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FAULT TOLERANCE AND SELF-HEALING IN IOT-ENHANCED P2P SYSTEMS

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Abstract: In this article different self-healing and fault-tolerance concepts and approaches that can be integrated in IoT enhanced P2P systems were studied. Overall, the main purpose of this article is to give an overview on importance of self-healing and fault tolerance in order to ensure seamless operation and reliable data transfer. In addition, there are some recommendations provided for improving resilience and reliability.

Key words: fault tolerance, self-healing, Internet of things (IoT), peer-to-peer networks, distributed systems, failure detection, replication, checkpointing and recovery, adaptive fault management, redundancy.

Annotatsiya: Ushbu maqolada IoT bilan boyitilgan P2P tizimlariga integratsiya qilinishi mumkin bo'lgan o'z-o'zini tiklash va nosozliklarga bardoshlilik (fault-tolerance) konsepsiyalari hamda yondashuvlari o'rganildi. Maqolaning asosiy maqsadi — uzluksiz ishlash va ishonchli ma'lumot uzatishni ta'minlash uchun o'z-o'zini tiklash hamda nosozliklarga bardoshlilikning ahamiyatini yoritishdir. Bundan tashqari, tizimlarning barqarorligi va ishonchliligini oshirish bo'yicha bir qator tavsiyalar berilgan.

Kalit so'zlar: nosozliklarga bardoshlilik, o'z-o'zini tiklash, narsalar interneti (IoT), teng-teng (P2P) tarmoqlar, taqsimlangan tizimlar, nosozliklarni aniqlash, replikatsiya, nazorat nuqtasi va tiklash, moslashuvchan nosozliklarni boshqarish, ortiqchalik.

Аннотация: В данной статье исследованы различные концепции и подходы к самовосстановлению и отказоустойчивости, которые могут быть интегрированы в P2P-системы, улучшенные с помощью Интернета вещей (IoT). Основная цель статьи заключается в том, чтобы дать обзор важности самовосстановления и отказоустойчивости для обеспечения бесперебойной работы и надежной передачи данных. Кроме того, представлены рекомендации по повышению устойчивости и надежности систем.

Ключевые слова: отказоустойчивость, самовосстановление, Интернет вещей (IoT), одноранговые сети, распределённые системы, обнаружение отказов, репликация, контрольные точки и восстановление, адаптивное управление отказами, избыточность.

INTRODUCTION

Various definitions of distributed P2P (Peer-to-Peer) networks have been provided in different literatures, according to [1] a distributed P2P network architecture is an architecture in which participants' portions of hardware resources are shared (storage, computing power, bandwidth of a network connection and etc.).

In addition, participants of distributed systems have the same goal to be achieved. Each node has its own part of the task and after completing it, nodes resubmit the outcomes to submission node. According to [2] there are two types of distributed systems homogeneous (Cluster) and heterogeneous (Grid, Cloud and P2P). They are used to solve certain types of tasks such as Quality of Service (QoS), Load Balancing and Fault Tolerance.

Fault tolerance is the ability of a system to continue functioning properly in case if a failure or malfunction of one or more of its components. Fault tolerance consists of two parts; faults detection and recovery. Furthermore, as it was mentioned [2] in distributed systems it is challenging to keep systems running after failures occur. There are many techniques used for fault tolerance such as Replication, Checkpointing and Logging etc.

As the research scope fault tolerance and self-healing in IoT enhanced P2P systems were chosen, which means that the scope of the studies are distributed P2P networks that connect IoT devices.

In the context of IoT-enhanced P2P systems, where a network of independent computers presents itself as a unified entity to users, fault tolerance takes on added significance. The distributed nature of these systems elevates concerns about hardware or software failures, necessitating specialized techniques for detection and recovery.

Resilience in such environments is achieved through the application of fault tolerance techniques, including retry mechanisms, replication, check pointing, message logging, etc. [2]. These mechanisms collectively contribute to maintaining seamless operation, even in the face of unexpected component disconnects or malfunctions.

The paper delves into foundational concepts of fault tolerance specific to IoT-enhanced P2P systems and explores self-healing mechanisms within this dynamic context. A comprehensive analysis of related work is presented, offering insights into the current state of research and development. The paper concludes, contributing to the ongoing discourse on bolstering the reliability of distributed systems amid the IoT and P2P connectivity era.

