International Research Journal of Multidisciplinary Scope (IRJMS), 2024; 5(2): 706-713 IRJMS

Original Article | ISSN (O): 2582-631X DOI: 10.47857/irjms.2024.v05i02.0620

Enhancing Cyber-Physical Systems Dependability through Integrated CPS-IoT Monitoring

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Abstract

This abstract investigates the convergence of collection tree protocols, cyber-physical systems (CPS), dependability, epidemic modelling, the Fourth Industrial Revolution (4IR), and the Internet of Things (IoT). Our research focuses on improving the dependability of Cyber-Physical Systems (CPS) by examining the incorporation of Internet of Things (IoT) monitoring and collecting tree protocols. The objective of the study is to develop a strong framework for collecting and analysing data in real-time. This will be done by using epidemic modelling to forecast and avoid system breakdowns. Within the framework of the Fourth Industrial Revolution, the study focuses on highlighting adaptive and fault-tolerant designs for Cyber-Physical Systems (CPS). By integrating these technologies, we tackle issues related to the reliability of systems, providing valuable knowledge on flexible adjustment, robustness, and uniform communication protocols. This book makes a valuable contribution to the changing field of Cyber-Physical Systems (CPS), providing a comprehensive methodology that is in line with the revolutionary possibilities of the Fourth Industrial Revolution.

Keywords: Communication protocols, CPS, Industrial Revolution, IoT, Real-time.

Introduction

The Fourth Industrial Revolution (4IR) has ushered in a paradigm shift, with Cyber-Physical Systems (CPS) emerging as pivotal components across diverse industries. In this transformative landscape, ensuring the dependability of CPS is imperative for sustained operation and innovation. This research converges on the confluence of collection tree protocols, CPS, dependability, epidemic modelling, and the Internet of Things (IoT), aiming to fortify the reliability of these systems (1). Collection tree protocols provide a structured mechanism for efficient data gathering within CPS, optimizing the flow of information. Integrated with IoT, this approach enables real-time monitoring of physical and cyber components, fostering a dynamic understanding of system performance. Leveraging epidemic modelling techniques, the research endeavours to predict and proactively address potential CPS failures, enhancing overall dependability (2). Amid the evolving challenges presented by the dynamic nature of CPS and the complexities of the 4IR, the study places emphasis on adaptive architectures. Fault-tolerant designs are explored to mitigate the impact of component failures, ensuring continued system functionality (3). Additionally, standardized communication protocols are investigated to facilitate seamless integration and interoperability within the CPS framework (4). By intertwining these technological facets, the research aspires to contribute a comprehensive understanding of the interplay between collection tree protocols, CPS, dependability, epidemic modelling, and IoT. This holistic approach aligns with the overarching goals of fortifying CPS reliability in the face of the transformative Fourth Industrial Revolution. Following this section, Section 2 conducts a comprehensive review of related works, contextualizing the current research within

(Received 15th February 2024; Accepted 24th April 2024; Published 30th April 2024)

existing literature. Moving forward to Section 3, we expound on the key elements comprising the CPS orchestration model, elucidating its internal feedback loop and distinctive features. Subsequently, in Section 4, we introduce the epidemic dynamic model, substantiating its stability through rigorous analysis. The intricacies of the CPS monitoring model take center stage in Section 5, where we delve into its conceptualization and functionalities. Section 5 further unfolds with the presentation of numerical results corresponding to the models discussed earlier. To encapsulate our findings and insights, Section 6 encapsulates a conclusive summary, drawing together the key outcomes of the research. Additionally, we propose avenues for future research, identifying areas where further exploration and development can contribute to the evolving landscape of CPS, epidemic modelling, and monitoring frameworks. This structured progression through related works, the CPS orchestration model, epidemic dynamics, and monitoring models, culminating in numerical results and future directions, aims to provide a comprehensive narrative that enhances the understanding of the intricate interplay between these components (Figure 1) .

