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Output difference feedback and system benefit control based dynamic heterogeneous redundancy architecture

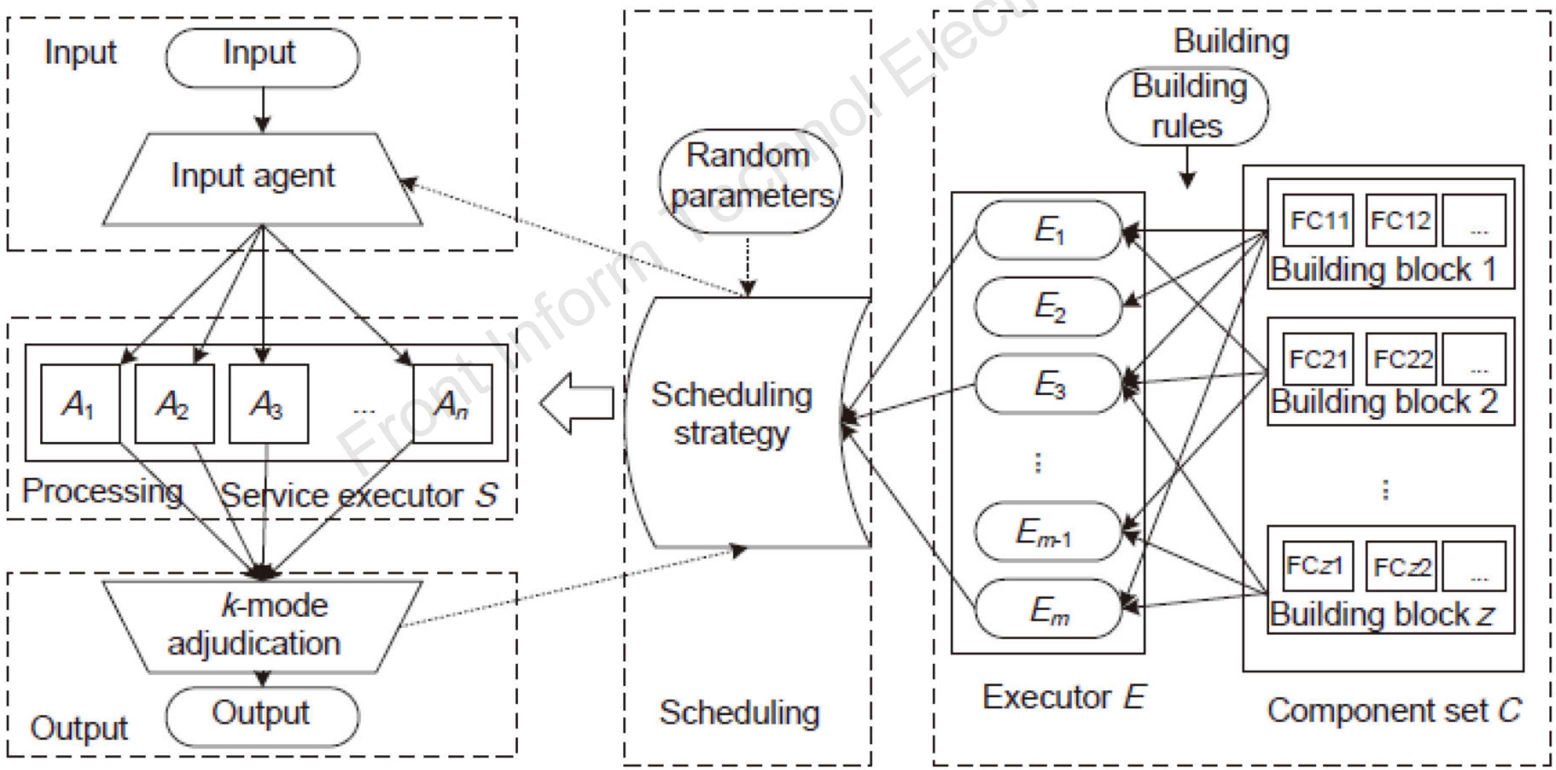
Key words: Mimic defense; Adjudication mechanism; Scheduling strategy; Executor output difference; System benefit

Sisi SHAO
E-mail: 361571409@qq.com
ORCID: https://orcid.org/0009-0005-9026-0133

Yimu JI
E-mail: jiym@njupt.edu.cn
ORCID: https://orcid.org/0000-0001-7019-3942

Motivation

- In many complex network environments, computational errors can lead to varying local adjudication results, rendering most current adjudication mechanisms ineffective.
- Moreover, current scheduling strategies prioritize system security but often overlook the effects of quality of service and system overhead.