REVIEW OF LITERATURE ON THE SUBJECT

Fault tolerance and self-healing in IoT-enhanced peer-to-peer (P2P) systems constitute a multidisciplinary research area that merges classical distributed-systems theory with the unique challenges of IoT environments, including resource constraints, scalability, and heterogeneity. As Castro and Liskov emphasize in their foundational work on Practical Byzantine Fault Tolerance, resilience in distributed environments depends on the system's ability to maintain service correctness even under arbitrary or malicious faults. Their principles of primary–backup ordering and client–server replication continue to guide fault-tolerant IoT architectures where high reliability is critical.

In large-scale decentralized networks, Jelasity, Montresor, and Babaoglu highlight the significance of gossip-based mechanisms for scalable membership management and monitoring. Their research demonstrates that peer-sampling and gossip protocols effectively disseminate system state information with minimal coordination overhead, which is particularly advantageous for IoT overlays that operate without centralized control. Similarly, Ganesh, Le, and Kermarrec developed the SCAMP protocol, showing that probabilistic membership can significantly enhance robustness and adaptability in large, dynamic P2P networks.

Bridging classical distributed-systems techniques with IoT-specific needs, Melo and colleagues proposed a multi-layer fault-tolerance framework separating responsibilities across the edge, fog, and cloud layers. This architecture allows for fast local detection and containment of faults while delegating complex analysis to higher layers, thus optimizing resource usage and improving service continuity. In parallel, Abdulrazak and co-authors introduced a self-healing model for IoT architectures that relies on an autonomous MAPE (Monitor–Analyze–Plan–Execute) control loop. Their approach enables systems not only to recover from failures but also to adapt dynamically, reconfiguring network overlays and reallocating resources to prevent fault recurrence.

Recent advances in the field reveal three dominant research directions. First, lightweight monitoring and prediction techniques—often using machine learning—allow on-device fault detection and predictive maintenance, reducing downtime in IoT networks. Second, as Payberah and collaborators demonstrate, resource-aware replication and failover strategies balance consistency and latency while addressing IoT devices' limited capacity. Third, decentralized coordination through gossip-based membership and recovery protocols provides resilience against frequent node churn and network fragmentation.

Comprehensive studies, including the analytical survey by Al-Salihi and co-authors, confirm that hybrid architectures—combining predictive analytics, hierarchical replication, and decentralized recovery—achieve the best trade-off between reliability and efficiency. Similarly, industrial IoT investigations, such as those analyzed by Abdulrazak's team, show that integrating self-healing mechanisms in smart grids and metering systems substantially improves fault recovery time and operational stability.

Despite significant progress, several challenges persist. The integration of fault tolerance with security mechanisms remains incomplete; as Melo et al. note, future systems must differentiate between benign and malicious faults more effectively. Another emerging issue is the need for explainable predictive fault models that remain lightweight enough for constrained IoT devices. Standardized benchmarks for evaluating IoT-P2P fault tolerance are also lacking, which makes it difficult to compare new approaches objectively.

In conclusion, the literature indicates that combining predictive edge analytics, resource-conscious replication, and gossip-driven coordination provides a promising foundation for resilient, self-healing IoT-enhanced P2P systems. As Castro, Liskov, Jelasity, Montresor, Babaoglu, and others demonstrate, the field's future depends on designing systems that can not only survive faults but also autonomously restore their functionality—turning inevitable failures into brief, self-correcting events.

RESEARCH METHODOLOGY

This study began with a comprehensive review of existing literature, focusing on key academic works, recent research findings, and notable developments related to the topic. Through this survey, the evolution of fundamental concepts, theories, and hypotheses was examined to understand how ideas have progressed and contributed to current knowledge.

A critical aspect of the review was identifying research gaps — areas that remain insufficiently explored or underdeveloped in prior studies. These gaps highlight opportunities for future investigations and potential applications in both theoretical and practical projects.

The methodologies used in previous studies were also analyzed to evaluate their strengths and weaknesses. By comparing diverse research designs and analytical frameworks, the most effective approaches for addressing similar research problems were identified.

