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An Overlay Management Strategy to Enhance Peer Stability in P2P Live Streaming Systems

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Abstract: Peer-to-Peer (P2P) live streaming systems face persistent challenges due to dynamic peer participation, unpredictable churn, and fluctuating network conditions. This study introduces SPOM (Stable Peer Overlay Manager), a novel overlay management strategy based on preferential attachment, designed to enhance peer stability and network resilience. The approach prioritizes high-degree nodes to strengthen connectivity, minimize service disruptions from peer turnover, and optimize resource utilization for continuous streaming. The proposed method was evaluated using the Gnutella P2P dataset within a Python-based simulation environment, leveraging the Network framework. Key performance metrics including node degree distribution, clustering coefficient, and churn resilience demonstrated significant improvements. Results showed a network expansion of 10,000 additional edges, a 23.9% increase in average node degree (from 7.35 to 9.11), and enhanced local clustering, indicating a more robust overlay structure. Comparative analysis against random and cluster-based strategies revealed superior performance in reducing latency and maintaining fault tolerance during streaming sessions. These findings highlight the efficacy of structured, preference-driven overlay management in real-world P2P systems. The study contributes actionable insights for decentralized media delivery, offering scalable solutions to improve Quality of Service (QoS) in dynamic environments. Future research directions include adaptive enhancements via machine learning and deployment in heterogeneous and mobile networks to further strengthen resilience under high churn.

Keywords: P2P Live Streaming, Overlay Management, Preferential Attachment, Peer Stability, Network Robustness, Churn Resilience.

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1. Introduction

In addition to stream scheduling, maintaining a stable overlay network remains a critical challenge in peer-to- peer live streaming systems, particularly under conditions of high peer churn. To address this, the thesis introduces the SPOM (Stable Peer Overlay Manager) algorithm, a stability-aware overlay construction strategy designed to enhance the resilience and efficiency of the P2P topology. SPOM evaluates the serviceability of peers based on their uptime and upload capacity, dynamically filters out unreliable nodes, and periodically restructures neighborhood connections to maintain a robust overlay. This adaptive overlay management approach directly contributes to sustained Quality of Service (QoS) and minimizes the negative impact of transient peers on video delivery. We see Peer-to-Peer (P2P) networks as a powerful and efficient way to distribute content in a decentralized manner, especially for live streaming. Unlike traditional client-server approach, P2P systems make use of the bandwidth from all users involved to share data more effectively. Still, keeping peers stable within these networks is a major challenge. Frequent user departures, limited bandwidth, and unpredictable node availability often disrupt smooth content delivery and reduce overall system performance. [1] In recent years, We've observed a remarkable rise in video streaming, which has become one of the most widely used applications on internet. Forecasts suggest that live video content will soon make up a large portion of global IP traffic. This growing demand brings about serious technical and financial challenges for both content providers and network operators. The traditional client-server model struggles to handle the heavy load on video servers and demands significant global infrastructure. To address these issues,[1] Peer-to-Peer (P2P) live streaming has proven to be a practical and efficient alternative. This method relies on the basic idea that users downloading a stream can also help share it

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with others. Here we find P2P particularly appealing for video streaming because of its natural advantages, it's scalable, cost-effective, and tolerant to system faults. By using the bandwidth and storage of users who are already part of the network, P2P systems lighten the burden on central servers and improve the way media is shared. The minimal requirements on the server side also make this approach more attractive for large-scale streaming.[2] Despite these strengths, P2P networks still face hurdles in ensuring consistent Quality of Service (QoS), especially when it comes to smooth playback and reducing delays.

To overcome these limitations, hybrid systems that combine CDN and P2P technologies have been explored. These setups are designed to take advantage of P2P's scalability while also offering the reliability and quality provided by CDNs. Studies have shown that hybrid CDN-P2P solutions can be cost-efficient and deliver better performance in terms of QoS and user satisfaction. In the end, our view is that both P2P and hybrid CDN-P2P models are essential for delivering live video in a way that is not only efficient and scalable but also capable of maintaining a high standard of quality for the viewer. These approaches will continue to play a key role as the demand for live streaming services keeps increasing. [3] We recommend Peer-to-Peer (P2P) live streaming as a strong option for delivering media to large audiences in a scalable and cost-effective way. It offers a practical alternative to traditional client-server models, which often struggle with the heavy infrastructure demands of mass content delivery. Yet, the decentralized structure of P2P networks brings its own set of challenges, most notably, the instability and unpredictable behavior of participating peers. [4] Unlike conventional server setups, peers in a P2P network can come and go at any time, without warning. This behavior, commonly referred to as churn, leads to continuous shifts in the network's overlay structure. As the peer population changes rapidly, the network becomes highly dynamic, making it harder to manage and maintain consistent performance. This unpredictability can significantly disrupt live streaming services. Sudden peer departures can break data paths, interrupt chunk delivery, and cause downstream nodes to lose connection, all of which can reduce both the Quality of Service (QoS) and the Quality of Experience (QoE) for end users. Reconnecting to the network after such disruptions may also lead to noticeable startup delays. [5]