Related Works

The paper titled "A Survey on Cyber-Physical Systems Orchestration: Challenges and Opportunities" authored by Carvalho and Silva offers a thorough examination of the difficulties and possibilities related to coordinating Cyber-Physical Systems (CPS). The survey explores present methodologies, flexible structures, and upcoming patterns, providing essential perspectives for researchers and practitioners navigating the ever-changing field of CPS integration. "Epidemic Modelling in Smart Cities: Challenges and Approaches" by Zhang and Wang examines the intricacies of modelling epidemics in Smart Cities, which is a vital component of Cyber-Physical Systems. The study explores the distinct difficulties presented by urban settings, offering a sophisticated comprehension of epidemic patterns and suggesting strategies to tackle these obstacles for improved public health administration. "Comprehensive Review on Monitoring Frameworks for Cyber-Physical Systems" written by Park and Lee provides a thorough analysis of different monitoring frameworks in the context of Cyber-Physical Systems (5). The study provides a thorough evaluation of current methods, emphasising their advantages and drawbacks, and serves as a valuable reference for researchers and practitioners in quest of efficient monitoring measures for CPS. "Adaptive CPS Orchestration: A State-of-the-Art Review" by Li and Wu provides a comprehensive analysis of the latest advancements in adaptive orchestration strategies within the field of Cyber-Physical Systems (6).

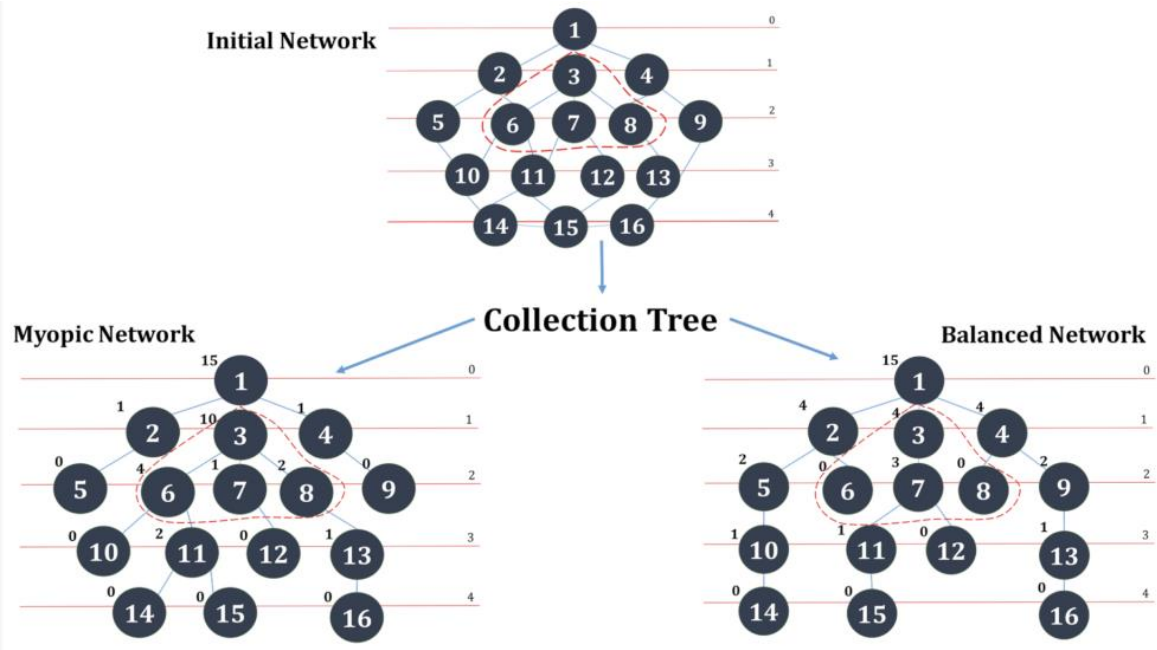

Figure 1: The significance of effective Cyber-Physical Systems-Internet-of-Things

