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[Alekhya Mutyala](#)*

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Article

A Survey on Peer-to-Peer Network Testing Techniques

Alekhya Mutyala

School of Computer Science and Engineering, VIT-AP University, Amaravathi. Andhra Pradesh, India;
alekhya.23mis7292@vitapstudent.ac.in

Abstract

Peer-to-peer (P2P) systems have emerged as a fundamental paradigm for decentralized resource sharing, communication, and computation across diverse application domains such as energy trading, distributed storage, social networking, and federated learning. Unlike traditional client-server architectures, P2P networks operate without centralized control, enabling nodes to act as both resource providers and consumers, thereby improving scalability, robustness, and system efficiency. However, the decentralized and dynamic nature of P2P systems introduces significant challenges in ensuring reliability, performance, and security, making testing a critical research area. This paper presents a comprehensive survey of peer-to-peer network testing techniques, integrating insights from existing literature on P2P architectures, simulation frameworks, and application-specific implementations. Early research primarily relied on analytical models and simulations to evaluate P2P systems, as real-world experimentation is often impractical due to large-scale deployment requirements. Simulation-based testing remains a widely adopted approach, though it suffers from limitations such as scalability constraints and lack of reproducibility in complex environments. Modern testing approaches for P2P systems include model-based testing, fault injection, stress testing, fuzzing, differential testing, and concurrency testing. These techniques address key challenges such as validating global system properties, handling peer churn, ensuring consistency, and managing heterogeneous network conditions. Additionally, load testing and performance evaluation methods have evolved to leverage decentralized testing frameworks, eliminating bottlenecks associated with centralized testing systems. Measurement-based techniques and sampling methods are also used to analyze large-scale P2P networks efficiently, though issues such as bias and incomplete data collection persist. The emerging application domains such as P2P energy trading and federated learning introduce new testing requirements, including real-time system validation, privacy preservation, and integration with physical systems. Advanced approaches like hardware-in-the-loop testing and AI-driven evaluation mechanisms are being explored to bridge the gap between simulation and real-world deployment. This survey consolidates key testing methodologies, identifies open challenges, and highlights future research directions in P2P network testing, emphasizing its critical role in enabling reliable, scalable, and intelligent decentralized systems.

Keywords: Peer-to-Peer networks P2P systems; network testing distributed systems decentralized architecture scalability; fault tolerance simulation-based testing load testing; fault injection fuzz testing federated learning; energy trading systems overlay networks network security reliability

1. Introduction

Peer-to-Peer (P2P) systems have emerged as a transformative paradigm in distributed computing, enabling decentralized communication, resource sharing, and collaborative computation without relying on centralized authorities. Unlike traditional client-server architectures, where a central entity manages services and resources, P2P networks distribute responsibilities among participating nodes, allowing each node to function both as a client and a

server [13]. This decentralized architecture significantly enhances scalability, fault tolerance, and resource utilization, making P2P systems highly suitable for large-scale and dynamic environments.

Over the years, P2P systems have evolved from simple file-sharing applications to complex infrastructures supporting diverse domains such as distributed storage, social networking, energy trading, and federated learning. Early studies on P2P overlay networks focused on structured and unstructured architectures, routing mechanisms, and resource discovery techniques [6,8]. These foundational works established the key principles of P2P systems, including self-organization, decentralization, and robustness. Additionally, P2P-based social networks have been proposed as alternatives to centralized platforms, offering improved privacy, data ownership, and resistance to censorship [9]. Similarly, modern decentralized storage systems such as IPFS demonstrate how P2P architectures can eliminate data silos and improve data availability and security [2].

In recent years, P2P systems have been widely adopted in emerging application domains. For instance, peer-to-peer energy trading frameworks enable prosumers to directly exchange electricity in decentralized markets, improving energy efficiency and reducing dependency on centralized grids [4,10]. Furthermore, the integration of artificial intelligence techniques such as multi-agent reinforcement learning and federated learning has enhanced the adaptability and intelligence of P2P systems [1,7,14]. These advancements allow P2P systems to handle complex decision-making processes, optimize resource allocation, and preserve user privacy in distributed environments.