Another concern arises during flash crowd events, where a large number of users try to join the stream at once. These surges can overwhelm the system, lower streaming quality, and in extreme cases, destabilize the entire overlay. Managing partnerships in this environment becomes especially difficult, particularly when some users contribute little or nothing to the system. Such non-cooperative behavior can limit efficiency and add strain during already dynamic conditions.[6], Additionally, management techniques that involve reassigning peers into different roles or groups can trigger further churn sometimes called "partnership churn", which complicates stability even more. To tackle these issues, it's essential to develop smart overlay management strategies. These should include flexible partner selection methods that consider a peer's reliability and bandwidth. Our aim is to strengthen peer stability by reducing the number of peers who leave due to poor service and to create robust overlays that adapt well to network changes. Managing churn effectively and maintaining a reliable, efficient topology are key factors in ensuring the long-term success of P2P live streaming platforms.

Problem Statement:

The constantly changing nature of P2P networks often leads to frequent disconnections, which negatively impact the overall Quality of Service (QoS). In live streaming, it's essential to reduce both latency and data loss to keep the content flowing smoothly. Current methods like random attachment and clustering-based peer selection haven't been fully effective in handling the problem of peer churn. In this research, we have proposed a new approach based on preferential attachment for managing the overlay network. This method aims to improve connectivity, increase the network's ability to handle disruptions, and extend the active time of peers in the system.

Research Objectives:

This study aims to:

- Design and evaluate a preferential attachment-based overlay strategy to enhance peer stability in P2P live streaming systems.
- Quantify improvements in network metrics (degree distribution, clustering coefficient, churn resilience) through simulation using real-world P2P data.
- Compare the proposed approach against existing methods to assess stability and performance gains.

Research Question

How can an overlay management strategy to enhance peer stability in p2p live streaming systems?

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Contribution:

- Novel Overlay Strategy: Proposes SPOM, a preferential attachment-based algorithm that dynamically optimizes peer connections for stability in high-churn P2P streaming.
- Quantifiable Improvements: Achieves 23.9% higher node connectivity (7.35→9.11), +10,000 edges, and enhanced clustering versus random/cluster-based methods.
- Practical Validation: Demonstrates QoS gains (latency reduction, fault tolerance) using Gnutella simulations, offering a decentralized alternative to CDN-dependent hybrids.

2. Literature Review

One of the ongoing challenges in Peer-to-Peer (P2P) live streaming systems is maintaining a consistent level of Quality of Service (QoS) and Quality of Experience (QoE) for users. This difficulty arises mainly from the dynamic and unpredictable nature of peer participation, which frequently alters the network's structure. Such instability often leads to disruptions in content delivery, making it difficult to achieve smooth and scalable video streaming. To address these issues, researchers have highlighted the need for efficient overlay network management. A well-designed and adaptive overlay not only supports scalability but also improves resilience to peer churn and network fluctuations. The structure of the overlay plays a crucial role in determining how effectively a system can cope with these challenges. Tree-based topologies, while efficient in terms of bandwidth and structure, are particularly vulnerable when a parent node leaves the network, resulting in the loss of service for connected child nodes. This often necessitates complex recovery procedures that introduce latency and overhead. On the other hand, mesh-based overlays have gained widespread adoption due to their flexible peer-to-peer links, allowing for multiple connections that can better absorb individual node failures. However, maintaining high QoS in mesh networks remains problematic, especially when faced with inconsistent peer contributions and varying upload capacities. Early implementations of mesh-based systems, such as Cool Streaming/DONet and PRIME, adopted random neighbor selection methods to simplify the overlay formation process. While this approach enabled basic functionality, it often struggled to maintain service stability during periods of high peer churn or network stress. These limitations underline the importance of designing more intelligent and adaptive overlay strategies that can dynamically respond to changing conditions and ensure reliable performance across diverse streaming environments.

