ is a Nash equilibrium (NE) in $\Gamma|_{\mathbf{h}_{i,t}}$ $\forall \mathbf{h}_{i,t}$, where $\Gamma|_{\mathbf{h}_{i,t}}$ is the subgame starting from $\mathbb{B}(\mathbf{h}_t, \pi_{i,t}^{\star,(\mathrm{A})})$.

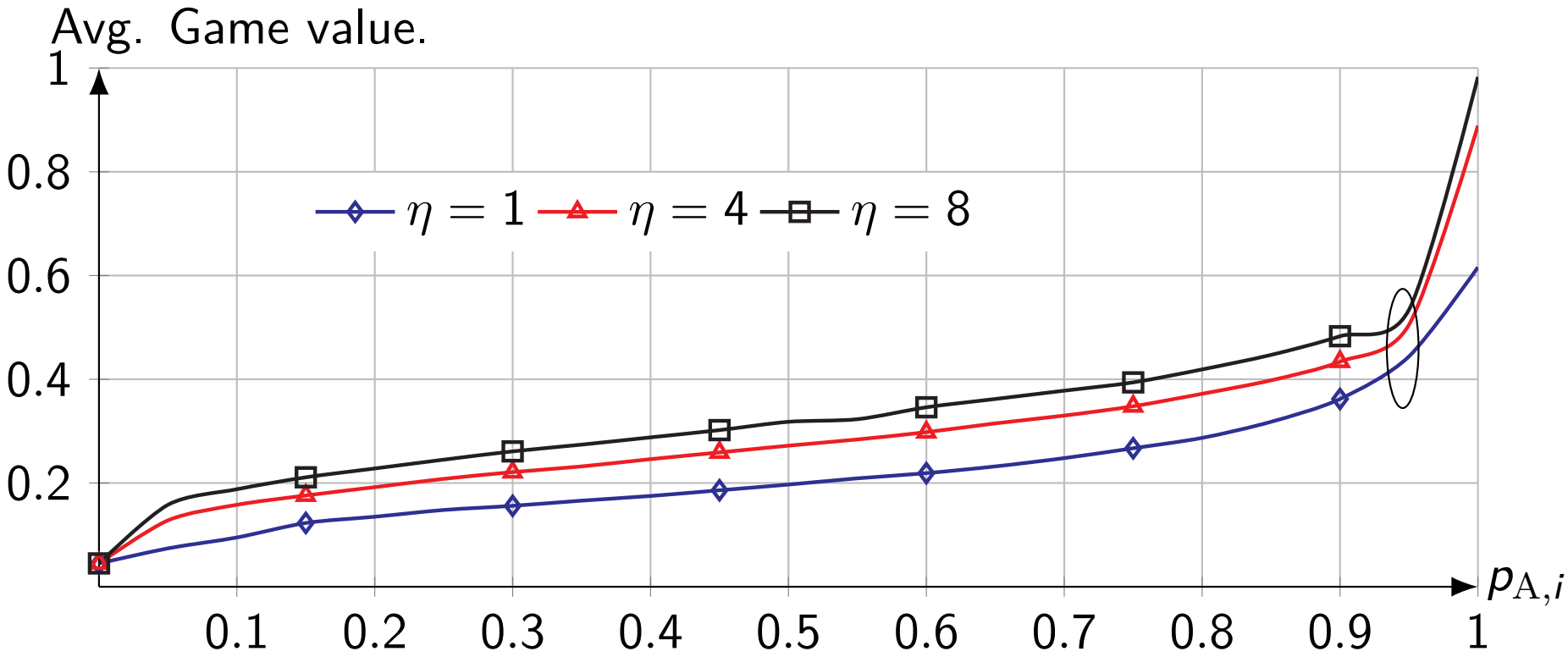
2. **Belief consistency:**
   For any $\mathbf{h}_{i,t}$ with $\mathbb{P}[\mathbf{h}_{i,t} \mid \boldsymbol{\pi}^\star, \mathbf{b}_1] > 0$, then

$$\begin{aligned}&\mathbb{B}(\mathbf{h}_{i,t}, \pi_{i,t}^{\star,(\mathrm{A})}) \\ &= \mathbb{B}(\mathbb{B}(\mathbf{h}_{i,t-1}, \pi_{i,t}^{\star,(\mathrm{A})}), \pi_{i,t}^{\star,(\mathrm{C})}(\mathbb{B}(\mathbf{h}_{i,t-1}, \pi_{i,t}^{\star,(\mathrm{A})})), o_t, \pi_{i,t}^{\star,(\mathrm{A})}).\end{aligned}$$

Theorem 4 (Existence of equilibrium and best response)

1. *For each strategy pair* π_i *in* Γ_i*, there exists a pair of best responses.*
2. Γ_i *has a perfect Bayesian equilibrium* (PBE).
3. *If* $s_{i,t} = 0 \iff b_{i,t} = 0$*, then* Γ_i *has a pure* PBE.
4. *The average value of* Γ_i *is not larger than* 1.

