Intrusion Tolerance as a Two-Level Game [1]

Visit to the University of Melbourne

Kim Hammar

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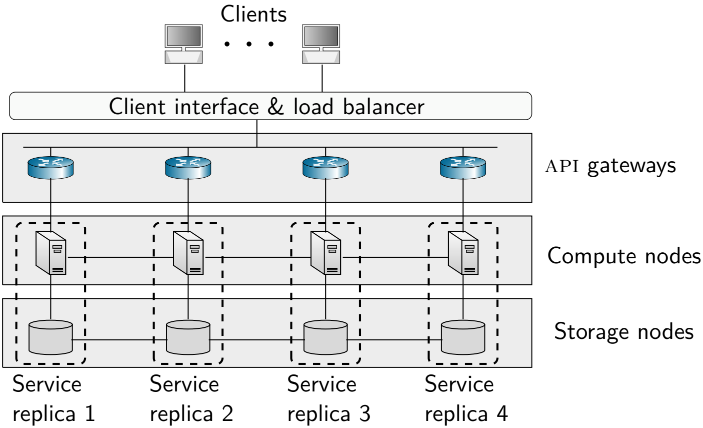
June 20, 2024

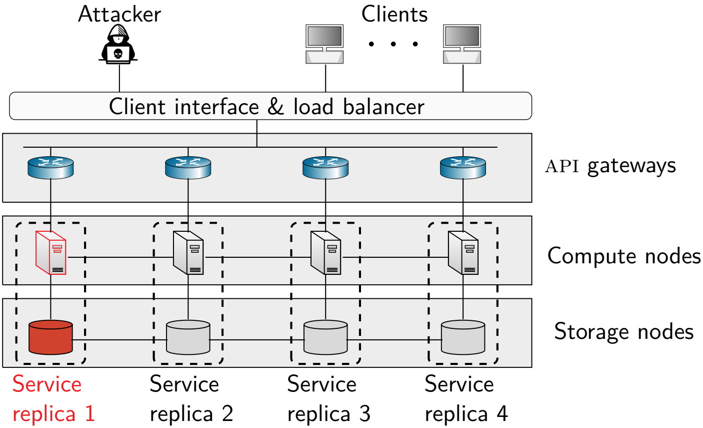
[1] Paper to appear in International Conference on Dependable Systems and Networks, IEEE DSN 2024, June 24-27, Brisbane, Australia

Use Case: Intrusion Tolerance



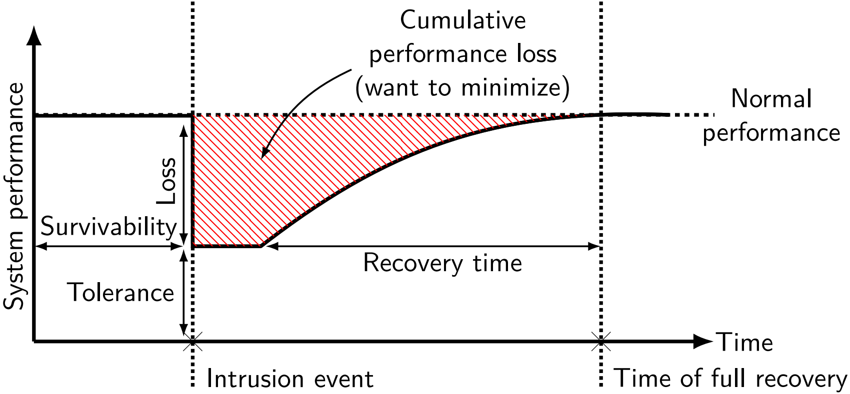
- A **replicated system** offers a service to a client population.
- The system should provide service without disruption.

Use Case: Intrusion Tolerance



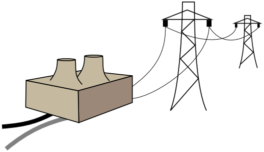
- An attacker seeks to intrude on the system and disrupt service.
- The system should **tolerate intrusions.**

Intrusion Tolerance (Simplified)



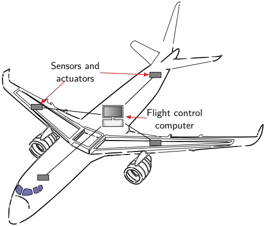
Increasing Demand for Intrusion-Tolerant Systems

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



Power grids
e.g., SCADA systems[2].

Safety-critical IT systems
e.g., banking systems, e-commerce applications[3], healthcare systems, etc.