Additionally, emerging trends and innovative practices within the field were explored, emphasizing recent shifts in theory, technology, and application. Finally, the findings of different studies were compared and summarized in a concise comparative table, outlining each work's main focus, methods, and outcomes to provide a clear, structured synthesis of existing knowledge.

ANALYSIS AND RESULTS

In this research, [2] has been considered as the base paper, and the study extends its work by focusing specifically on Peer-to-Peer (P2P) distributed systems, which have significant potential applications in the field of the Internet of Things (IoT). The P2P-based Network Management (P2PBNM) system [4] integrates multiple techniques to achieve fault tolerance and self-healing capabilities, ensuring resilient and reliable network management in distributed environments.

The system organizes peers into groups based on the administrative services they provide. This peer grouping facilitates the replication of management components and improves the overall availability of management services. Each group of peers is assigned specific management responsibilities, allowing for distributed and balanced control. Replication of management components within peer groups further strengthens the system's fault tolerance. If a peer fails, other peers within the group can seamlessly take over its functions due to the presence of redundant components, thereby maintaining service continuity.

A proactive peer organization strategy is implemented by arranging peers according to the services they expose. This anticipatory approach ensures the presence of backup peers ready to assume control in case of a failure, thus enhancing system robustness. Additionally, a dedicated monitoring service continuously observes the operational state of managed devices or systems. By periodically verifying system conditions and comparing them against predefined criteria, this service detects anomalies and faults efficiently. Once anomalies are detected, the healing service activates a predefined recovery work plan to correct the fault and restore the system to a healthy state.

The self-healing capability of P2PBNM is achieved through specialized management components responsible for both monitoring and healing functions. These components are dynamically loaded and synchronized with the grouping service to maintain communication and coordination among peers offering similar services. To further enhance reliability, the recovery work plan is replicated across multiple peers. This redundancy ensures that several peers are capable of executing healing procedures simultaneously, thereby improving both responsiveness and scalability.

Dynamic binding of self-healing services allows administrators to associate recovery-enabled services with managed elements during runtime. This process involves interaction with healing and monitoring groups, obtaining relevant service identifiers, and linking them dynamically. Moreover, monitoring peers operate in a token-signalized round-robin pattern, forming a structured ring where monitoring tasks are performed sequentially at fixed intervals. This mechanism ensures systematic and efficient supervision of network components.

Communication and coordination among peers play a crucial role in the overall system functionality. These interactions enable the replication of management components, synchronization of self-healing modules, and coordination of both monitoring and healing activities. Collectively, these techniques form the foundation of the P2PBNM system's robust fault tolerance and self-healing mechanisms, ensuring reliable, autonomous, and continuous operation of distributed network management services.

In addition, [5] highlights the use of the Checkpointing-and-Recovery technique as an effective recovery strategy for maintaining reliability in task execution within P2P-Grid environments. This technique involves periodically saving the state of computations at specific checkpoints, allowing the system to recover tasks from the most recent checkpoint in the event of node failures. Together, these approaches strengthen the resilience of distributed systems by minimizing downtime and ensuring uninterrupted service continuity.

The discussed text provides an in-depth analysis of techniques and mechanisms employed in a Peer-to-Peer Grid (P2P-Grid) environment to address challenges related to the reliability of task execution. A central focus is placed on developing effective fault-tolerance strategies capable of adapting to the dynamic nature of distributed systems. One of the primary mechanisms highlighted is failure detection, which is achieved through the use of a probe-based approach. In this method, nodes periodically send "can you hear me?" messages to neighboring peers and await acknowledgment responses. This process allows for quick identification of node failures or departures, thereby reducing system unavailability intervals and enabling faster recovery actions to maintain the operational continuity of the grid network.

Another critical mechanism explored is the Checkpointing-and-Recovery technique, which serves as the foundation for fault tolerance in P2P-Grid systems. Checkpointing involves saving the state of computations at specific time intervals, while recovery enables resumption of tasks from the last saved checkpoint after a failure. This mechanism ensures that task execution can continue with minimal data loss or computational redundancy even in highly unstable environments where nodes frequently join and leave the system. To further improve system dependability, checkpointing nodes are introduced to handle reliability issues arising from this dynamic node behavior.