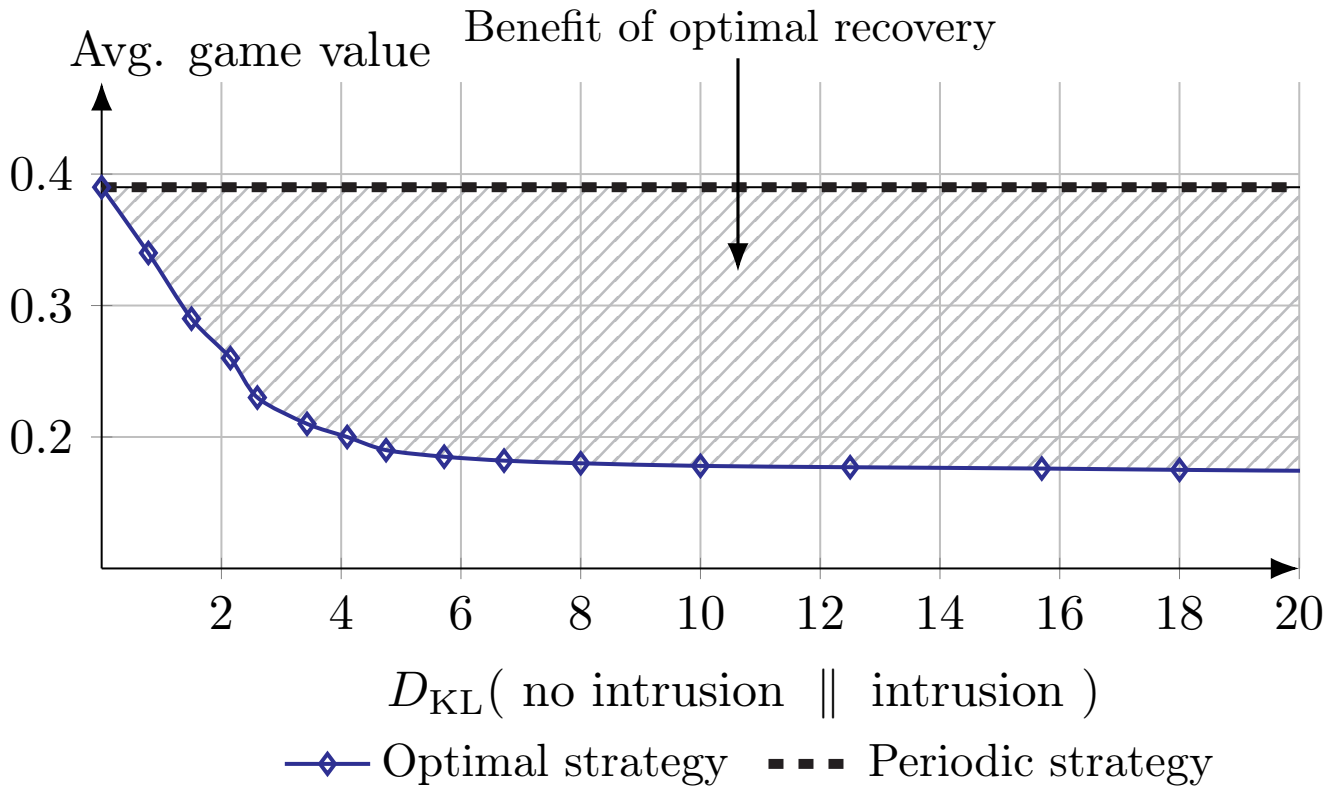
Value of the Local Recovery Game



Avg. Game value in function of the intrusion probability $p_{\mathrm{A},i}$.

- We can compute the game value using **Heuristic Search Value Iteration** (HSVI).