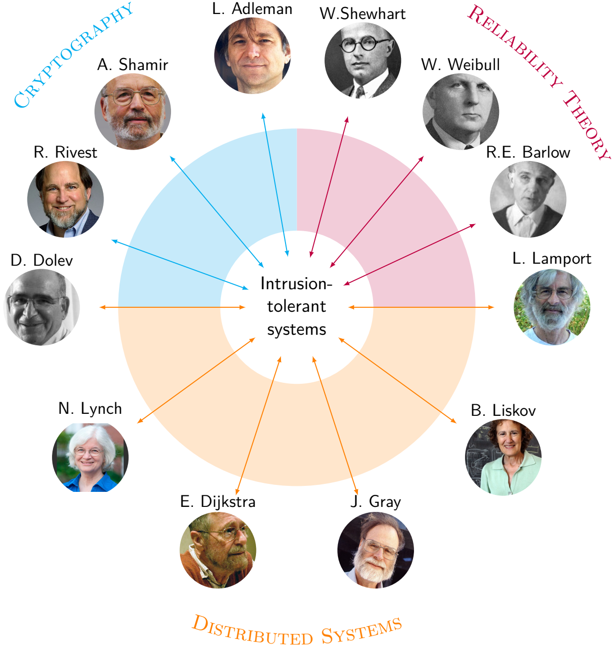
Real-time control systems
e.g., flight control computer[4].

[2] 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.

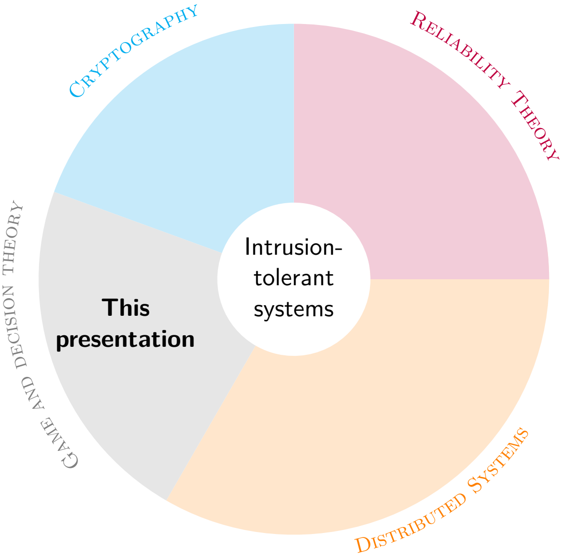
[3] Jukka Soikkeli et al. "Redundancy Planning for Cost Efficient Resilience to Cyber Attacks". In: *IEEE Transactions on Dependable and Secure Computing* 20.2 (2023), pp. 1154–1168. DOI: 10.1109/TDSC.2022.3151462.

[4] 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.

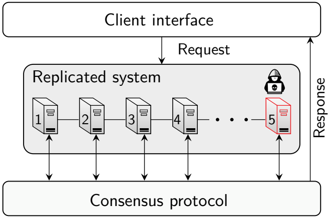
Theoretical Foundations of Intrusion Tolerance



Our Contribution

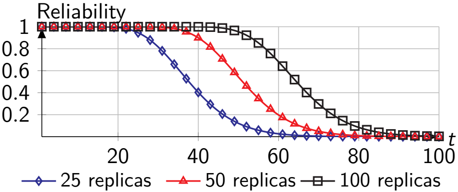


Building Blocks of An Intrusion-Tolerant System



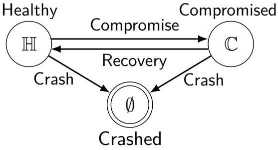
1. Intrusion-tolerant consensus protocol

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

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Abstract. Rampart is a toolkit of protocols to facilitate
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component servers by an attacker. At the core of
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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
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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
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modifications to the programs of a group member follow
illicit access to, or capture of, a group member. T

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Practical Byzantine Fault Tolerance and Proactive Recovery

MIGUEL CASTRO
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BARBARA LISKOV
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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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An architecture for adaptive intrusion-tolerant applications

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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

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Received 26 October 2005; r

Published 2006

- Fixed number of replicas
- Periodic recoveries

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

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Published 2011

- Fixed number of replicas
- Periodic recoveries

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

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Spread Concepts LLC — {yairamir}@spreadconcepts.com

Published 2018

- Fixed number of replicas
- Periodic recoveries

Prior Work on Intrusion-Tolerant Systems

The Rampart Toolkit for Building High-Integrity Services

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An architecture for adaptive intrusion-tolerant applications

Partha Pal[1,*] and Paul Rubel[1], Michael Atighetchi[1], William H. Sanders[2], Mouna Seri[2], HariGovind Rama Tod Courtney[3], Adnan Agbaria[2], Michel Cukier[3], Jea

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

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The SecureRing Protocols for Securing Group Communicat

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Resilient Intrusion Tolerance through Proactive a

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

Amy Babay*, Thomas Tantillo*, Trevor Aron, Marco Platania, and Yair Amir

Abstract
The SecureRing group communication protocols provide reliable ordered message delivery and group membership services despite Byzantine faults such as might be caused by modifications to the programs of a group member following illicit access to, or capture of, a group member. The

processors within an asynchronous distributed syst pose a consistent total order on messages, and consistent group memberships.
The approach adopted by SecureRing to protect Byzantine faults is to optimize the performance mal (fault-free) operation a

Practical Byzantine Fault Tolerance and Proactive Recovery

MIGUEL CASTRO
Microsoft Research
and
BARBARA LISKOV
MIT Laboratory for Computer Science

Skynet: a Cyber-Aware Intrusion Tolerant Overseer

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

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Published 2023

- Fixed number of replicas
- Periodic recoveries

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

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

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

Prior Work on Intrusion-Tolerant Systems

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Resilient Intrusion Tolerance through Proactive and Reactive Recovery

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

Can we do better by leveraging game-theoretic strategies?