Main idea

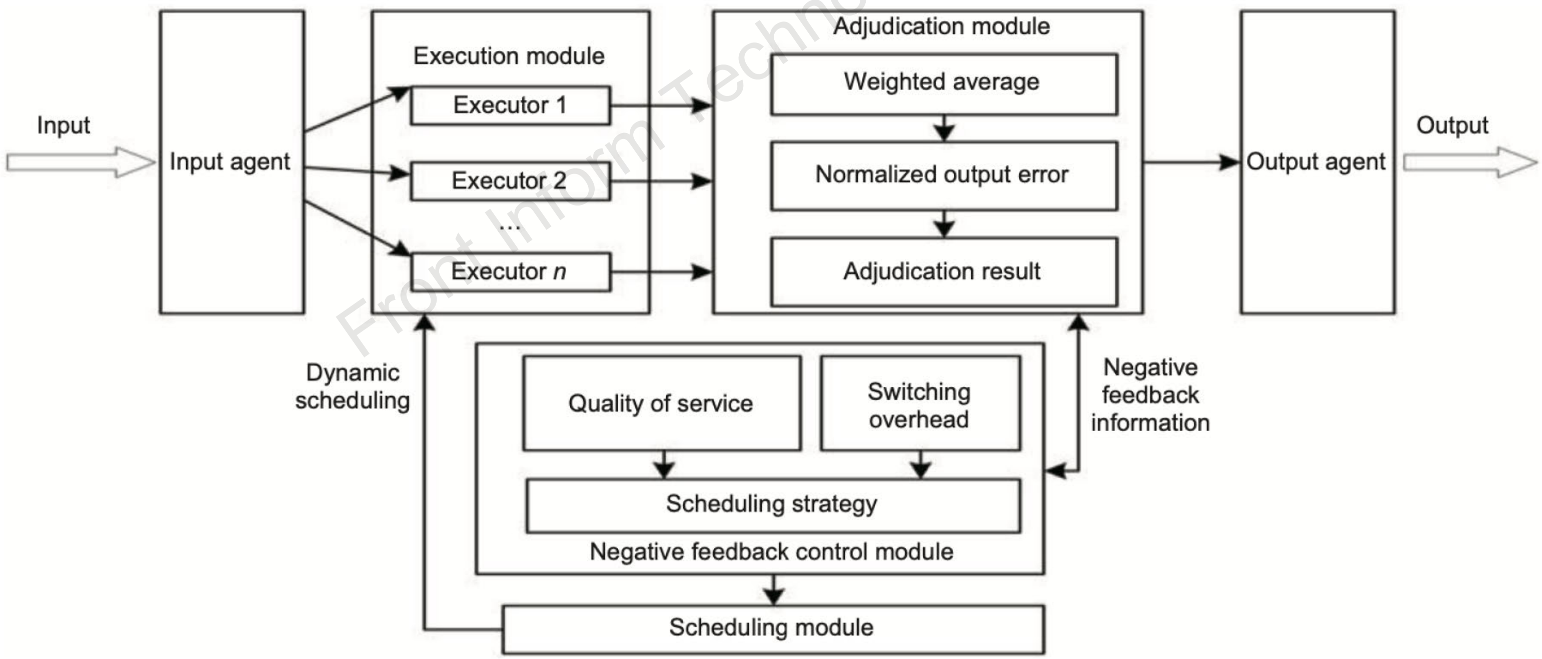
1. For the adjudication module of the dynamic heterogeneous redundancy (DHR) architecture, we propose an adjudication mechanism based on the output difference feedback. This mechanism calculates each executor's output difference by confidence and local adjudication results, ensuring effective adaptation to network environments with inherent output differences.

2. For the scheduling module of the DHR architecture, we propose a scheduling strategy for executors based on system benefit, which models the quality of service and switching overhead as a bi-objective optimization problem. It is solved via a heuristic algorithm to increase the security gain of the system.

3. Simulations evaluate our architecture across multiple dimensions, comparing system overhead, scheduling period, attack success rate, and failure rate against existing methods.

