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Nonlinear Dynamics of Information Flow in Secure, Distributed Internet-Based Academic and Library Service Networks

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ABSTRACT

The increasingly interconnected repositories, cloud platforms, authentication services and information-access systems (IAS) of distributed Internet-based academic and library service networks introduce increasingly complex interactions between service demand and availability of resources, communication delay, and security disturbances. This paper suggests a nonlinear dynamical model to describe how information flows and is stable in such an environment. The model is a four-dimensional coupled state variable model of service load, response delay, availability of the resources, and security disturbance. Five operating scenarios are performed to evaluate the computational evaluation: normal operation, high load and moderate cyber threat, severe disturbance, and adaptive recovery. Equilibrium conditions and the analysis of the Jacobian eigenvalues are used to discuss the stability. The results indicate that the response time can be prolonged to 318ms when disturbances are severe, information-flow efficiency can be lowered to 86.9%, and negative stability margin of −0.03 can be generated. The adaptive recovery decreases the response time to 128 ms, increases the efficiency to 95.1% and restores the positive stability margin to 0.24.

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1. INTRODUCTION

The academic and library service environment has become a dynamic, distributed system that enables the facilitation of scholarly communication, access to research data, preservation of institutional knowledge, and online information discovery. Digital libraries, institutional repositories, research-data platforms, and services for cloud storage, cloud processing, authentication, metadata services, and Internet information-access mechanisms are typical components of modern academic information infrastructures. These components function within distributed systems where requests, data and interactions with services and computations are constantly being passed and received between users, repositories, servers and computation.

A multitude of factors such as service demand, communication delay, availability of resources, network structure, security disturbance and recovery mechanisms, all affect the performance of information flow in such environments. Expansion in service usage can increase processing and communication demands, and lack of resources can exacerbate response delay. Security disturbances may also hinder information exchange, diminish effective capacity of resources and change the normal behavior of services. These effects can interact dynamically and if one variable changes, it could ripple through the network and affect several service conditions.

Previous work often looks at network performance, distributed services, information retrieval, cloud based academic systems and security separately. Relatively little research, however, has been conducted on the coupling effect between service load, response delay, resource availability, and security disturbance in the distributed academic and library services networks, which is nonlinear.

For this reason, this study proposes and numerically tests a nonlinear dynamical model for the analysis of information flow, delay, resources available resources, security addition, stability and recovery. The main contributions are four-state nonlinear information-flow model, load, delay, resources, and security disturbance representation, equilibrium and Jacobian/eigenvalue stability analysis, evaluation under five operating conditions, and adaptive recovery analysis under severe security disturbance.

2. Related Work

Most distributed digital-library or academic information services have embraced networked architectures for the purposes of remote access, resource sharing, metadata exchange, repository integration and scholarly communication [2]. Academic resources can be accessed from geographically dispersed information systems using a combination of distributed servers and Internet-based platforms, such as digital libraries, institutional repositories, and research-data services [11]. The architectures, while more usable and scalable, also contain more reliance on communication infrastructure and service coordination.

These are being expanded even more by systems of scholarly information provided through the Internet and cloud array systems, which offer scalable storage, elastic computing resources, centralized authentication, and remote service delivery [7]. It is possible that cloud-supported academic platforms could enhance the use of resources and the availability of resources, which has been shown to be sensitive to workload variation, the communication latency, resource contention, and service disruptions [2]. The more services that are linked together, the more complex becomes the flow of information based on dynamic interactions between the components of the network [9].

In digital-library setting, security and privacy is also an important issue [1]. A lack of information can lead to response delay as well as unauthorized access, compromised credentials, malicious traffic, data leakage, denial-of-service events, and disruption of service [5]. The study of security is usually limited to access control, encryption, authentication, privacy protection and threat mitigation, and the analysis of operational service behaviour is done separately from the study of security [7].

Complex networks and nonlinear dynamics have given rise to some valuable tools for studying a system with several interacting variables that affect one another through feedback [3]. A variety of tools, such as nonlinear models, equilibrium analysis, Jacobian matrices, eigenvalues and stability conditions have been employed to identify dynamic transitions, disturbances, and recovery in interconnected systems [6]. Likewise, research on distributed services resilience focus on the robustness, recovery ability, service continuity and adaptation of resources in abnormal situations [4]. The importance of maintaining functional connectivity and recovery capacity for network resilience to malicious disturbances has also been researched [8]. Studies of the dynamical recovery provide additional insight to the ability of complex networks to recover from local attacks toward normal operating conditions [12].