To enhance fault resilience, redundancy in checkpointing is incorporated as an additional safeguard. The simplest redundancy model involves storing checkpointing information across multiple storage nodes within the grid. Idle nodes are utilized as storage peers, and checkpointing peers can exchange checkpoint data from different working peers to prevent data loss and increase recovery efficiency. This redundancy ensures that even in the event of node failure, recovery data remains accessible, thus improving both fault tolerance and system robustness.

The P2P-Grid system model presented in the text consists of four major components: the Dispatcher, Working Peer (WP), Working Candidate Peer (WCP), and Checkpointing Peer (CPP). The Dispatcher oversees administrative operations and task coordination, while Working Peers execute assigned computational tasks. Working Candidate Peers are responsible for handling checkpointing processes, and Checkpointing Peers store checkpoint data for recovery purposes. This hierarchical and distributed structure enables efficient workload distribution and optimized task management across the network.

The roles and selection criteria for each peer are defined based on factors such as processing speed, peer lifetime, computational capacity, and data transmission capabilities. Peers with higher performance and longer lifetimes are prioritized for critical roles like dispatching and checkpointing, ensuring stable task execution and minimal interruptions. The system also incorporates adaptive failure detection mechanisms designed to adjust dynamically to evolving network conditions. The concept of Average Failure Detection Time (AFDT) is introduced as a metric to evaluate the responsiveness and efficiency of failure detection methods. The main objective of adaptive failure detection is to rapidly identify failed or disconnected nodes and to replace them promptly by utilizing stored checkpoints, thereby minimizing downtime.

Finally, the text provides a comparative analysis of the proposed approach with other existing fault-tolerant frameworks, including Dome, Condor, Gridbus, and XCAT3. These comparisons emphasize the distinctions in system goals, operational mechanisms, and the degree of adaptability to dynamic network environments. The P2P-Grid approach presented in [5] focuses particularly on enhancing fault tolerance against repeated node participation and diverse failure scenarios. Overall, the text presents a comprehensive framework that integrates proactive failure detection, checkpointing, redundancy, and adaptive recovery techniques to ensure the reliability, continuity, and resilience of computational processes in P2P-Grid environments.

The paper [6] delves into the intricacies of structured Peer-to-Peer (P2P) networks, emphasizing the challenges associated with maintaining ring topology amidst churn and failures. It critiques existing solutions such as Chord, citing their struggles with temporary inconsistencies and the complexity of synchronized join/leave algorithms involving multiple peers. In response, the paper proposes a novel approach, advocating for the management of ring topology through a self-organizing system driven by feedback loops, aiming to streamline operations and enhance resilience. The Relaxed-Ring Design, a central focus of the paper, introduces several innovative concepts:

• Join Algorithm Optimization: The join algorithm is restructured into two steps, each requiring the agreement of only two peers. This strategic division mitigates the need for expensive synchronization, presenting a more efficient alternative to traditional approaches.

• Branching for Resilience: Unlike traditional structures like Chord, the Relaxed-Ring Design permits branches off the core ring. Peers are only required to connect to their successors, eliminating the need for connections to predecessors. This adaptation enhances resilience, particularly in scenarios involving connectivity issues.

• Feedback Loop Implementation: Drawing inspiration from control systems, the design incorporates feedback loops from monitors to actuators, establishing a mechanism to autonomously maintain ring structure. Join and failure events are modeled as perturbations, contributing to the self-organizing nature of the system.

• Failure Recovery Strategies: The paper Relaxed-Ring [6] outlines a robust failure recovery mechanism triggered by the predecessor via the successor list. This mechanism unifies leave events, addresses false suspicions, and ensures the propagation of successor list changes. Additional safeguards are provided through the utilization of predecessor lists and fingers as backup resources.

• The Analysis section of the paper further solidifies the proposed approach:

• Consistency Guarantees: The authors rigorously prove lookup consistency guarantees, establishing the reliability of the Relaxed-Ring Design. Additionally, the paper argues that the introduction of branches does not permit responsibility range overlaps, adding a layer of formal assurance.