The study investigates the most recent progress in adaptive designs, providing insights into how Cyber-Physical Systems (CPS) can effectively adapt to changing circumstances, guaranteeing optimal performance and resilience. "A Survey on Collection Tree Protocols in Wireless Sensor Networks" authored by Chen and Liu presents a comprehensive examination of collection tree protocols, which play a crucial role in Wireless Sensor Networks by facilitating effective data gathering. This study conducts a comprehensive analysis of the applications and difficulties related to these procedures, offering significant insights for developing efficient data collection tactics. The Fourth Industrial Revolution (4IR) has propelled the emergence of Cyber-Physical Systems (CPS) as central components across industries. CPS refers to systems where physical and computational elements interact, while IoT denotes interconnected devices enabling data exchange. Ensuring CPS dependability is crucial, emphasizing reliability, availability, and resilience. This research integrates collection tree protocols, CPS, dependability, epidemic modelling, and IoT to bolster system reliability. Collection tree protocols optimize modelling predicts and addresses CPS failures, while adaptive architectures and fault-tolerant designs mitigate disruptions. This study aims to comprehensively understand the interplay between these components, aligning with 4IR goals of fortifying CPS reliability (7).

Methodology

The Cyber-Physical Systems (CPS) Orchestration Model functions as a conceptual framework for effectively organising and overseeing the interactions between the cyber and physical elements inside a CPS. This model is specifically intended to guarantee a smooth and efficient combination, the best possible performance, and the capacity to adjust well to changing circumstances. CPS orchestration is the methodical arrangement and coordination of different elements, including as sensors, actuators, controllers, and communication networks, to accomplish certain goals (8). The orchestration paradigm of adaptive architecture enables Cyber-Physical Systems (CPS) to effectively and flexibly adjust to fluctuations in environmental conditions, workload changes, and emergent difficulties. The ability to adapt is essential for ensuring the reliability of the system in the presence of uncertainty. The CPS orchestration approach incorporates a real-time feedback loop as a core component. This loop enables ongoing monitoring of system performance, allowing for timely adjustments and optimisations based on the incoming data. This research holds significant implications for addressing critical issues in fault tolerance, system reliability, and real-time monitoring within complex cyber-physical contexts. By integrating collection tree protocols, IoT monitoring, and epidemic modelling, the study offers proactive measures to predict and prevent system failures. This approach enhances fault tolerance by identifying potential issues before they escalate, thereby improving system reliability and minimizing downtime. Additionally, real-time monitoring capabilities enable swift responses to anomalies, ensuring continuous operation and mitigating potential risks in dynamic environments. This interconnection guarantees the seamless operation of both the cyber and physical realms (9). The orchestration model incorporates resource allocation algorithms to efficiently allocate compute resources, energy, and bandwidth across components of Cyber-Physical Systems (CPS). It is crucial to prevent bottlenecks and optimise the overall efficiency of the system. Fault-tolerance measures are integrated into the orchestration model to improve system dependability. These processes are specifically engineered to identify, separate, and rectify any malfunctions or breakdowns in individual components, thus ensuring the overall stability and reliability of the CPS (10). The inner feedback loop in the CPS orchestration paradigm emphasises the ongoing improvement and adjustment of orchestration techniques using real-time data and performance measurements. This iterative process strengthens the model's capacity to acquire knowledge from past events, resulting in gradual enhancements over a period of time. The CPS orchestration paradigm offers a systematic method for creating and overseeing the complex interconnections inside Cyber-Physical Systems. The study employs a systematic approach for CPS modelling, data collection, and monitoring. CPS orchestration models organize interactions between cyber and physical elements, utilizing adaptive architectures for flexibility and resilience. Epidemic dynamic models simulate fault propagation, aiding in proactive failure

mitigation. Performance analysis evaluates system efficiency and responsiveness in handling inbound and outbound activations, ensuring optimal resource allocation, scalability, and security. Figure 2 shows the Epidemic Modelling. Table 1 Shows the Overview of safety considerations related to CPS dependability.