There is, however, little research that combines the information-service load, the response delay, the availability of information resources, and disturbance of information resources by security in a single nonlinear dynamical system in an academic and/or library service network. This inspires the proposed information-flow dynamics, stability, disturbance propagation and adaptive recovery analysis model [9] of coupled information flow.3. Proposed Nonlinear Information-Flow Model

3. Proposed Nonlinear Information-Flow Model

3.1 Distributed Academic and Library Service Network

The considered system is secure and distributed academic information service environment, where the different information resources can be used via interfaces connected on Internet. It includes user and researcher accessing nodes, digital-library servers, institutional repositories, research-data repositories, authentication services, metadata and search services, cloud-based information platforms, and distributed computing and communication resources. Access to the system is granted via web portals, mobile access interfaces, application programming interfaces or any other means of remote access. The Internet-based access layer receives an incoming request and passes it through the authentication and security layer where access control, authorization, encryption, and threat-monitoring functions are performed.

Service requests are then passed to the distributed information-service layer which was successfully verified. This layer is the digital library, institutional repository, research-data repository, metadata/search service and cloud information service. These components enable scholars to retrieve a variety of resources, access documents, share research data, discover metadata, index, store documents, and process documents in the cloud. The underlying network and computing resource layer supports the delivery of services, through the provision of servers, databases, storage systems, cloud infrastructure and communications.

The overall architecture of the system is designed to be layered from user access to security processing, distributed information services, to supporting network resources as depicted in Figure 1. The figure also focuses on the main information flow and feedback between the layers of security, services and resources. This architecture is used to form the basis of the nonlinear model to follow, in which the load of services, the delay to respond, the resources available, and disturbance of security are represented as the dynamically coupled state variables.