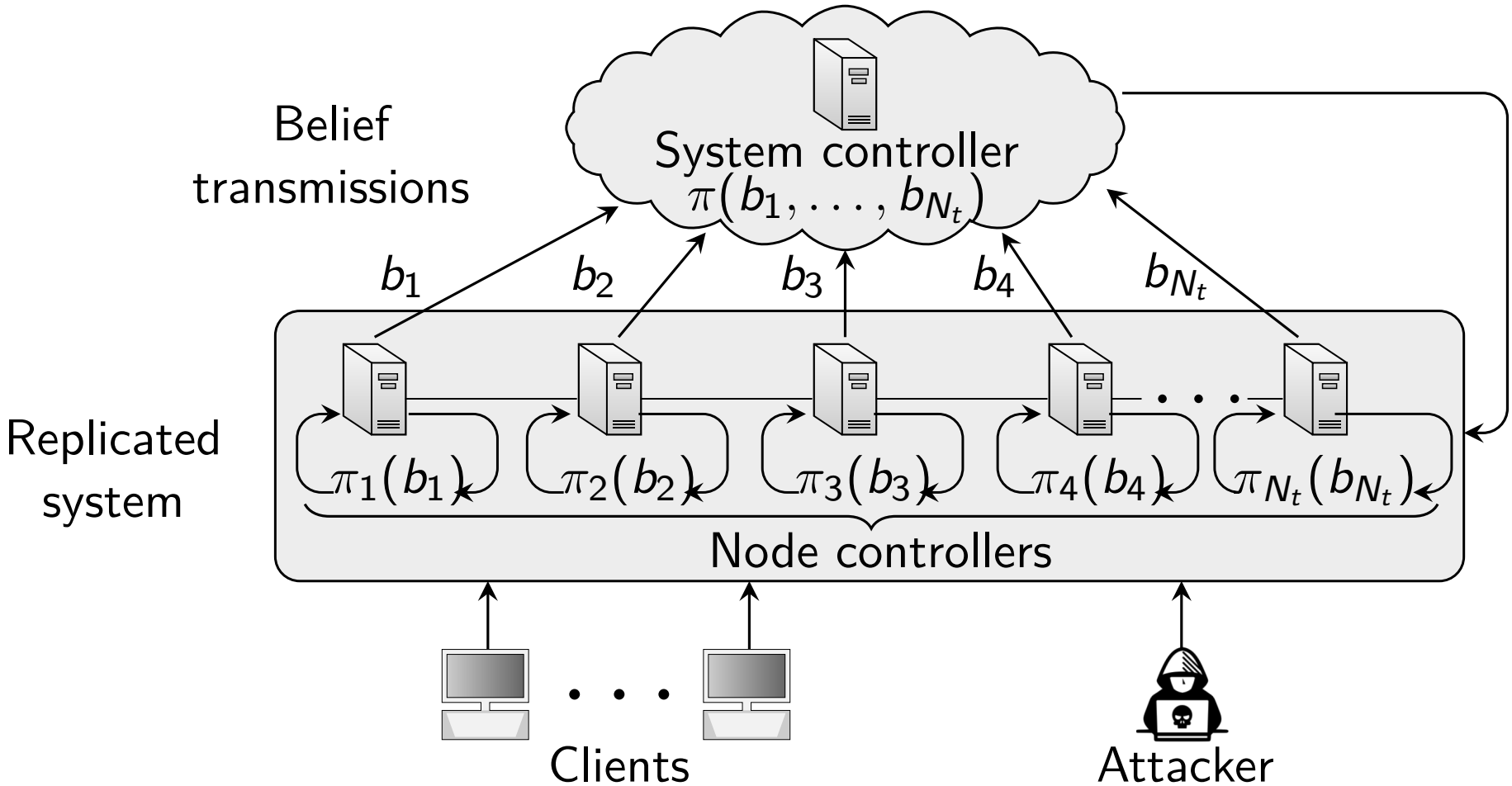
The Benefit of Strategic Recovery



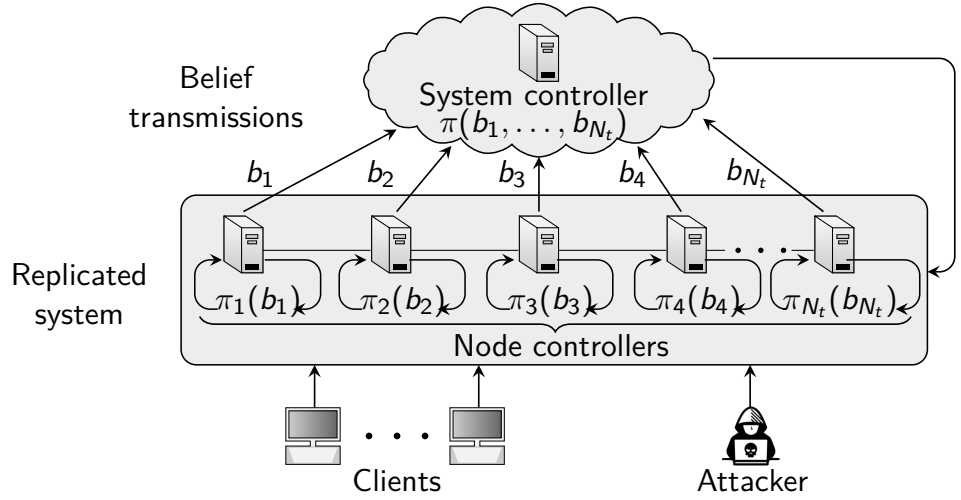
Key insight

Strategic recovery can significantly reduce operational cost given that an **intrusion detection model is available**.

Intrusion Tolerance as a Two-Level Game



The Global Replication Game



- **Constrained stochastic game** Γ.
- Players: (C)ontroller and (A)ttacker.
- States: $\mathcal{S}_{\mathrm{S}} = \{0, 1, \ldots, s_{\max}\}$, the number of healthy nodes.

- Controller actions: Add $a_t^{(\mathrm{C})} \in \{0, 1\}$ nodes.
- Attacker actions: $\mathbf{a}_t^{(\mathrm{A})} \in \{\mathrm{F}, \mathrm{A}\}^{N_t}$.

- **Markov** strategies:

$$\pi^{(\mathrm{C})} : \mathcal{S}_{\mathrm{S}} \to \Delta(\{0, 1\})$$
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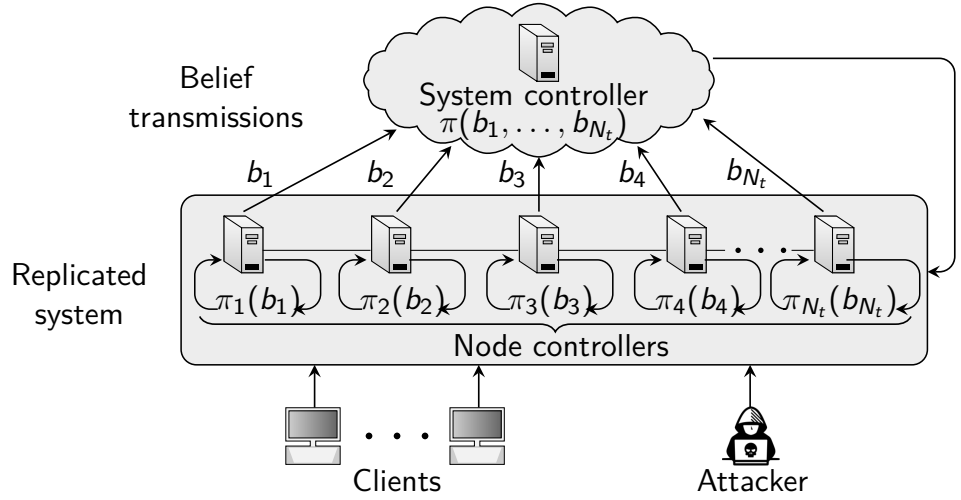

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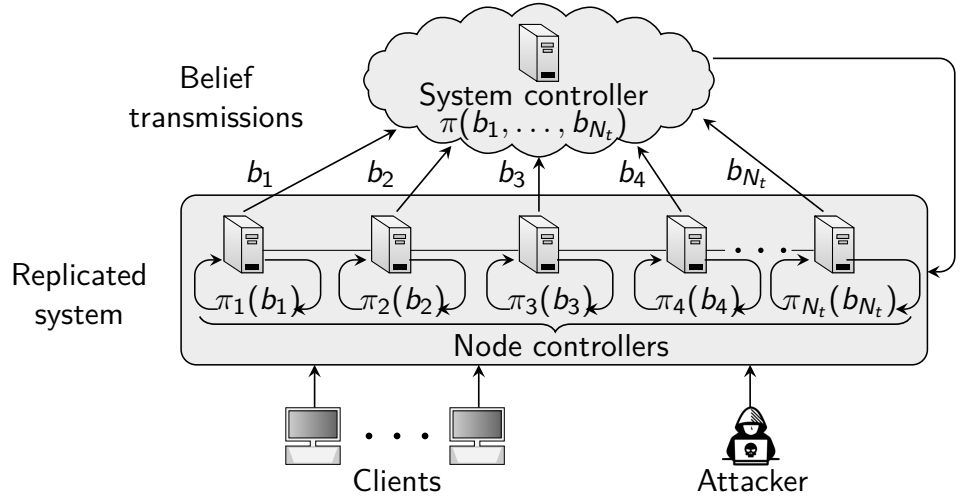
$$\pi^{(\mathrm{C})} : \mathcal{S}_{\mathrm{S}} \to \Delta(\{0, 1\})$$
$$\pi^{(\mathrm{A})} : \mathcal{S}_{\mathrm{S}} \to \Delta(\{\mathrm{F}, \mathrm{A}\}^{N_t}).$$

The Global Replication Game



- **Constrained stochastic game** Γ.
- Players: (C)ontroller and (A)ttacker.
- States: $\mathcal{S}_{\mathrm{S}} = \{0, 1, \ldots, s_{\max}\}$, the number of healthy nodes.

- Controller actions: Add $a_t^{(\mathrm{C})} \in \{0, 1\}$ nodes.
- Attacker actions: $\mathbf{a}_t^{(\mathrm{A})} \in \{\mathrm{F}, \mathrm{A}\}^{N_t}$.