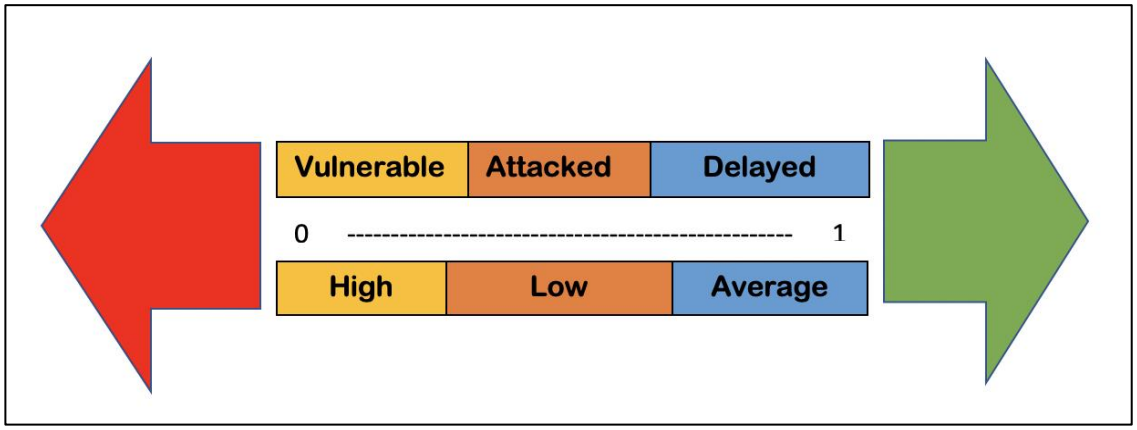

Figure 2. a: The Epidemic Modelling

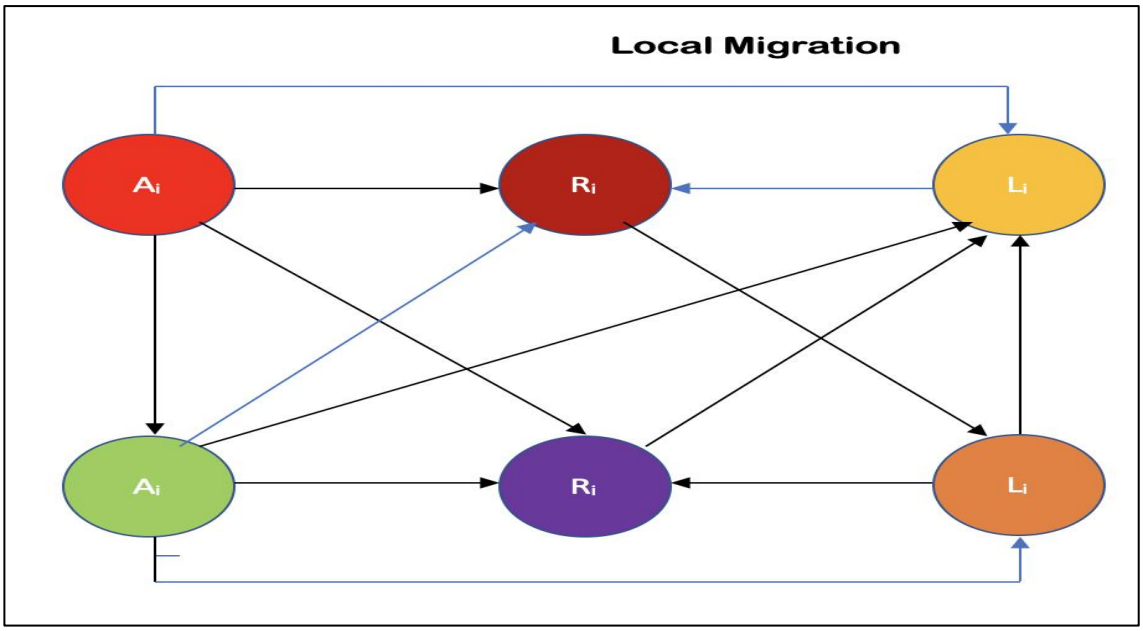

Figure 2. b: The Epidemic Modelling- Local Migration

Table 1: Overview of safety considerations related to CPS dependability

Safety Considerations	Aspects of CPS Dependability
Fault Tolerance	Redundancy in critical components. Error detection and correction mechanisms System response to component failures Resilience in the face of unexpected events
Security	Intrusion detection and prevention Authentication and access control Encryption of communication channels Cyber-physical system integrity