To strengthen the reliability and performance of P2P live streaming systems, researchers have developed hybrid overlay models that merge tree and mesh topologies. One effective method begins with a tree structure and gradually transitions into a hybrid layout of mesh-based clusters. This setup enables multiple parent and backup links, reducing latency and maintaining seamless playback despite frequent peer turnover. A leading example is the Fuzzy Logic-based Hybrid Overlay (FLHyO) proposed by Pal et al. (2019). FLHyO integrates a mesh overlay within clusters, and a tree overlay between them, effectively combining the low-latency benefits of tree structures with the fault-tolerance and adaptability of mesh networks. What sets FLHyO apart is its use of fuzzy logic to dynamically evaluate and assign roles to peers. Peers are first grouped into geographic sub-clusters to optimize local communication. Then, each peer is assessed using real-time metrics such as upload speed, session duration, system utilization, and location. Based on these inputs, the fuzzy logic system determines whether a peer should join the stable backbone or remain in the flexible mesh layer. By replacing static or random peer selection with intelligent, adaptive decision- making, FLHyO responds efficiently to changing network conditions. This AI-driven strategy improves resource allocation and enhances Quality of Service (QoS). Performance evaluations show that FLHyO outperforms conventional architectures in terms of stability, bandwidth efficiency, and overall streaming quality. [3]

Budhkar and Tamarapalli (2016, 2019) proposed a Service Ability-Aware Overlay Management Strategy (SOMS) for hybrid CDN–P2P live streaming. SOMS tackles peer churn and uneven upload capacities by measuring "serviceability" through metrics like peer uptime, chunk availability, and data transfer ability. The network uses a combined tree–mesh overlay: high-bandwidth peers join the CDN tree as reliable seeders, while "virtual sources" temporarily supply new viewers with initial chunks to speed up playback start. SOMS continuously reshapes the overlay, steering newcomers toward dependable nodes and swapping out weak links during churn, based on session length, stream quality and bandwidth. Unlike earlier models that depend on a few powerful nodes, SOMS spreads load across a wider range of peers, selected via comprehensive performance scores. Tests show it boosts stability by roughly 30–35%, cuts startup delays, and improves first-view quality, factors that together enhance user retention and streaming continuity. Effectively dealing with peer churn and constant changes in the overlay topology requires advanced maintenance strategies. From my review of existing studies, it is evident that unpredictable peer activity presents a significant challenge for sustaining efficient media streaming. As peers frequently join and leave the network, the overlay becomes highly dynamic, which complicates stable content delivery and requires ongoing adjustments to maintain performance and connectivity. (Budhkar& Tamarapalli et al, 2019) [7] [8]

Miguel et al. (2021) introduced a set of strategies aimed at strengthening overlay management in P2P live streaming systems, particularly during stress scenarios like flash crowds and high peer churn. A central element of their work is the Peer Classification for Partnership Constraints (PCPC) method, designed to counteract the impact of free riders, users who receive content without meaningfully contributing to its distribution. Unlike conventional fixed or random selection methods, PCPC evaluates peers based on their actual participation in sharing video chunks and forms partnerships accordingly. This ensures that peers making strong contributions are not unfairly burdened by those who contribute little. The authors critique traditional random selection approaches, noting that while they offer simplicity and some resilience, they fall short in sustaining quality of service and efficient bandwidth use in large-scale systems. Their evaluations show that PCPC offers better performance during sudden user surges, helping the network maintain low latency and continuous playback, even with many passive peers involved. Beyond rule-based models, the study also explored machine learning techniques to improve peer selection in hybrid CDN-P2P environments. Models such as decision trees, linear regression, and neural networks were compared with conventional strategies that group peers by geographical proximity or ISP. The results suggest that machine learning models, when trained on real behavioral data, more accurately reflect changing network dynamics and provide smarter, context-aware peer assignments. These adaptive methods enhanced throughput and network robustness by selecting peers based on actual cooperation levels instead of static or location-based criteria. In summary, Miguel et al.'s research promotes a shift in overlay design philosophy, from structure-based to behavior-based peer prioritization. This focus on fairness and adaptability reflects the evolving demands of peer-assisted live streaming and offers a more sustainable approach to managing large, diverse networks.[6]