- **Markov** strategies:

$$\pi^{(\mathrm{C})} : \mathcal{S}_{\mathrm{S}} \to \Delta(\{0, 1\})$$
$$\pi^{(\mathrm{A})} : \mathcal{S}_{\mathrm{S}} \to \Delta(\{\mathrm{F}, \mathrm{A}\}^{N_t}).$$

System Controller Objective

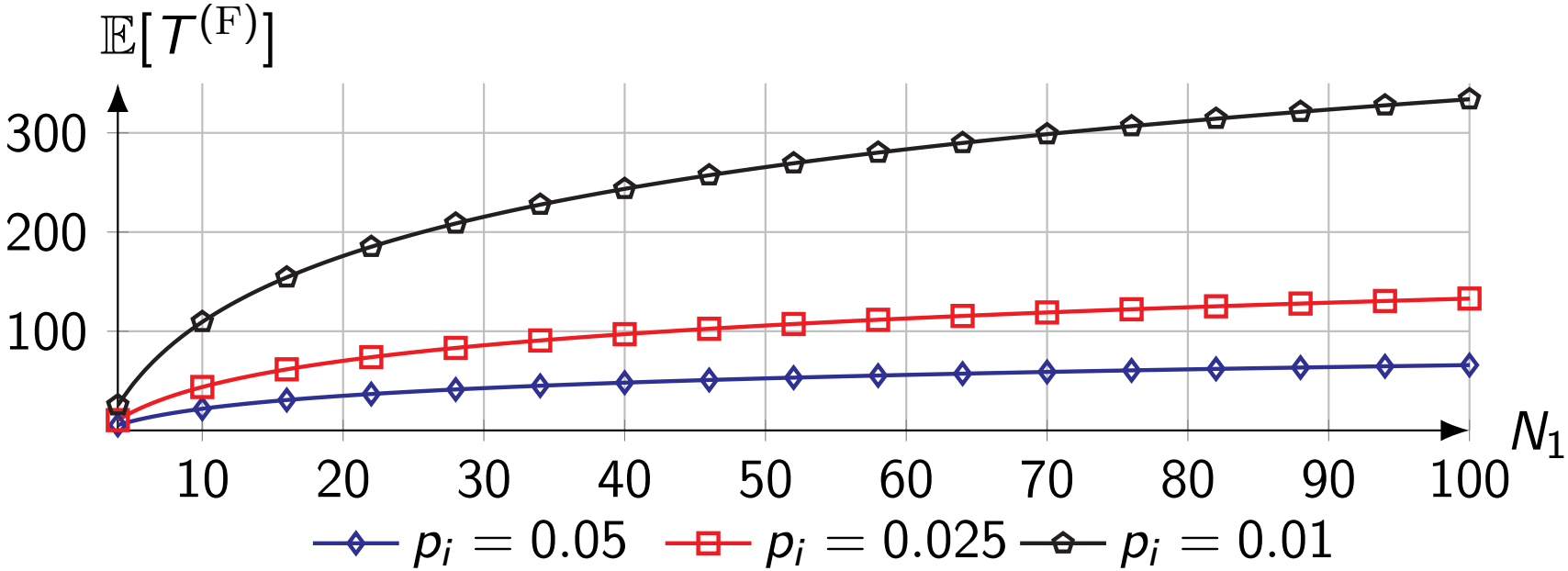
- **Zero-sum** game.
- Cost: $J \triangleq \lim_{T\to\infty} \sum_{t=1}^{T} \frac{a_t^{(\mathrm{C})}}{T}$.
- Constraint: $T^{(\mathrm{A})} \geq \epsilon_{\mathrm{A}}$, where $T^{(\mathrm{A})}$ is the availability.

ϵ_{A}	*Allowed service downtime per year*
0.9	36 days
0.95	18 days
0.99	3 days
0.999	8 hours
0.9999	52 minutes
0.99999	5 minutes
1	0 minutes

System Reliability Analysis

- The **Mean-time-to-failure** (MTTF) is the mean hitting time of a state where $s_t \leq f$:

$$\mathbb{E}[T^{(\mathrm{F})} \mid S_1 = s_1] = \mathbb{E}_{(S_t)_{t\geq 1}}\Big[\inf\{t \geq 1 \mid S_t \leq f\} \mid S_1 = s_1\Big].$$



The MTTF in function of the number of initial nodes N_1 and failure probability per node p_i.

Theorem 5 (Best Response and Equilibrium Existence)

Assuming

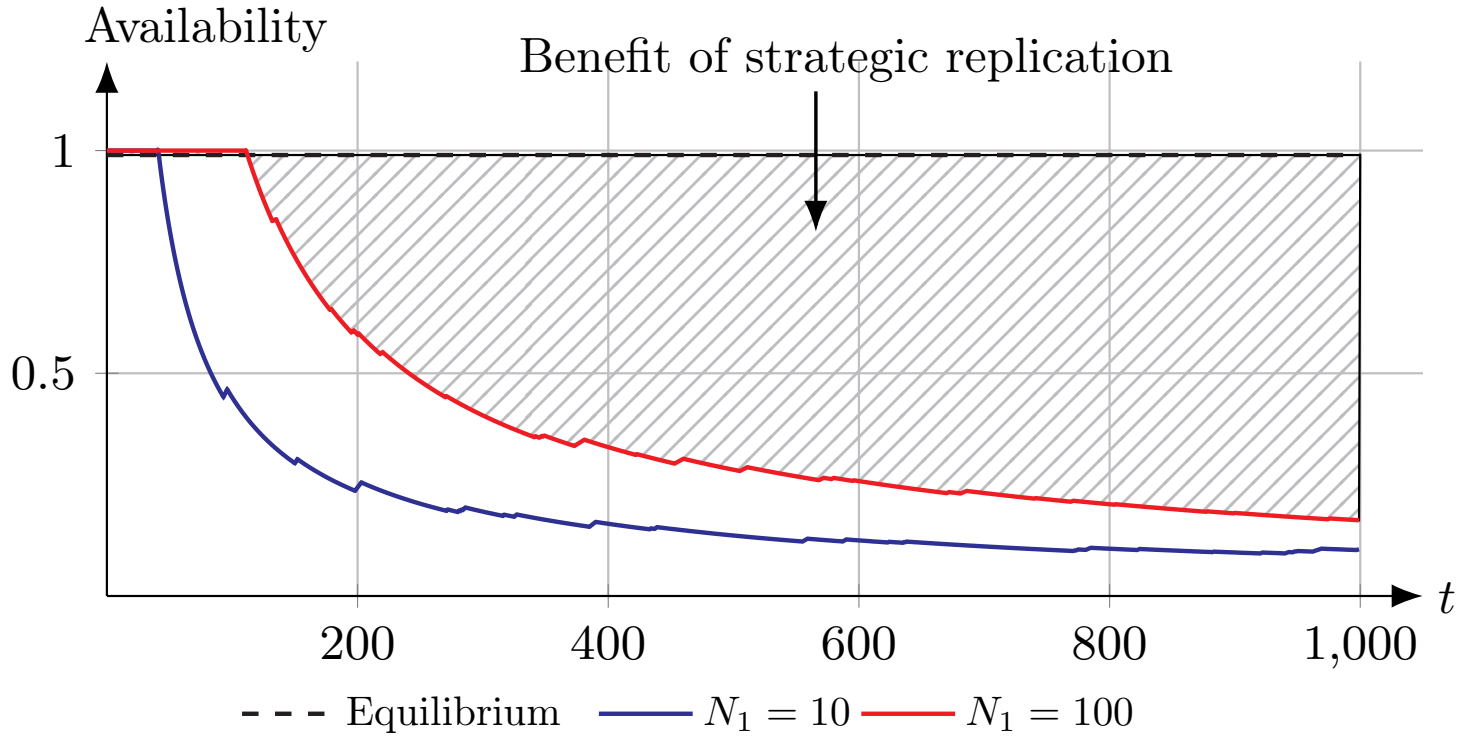
(A) *The Markov chain induced by each strategy pair π is* ***unichain****.*

(B) *The availability constraint is feasible.*

Then the following holds.