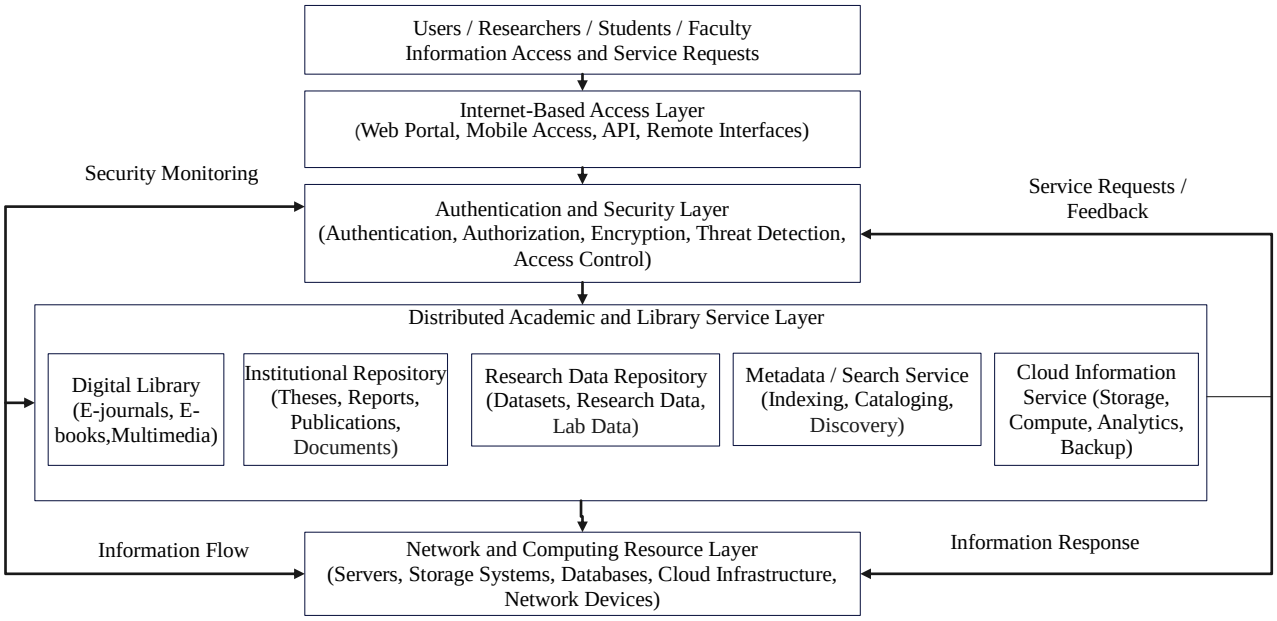

Fig. 1. Secure Distributed Academic Library Network Architecture

3.2 Dynamic State Representation

The dynamic behavior of the distributed academic and library service network is represented using four time-dependent state variables that capture the principal operational conditions of the system. The overall state vector is defined as

$$X(t) = [L(t), D(t), R(t), S(t)]^T, \quad (1)$$

where $L(t)$ represents the normalized information or service load generated by user requests and information-processing activities, $D(t)$ denotes the service-delay state associated with communication and processing latency, $R(t)$represents the available computational and network resource state, and $S(t)$denotes the security-disturbance state reflecting the intensity of abnormal or disruptive security conditions. These four variables provide a compact representation of the network condition at any time t. The state variables are also normalized in such a way as to be compared directly with each other when calculating. The states are coupled back and forth in a nonlinear manner. An increase of service load may also cause delay and resource increase, and any security disturbances may cause additional delay and load increase as well as effective resource decrease. Therefore, the state representation in Equation (1) serves as the foundation for the following subsections for the development of the nonlinear differential equations.

3.3 Nonlinear Service-Load Dynamics

The load development of information-service is simulated by a nonlinear differential equation considering the total information demand, the natural decrease of the load, the reduction of load supported

by the resources and the amplification of load due to security. The service-load dynamics are given by:

$$\frac{dL}{dt} = \lambda - \alpha L - \beta LR + \gamma LS, \quad (2)$$

where λ represents the incoming service-request intensity, α denotes the natural load-dissipation coefficient, β represents the effectiveness of available resources in reducing accumulated service load, and γ denotes the influence of security disturbance on load growth. The interaction term $-\beta LR$ indicates that greater resource availability can reduce the effective service load, whereas the term $+\gamma LS$ represents additional load generated when service demand interacts with security disturbances.

The nonlinear products LRLR and LSLS will be highlighted as important because they enable the model to have coupled behaviour that could not be captured adequately by a purely linear model. When the service load varies, there are sufficient resources to stabilize the load in normal operating conditions. As for the information-service burden, however, on the opposite side of this coin, we can see that as the level of security disturbance rises, so do the requirements for processing, verification, filtering and/or recovery actions. Thus, equation (2) models the dynamic changes of service load depending on the operational demand and the present security and resources state of the distributed network.

3.4 Nonlinear Delay Dynamics

Combination of communication delays, processing delays and access delays in the process of handling information request across distributed academic services and library services is the service-delay state. Its behavior is described by a dynamic model as

$$\frac{dD}{dt} = \eta L - \mu D + \delta DS - \xi RD, \quad (3)$$

whereη represents the influence of service load on delay growth, μ denotes the natural delay-dissipation coefficient, δ represents the effect of security disturbance on delay, and ξ indicates the contribution of available resources to delay reduction. The positive term ηL reflects the increase in delay caused by greater information-service demand, while $-\mu D$ represents the natural reduction of accumulated delay as requests are processed.

The nonlinear interaction term $+\delta DS$ captures the additional delay produced when existing service delay coincides with elevated security disturbance. These conditions could result in extra authentication, filtering, verification or recovery processes. In contrast, the term $-\xi RD$ represents the ability of available network and computing resources to reduce the accumulated delay. As a result, equation (3) reflects the trade-off between the delay increase due to workload and security deterioration due to security requirements, and delay decrease due to computational and communication resources, respectively.

3.5 Resource-Availability Dynamics

The resource-availability state is the state related to the capacity of both computation and storage and communication that is still available to support distributed academic and library services. Its dynamic behavior is expressed as

$$\frac{dR}{dt} = \rho(1 - R) - \theta LR - \phi SR, \quad (4)$$

where ρdenotes the resource-recovery coefficient, θ\theta represents the rate at which service load consumes available resources, and ϕdenotes the degradation of resources associated with security disturbance. The term $\rho(1 - R)$models the gradual restoration of resources toward their available operating capacity when system pressure decreases.