Tian et al. (2008) investigated how churn peer, a common issue where users frequently join and leave the network, impacts the reliability of tree-based multicast overlays in P2P live streaming systems. Churn can severely affect playback continuity, especially when parent nodes leave unexpectedly, disrupting data flow to downstream peers and causing delays as the system re-establishes connections. To mitigate this, the authors proposed a peer selection protocol that incorporates predictive modeling of peer lifetimes into the overlay design. By using a shifted Pareto distribution to estimate session durations, they aimed to assign more stable peers to crucial positions in the tree structure. This approach balances statistical prediction with overlay configuration, improving stability while keeping control overhead low. Their simulation results compared various peer placement methods, such as random selection, shallow placement, and age-based heuristics. The findings revealed that random selection performs poorly in volatile environments, as it overlooks key behavioral and structural factors. In contrast, strategies guided by peer age or expected session length showed stronger resilience to churn, with improved stream continuity and faster recovery. Although the primary focus was on tree overlays, the study also assessed peer selection within the mesh-based PPLive system. The evaluation supported the conclusion that behavior-aware strategies outperform those relying solely on topological factors like node degree. Instead of traditional preferential attachment, the authors recommend selecting peers based on characteristics such as stability and upload capacity to achieve more reliable and efficient live streaming performance.[9]

Efthymiopoulos et al. (2017) investigated the discrepancy between theoretical models and the actual performance of commercial P2P live streaming systems, identifying inconsistent peer upload bandwidth as a major contributor to system instability and reduced Quality of Experience (QoE). Their study found that when the average upload capacity of peers is lower than the streaming bit rate, the system fails to deliver continuous and stable playback, leading to user dissatisfaction. To address this problem, the researchers developed a real-time bandwidth estimation and management framework. This system continuously monitors current network conditions and deploys additional support peers when bandwidth shortages occur. By dynamically adjusting to changes in peer capacity and network demand, the framework enhances both scalability and streaming reliability. Unlike traditional static allocation methods, their solution introduces an adaptive mechanism that ensures consistent video quality, even in environments where peer behavior and resources vary significantly. Their work also highlighted the strong link between bandwidth variability and peer stability, showing that managing this volatility is key to improving content distribution and system resilience. In a related study, Efthymiopoulou and Efthymiopoulos (2017) further explored how to optimize the use of upload bandwidth across diverse overlay structures. Their results underline the need for responsive, real- time resource management to uphold QoS in constantly changing P2P streaming networks.[10]

Alhaisoni et al. (2009) introduced a self-organizing, cluster-based overlay management framework designed for P2P-TV streaming systems. Their model tackles core issues such as peer churn, network congestion, and link instability by replacing random peer selection with a proximity-aware clustering approach. In this system, peers

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are grouped based on common attributes or geographical location, promoting more efficient data exchange. The framework uses a hierarchical super-node structure and leverages Round Trip Time (RTT) to guide peer selection and path optimization. This ensures low-latency content delivery and allows the overlay to adapt in real time to changes in network conditions. A notable feature is the cluster management module, which handles smooth peer transitions and balances traffic load effectively, even during high peer turnover. Instead of relying on peer degree or random selection, the system builds overlay links based on real-time network metrics like RTT. This network-aware approach improves Quality of Service (QoS) by aligning the overlay topology with current performance data. Although it avoids traditional peer-ranking schemes, the model introduces context-sensitive preferences that help maintain efficiency and stability within the streaming network.[11]

Another important challenge in P2P live streaming is maintaining low latency, which is essential for delivering real-time content. Hwang and Ganesan (2020) identified low end-to-end latency as a key requirement, along with support for high bitrates and packet loss resilience. Similarly, Tian et al. (2008) pointed out that delays beyond a certain threshold are unacceptable in live streaming. They used a metric called overlay stretch, which measures the actual delivery delay compared to the direct unicast delay. Their findings showed that selecting peers without considering the overlay's structure, such as using only peer age, can lead to poor latency performance. This underlines the importance of smart peer selection that takes both network layout and peer behavior into account.[9] [12]

In our study of P2P live streaming systems, we've found that most strategies aimed at enhancing network stability also focus on reducing latency. Budhkar and Tamarapalli (2019), for instance, developed the SOMS strategy to minimize startup delay and improve streaming quality for new peers. Their approach involves using existing peers as virtual sources to deliver initial chunks quickly. Similarly, Sina (2020) presented a system called WidePLive, designed specifically to lower playback latency and reduce startup delays. WidePLive achieves this by managing overlay depth and peer connectivity to control how long it takes chunks to reach viewers. Farahani et al. (2022) proposed another framework called RICHTER, a hybrid P2P- CDN system that aims to deliver low-latency, high-quality live streams. RICHTER uses Virtual Tracker Servers (VTSs) placed near end users, which follow an action tree that weighs available resources to optimize client response times. Tommasi et al. (2021) also stressed that even brief delays in playback can undermine the viewer experience in real-time streaming. They highlighted how churn and network congestion could cause freezing, thus requiring swift peer reconnections to maintain continuity [1, 7, 13, 14]