1. *For each strategy pair π, there exists a pair of stationary best responses.*
2. *Best responses can be computed by using* ***linear programming****.*
3. *A constrained, stationary Markov perfect equilibrium (MPE) exists.*

The Benefit of Strategic Replication

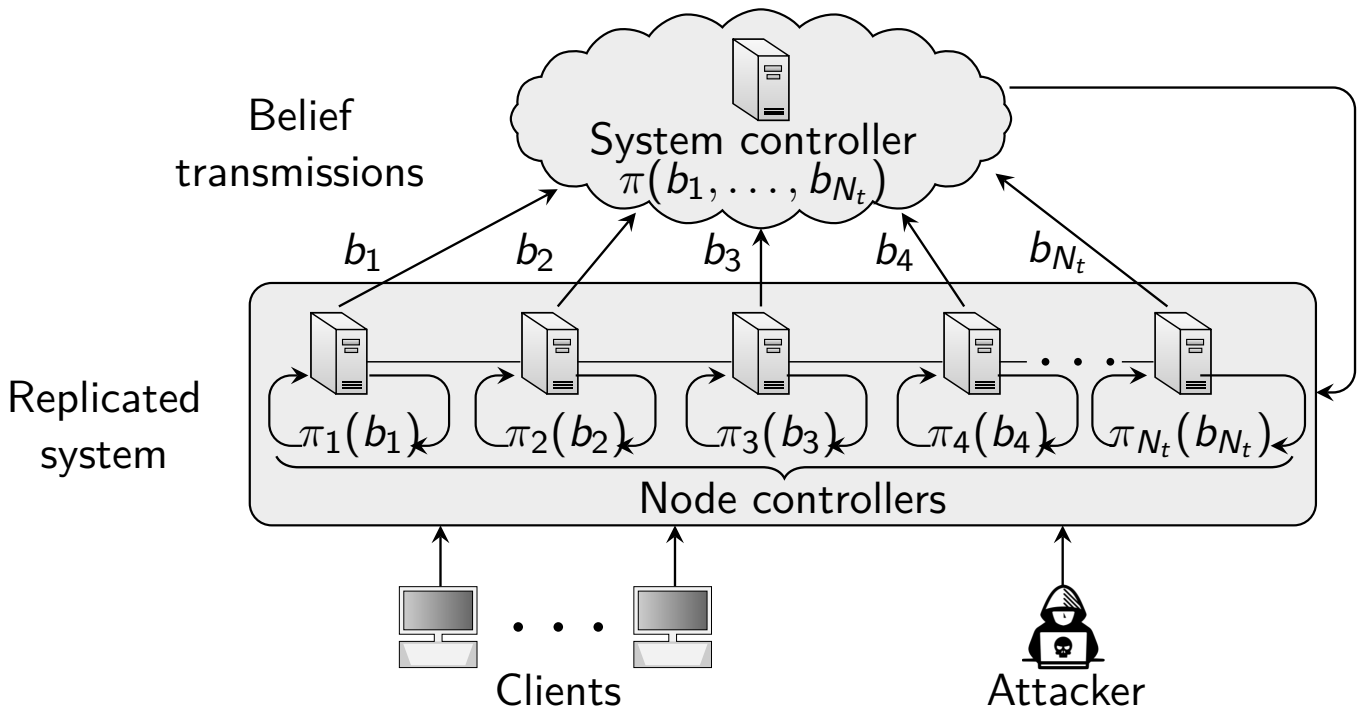


Key insight

Strategic replication can **guarantee a high service availability in expectation**. The benefit of strategic replication is mainly prominent for long-running systems.

Summary of the Game-Theoretic Model

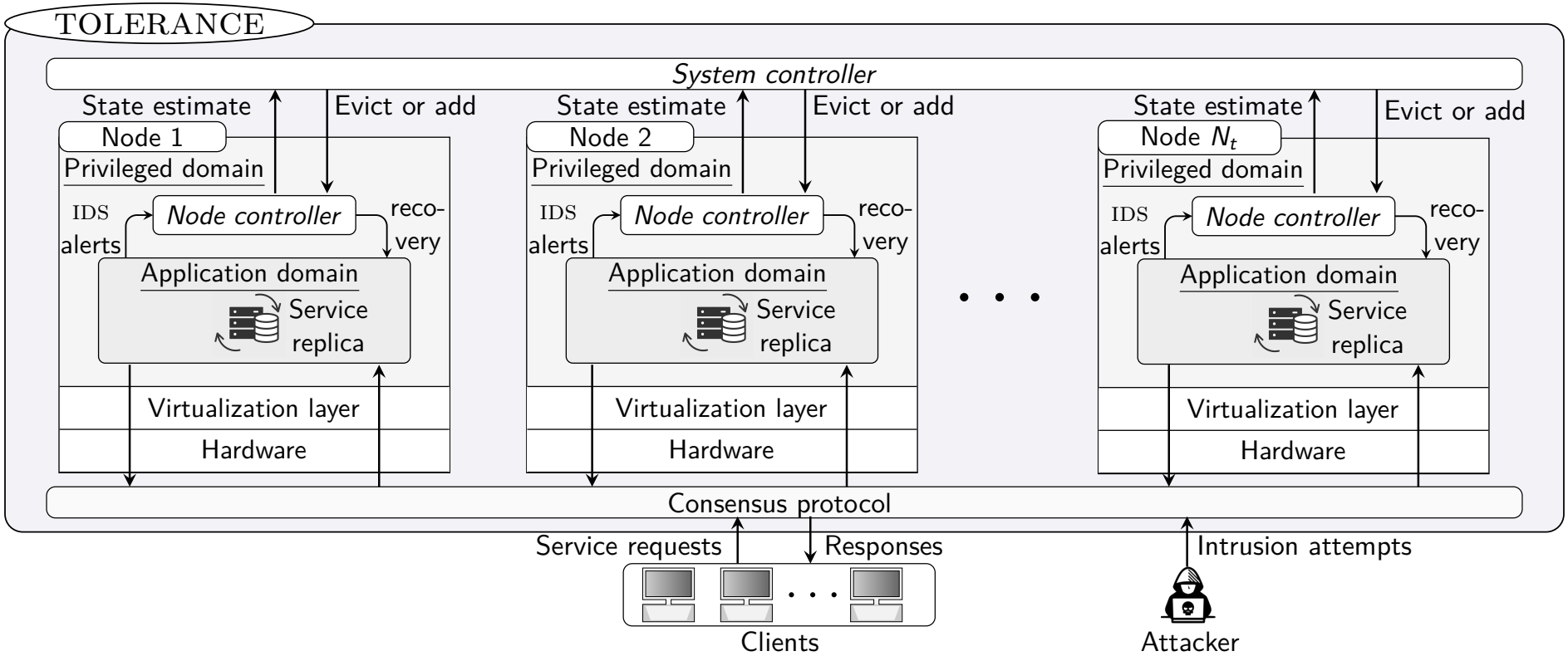
- Partially observed stochastic game models intrusion recovery.
  - **Threshold structure** of best responses.
  - Existence of *perfect Bayesian equilibria*.
- Constrained stochastic game models replication control.
  - **Threshold structure** of best responses.
  - Existence of *Markov perfect equilibria*.