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

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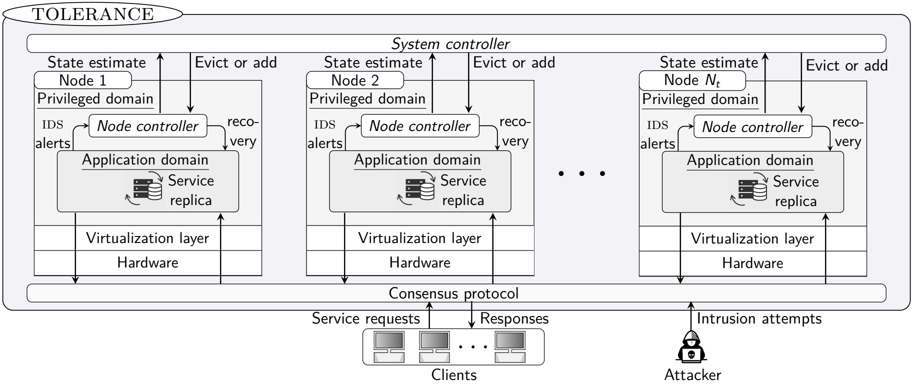
The TOLERANCE Architecture

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)

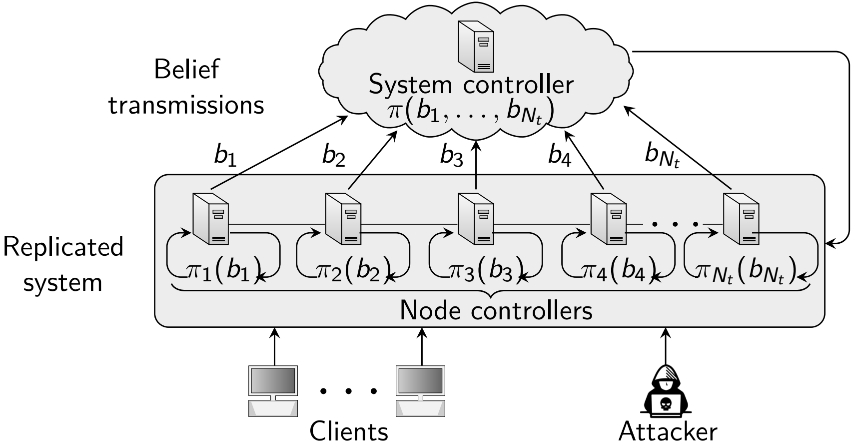
Each replica executes the same request sequence. (Safety)

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

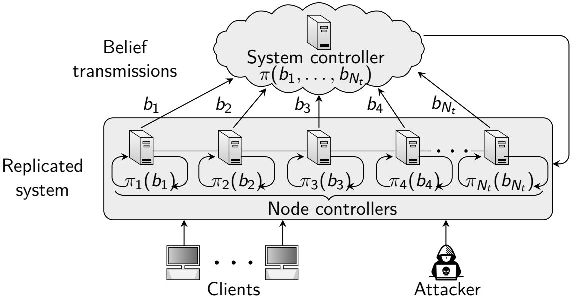
The probability that the system controller fails is negligible.

Assumption 2

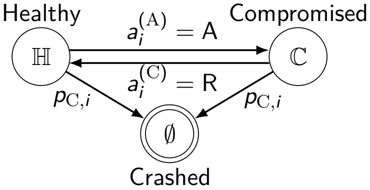
Compromise and crash events are statistically independent across nodes.

Assumption 3

The attacker can infer the observations of the controllers.



The Local Recovery Game

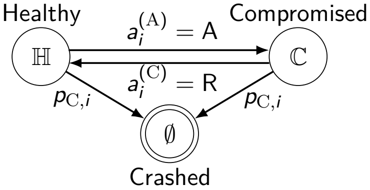


- **Partially observed stochastic game Γ_i.**
- Players: (C)ontroller and (A)ttacker.

- 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.

The Local Recovery Game



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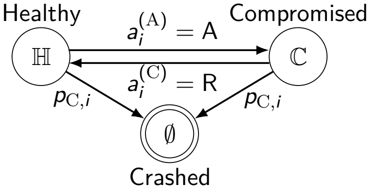

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- Observation $o_{i,t} \sim z_i(\cdot|a^{(\mathrm{A})})$: IDS alerts at time t.