The nonlinear interaction term $-\theta LR$ represents resource consumption caused by information-service activity. The more requests that are serviced, the more the capacity of the network and of the computer resources is consumed to process them, to move information, and to keep the service available. The term $-\phi SR$captures additional resource reduction when security disturbances require filtering, authentication, monitoring, isolation, or recovery operations. Therefore, the availability of resources declines more quickly when demand for service is high and security disturbance is also high. The overall resource recovery/loss in the distributed system network is thus described by the equation (4). An important point from this dynamic representation is to assess whether the system has adequate capacity that will allow them to maintain acceptable information flow and service performance for normal, high load and disturbed operating conditions.

3.6 Security-Disturbance Dynamics

The security-disturbance state indicates how severe the abnormal security condition is that may affect access to information, service delivery and utilization of resources in the distributed academic and library

service network. Note that its dynamic behavior is modeled as

$$\frac{dS}{dt} = \kappa S(1-S) + \omega L - \psi RS, \quad (5)$$

where κ denotes the intrinsic disturbance-growth coefficient, ω represents the influence of service load on security exposure, and ψ denotes the effectiveness of available resources in suppressing the disturbance state. The term $\kappa S(1-S)$models the nonlinear growth of disturbance intensity, while ωL captures the increases in exposure that may arise as service demand and system activity grow. The term $-\psi RS$ represents the reduction of disturbance through available computational, network, and security-support resources.

From equation (5) we can see that the security disturbance is not an independent process. Instead, it depends on the aspects of pressure and resources available during the operations. When the system is active, it can be subject to higher levels of exposure, attack surface and propagation of disturbance. With higher resource availability, authentication, filtering, monitoring and response actions can manage disturbance intensity, increase system resilience.

The proposed model has four interacting states: Service Load L, Response Delay D, Resource Availability R and Security Disturbance S as shown in the Fig. 2. The figure emphasizes the main feedback loop, the positive one from L to D, and the negative one from L to R; the positive one from S to L and from S to D; the negative one from S to R; and the negative one from R to L, R to D, and R to S. The nonlinear coupling relationships for load amplification, delay growth, resource degradation, disturbance propagation, stabilization and recovery are thus summarized graphically in Figure 2.

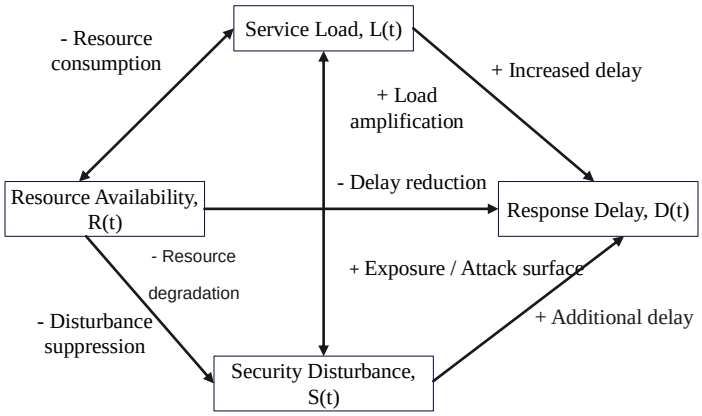

Fig. 2. Nonlinear Feedback Structure of the Proposed Model

4. Computational Methodology

The proposed model of information-flow is tested under controlled computational conditions to consider the dynamic behaviour of distributed academic (and library) service networks under various load states and security levels. The computational study is carried out for 1000 s with a time step of 0.1 s and the number of the computational point is 10,001 for the each run. The service nodes, totaling 50, and the repository or service nodes, totaling 10, are located in the considered service environment, symbracing distributed digital-library, institutional-repository, research-data, search, authentication, and cloud-supported information services. For reducing the reliance on a single run, there are 30 independent runs taken for each operating condition.

A service load of 0.30, service delay of 0.15, resource availability of 0.85 and a security disturbance of 0.05 are used to define the initial dynamic state. The initial values are a lightly loaded and stable operating condition for the network dynamics to evolve from. The nonlinear coefficients for load dissipation, resource interaction, delay behavior, disturbance growth and adaptive response are summarized in Table 1. Unless otherwise specified by the operating scenario, the parameters values are kept the same during the computational analysis.