Method

- The adjudication module selects the executor with the smallest output difference using a weighted average, considering the impact of each executor's output deviation on the global adjudication result.
- The negative feedback control module determines the scheduling strategy by calculating the quality of service and switching overhead, considering the benefits and overhead of the system after the introduction of the DHR architecture.



DHR architecture based on output difference feedback and system benefit control

Method

- This adjudication mechanism obtains the weighted average of the output results of n executors, considering the local adjudication results and the confidence levels of the executors.
- The normalized output difference between $y_i(t)$ and $\overline{Y}(t)$ is then calculated.
- Finally, the adjudication mechanism selects the local adjudication result with the smallest output difference as the global adjudication result, which is then sent to the output agent.

Algorithm 1 Adjudication algorithm for executors based on output difference

Initialize $e_{\min}(t) = 1$
for $i = 1, 2, \ldots, n$
  $\overline{Y}(t) = \frac{\sum_{i=1}^{n} h_i(T) \times y_i(t)}{\sum_{i=1}^{n} h_i(T)}$
  $e_i(t) = \left| \frac{y_i(t) - \overline{Y}(t)}{\overline{Y}(t)} \right|$
  if $e_i(t) < e_{\min}(t)$
    $e_{\min}(t) = e_i(t)$
    $\mathrm{ID}_{\min} = i$
  end if
end for
Output the local adjudication result of the executor corresponding to $\mathrm{ID}_{\min}$ as the global adjudication result
for $i = 1, 2, \ldots, n$
  if $i \in S$
    $h_i(t) = \frac{\zeta_i(t-1) h_i(t-1) + f(|Y(t) - y_i(t)| \leq \eta)}{\zeta_i(t-1) + 1}$
  else
    $h_i(t) = h_i(t-1)$
  end if
end for

Method

- The quality of service and the switching overhead of a mimic active defense system are modeled as a bi-objective optimization problem, where the system benefit is directly proportional to the quality of service and inversely proportional to the switching overhead.
- After obtaining the objective function, the particle swarm optimization (PSO) algorithm is used to efficiently explore the feasible solution space, aiming to quickly find the optimal value of the bi-objective optimization problem.

Algorithm 2 Scheduling algorithm for executors based on system benefit

if $t_{\text{now}} - t_{\text{last}} == \Delta t$
  for $v = 1, 2, ..., N$ /* v is the scheduling scheme and N is the number of possible scheduling strategies in the system */
    $H(t) = \frac{1}{n}\sum_{i=1}^{n} h_i(t)$
    $D(t) = \frac{1}{n}\sum_{i=1}^{n} d_i(t)$
    $C_{\text{run}} \approx \sum_{i=1}^{n} t_i \times C_i$
    $Q_u = H(t) \times D(t) \times \left(\frac{1}{n}\sum_{i=1}^{n} t_i \times c_i\right)^{-1}$
    $C_{\text{switch}} = \sum_{i=1}^{x} C_{\text{input}} + \sum_{j=1}^{y} C_{\text{output}}$
  end for
  The optimization problem is obtained by modeling the bi-objective optimization problem according to Eq. (14)
  The optimization problem is solved by the PSO algorithm, and the result obtained is used as the switching strategy
end if
if $h_i(T) < \xi$
  Select the scheduling strategy with the highest system efficiency for switching
end if