Node Controller Strategy

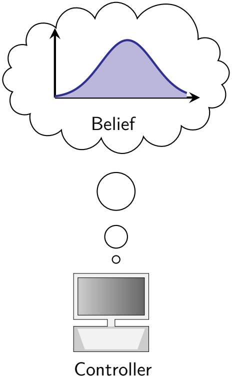
- The controller computes the **belief**

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

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

- Controller strategy:

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

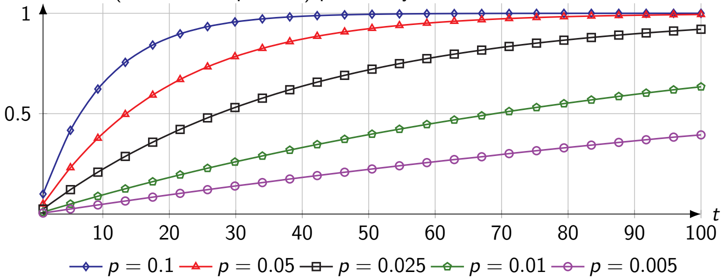


Node Controller Objective

- **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.

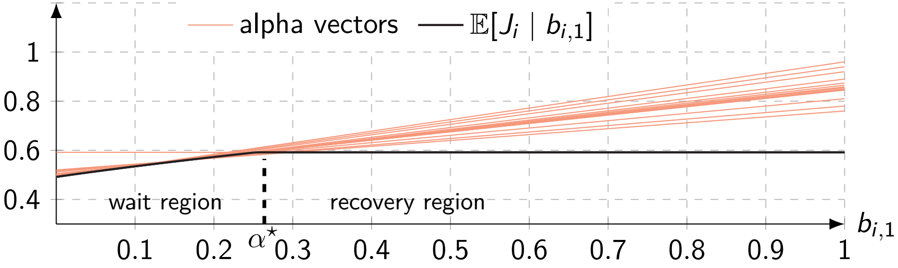
- Bounded-time-to-recovery constraint: The time between two recoveries can be at most Δ_{R}.

Failure (crash or compromise) probability.



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

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

where $\alpha^\star_{i,t} \in [0,1]$ *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

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

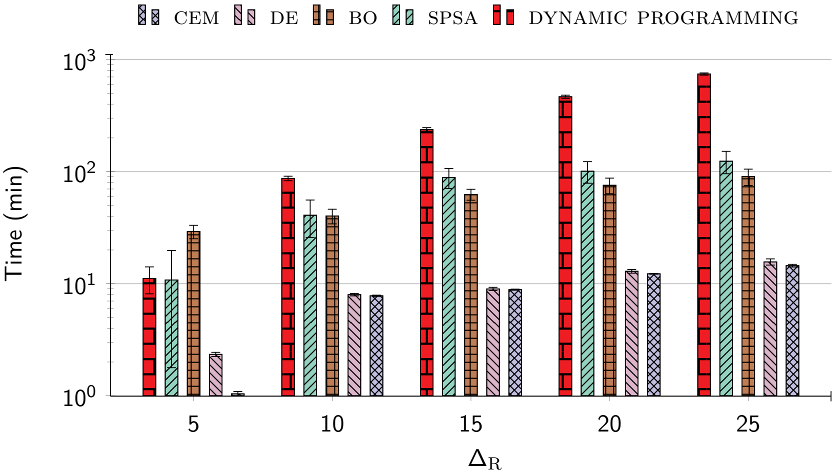
$J_\theta \leftarrow \mathbb{E}_{\pi^{(\mathrm{C})}_{i,\theta}}[J_i]$.

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

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

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

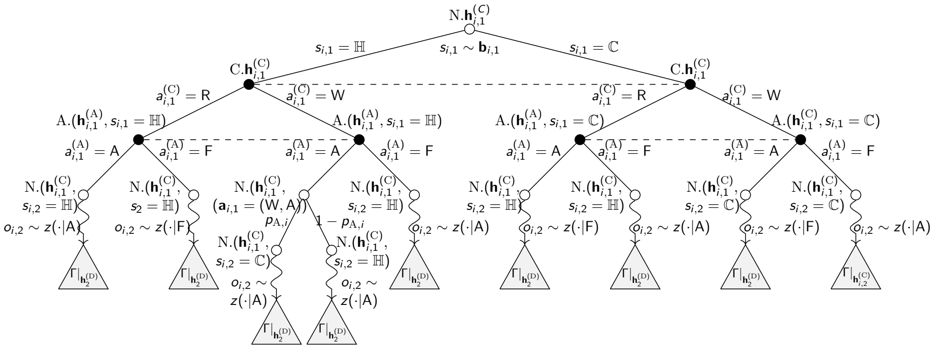
2. **Belief consistency:**
   For any $\mathbf{h}_{i,t}^{(\mathrm{C})}$ with $\mathbb{P}[\mathbf{h}_{i,t}^{(\mathrm{C})} \mid \boldsymbol{\pi}^\star, \mathbf{b}_1] > 0$, then