Table 1. Computational and Nonlinear Model Parameters

Parameter	Description	Value
λ	Incoming request coefficient	0.18
α	Load dissipation coefficient	0.22
β	Resource-load interaction coefficient	0.35
γ	Security-load coupling coefficient	0.28
η	Load-delay coupling coefficient	0.32
μ	Delay dissipation coefficient	0.25
δ	Security-delay coupling coefficient	0.30
ξ	Resource-delay reduction coefficient	0.40
ρ	Resource recovery coefficient	0.30
θ	Load-resource consumption coefficient	0.25
ϕ	Security-resource degradation coefficient	0.35
κ	Disturbance growth coefficient	0.20
ω	Load-security coupling coefficient	0.12
ψ	Security-response coefficient	0.45

As indicated in Table 1, the coefficients indicate the relative intensity of the interaction between service load, response delay, availability of resources and security disturbance. For example, the resource-delay reduction coefficient $\xi = 0.40$ represents the contribution of available resources to delay mitigation, whereas the security-response coefficient $\psi = 0.45$ represents the ability of resources to suppress disturbance under the reference operating condition. . The time derivative of all four state variables is set to zero to obtain the equilibrium condition:

$$\frac{dL}{dt} = \frac{dD}{dt} = \frac{dR}{dt} = \frac{dS}{dt} = 0, \quad (6)$$

The corresponding equilibrium state is expressed as

$$X^* = [L^*, D^*, R^*, S^*]$$

The equilibrium values represent the operating situation with which the network changes into, if neither loading nor resource levels nor disturbance conditions are altered. Equilibrium solution is computed independently for each operating scenario to provide insight on the difference in the behavior of stable and unstable systems. Local stability is then considered by performing an eigenvalue analysis of the Jacobian. The Jacobian matrix of the nonlinear model is given by

$$J(X^*) = \left[\frac{\partial f_i}{\partial x_j}\right]_{X=X^*}, \quad (7)$$

where f_i denotes the nonlinear state equations and x_j represents the state variables L, D, R, and S. If all the real parts of the Jacobian eigenvalues are negative, then the equilibrium point is locally stable. A positive dominant real part means that there is growth from a small disturbance rather than decay, and that there is a transition toward an unstable operating condition. Five scenarios are established to assess the model for other working environments as shown in Table 2. All scenarios change the load of the requests sent in, the initial amount of available resources, the intensity of the disturbance to the security, and the strength of the security response, but the nonlinear coefficients in Table 1 are kept constant. The elevated level of service demand is tested in function S2, a moderate level of cyber-security disturbance is applied in function S3, a severe disturbance with less adapted response is applied in function S4, while a stronger adaptive response is applied at the same level of cyber-security disturbance in function S5.

Table 2. Operating and Security Scenarios

Scenario	Request Load	Initial Resource Availability	Initial Disturbance Level	Security-Response Strength
S1: Normal service	300 req/s	85%	0.05	0.45
S2: High service load	850 req/s	75%	0.10	0.45
S3: Moderate cyber threat	550 req/s	70%	0.35	0.45
S4: Severe disturbance	700 req/s	55%	0.75	0.25
S5: Adaptive recovery	700 req/s	55%	0.75	0.70

S4 and S5 both have the same request load, initial resource availability and disturbance level as shown in Table 2. The difference is the force of their response to security, which goes up from 0.25 with S4 to 0.70 with S5. This controlled comparison allows us to conclude whether or not stronger adaptive response will be able to suppress disturbances, restore the availability of resources, decrease service delay and restore the system towards a stable operating region.In general, a computational approach consisting of time domain simulation, steady state solution, eigenvalue analysis in Jacobian form, and scenario comparison. This structure enables the proposed nonlinear framework to be assessed not only for performance of the services but also for the dynamic stability and recovery characteristics when faced with increasingly strained network conditions.