Despite these advantages, P2P systems introduce several challenges due to their decentralized and dynamic nature. One of the primary challenges is peer churn, where nodes frequently join and leave the network, resulting in continuously changing network topologies. This dynamic behavior complicates system design, evaluation, and validation [3]. Additionally, the lack of centralized control makes it difficult to ensure coordination, consistency, and consensus among nodes. Security vulnerabilities, heterogeneous network conditions, and unpredictable workloads further increase the complexity of P2P systems.

Testing P2P systems is significantly more challenging compared to traditional centralized systems. In centralized systems, testing can be conducted in controlled environments with predictable configurations. However, P2P systems operate in distributed, heterogeneous, and non-deterministic environments, making it difficult to reproduce real-world conditions [12]. Simulation-based testing has been widely used to evaluate P2P systems, as it allows researchers to model large-scale networks and analyze system behavior efficiently. However, simulation approaches often suffer from limitations such as scalability constraints, lack of realism, and difficulty in validating results against real-world scenarios.

To address these challenges, researchers have proposed various testing techniques tailored to P2P systems. These include model-based testing, fault injection, fuzz testing, stress testing, and concurrency testing, which aim to evaluate system reliability, robustness, and performance under different conditions [3]. Additionally, decentralized load testing approaches have been introduced to overcome bottlenecks associated with centralized testing infrastructures, enabling scalable and realistic performance evaluation [11]. Measurement-based techniques and sampling methods have also been developed to analyze large-scale P2P networks efficiently, although they may introduce biases and inaccuracies [15].

Another important aspect of P2P system evaluation is the use of simulation tools and experimental testbeds. A variety of P2P simulators have been developed to support large-scale testing and performance evaluation, each with its own advantages and limitations [12]. While simulation provides a practical approach for studying P2P systems, real-world experimentation remains essential for validating system behavior under realistic conditions. However, conducting large-scale experiments is often resource-intensive and difficult to manage.

The increasing complexity of modern P2P applications, particularly those involving machine learning and blockchain technologies, has introduced new challenges in testing and evaluation. For example, P2P-based federated learning systems require testing frameworks that can ensure data privacy, model accuracy, and communication efficiency [1,7]. Similarly, energy trading systems must

be evaluated for economic efficiency, scalability, and reliability under varying market conditions [4,10]. These requirements highlight the need for advanced testing methodologies that can handle the unique characteristics of modern P2P systems.

Given the diversity of P2P applications and the complexity of their testing requirements, there is a strong need for a comprehensive survey that consolidates existing testing techniques and identifies open research challenges. This paper aims to provide a systematic review of peer-to-peer network testing techniques, covering traditional approaches, recent advancements, and emerging trends.

The main contributions of this paper are as follows. First, we provide an overview of P2P architectures and their evolution across different application domains. Second, we classify and analyze existing testing techniques, including simulation-based testing, model-based testing, load testing, and measurement-based approaches. Third, we discuss the key challenges associated with testing P2P systems, such as scalability, heterogeneity, reproducibility, and security. Finally, we identify open research directions and future trends, particularly in the context of intelligent and application-driven P2P systems.

2. Literature Survey

a. Fundamentals of Peer-to-Peer Architectures

Peer-to-Peer (P2P) systems have been extensively studied as an alternative to traditional client-server architectures. Early research focused on defining the fundamental characteristics of P2P systems, including decentralization, resource sharing, and self-organization. Pourebrahimi et al. [13] highlighted that P2P systems distribute computation and resources among nodes, thereby eliminating bottlenecks associated with centralized systems. Similarly, Lua et al. [8] provided a comprehensive classification of P2P overlay networks into structured and unstructured systems, emphasizing their scalability, fault tolerance, and routing efficiency. Structured P2P systems, typically based on Distributed Hash Tables (DHTs), offer deterministic data placement and efficient search mechanisms. In contrast, unstructured P2P systems rely on probabilistic search techniques, which are simpler but less efficient in large-scale environments. Li and Wu [6] analyzed various searching techniques in P2P networks, including blind and informed search strategies, highlighting the trade-offs between search efficiency and network overhead. These foundational studies laid the groundwork for understanding the behavior and limitations of P2P systems.

b. Simulation and Modeling of P2P Systems

Due to the large-scale and distributed nature of P2P systems, simulation has become a widely used approach for evaluating their performance. Naicken et al. [12] conducted a comprehensive survey of P2P network simulators, comparing their features, scalability, and usability. The study emphasized that simulation is often preferred over real-world experimentation due to its flexibility and lower cost. However, the authors also identified several limitations, including poor scalability, lack of documentation, and difficulties in reproducing real-world conditions.