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

Theorem 4 (Existence of equilibrium and best response)

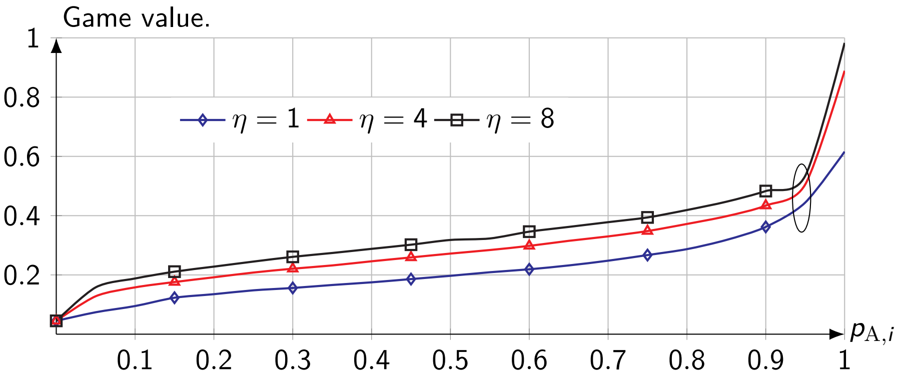
1. *For each strategy pair* $\boldsymbol{\pi}_i$ *in* Γ_i*, there exists a pair of best responses.*
2. Γ_i *has a perfect Bayesian equilibrium* (PBE)*.*
3. *If* $s_{i,t} = 0 \iff b_{i,t} = 0$*, then* Γ_i *has a unique pure* PBE*.*
4. *The value of* Γ_i *is not larger than* 1*.*

Idea Behind the Proof of Equilibrium Existence



- Fix the time horizon T. Then we can convert the game to extensive form, and hence it has a value.
- As $T \to \infty$, the **discount factor** $\gamma \in [0, 1)$ implies that $\lim_{t\to\infty} \sum_t \gamma^t C_t = 0$, which means that a value exists.