Experiment Setup - Testbed

The TOLERANCE Architecture

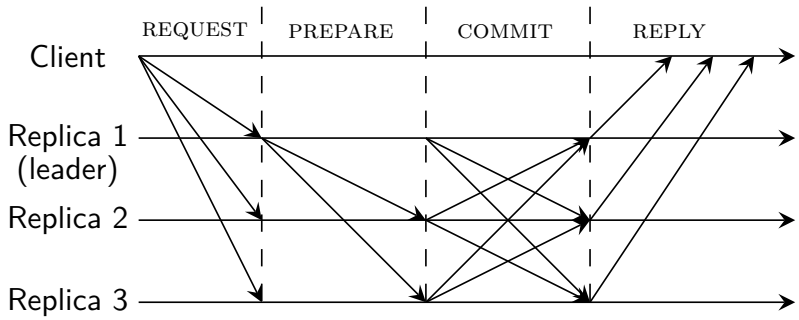
Tw**o**-**le**vel **r**ecovery **an**d replication **c**ontrol with f**e**edback.



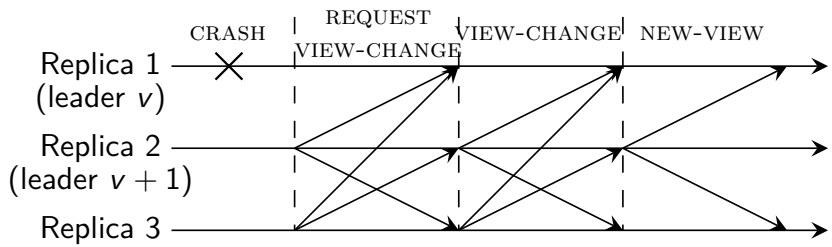
- A replicated web service which offers two operations:
  - A **read** operation that returns the service state.
  - A **write** operation that updates the state.

Intrusion-Tolerant Consensus Protocol (MINBFT)