5. Results and Discussion

5.1 Service-Load and Response-Delay Dynamics

Service load and response delay were analyzed for each of the five operating scenarios and the effect of the increased demands, security disturbance, and adaptive response on the performance of distributed academic and library services was investigated. Average service load was measured during the entire computation period, and Average response time was computed as

$$T_{avg} = \frac{1}{N}\sum_{i=1}^{N} T_i$$

whereT_i denotes the response time associated with the ith service request and N represents the total number of evaluated requests.The normal operating condition S1 has the lowest and least fluctuating service load as seen in Figure 3(a), which approaches 34.2%. Due to increased intensity of the requests, S2 generate a significantly higher (but capped) load of about 71.8%. With moderate traffic and a high level of security disturbance, the service load finds equilibrium around 62.4% under S3. The service load of S4 is the highest, at 88.6%, and is considered to be in a high degree of operating stress. S5, on the other hand, shows a strong transient response, followed by a decrease towards around 51.7% while the stronger adaptive response damps the perturbation and increases the resource availability.

A similar trend is observed for service delay in Figure 3(b). Under high service demand, the average response delay for S1 is around 92 ms while for S2 it is 184 ms. S3 puts less strain on the request than S2 does, but has a larger security disturbance which makes the response delay about 216 ms, showcasing that service delay is influenced by more than just the workload. S4 experiences the greatest degradation with response delay rising to ~318 ms. The delay is improved to around 128ms in the condition of adaptive response (S5), which is 59.7% less than in S4.

Overall, it can be seen from Figure 3 that for both service load and response delay, the impact of the changes in operational and security conditions is nonlinear. The difference between S4 and S5 is especially notable, demonstrating that increased adaptive security response can lead to significant decreases in accumulated load while still resulting in a delay between the two scenarios despite the same initial request intensity, resource availability and disturbance levels.

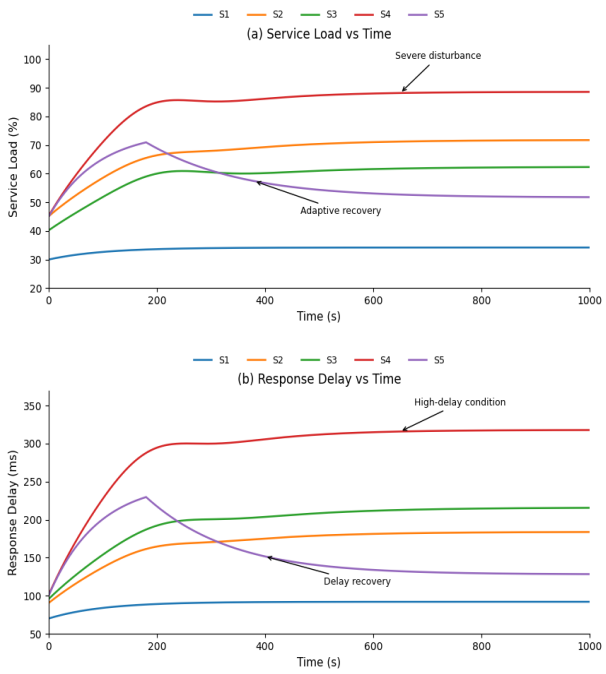

Fig. 3. Service Load and Response Delay under Different Operating Scenarios

5.2 Resource Availability and Security-Disturbance Dynamics

The impact of abnormal operating conditions on the resilience of the distributed academic, library service network was analysed through the concepts of resource availability and security-disturbance behavior. Resource utilization, resource availability, security-disturbance state, recovery time, and disturbance suppression are the key factors taken into

account in this subsection. The recovery time is the time needed to restore the operating value of the system within ±5% of its stable operating value; the disturbance suppression is defined as

$$DSR = \frac{S_{peak} - S_{fimal}}{S_{peak}} \times 100$$

where$\boldsymbol{S_{peak}}$is the peak disturbance level and $\boldsymbol{S_{fimal}}$ is the final disturbance level after the dynamic response has evolved. As the network's operating stress and disturbance intensity increase, the availability of resources diminishes gradually from S1 to S4, as illustrated in Figure 4. With the normal condition S1, the network has the maximum resource availability of 85% and very low final disturbance level of 0.04. In S2, the resources are reduced to 75% and the disturbance level is slightly increased to 0.09. Moderate threat condition (S3) further depletes resources to 70% and the disturbance level is raised to 0.23. The lowest availability of resources is in S4, where availability is 55% and the final disturbance level is high, increasing to 0.61, suggesting that disturbance was high and recovery capability was weak. This situation is also linked to the highest resource utilisation of 91.2% which indicates strong pressure on the supporting service infrastructure.