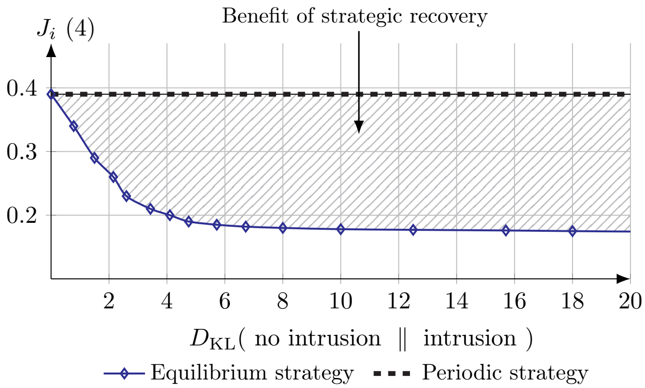
Value of the Local Recovery Game



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

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

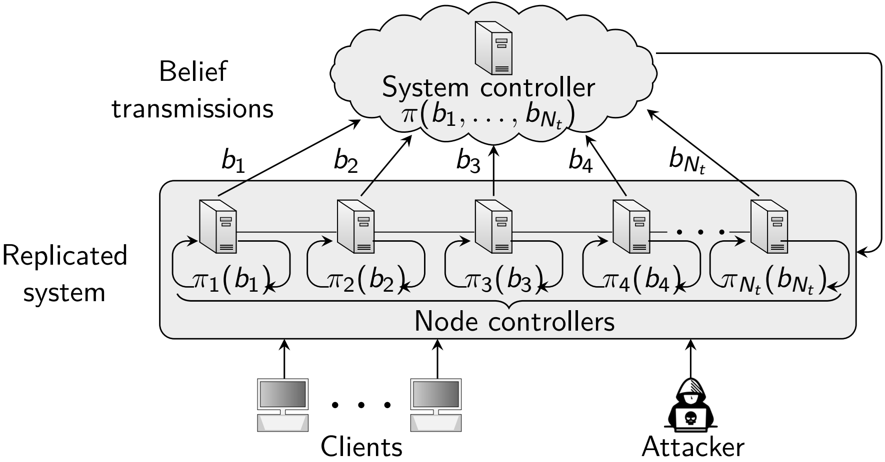
The Benefit of Strategic Recovery



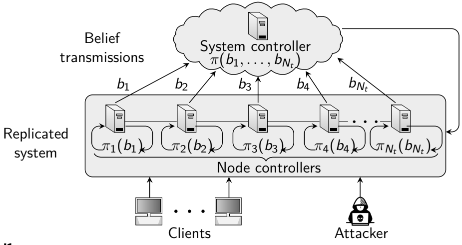
Key insight

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

Intrusion Tolerance as a Two-Level Game



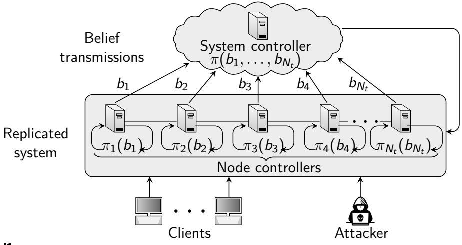
The Global Replication Game



- **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: $\mathbf{a}_t^{(\mathrm{A})} \in \{\mathsf{F}, \mathsf{A}\}^{N_t}$.
- **Markov** strategies:

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

The Global Replication Game



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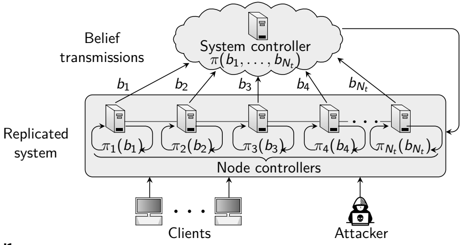

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- **Markov** strategies:

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

System Controller Objective

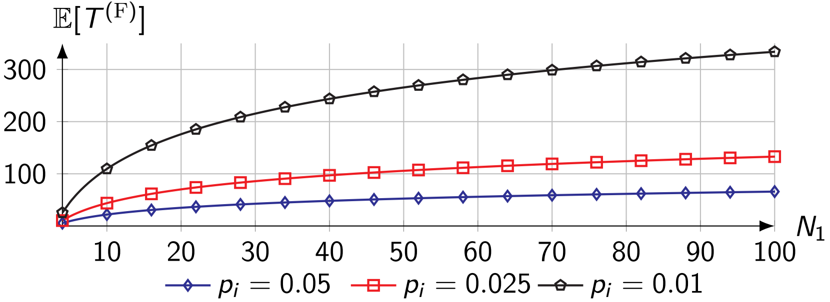
- **Zero-sum** game.
- Cost: $J \triangleq \lim_{T\to\infty} \sum_{t=1}^{T} \frac{a_t^{(\mathrm{C})}}{T}$.
- Constraint: $T^{(\mathrm{A})} \geq \epsilon_{\mathrm{A}}$, where $T^{(\mathrm{A})}$ is the availability.

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 Existence and Computation)

Assuming

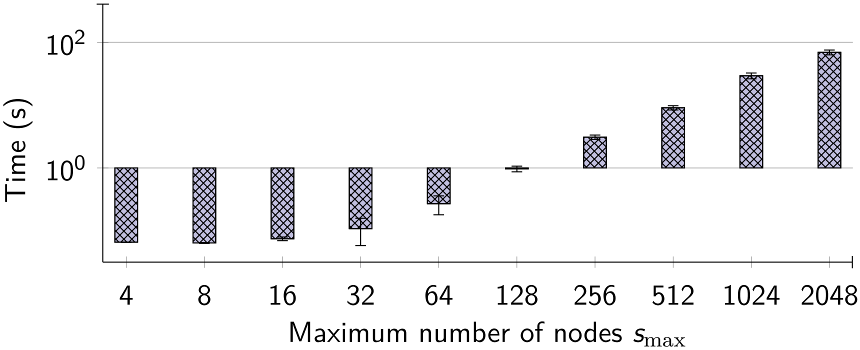
(A) *The Markov chain induced by each strategy pair $\boldsymbol{\pi}$ is* ***unichain****.*

(B) *The availability constraint is feasible.*

Then the following holds.

1. *For each strategy pair $\boldsymbol{\pi}$, there exists a pair of stationary best responses.*
2. *Best responses can be computed by using* ***linear programming****.*

Efficient Computation of Best Responses



Mean compute time to obtain a best response in the replication game.

Definition 6 (Markov perfect equilibrium (MPE))

A strategy pair $\boldsymbol{\pi}^\star = (\pi^{(\mathrm{C}),\star}, \pi^{(\mathrm{A}),\star})$ is a **Markov perfect equilibrium** if each player follows a Markov behavior strategy and $\boldsymbol{\pi}^\star$ is a Nash equilibrium regardless of the initial state.

Theorem 7 (Existence of equilibrium in the global game)

Assuming

(A) *The Markov chain induced by each strategy pair* $\boldsymbol{\pi}$ *is* ***unichain****.*

(B) *The availability constraint is feasible.*

Then the following holds.

1. *A constrained, stationary Markov perfect* equilibrium *(MPE) exists.*
2. *Computing the equilibrium is PPAD-complete.*

Challenge

Equilibrium computation is intractable in general.

Challenge

Equilibrium computation is intractable in general.