Simulation-based testing allows researchers to model various network conditions, including node churn, network latency, and workload distribution. Despite its advantages, simulation often fails to capture the complexity and unpredictability of real-world P2P systems. As a result, hybrid approaches that combine simulation with real-world experimentation have been proposed to improve the accuracy of performance evaluation.

c. Testing Challenges in Peer-to-Peer Systems

Testing P2P systems presents unique challenges due to their decentralized and dynamic nature. Garcia and Souza [3] provided a detailed analysis of the challenges associated with software testing in P2P systems. They identified key issues such as peer churn, non-deterministic behavior,

heterogeneity of nodes, and difficulty in validating global system properties. These challenges make it difficult to apply traditional testing methodologies designed for centralized systems.

Another significant challenge is ensuring reproducibility in testing environments. Since P2P systems operate in dynamic networks where nodes frequently join and leave, it is difficult to replicate the same conditions for testing. Additionally, the lack of centralized control complicates coordination and synchronization among nodes, making it harder to verify system correctness and performance.

d. Load Testing and Performance Evaluation

Load testing is a critical aspect of evaluating the performance and scalability of P2P systems. Traditional load testing approaches rely on centralized testing frameworks, which can become bottlenecks when simulating large-scale systems. To address this issue, Meira et al. [11] proposed a peer-to-peer load testing approach that distributes the testing workload across multiple nodes. This approach improves scalability and allows for more realistic simulation of large-scale network conditions.

Decentralized load testing techniques leverage the inherent properties of P2P systems to generate distributed workloads, enabling more accurate evaluation of system performance under heavy load conditions. These methods are particularly useful for testing applications that require high scalability, such as distributed storage systems and blockchain networks.

e. Measurement and Sampling Techniques

Measuring and analyzing large-scale P2P networks is a challenging task due to their size and dynamic nature. Stutzbach et al. [15] addressed the problem of unbiased sampling in unstructured P2P networks. They proposed advanced sampling techniques to reduce bias and improve the accuracy of network measurements. Their work highlights the importance of efficient data collection methods for understanding the behavior of P2P systems.

Measurement-based techniques are essential for evaluating real-world P2P systems, as they provide insights into network topology, peer behavior, and system performance. However, these techniques often face challenges such as incomplete data, measurement bias, and scalability issues.

f. P2P Systems in Modern Applications

Recent advancements in P2P systems have expanded their application domains beyond traditional file sharing.

One prominent application is decentralized energy trading, where prosumers can directly exchange electricity without relying on centralized authorities. Guo et al. [4] proposed an efficient and incentive-compatible P2P energy trading mechanism, addressing challenges related to computational efficiency and trust. Similarly, Mehdinejad et al. [10] developed a robust decentralized framework for local electricity markets, incorporating optimization techniques to handle uncertainty and ensure system reliability.

Another emerging application is federated learning, where P2P systems enable collaborative model training without sharing raw data. Li et al. [7] introduced a clustered federated learning approach that leverages P2P communication to improve model performance and scalability. Atanayaka et al. [1] further explored the use of P2P federated learning for anomaly detection in wireless networks, highlighting its potential for privacy-preserving applications.

In addition, reinforcement learning techniques have been integrated into P2P systems to enhance decision-making and adaptability. Sanayha and Vateekul [14] proposed a multi-agent reinforcement learning approach for P2P energy trading, demonstrating improved efficiency and reduced energy costs.

g. Decentralized Storage and Social Networks

P2P systems have also been widely adopted in decentralized storage and social networking applications. Daniel and Tschorsch [2] provided a qualitative comparison of next-generation P2P data networks, including IPFS, highlighting their advantages in terms of data availability, security, and decentralization. These systems eliminate the need for centralized storage providers and enable users to maintain control over their data.

Similarly, Masinde and Graffi [9] explored the use of P2P architectures in social networks, emphasizing their potential to improve privacy, security, and user autonomy. However, these systems also face challenges related to scalability, data management, and user experience.

h. Use Graph Theory

Stress testing of network [5] demonstrates how scaling the blockchain network and introducing surges in transactions can affect network characteristics, such as mining power distribution, indicated by changes in average degree centrality.