Figure 4, however, demonstrates that S5 performs well in the presence of stronger adaptive response. The resource availability becomes 78% and the last disturbance level is reduced to 0.12. This is a significant decrease in disturbance and recovery of resources when compared with S4. These findings show that recovery behaviour is worsened by severe disturbance, and security disturbance is better suppressed by adaptive response, in both respects worsening resource condition and degrading the resilience of the system.

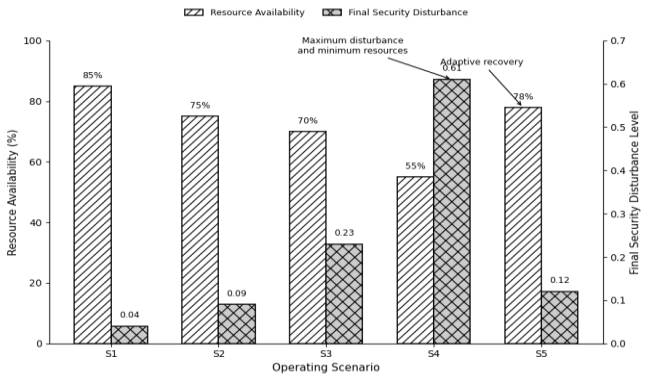

Fig. 4. Resource Availability and Security-Disturbance Dynamics

5.4 Stability Analysis and Transition between Operating Regions

The operation stability of the distributed academic and library service network was investigated based on the equilibrium solutions and the Jacobian eigenvalues derived for each of the operating scenarios. The local stability is computed at the corresponding equilibrium from the real parts of the eigenvalues of the Jacobian matrix. The stability margin is the difference between the open loop gain and the closed loop gain and is used as an indicator of system stability in a compact measure.

$$SM = -\max\left[Re(\lambda_i)\right]$$

where$\boldsymbol{\lambda_i}$denotes the Jacobian eigenvalues. A positive stability margin indicates that all dominant perturbations decay with time, whereas a negative value indicates that at least one perturbation mode grows and the operating point becomes locally unstable. Accordingly, $SM > 0$ represents stable operation, $SM = 0$denotes the stability boundary, and $SM < 0$ indicates instability.The stability results indicate that there is a clear transition in all five operating scenarios. S1 is the best-stabilized at 0.31, meaning that the small perturbations are decaying rapidly under the normal service conditions. The margin of S2 is smaller at 0.17 with increased values of the service demand but remains stable. In S3, the moderate security disturbance further reduces the value to 0.11, due to the existence of an extra non-linear coupling among service load, delay and resource availability. The most critical condition is in S4 where the stability margin is at −0.03. This negative value is a sign of local instability and serves to verify that the high resource pressure, high severity of the disturbance and low response strength take the system outside the stable operating range. When the stronger adaptive response is used, however, the stability margin in S5 is recovered to 0.24. The shift from −0.03 in S4 to 0.24 in S5 shows the ability of the recovery mechanism to return the network to a stable operating region from an unstable or highly stressed condition. This result verifies that adaptive response strength is at the core of maintaining resilient information flow under adverse conditions.

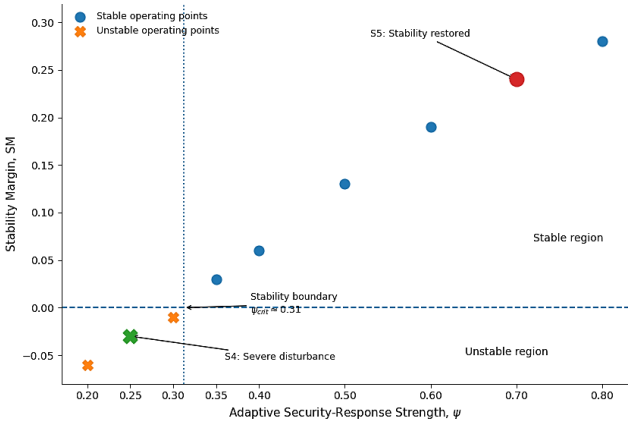

Fig. 5. Stability Transition with Adaptive Response Strength

5.5 Effect of Adaptive Security-Response Strength

The influence of adaptive security-response strength was further examined by varying the response coefficient ψ over the range

$$0.20 \leq \psi \leq 0.80$$

to determine how recovery capability affects system stability. For each selected value of $\boldsymbol{\psi}$, the equilibrium solution of the nonlinear model was obtained and the corresponding Jacobian eigenvalues were evaluated to calculate the stability margin. The analyzed response-strength values were 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, and 0.80, with the corresponding stability margins of −0.06, −0.02, 0.06, 0.13, 0.19, 0.24, and 0.28, respectively.