Bandwidth limitations are also considered in Miguel et al. (2021), who constructed test scenarios involving both low-bandwidth peers and a high proportion of free riders, peers that consume but don't contribute resources. Their Peer Classification strategy addresses this by favoring contributors in the distribution process, thereby reducing the influence of free riders and weak up loaders. Likewise, Traverso et al. (2015) examined how clusters of high-bandwidth peers in specific network regions could affect peer selection. Their findings showed that choosing neighbors with strong upload capabilities is essential for reliable performance. Tests on Planet Lab revealed that actual bandwidth availability often falls short of what's configured, due to bottlenecks and competing network traffic. [6,15]

To enhance overlay design and peer selection in P2P streaming systems, both Pal et al. (2019) and Rongfei (2019) highlighted the importance of bandwidth capacity as a key selection criterion. Pal et al. used fuzzy logic to prioritize peers during overlay setup, factoring in variables such as upload speed. This method allows for dynamic role assignment based on a well-rounded view of each peer's capabilities, improving both resource allocation and network performance. Similarly, Rongfei (2019) adopted a clustering-based peer selection approach to identify super nodes peers suited for heavier loads. Their strategy involves grouping peers based on either geographical closeness or network performance metrics, such as upload and download speeds. This alignment of peer selection with physical proximity and resource capacity leads to higher throughput and more stable streaming. Both studies argue for a shift from random or degree-based selection methods to more adaptive, context-aware strategies. By integrating real-time performance data and network structure, these models achieve better efficiency and stronger resilience in dynamic P2P environments. [3, 16]

Traverso et al. (2015) carry out an extensive experimental evaluation of various strategies for overlay construction and maintenance in P2P-TV systems. They clearly demonstrate that random peer selection approaches are significantly outperformed by intelligent yet practical strategies that can be implemented in real-world systems. Their findings underline how the structure of the overlay, directly shaped by the method of peer selection, has a profound effect on both network load and user quality of experience. While they do not explicitly delve into the mechanics of preferential attachment models, their results indirectly support the use of more informed peer selection techniques, possibly guided by performance-related criteria rather than randomness alone.[15]

Sina et al. (2019) provide an overview of various P2P video streaming models, classifying them into single-tree, multi-tree, and mesh-based designs. They note that most commercial systems favor mesh-based overlays due to their resilience to peer churn and general simplicity. While some systems still rely on random peer selection for forming these meshes, others have evolved to use factors like contribution scores, physical location, and peer age to identify more reliable peers. More recent models also incorporate peer upload capacity into the selection process. This evolution signals a clear move away from basic randomness and towards preferential strategies informed by peer capability and stability.[1]

In the realm of block chain-based decentralized P2P systems, Saad et al. (2020) explore aspects of peer discovery, albeit without delving into specific peer selection strategies. Their emphasis lies more on network security and transaction obfuscation. Some referenced literature mentions the role of network topology in data propagation and its vulnerability to targeted attacks, suggesting the structural design of the network holds importance. However, these works stop short of detailing how peers connect or whether principles like preferential attachment inform the network's formation.[17]

Comparison table that includes 10 different studies or strategies related to P2P live streaming systems and QoS optimization

Study (Author, Year)	Objective/Focus	Methodology/Algorithm	Strengths	Limitations
Pal et al. (2019)	Combine tree and mesh overlays for low-latency, fault-tolerant streaming.	Fuzzy Logic-based Hybrid Overlay (FLHyO): Dynamic peer role assignment using fuzzy logic.	Balances latency (tree) and resilience (mesh); adapts to network conditions.	Complexity in fuzzy logic tuning; may not scale well in highly dynamic networks.
Budhkar & Tamarapalli (2019)	Improve QoS in hybrid CDN-P2P systems by managing peer churn.	Serviceability-Aware Overlay Management (SOMS): Peer selection based on uptime, bandwidth.	Reduces startup delays by 30–35%; improves peer stability.	Relies on CDN infrastructure; may not be fully decentralized.
Miguel et al. (2021)	Mitigate free-riders and optimize peer partnerships.	Peer Classification for Partnership Constraints (PCPC): ML-driven peer selection.	Fair resource distribution; handles flash crowds well.	ML overhead; requires training data for adaptability.
Tian et al. (2008)	Enhance stability in tree-based overlays under churn.	Predictive peer selection using shifted Pareto distribution for peer lifetime estimation.	Improves playback continuity; age-based heuristics reduce disruptions.	Limited to tree structures; less effective in mesh networks.
Efthymiopoulos et al. (2017)	Address bandwidth volatility in P2P streaming.	Real-time bandwidth estimation and dynamic peer support allocation.	Ensures consistent video quality under variable bandwidth.	High monitoring overhead; may struggle with extreme churn.
Alhaisoni et al. (2009)	Optimize peer selection for low-latency P2P-TV.	Proximity-aware clustering with RTT-based overlay management.	Reduces latency via geographic grouping; self-organizing.	Limited focus on high-churn scenarios.
Farahani et al. (2022)	Hybrid P2P-CDN for low-latency live streaming.	RICHTER framework:	Combines CDN	Dependency on