Human Factors	User interface design for clear feedback Training programs for system operators Human-in-the-loop considerations Emergency shutdown procedures
Compliance and Standards	Adherence to industry-specific regulations Certification against safety standards Continuous monitoring for compliance Integration with safety protocols
Emergency Response	Automated response to critical incidents Integration with emergency services Communication protocols during emergencies. Containment and mitigation strategies.
System Monitoring	Real-time monitoring of critical parameters. Predictive maintenance for potential issues. Anomaly detection in system behaviour Continuous health assessments

The Epidemic Dynamic Model is a mathematical framework employed to simulate and analyse the dissemination of illnesses or events across a population or network inside the realm of Cyber-Physical Systems (CPS), these models can be modified to simulate the spread of faults, failures, or disturbances inside the system. The integrated technologies work synergistically to monitor physical processes, gather sensor data, and facilitate proactive fault management. Collection tree protocols optimize data gathering within CPS, while IoT monitoring provides real-time insights into system performance. Epidemic modelling techniques enable predictive analysis of potential failures, allowing for proactive fault management. This coordinated approach enhances fault tolerance by identifying, analysing, and addressing issues before they impact system operation, thereby improving overall reliability and performance (11). For example, a node that is in good health may change to a "faulty" state when it encounters specific conditions or interactions. The model accurately represents the changing nature of these transitions as time progresses. In the context of CPS, the transmission mechanism refers to the way defects or failures spread across the system, similar to how a disease spreads in epidemiological models (12). These aspects may encompass elements such as inter-node communication, interdependencies, or the utilisation of shared resources. Nodes possess mechanisms to rectify defects or failures, similar to the recuperation or restoration phase in epidemic models. Deployment involves integrating CPS and IoT components, employing resilient communication protocols, and efficient resource allocation algorithms. Monitoring structures facilitate real-time data collection and analysis, leveraging scalable architectures. Technological requirements include robust communication networks, sensor networks, and computational resources to support seamless integration and interoperability. This could encompass the existence of primary defects or the lack of any problems. The model functions within a predetermined time period, enabling the simulation to accurately depict the progression of states and interactions among nodes (13). Data analytics methods are employed to analyse sensor data and identify patterns indicative of potential failures or anomalies. Communication protocols ensure seamless data exchange between CPS components and IoT devices, facilitating real-time monitoring and analysis. Sensor networks collect and transmit data from physical processes, enabling continuous monitoring of system behaviour. Together, these technologies enable integrated monitoring goals by providing timely insights into system performance and facilitating proactive fault management strategies.

Results and Discussion

In Cyber-Physical Systems (CPS), performance analysis based on inbound and outbound activation scenarios entails analysing the system's efficiency and responsiveness regarding the initiation and termination of activities, data flows, or communication between different components (14). The implementation, modification, and

optimization of integrated monitoring frameworks play a crucial role in enhancing the reliability of manufacturing systems, smart city deployments, and critical infrastructure. By customizing monitoring frameworks to suit specific application domains, such as manufacturing or smart city environments, organizations can tailor proactive fault management strategies to address unique challenges. Continuous optimization of monitoring frameworks based on feedback and performance data ensures ongoing reliability improvements and adaptability to evolving cyber-physical contexts. Figure 3 shows the Performance Monitoring of Incoming Activities and Outcoming Activities. In the context of inbound and outbound activation scenarios, here's how you might approach performance analysis:

Activation from the inside: Latency Analysis: Determine how long it takes the system to respond to incoming requests or inputs. Calculate the time elapsed between the commencement of the activation signal and the matching system reaction $RT_{inbound}$:

$$RT_{inbound} = t_{response} - t_{activation} \quad [1]$$

Throughput Evaluation: Examine how quickly the system processes and manages incoming activations. Consider the amount of inbound data or transactions that the system can handle properly. $TP_{inbound}$:

$$TP_{inbound} = \frac{Volume\ of\ Inbound\ Data}{Time} \quad [2]$$

Activation from the outside: Latency in Data *Transmission*: Determine how long it takes the system to send data or signals to external entities in response time ($LT_{inbound}$) to outbound activation:

$$LT_{outbound} = t_{transmission} - t_{activation} \quad [3]$$

Outbound Communication Throughput: Determine the rate at which data is transferred to external systems or devices. Consider the ability to manage several outbound activations at the same time $TP_{Outbound}$:

$$TP_{outbound} = \frac{Volume\ of\ Outbound\ Data}{Time} \quad [4]$$

CPU and Memory Utilisation: Track the use of computational resources during both inbound and outbound activations. ($CPU_{Utilization}$) Determine potential bottlenecks or inefficiencies in resource utilization ($Memory_{Utilization}$).

Bandwidth Utilisation: Examine how much network bandwidth is used during data transfer, both inbound and outward. Improve communication efficiency by optimising bandwidth allocation ($BW_{Utilization}$).

$$BW_{Utilization} = \frac{Transmitted\ Data\ size}{Time} \quad [5]$$

Testing for Scalability: Scalability in response to rising inbound activation requests: Determine how effectively the system scales. Examine performance under various loads and circumstances.

$$SF_{Inbound} = \frac{TP_{inbound\_new}}{TP_{inbound\_original}} \quad [6]$$

Outbound Scalability: Examine the system's ability to scale when dealing with several outbound activations at the same time. Consider circumstances in which outbound communication demands increase.

$$SF_{outbound} = \frac{TP_{outbound\_new}}{TP_{outbound\_original}} \quad [7]$$

Inbound Reliability: Determine the system's ability to consistently respond to inbound activations. Determine the system's availability under various activation scenarios.

$$R_{Inbound} = \frac{Successfull\ inbound\ Activities}{Total\ inbound\ Activities} \quad [8]$$

Outgoing Reliability: Assess the dependability of outgoing communications as well as the system's capacity to transfer data when needed

$$R_{outbound} = \frac{Successfull\ outbound\ Activities}{Total\ outbound\ Activities} \quad [9]$$

Inbound Security: Examine the security measures in place to safeguard the system against potential dangers connected with inbound activations.

Outbound Security: Assess the security policies that control outbound data transactions to ensure data integrity and confidentiality.

Inbound Adaptability: Evaluate the system's ability to adjust to changes in inbound activation patterns. Consider dynamic changes in response to different activation frequencies.

$$AI_{Inbound} = \frac{TP_{inbound\_new} - TP_{inbound\_Original}}{TP_{inbound\_original}} \quad [10]$$

Outbound Adaptability: Assess the system's ability to respond to changing outbound activation requirements. Examine how well the system adapts to changes in outbound communication requirements.

$$AI_{outbound} = \frac{TP_{outbound\_new} - TP_{outbound\_Original}}{TP_{outbound\_original}} \quad [11]$$