Major results

Average confidence

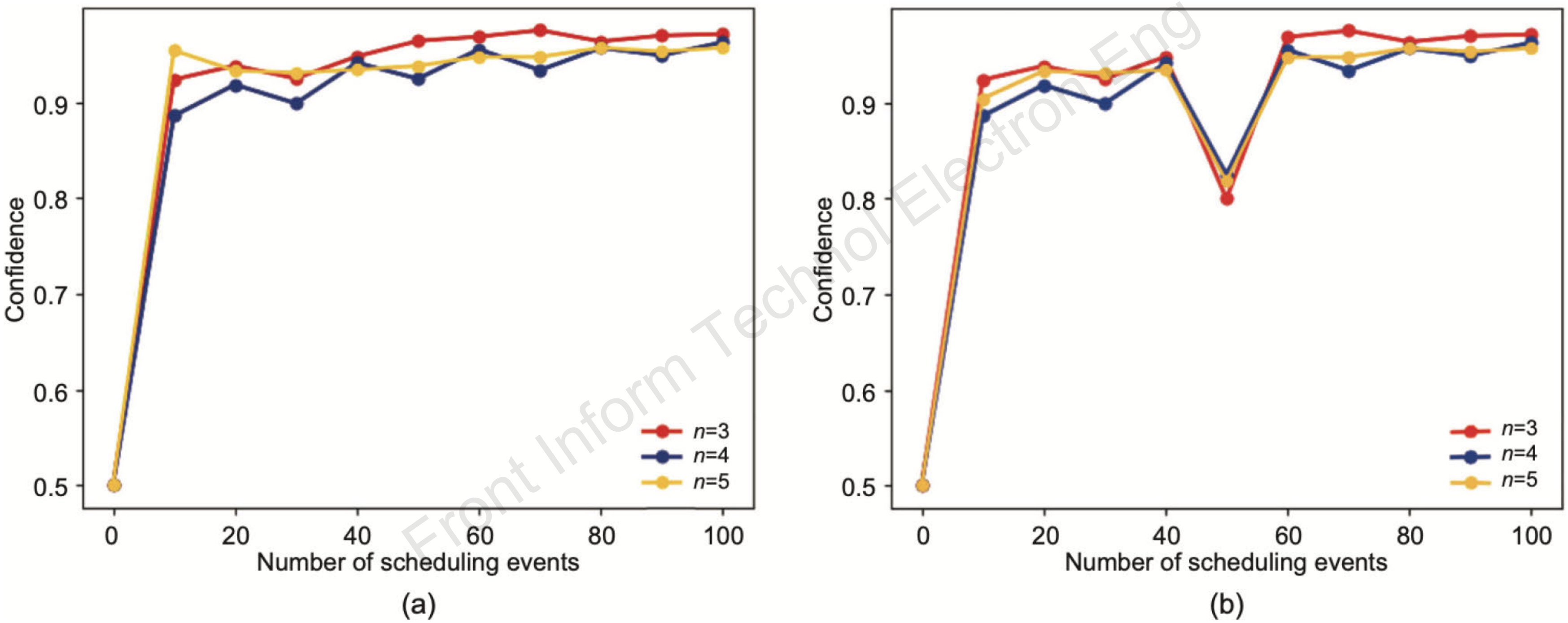


Fig. 3 Average confidence under non-attack (a) and under attack (b)