3. Discussion

The analysis of existing literature on peer-to-peer (P2P) network testing techniques reveals significant advancements in both foundational concepts and application-specific implementations. Over time, P2P systems have evolved from simple decentralized file-sharing architectures to complex, intelligent, and domain-driven systems supporting applications such as energy trading, federated learning, and distributed storage. This evolution has directly influenced the complexity of testing methodologies required to ensure system reliability, scalability, and security.

Table 1. Comparison of Peer-to-Peer Network Testing and Application-Based Studies.

Ref	Category	Technique/Approach	Key Contribution	Limitations
[1]	FL + Security	P2P Federated Learning	Privacy-preserving anomaly detection in O-RAN	Limited scalability validation
[2]	Storage Systems	IPFS-based P2P networks	Comparison of next-generation decentralized storage systems	Data availability and adoption challenges
[3]	Testing	Software testing techniques	Comprehensive analysis of testing challenges in P2P systems	Lack of standardized testing frameworks
[4]	Energy Trading	Incentive-compatible mechanism	Efficient and scalable P2P energy trading model	Complex consensus and implementation
[5]	Search Techniques	Routing and search algorithms	Efficient search mechanisms in P2P networks	High overhead in unstructured systems
[6]	Federated Learning	Clustered P2P FL	Adaptive clustering without centralized control	Communication overhead
[7]	P2P Architecture	Overlay network classification	Comparison of structured and unstructured P2P systems	Limited to early-stage architectures
[8]	Social Networks	Decentralized OSN	Privacy-preserving social networking framework	Scalability and usability issues
[9]	Energy Trading	Robust optimization	Decentralized electricity trading framework	High computational complexity
[10]	Testing	P2P Load Testing	Distributed load generation	Limited real-world validation

			tion without centralized bottlenecks	tion
[11]	Simulation	P2P simulators	Comparative study of simulation tools	Scalability and realism limitations
[12]	P2P Basics	Distributed system model	Fundamental concepts and characteristics of P2P systems	Lack of modern application coverage
[13]	AI + Energy	Multi-agent RL	Intelligent optimization in energy trading	High computational cost
[14]	Measurement	Sampling techniques	Unbiased sampling in large-scale P2P networks	Complex implementation and bias risks

One of the key observations from the literature is that simulation-based testing remains the most widely adopted approach for evaluating P2P systems. Studies such as [12] highlight the importance of simulators in modeling large- scale distributed environments. Simulation enables researchers to analyze system behavior under varying conditions, in- cluding node churn and network latency. However, despite its advantages, simulation often lacks realism and fails to capture the dynamic and unpredictable nature of real- world P2P networks. This limitation creates a gap between simulated results and actual system performance.

Another critical insight is the inherent difficulty in test- ing decentralized systems compared to centralized archi- tectures. As discussed in [3], P2P systems introduce chal- lenges such as non- deterministic behavior, heterogeneous nodes, and lack of centralized control. These factors make it difficult to validate global system properties and ensure consistent performance across the network. Traditional test- ing techniques, which rely on controlled environments and predictable configurations, are often inadequate for P2P systems.

To address these challenges, various advanced testing techniques have been proposed, including model-based test- ing, fault injection, fuzz testing, and stress testing. These approaches aim to evaluate system robustness under adverse conditions and identify potential vulnerabilities. In partic- ular, decentralized load testing approaches, such as those proposed in [11], demonstrate the effectiveness of leveraging P2P principles to generate scalable and realistic workloads. By distributing the testing process across multiple nodes, these methods eliminate bottlenecks associated with central- ized testing frameworks and improve scalability.

Measurement and sampling techniques also play a cru- cial role in understanding P2P network behavior. The work presented in [15] highlights the importance of unbiased sam- pling methods for accurately estimating network properties. However, these techniques often face challenges related to incomplete data collection and measurement bias, which can affect the accuracy of the results. Therefore, there is a need for more robust and adaptive measurement frameworks that can handle the dynamic nature of P2P systems.