Theorem 8

Given any attacker strategy, there exists a best response ***control strategy that is decreasing in*** s**.**

Efficient Computation of Equilibria

Challenge

Equilibrium computation is intractable in general.

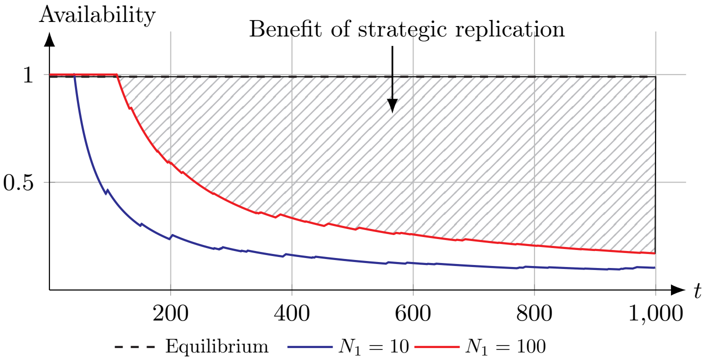
Theorem 9

Given any attacker strategy, there exists a best response ***control strategy that is decreasing in*** s**.**

Corollary 10

Given that the controller strategy is decreasing in s*, a weakly dominating strategy for the attacker is to minimize* $\mathbb{E}[S]$*.*

The Benefit of Strategic Replication

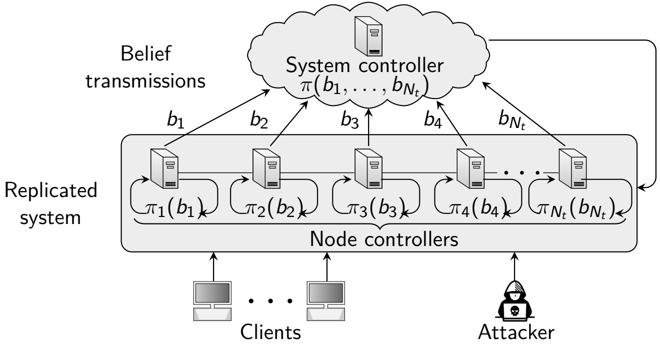


Key insight

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

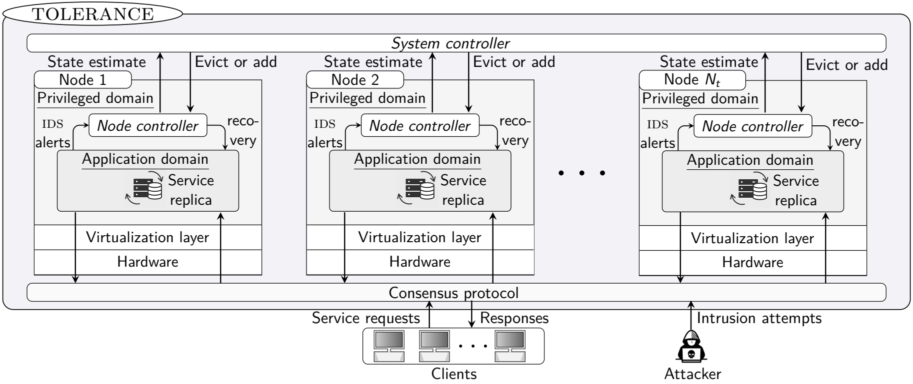
- Partially observed stochastic game models intrusion recovery.
  - **Threshold structure** of best responses.
  - Existence of *perfect Bayesian equilibria*.
- Constrained stochastic game models replication control.
  - **Threshold structure** of best responses.
  - Existence of *Markov perfect equilibria*.