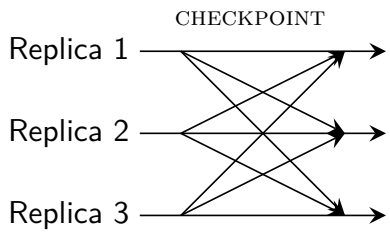
a) Normal operation



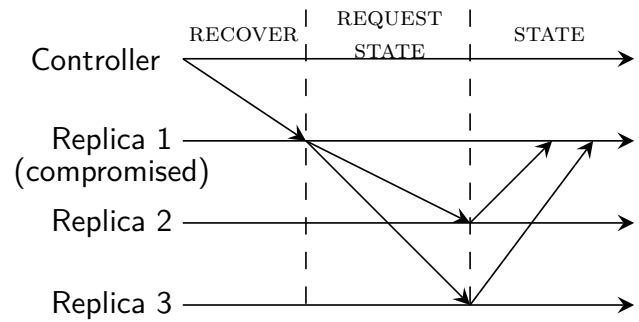
b) View change



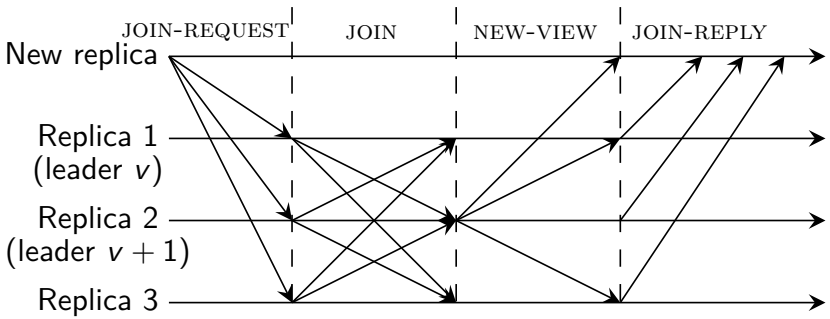
c) Checkpoint



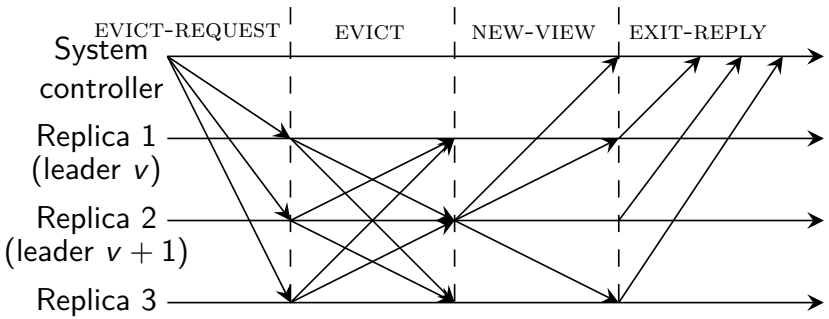
d) State transfer



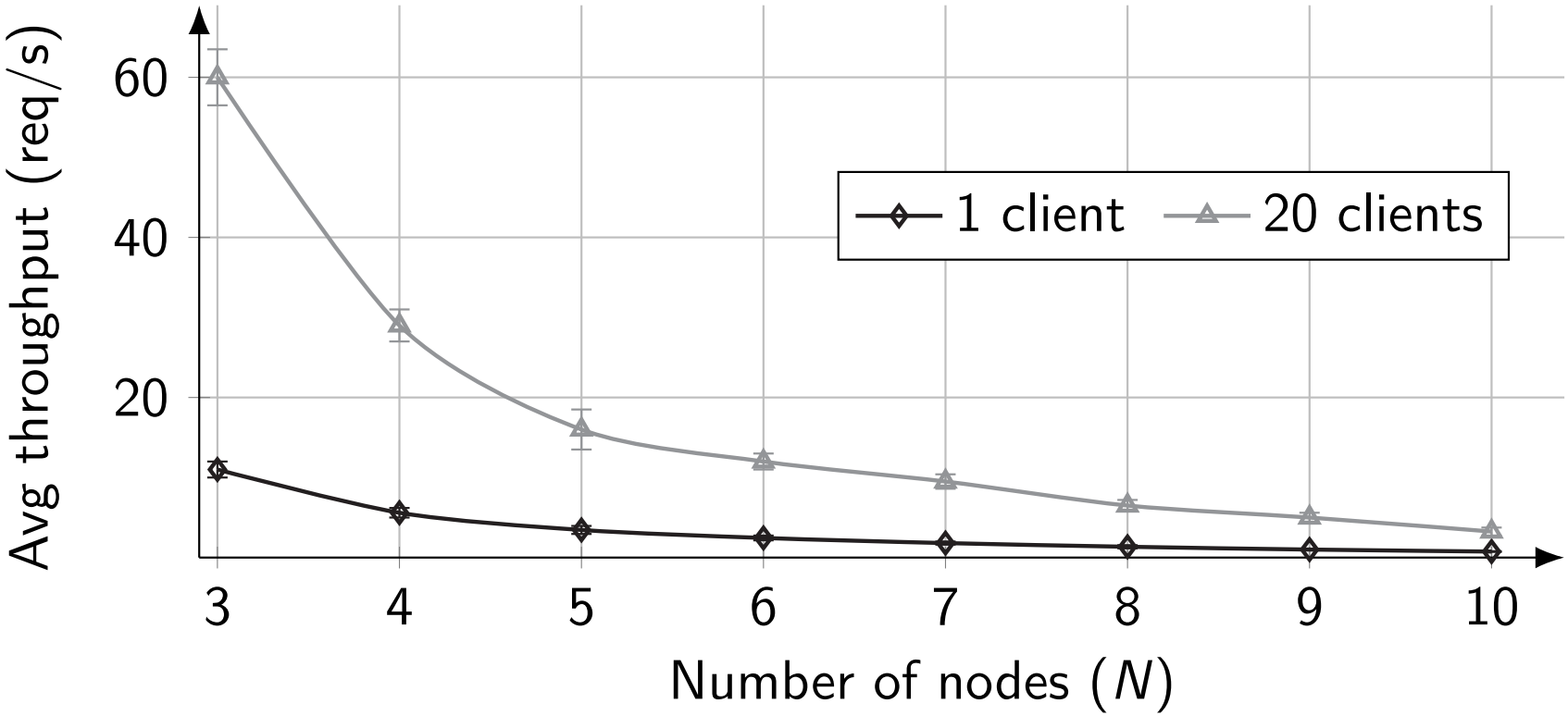
e) Join



f) Evict



Intrusion-Tolerant Consensus Protocol



Average throughput of our implementation of MINBFT.

Experiment Setup - Emulated Intrusions

Replica ID	*Intrusion steps*
1	TCP SYN scan, FTP brute force
2	TCP SYN scan, SSH brute force
3	TCP SYN scan, TELNET brute force
4	ICMP scan, exploit of CVE-2017-7494
5	ICMP scan, exploit of CVE-2014-6271
6	ICMP scan, exploit of CWE-89 on DVWA
7	ICMP scan, exploit of CVE-2015-3306
8	ICMP scan, exploit of CVE-2016-10033
9	ICMP scan, SSH brute force, exploit of CVE-2010-0426
10	ICMP scan, SSH brute force, exploit of CVE-2015-5602

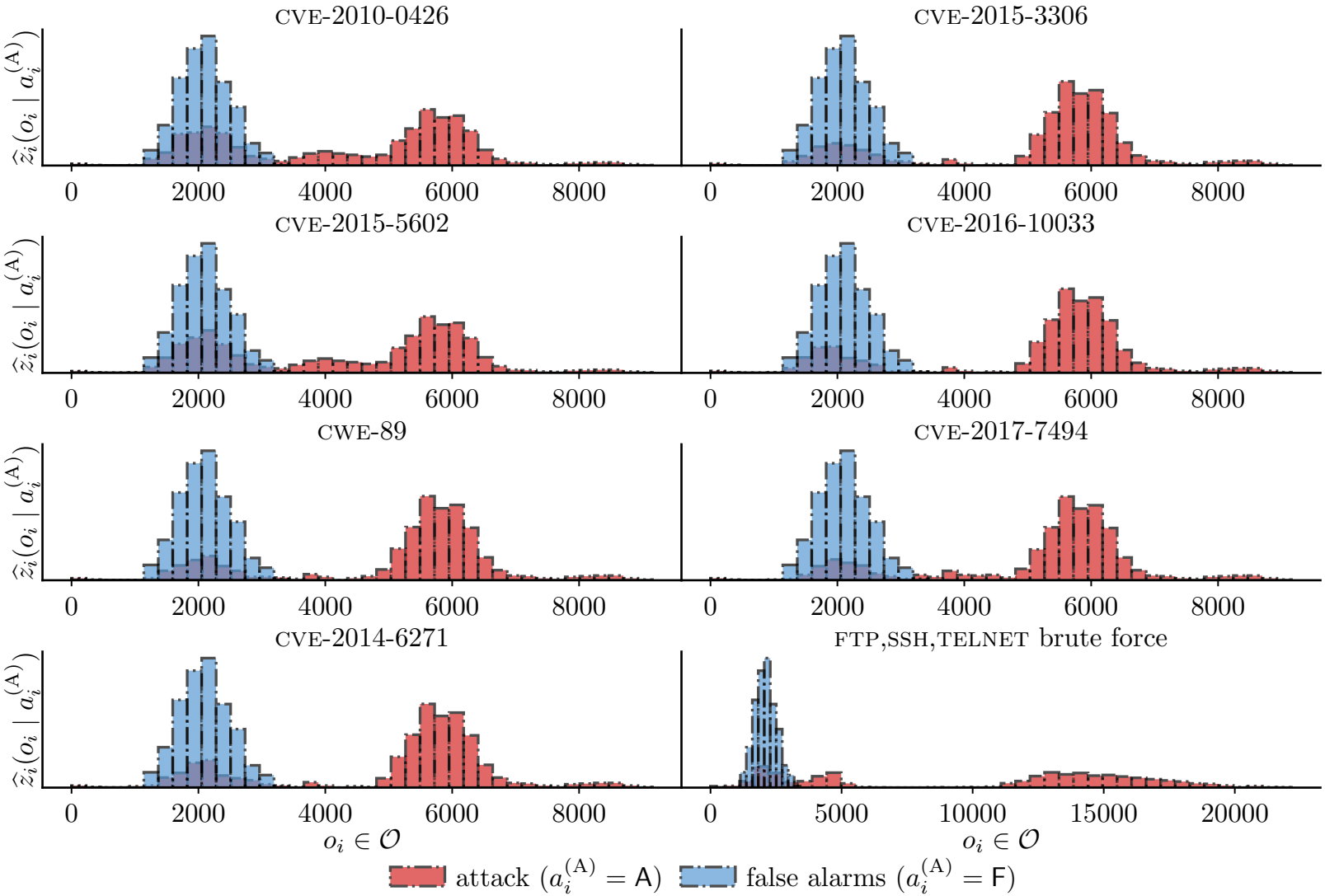
Table 1: Intrusion steps.