The emergence of application-specific P2P systems has introduced new testing requirements. For instance, P2P en- ergy trading systems must ensure economic efficiency, scal- ability, and reliability under varying market conditions [4,10]. Similarly, federated learning systems require testing frameworks that can guarantee data privacy, model accuracy, and communication efficiency [1,7]. These applications highlight the need for domain-specific testing approaches that go beyond traditional performance evaluation metrics.

Furthermore, the integration of artificial intelligence techniques, such as reinforcement learning, has added an- other layer of complexity to P2P systems. As shown in [14], intelligent decision-making mechanisms can significantly improve system performance but also introduce challenges in terms of verification and validation. Testing such systems requires new methodologies that can evaluate both system behavior and learning outcomes.

Despite the progress made in P2P network testing, several research gaps remain. First, there is a lack of standardized testing frameworks and benchmarks, making it difficult to compare different approaches. Second, existing testing techniques often struggle to handle large-scale, highly dynamic environments. Third, security and privacy concerns in decentralized systems are not fully addressed by current testing methodologies. Finally, emerging technologies such as blockchain and edge computing introduce additional challenges that require further investigation.

The discussion highlights that while significant advancements have been made in P2P network testing, there is still a need for more comprehensive, scalable, and adaptive testing solutions. Future research should focus on developing hybrid testing frameworks that combine simulation, real-world experimentation, and intelligent analysis techniques. Such approaches will be essential for ensuring the reliability and performance of next-generation P2P systems.

4. Conclusion

Peer-to-Peer (P2P) systems have established themselves as a fundamental paradigm for building decentralized, scalable, and resilient distributed applications. Over the years, the transition from traditional client-server architectures to P2P-based models has enabled systems to eliminate single points of failure, improve resource utilization, and support large-scale participation. This survey has explored the evolution of P2P systems and provided a comprehensive analysis of testing techniques designed to evaluate their performance, reliability, and robustness.

The study reveals that testing P2P systems is inherently more complex than testing centralized systems due to their decentralized control, dynamic topology, and heterogeneous node behavior. Factors such as frequent node churn, unpredictable communication patterns, and distributed decision-making introduce significant challenges in ensuring system correctness and stability. These characteristics make it difficult to replicate real-world conditions and validate system behavior using conventional testing methodologies.

A wide range of testing techniques have been discussed, including simulation-based testing, load testing, model-based testing, and measurement-driven approaches. Simulation remains a dominant method due to its ability to model large-scale systems efficiently, but its limitations in capturing real-world dynamics reduce its reliability for practical validation. On the other hand, decentralized load testing approaches and measurement-based techniques provide more realistic insights into system performance but often face challenges related to scalability, cost, and implementation complexity.

Another key observation is that modern P2P applications have significantly expanded the scope of testing requirements. Emerging domains such as decentralized energy trading, federated learning, and distributed storage systems require testing frameworks that not only evaluate system performance but also ensure data privacy, security, fairness, and adaptability. These applications often involve intelligent and data-driven components, which introduce additional challenges in verifying system behavior and ensuring consistent outcomes.

Moreover, the integration of advanced technologies such as artificial intelligence, blockchain, and edge computing has further increased the complexity of P2P systems. These technologies enhance system capabilities but also demand more sophisticated testing strategies that can evaluate both functional and non-functional aspects. Ensuring trust, transparency, and security in such systems is becoming increasingly critical, especially in applications that involve sensitive data or financial transactions.

Despite significant progress, several research gaps remain in the field of P2P network testing. There is a lack of standardized testing frameworks and benchmarks, which makes it difficult to compare different approaches and validate results consistently. Additionally, existing testing techniques often struggle to handle large-scale, highly dynamic environments with diverse node characteristics. Security and privacy testing also require more attention, particularly in the context of emerging decentralized applications.

Looking forward, future research should focus on developing hybrid and adaptive testing frameworks that combine the strengths of simulation, real-world experimentation, and intelligent analytics. The use of machine learning techniques for predictive testing and anomaly detection can further enhance the effectiveness of testing methodologies. Additionally, the development of standardized tools, datasets, and evaluation metrics will be essential for advancing research in this field.

P2P network testing remains a critical area of research that directly impacts the reliability and scalability of decentralized systems. As P2P technologies continue to evolve and expand into new application domains, the need for robust, efficient, and adaptive testing techniques will become even more important. Addressing the existing challenges and research gaps will play a vital role in enabling the widespread adoption of next-generation decentralized systems.

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