Experiment Setup - Testbed

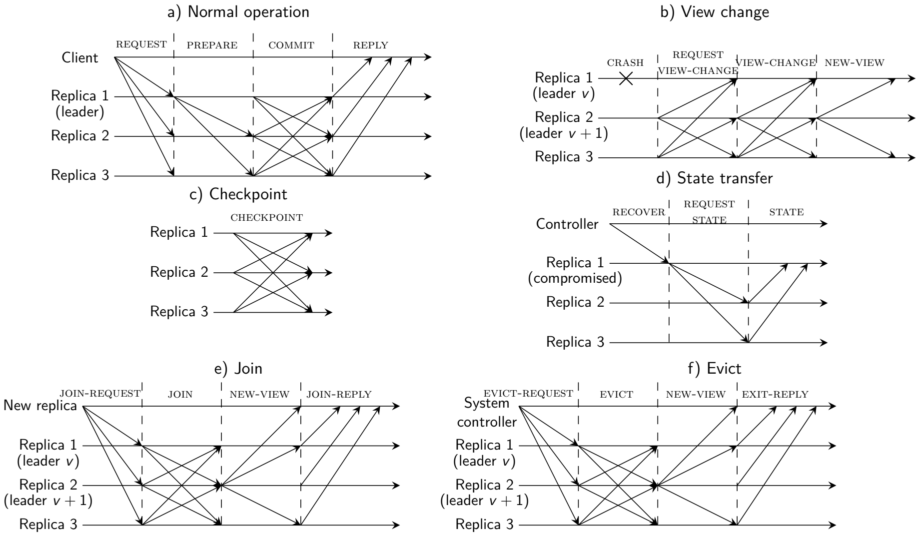
The TOLERANCE Architecture

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

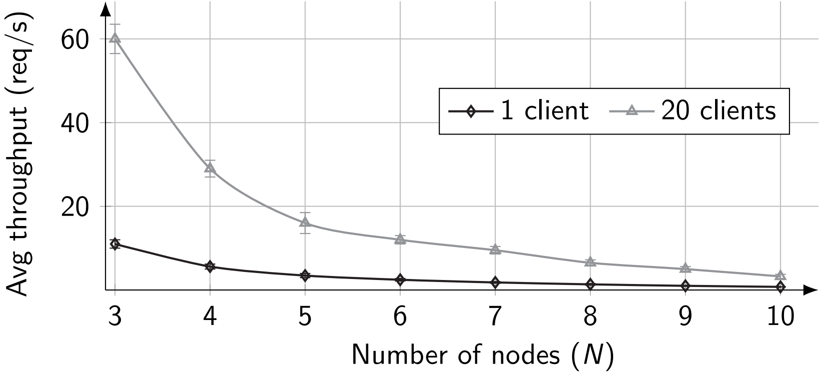


- A replicated web service which offers two operations:
  - A **read** operation that returns the service state.
  - A **write** operation that updates the state.

Intrusion-Tolerant Consensus Protocol (MINBFT)



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

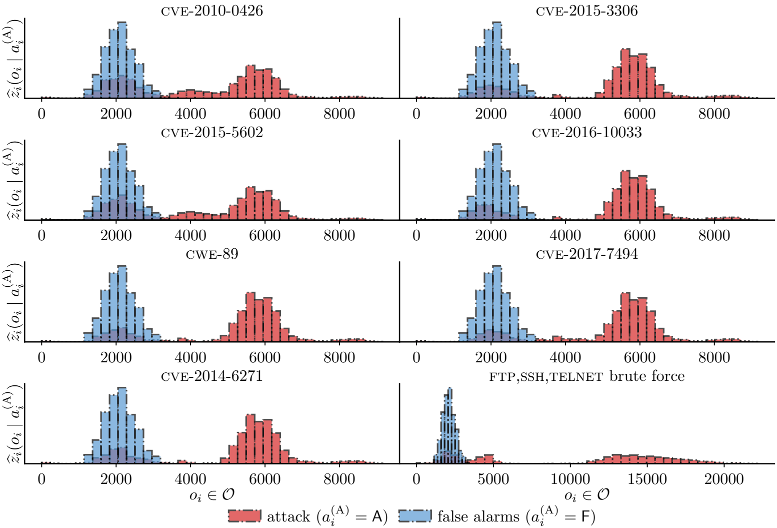
Table 1: Intrusion steps.

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

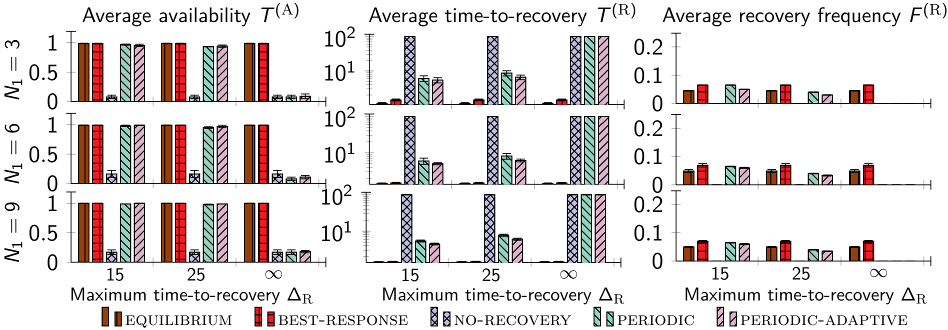
Table 2: Background services.

Estimated Distributions of Intrusion Alerts



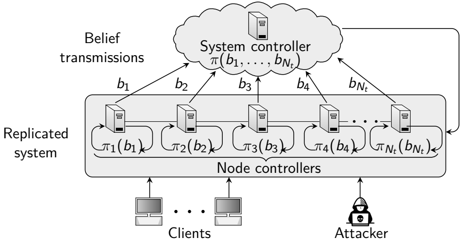
- **We estimate the observation distribution** z with the empirical distribution $\widehat{Z}$ based on M samples.
- $\widehat{z} \rightarrow^{\text{a.s}} z$ as $M \rightarrow \infty$ (Glivenko-Cantelli theorem).

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.