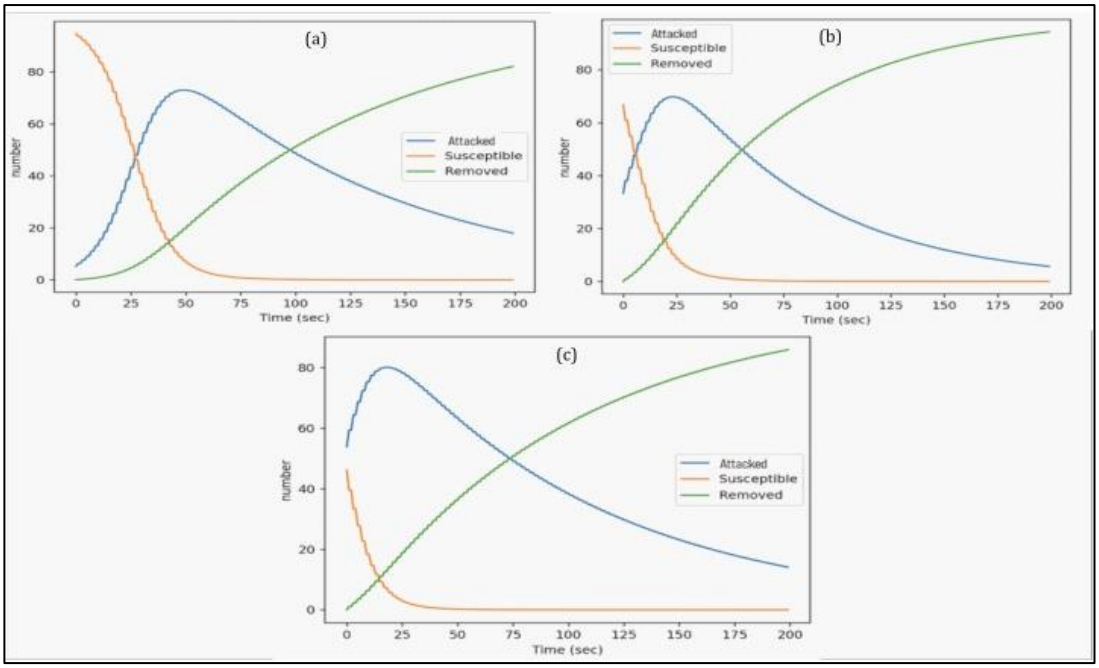

Figure 3: Performance Monitoring of Incoming Activities and Outcoming Activities

Quantitative evaluation assesses reliability metrics, response times, and resource utilization, while qualitative analysis considers user satisfaction and fault tolerance. The monitoring framework enhances operational efficiency by predicting and preventing CPS failures, improving system reliability and resilience. Comparative analysis with existing research projects highlights the framework's effectiveness and contributions to CPS dependability.

Conclusion

On conclusion, a full performance analysis based on both incoming and outgoing activation scenarios is a key part of making sure that Cyber-Physical Systems (CPS) work well and reliably. By checking latency, throughput, resource utilisation, scalability, dependability, security, and flexibility, we can get a full picture of how CPS reacts to events, handles information, and interacts with its surroundings (15). By looking closely at inbound activation, we can see how the system reacts to incoming signals, which is important for uses that need quick and accurate reactions. At the same time, looking at outbound activation scenarios shows how well the system sends data to outside sources, which is necessary for smooth contact within the larger network. Metrics for resource utilisation and scaling are important ways to see how efficient and capable something is, and they help with optimisation efforts. Reliability assessments make sure that the system works reliably, and security assessments make sure that data is kept safe while it is being sent (16). The adaptability metrics show how well the system can handle changing activation patterns, which is very important in settings that are always changing. This complete approach gives researchers and practitioners the tools they need to improve CPS performance, which leads to the creation of strong and effective systems in many areas.

The study situates itself within existing literature, exploring CPS orchestration, epidemic modelling, and monitoring frameworks. Comparative analysis with related works underscores unique contributions and insights. Future research avenues include further exploration of adaptive architectures, scalability, and security measures to address evolving CPS challenges in the dynamic landscape of the 4IR.

Abbreviation

CPS: Cyber Physical System
IoT: Internet of Things

Acknowledgement

Not applicable.

Author Contributions

All authors contributed to the study conception and design.

Conflict of Interests

The authors declare that they have no competing interests.

Ethics Approval

Not applicable.

Funding

No funding received by any government or private concern.

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