Major results

Scheduling randomness

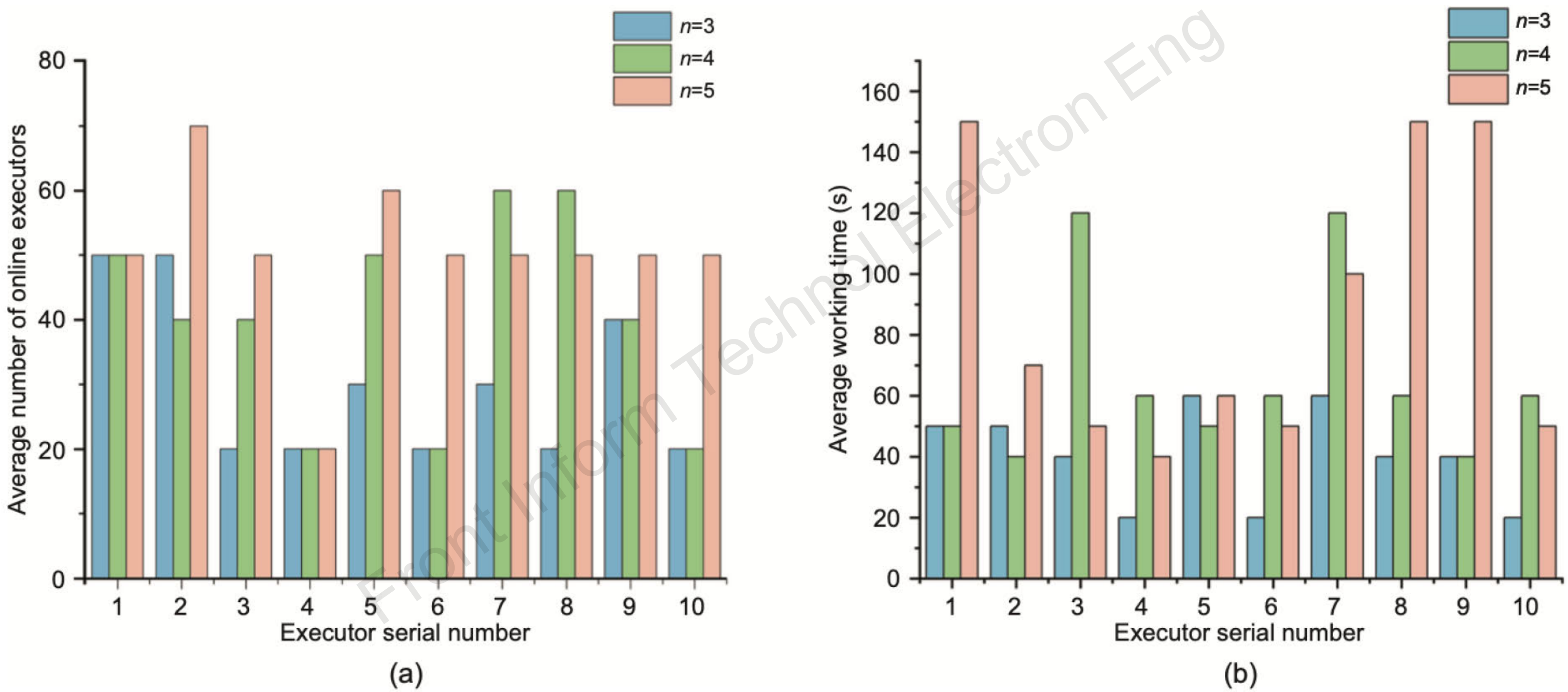


Fig. 4 Scheduling randomness: (a) average number of online executors; (b) average working time of executors