Experiment Setup - Background Traffic

Background services	*Replica ID(s)*
FTP, SSH, MONGODB, HTTP, TEAMSPEAK	1
SSH, DNS, HTTP	2
SSH, TELNET, HTTP	3
SSH, SAMBA, NTP	4
SSH	5, 7, 8, 10
DVWA, IRC, SSH	6
TEAMSPEAK, HTTP, SSH	9

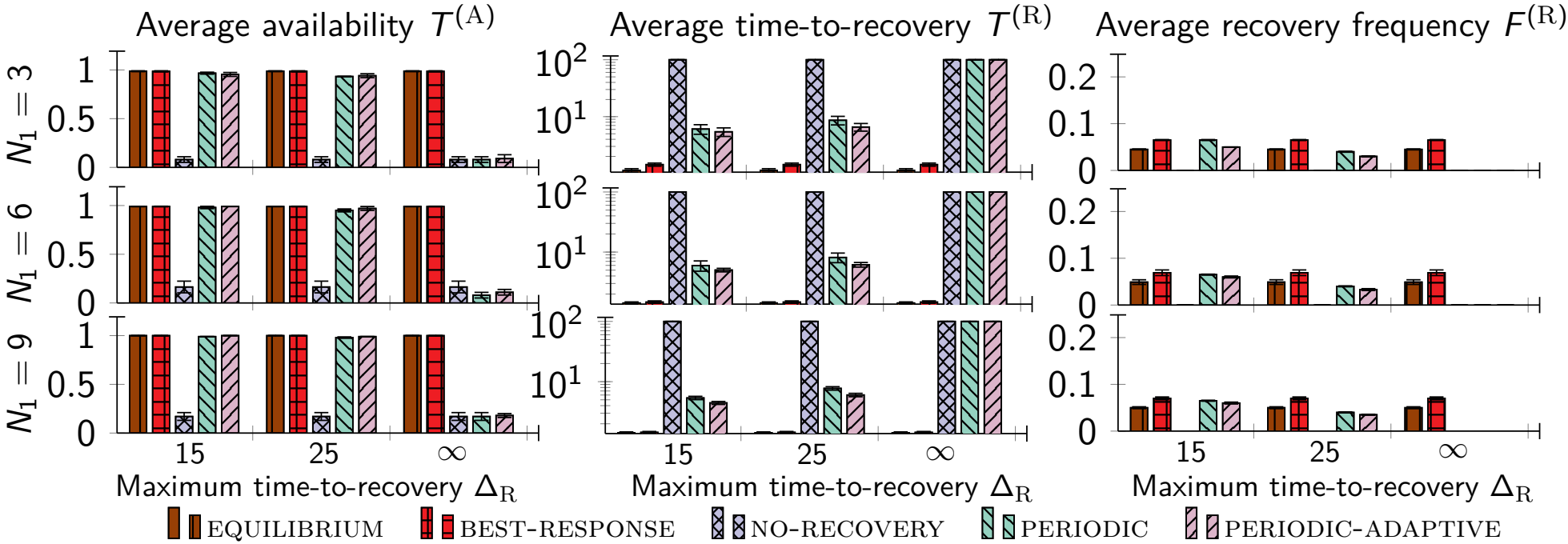
Table 2: Background services.

Estimated Distributions of Intrusion Alerts



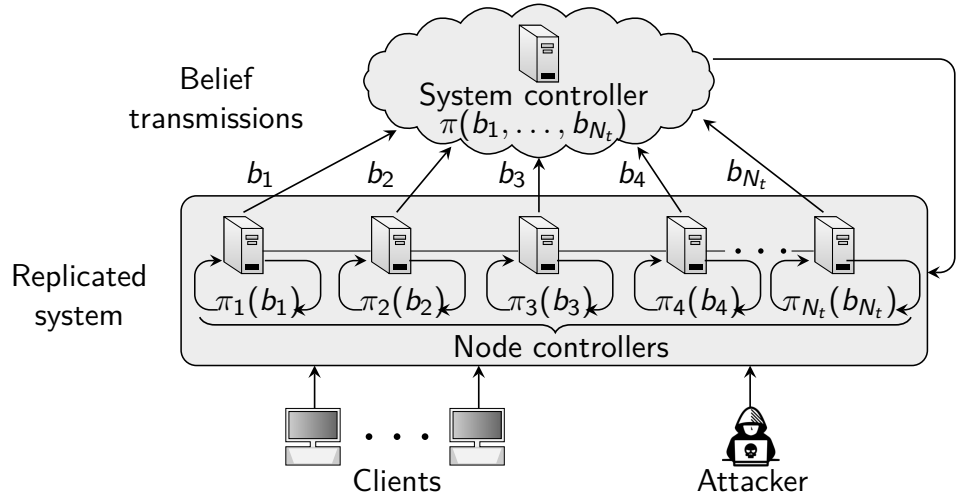
- **We estimate the observation distribution** z with the empirical distribution $\widehat{Z}$ based on M samples.
- $\widehat{z} \to^{a.s} z$ as $M \to \infty$ (Glivenko-Cantelli theorem).

Comparison with State-of-the-art Intrusion-Tolerant Systems



Comparison between our game-theoretic control strategies and the baselines; x-axes indicate values of Δ_R; rows relate to the number of initial nodes N_1.

Conclusion



- We present a **game-theoretic model of intrusion tolerance**.
- We establish structural results.
- We evaluate the equilibrium strategies on a testbed.
- Our game-theoretic strategies have stronger theoretical guarantees and significantly better practical performance than the control strategies used in state-of-the-art intrusion-tolerant systems.