From the results, it can be seen that the transition between unstable and stable operation is evident as the adaptive response strength increases. At lower response levels, specifically $\psi = 0.20$ and$\psi = 0.30$, the stability margins are negative, indicating that the system remains in an unstable operating region and that disturbances are not sufficiently suppressed. When the response strength increases to$\psi = 0.40$, the stability margin becomes positive at **0.06**, showing that the system crosses the stability boundary and enters a stable operating condition. Further increases in ψ progressively improve the stability margin, reaching **0.13** at$\psi = 0.50$, **0.19** at$\psi = 0.60$, **0.24** at$\psi = 0.70$, and **0.28** at $\psi = 0.80$.

As illustrated in **Figure 5**, the relationship between $\psi$and stability margin is monotonic and clearly demonstrates the stabilizing role of adaptive response. The horizontal reference line at $SM = 0$ separates the unstable and stable operating regions, with points below the line representing unstable behavior and points above the line representing stable behavior. . Therefore, the results shown in Figure 5 clearly demonstrate that the augmentation of the adaptive security-response strength is an effective way of changing the behavior of the distributed academic and library service network from a disturbance-dominated unstable situation to a stable and resilient operation of the information-flow.

5.6 Overall Discussion

The overall results indicate that the interactions between service load, response delay, resource availability, security disturbance, and adaptive recovery are coupled nonlinear, thus largely controlling the behavior of the distributed academic and library service network. The significance of the comparison is between S4 and S5, as they have the same intense disturbance parameters with varying response strength. The weak response capability yields the worst operating condition, with a response time of 318 ms, and an information-flow efficiency of 86.9%, service availability of 91.4%, final disturbance level of 0.61, a recovery time of 176 s, and a negative stability margin of −0.03. These values represent a very stressed and locally unstable operating state.

S5 proves, however, that a greater adaptive response significantly enhances service performance and dynamic stability. The response time is reduced by 59.7% from 318ms to 128ms. The efficiency of information-flow improves by 9.5% and the availability of services improves by 11.6%. The final disturbance is lowered from 0.61 to 0.12, and the recovery time from 176 to 52 s. Most importantly, the stability margin changes from −0.03 to 0.24, which marks a transition from an unstable operating condition to a stable recovered operating condition. The results validate that the level of service depends on more than the load on the request. Rather than this, the behavior of a network is produced by a nonlinear coupling between the workload, the delay, the depletion of resources, the growth of the disturbance, and the strength of the recovery. This result thus validates the proposed nonlinear framework as a valuable tool for stability, disturbance propagation and recovery analysis of secure distributed academic and library service environments.

6. Conclusion

This study proposed a nonlinear dynamical model for studying information flow in secure, distributed

academic and library service networks on the Internet. The proposed model represents the coupling of information-service load, response delay, resource availability, security disturbance and adaptive recovery. This framework integrates time domain simulation, equilibrium and Jacobian stability analysis and offers a comprehensive approach to observing the interplay between operational pressure and security effects on a service's behavior. The results indicate that growing disturbance intensity can severely affect the network performance by increasing the response delay, decreasing resources, decreasing information-flow efficiency, and shifting the network to an unstable operating regime. For severe disturbance, the stability margin is negative, which means there is local instability. Instead, larger adaptive response significantly enhances recovery through lessened disturbance intensity, decreased response time, resource restoration, and a return to the positive region of the stability margin. The results validate that service behavior is determined by interactions that are not linear, but are rather caused by the interaction of several system states, not only by workload. Further studies will involve the validation of the framework based on real-world academic-network traces, institutional repository logs, real service-demand profiles, deployed academic information infrastructures, and cyber-event records. This validation can also be used to evaluate the applicability of the model in real service and security environment.

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