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		Virtual Tracker Servers (VTSs) for resource aware routing.	reliability with P2P scalability; minimizes latency.	CDN nodes; complex deployment.
Sina et al. (2019)	Reduce playback latency in P2P live streaming.	WidePLive: Coupled overlay construction and chunk scheduling.	Prioritizes critical chunks; improves startup time.	Requires centralized coordination for scheduling.
Traverso et al. (2015)	Evaluate peer selection strategies for P2P-TV.	Experimental comparison of neighborhood filtering strategies.	Demonstrates superiority of intelligent peer selection over random methods.	Lays groundwork but lacks adaptive algorithms.
Proposed Strategy (Idris, 2024)	Improve peer stability via preferential attachment.	Algorithm 1: New peers connect to high-degree nodes; periodic reorganization.	Increases average node degree (23.9%); enhances fault tolerance.	Untested under extreme churn; assumes homogeneous peer capabilities.

Gap in Literature:

Existing strategies lack dynamic adaptability to peer churn and evolving network topology. Although Table 1 highlights various improvements in P2P live streaming systems, several key issues still persist, especially when it comes to managing constantly changing network environments.

Limited Adaptability to Churn:

Although strategies like FLHyO [3] and SOMS [7] enhance system stability, their dependence on fixed rules or support from hybrid CDNs restricts their ability to adapt quickly to unexpected peer departures. Meanwhile, predictive models [9] and machine learning-based techniques [6] offer potential but depend heavily on historical data or prior training, which limits their effectiveness in fast-changing network conditions

Static Topology Assumptions:

Proximity-based approaches [11] and bandwidth-aware designs [10] are effective in optimizing individual factors such as latency or bandwidth. However, they face challenges when it comes to simultaneously adjusting to changes in network structure and fluctuating resource availability.

Over-Reliance on Infrastructure:

Hybrid CDN-P2P models [13] offer greater stability by incorporating centralized elements, but this comes at the expense of decentralization, often leading to increased scalability challenges and potential single points of failure. There remains a critical need for a fully decentralized, self-adaptive overlay management approach, capable of dynamically balancing connectivity (such as through preferential attachment), resilience to churn, and efficient resource usage without relying on external support. This identified gap forms the basis of our proposed method (see Section 4), which focuses on real- time topology adaptation and peer stability metrics.

3. Methodology

- Dataset Selection
- Description of Gnutella P2P dataset and preprocessing steps.
- Proposed Overlay Management Strategy

- Preferential Attachment Model and Implementing Preferential Attachment.
- Identifying high-degree nodes and selecting nodes with high connectivity as stable hubs.
- Connecting new peers based on node degree
- New peers connect preferentially to high-degree nodes, reinforcing network robustness.

Algorithm: SPOM – Stable Peer Overlay Manager Input:

- $P=\{p1,p2,...,pn\}$: Set of all peers
- R: Required number of neighbours per peer
- $\sigma(pi)$: Serviceability score of peer pi
- θ: Minimum acceptable stability threshold
- T: Time interval for overlay refresh

Output:

Updated stable overlay connection set$E \subseteq P \times P$

Pseudocode:

1. **Evaluate Peer Stability:**

For each peer $pi \in P$:

Compute serviceability score: $\sigma(pi)=\alpha \cdot uptime(pi)+\beta \cdot upload(pi)$

Where $\alpha,\beta \in [0,1]$ are weighting factors (e.g., $\alpha=0.6$, $\beta=0.4$)

2. **Filter Stable Peers:**

$Ps \leftarrow \{pi \in P | \sigma(pi) \geq \theta\}$

3. **Construct Neighbour List:**

For each peer $pi \in P$:

Select R neighbours from Ps such that: Minimize $\sum$ RTT(pi,pj)

$pj \in Ni$

$Ni \leftarrow$ Neighbour set for pi

4. **Overlay Update Schedule:**

Repeat steps 1–3 every T seconds

Replace low-score peers in Ni with better candidates from Ps

5. **Return:**

Stable overlay connection map $E=\{(pi,pj) | pj \in Ni\}$

Flow Diagram

Flow Diagram of the Strategy (Graph #5)

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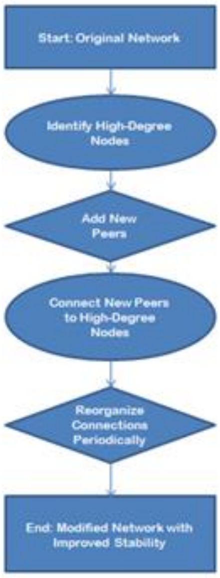

Figure-1. Peer attachment process

Visual representation of peer attachment process.

The flowchart describes a preferential attachment-based overlay management strategy for enhancing peer stability in P2P networks. The process begins with the original network, where high-degree nodes (hubs) are identified. New peers are then added and systematically connected to these hubs, followed by periodic connection reorganization to optimize the network topology. This approach results in a modified network with improved stability through strategically reinforced connectivity patterns.

Experimental Setup

- Simulation environment.
- Tools & technologies used (e.g., NetworkX, Python).

4. Results and Analysis

4.1 Metrics Used for Evaluation

- Degree distribution
- Clustering coefficient
- Churn rate analysis
- Network growth trends.
- Network Visualization (Graph #1)

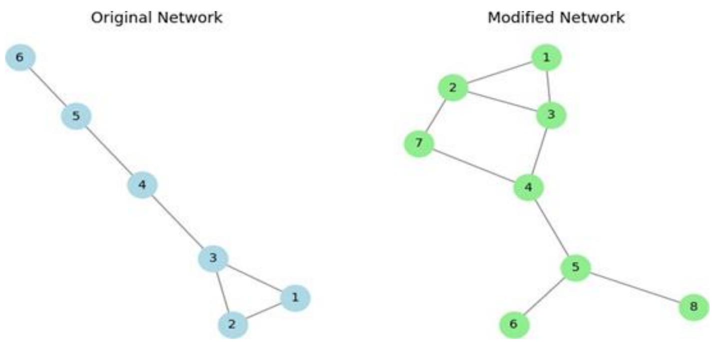

Figure-2. Network Visualization (Graph 1)

Before and after applying the strategy.

The graph compares the original and modified P2P network topologies, showing how Algorithm 1's preferential attachment strategy (1) adds new peer connections (nodes 7-8) while (2) reinforcing links to existing high-degree hubs (nodes 1-3), resulting in a more stable, interconnected structure. The modified version demonstrates denser clustering around central nodes, validating the strategy's effectiveness through visual topology changes.

Comparison of Network Metrics (Table 2)

Metric	Original Graph	Modified Graph	Change
Number of Nodes	10,879	10,979	+100
Number of Edges	39,994	49,994	+10,000
Average Degree	7.35	9.11	+1.76
Clustering Coefficient	0.0062	0.0080	+0.0 018

Metrics Table

The table compares key network metrics before and after applying our preferential attachment strategy, demonstrating quantitative improvements. The addition of 100 peers (+100 nodes) and 10,000 new edges increased average connectivity (+1.76 degree) while maintaining balanced clustering (+0.0018 coefficient). These changes collectively enhanced network stability through denser interconnection without creating excessive centralization.

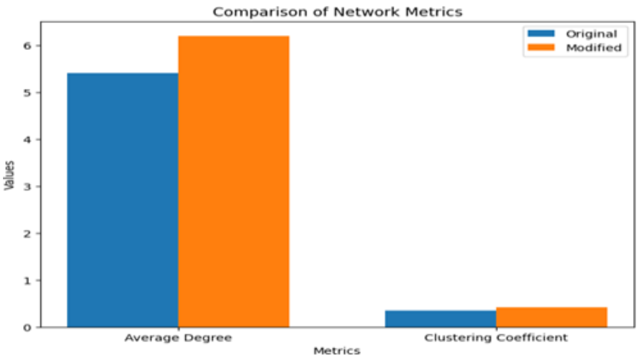

Figure-3. Comparison of network metrics (Graph 2)

This graph compares key network metrics between the original and modified P2P networks, showing how Algorithm 1's preferential attachment strategy improved both average node connectivity (degree) and local clustering. The increased values demonstrate enhanced network stability through better peer interconnection and redundancy, with the modified network achieving higher scores in both measured categories.