• Handling Failure Scenarios: The analysis evaluates the system's performance in various failure scenarios, including concurrent crashes and joins. It sheds light on the intricate interplay between join and failure loops, offering insights into the system's robustness.

• Addressing Difficult Cases: The paper extends its scrutiny to challenging scenarios such as branch failures and network partitions. Specific limitations are identified and formalized, contributing to a comprehensive understanding of the system's capabilities.

In the Comparison to Related Work section, the authors position the Relaxed-Ring Design against existing solutions like Chord and DKS. The argument centers on the design's superior resilience and compatibility with realistic failure detectors.

The Conclusion succinctly synthesizes the paper's contributions:

• Self-Management through Feedback Loops: The paper effectively demonstrates that ring topology can be autonomously managed using feedback loops, underscoring the self-organizing capabilities of the proposed design.

• Robustness during Churn: The simplified join process and unified leave mechanisms make the Relaxed-Ring Design resilient to failures during churn, addressing a critical aspect of P2P network management.

• Towards Reliable Applications: The provision of formal guarantees and the identification of limitations contribute valuable insights for building reliable applications in the context of structured P2P networks.

To enhance the precision of the analysis across various research endeavors addressing fault tolerance on diverse platforms, the creation of a comprehensive comparative table (refer to Table 1) is suggested summarizing key findings and distinctions (Table 1).

Table 1. Different fault detection and tolerance techniques used in p2p distributed systems

Article	*Platform*	*Techniques implemented*	*Faults found*	*Proactive / Reactive or Combined*	*Support Large Scale*	*Contribute to Load Balancing*	*Availability*	*Reliability*	*Recovery techniques implemented*	*Overall remark*
P2PBNM ***[4]***	P2P based network management systems (P2PBNM)	Peer Grouping, Monitoring and Healing Services, Token-Signalized Round-Robin Execution, Peer Communication and Coordination	Connectivity Issues, Hardware Failures, Software/Application Failures, Performance Degradation, Security Threats, Configuration Errors, Resource Exhaustion, Service Availability, Environmental Conditions	Combined	✓	✓	✓	✓	Replication of management components, Replication of healing workplan,	The experiments have shown that there is a trade-off among total traffic and the mean duration for the self-recovery procedure
P2P-Grid [5]	P2P-Grid systems	Peer Roles, Adaptive Failure Detection, Blocking check pointing	Node Failures and Departures	Proactive	-	-	-	-	Checkpointing, Checkpointing Nodes, Working Candidate Peers (WCP)	4 roles for peers were introduced. In addition, there was used blocking check pointing.
Relaxed-Ring ***[6]***	Implemented with Mozart-Oz programming system	Feedback loops for self-management	Node failures, network failures, broken links	Combined	✓	-	✓	✓	Maintaining backup routing information, redirecting requests, triggering stabilized join process	Introduced "relaxed ring" topology, which is self-organizing and fault-tolerant. In comparison with a strict ring topology, relaxed ring handles failures and temporary network issues better.

CONCLUSIONS AND SUGGESTIONS

In conclusion, the investigation into "Fault Tolerance and Self-healing in IoT enhanced P2P systems" through the analysis of three pertinent articles has provided valuable insights into the evolving landscape of resilient peer-to-peer networks. The comparative table I constructed has served as a systematic tool to distill the nuances, strengths, and limitations inherent in each approach.

Across the examined articles, common themes emerged, highlighting the critical role of fault tolerance and self-healing mechanisms in mitigating the challenges posed by the dynamic nature of IoT-enhanced P2P systems. Each research work contributed distinct perspectives, shedding light on diverse strategies for ensuring system robustness and continuity.

Through this exploration, the significance of adaptive and intelligent fault detection mechanisms is recognized, coupled with efficient recovery strategies, in sustaining the integrity and performance of IoT-enhanced P2P networks.

In the broader context of P2P systems, this exploration into fault tolerance and self-healing mechanisms stands as a testament to the ongoing efforts to fortify the foundations of our interconnected world. As technology advances and IoT integration becomes more pervasive, the lessons drawn from this study will undoubtedly inform the development of robust, fault-tolerant, and self-healing P2P systems, ensuring the seamless functioning of the interconnected devices that define our modern digital landscape.

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