Major results

System benefits

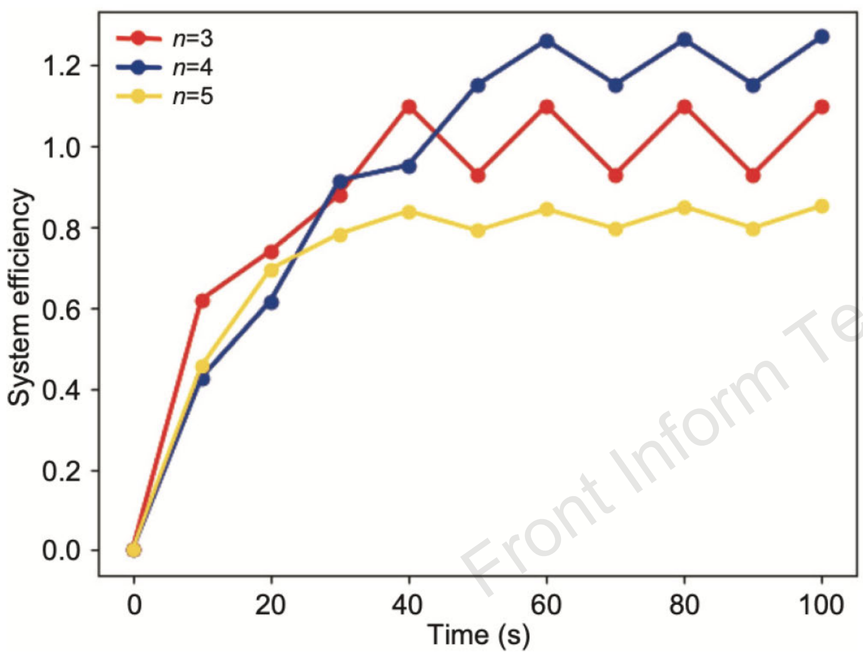


Fig. 5 System benefits with different margins

System overhead

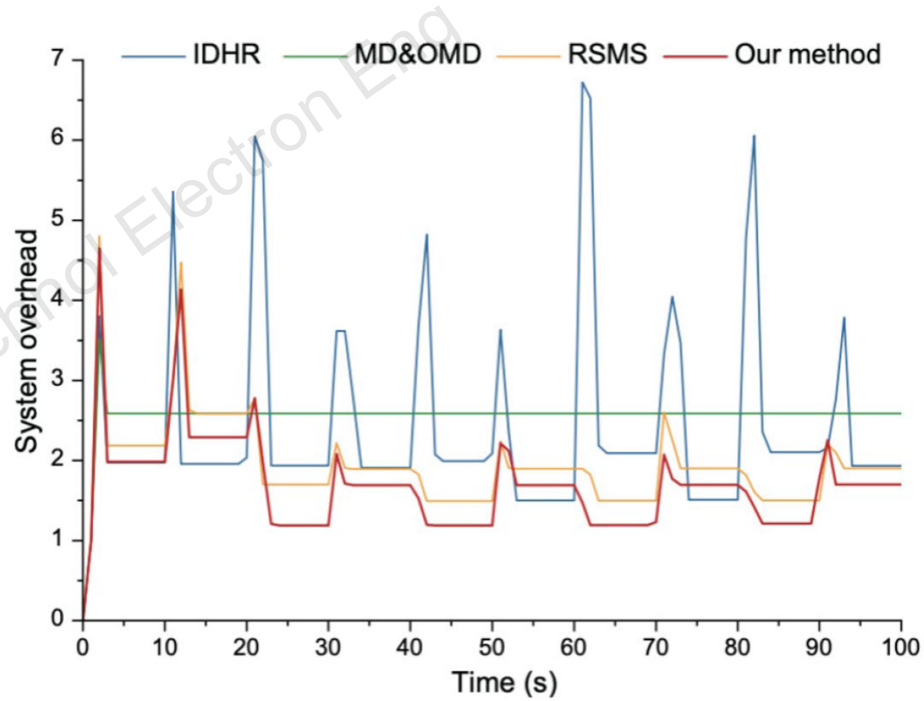


Fig. 6 System overhead under several methods

Major results

Attack success rate

Table 4 Attack success rate under several methods

Number of probes	Attack success rate				
	IDHR	MD	OMD	RSMS	Our method
1	0.058 90	0.379 00	0.379 00	0.054 30	0.031 60
2	0.059 30	0.519 00	0.519 00	0.054 30	0.032 50
3	0.059 30	0.570 00	0.570 00	0.054 30	0.032 50
4	0.059 30	0.589 00	0.589 00	0.054 30	0.032 50
5	0.059 30	0.596 00	0.596 00	0.054 30	0.032 50
6	0.059 30	0.598 50	0.598 50	0.054 30	0.032 50
7	0.059 10	0.599 40	0.599 40	0.054 30	0.032 50
8	0.059 10	0.599 80	0.599 80	0.054 30	0.032 50
9	0.059 10	0.599 90	0.599 90	0.054 30	0.032 50
10	0.059 10	0.599 97	0.599 97	0.054 30	0.032 50

Major results

Average failure rate

Table 5 Average failure rate under several algorithms

Method	Equal failure rate		
	$n=3$	$n=4$	$n=5$
IDHR	2.2000×10^{-3}	8.0227×10^{-5}	1.8134×10^{-4}
MD	3.6751×10^{-4}	1.3350×10^{-5}	6.4437×10^{-5}
OMD	1.3000×10^{-3}	8.4503×10^{-5}	1.6772×10^{-4}
RSMS	7.1909×10^{-4}	2.3656×10^{-5}	9.2103×10^{-5}
Our method	1.6448×10^{-4}	2.0879×10^{-5}	1.4268×10^{-5}
Method	**Unequal failure rate**		
	$n=3$	$n=4$	$n=5$
IDHR	7.6647×10^{-4}	1.5152×10^{-5}	3.5186×10^{-5}
MD	1.1419×10^{-4}	8.8765×10^{-7}	6.7820×10^{-6}
OMD	3.5989×10^{-4}	1.0583×10^{-5}	1.1182×10^{-5}
RSMS	2.7664×10^{-4}	3.8064×10^{-6}	2.5745×10^{-5}
Our method	1.4400×10^{-5}	1.8190×10^{-6}	1.2340×10^{-5}

Conclusions

1. The adjudication mechanism considers the impact of each executor's output differences on the global adjudication result, enabling effective adaptation to varying network environments.

2. The scheduling strategy introduces metrics such as heterogeneity, switching overhead, and quality of service to improve the system's defense against attacks.

3. The proposed method has high system benefits while maintaining a low attack success rate and average failure rate.

Biography

Sisi Shao received her Ph.D degree from Nanjing University of Posts and Telecommunications (NJUPT) in 2025. She is currently a Lecturer in the School of Cyberspace Security, Wuxi University. Her research interests include cyberspace security, endogenous safety, and mimic defense.

Yimu Ji received his Ph.D degree from Nanjing University of Posts and Telecommunications (NJUPT) in 2007. He is currently a Professor in the School of Computer Science, NJUPT. His research interests include the security and applications in cloud computing, big data, IoT, and AI. He led and participated in numerous national, provincial, and ministerial projects, obtaining 7 provincial and municipal science and technology progress awards. He has published over 50 SCI papers and holds 10 invention patents and 3 software copyrights.