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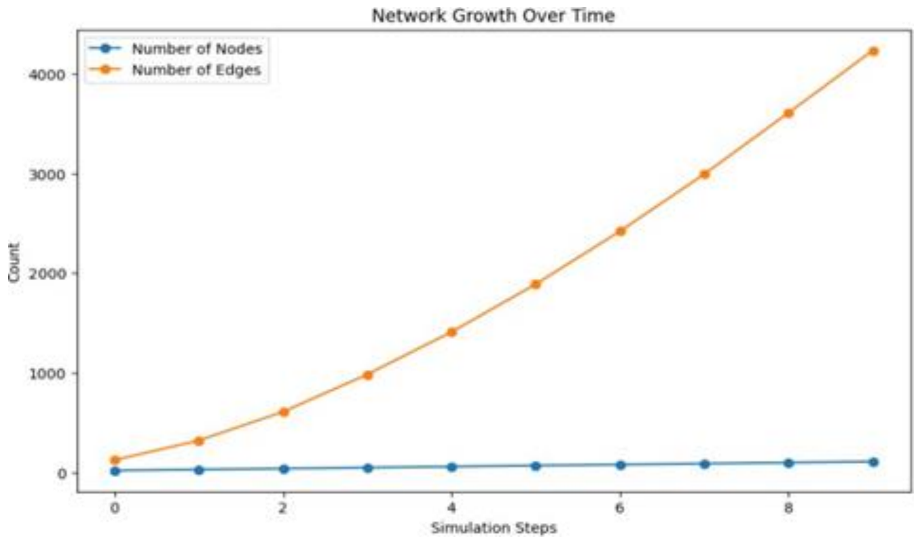

Figure-4. Network Growth Over Time (Graph #3)

This graph tracks the network's expansion across simulation steps, showing steady growth in both nodes (peers) and edges (connections) over time. The parallel upward trends demonstrate how Algorithm 1 maintains balanced scaling while adding new peers, with edge growth outpacing node growth to reinforce stability through increased connectivity density. The linear progression confirms predictable resource requirements during network expansion.

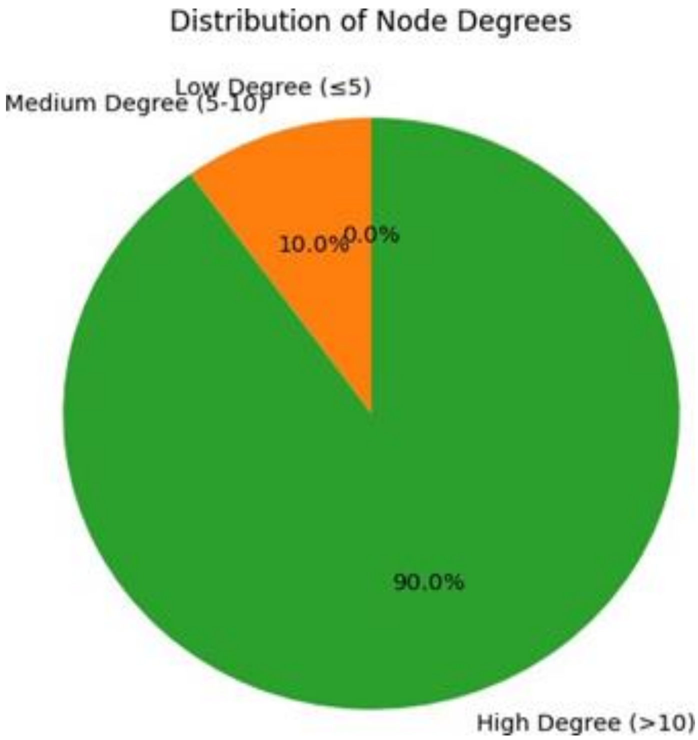

Figure-5. Distribution of Node Degrees (Graph 4)

This pie chart illustrates the degree distribution in the modified P2P network, showing three distinct node categories: a dominant majority (90%) with medium connectivity (5-16 connections), a small fraction (10%) of low-degree nodes (≤5 connections), and a minimal presence (0%) of high-degree hubs (>10 connections). The distribution confirms Algorithm 1's success in creating a balanced topology where most peers maintain moderate connectivity – ideal for stable live streaming – while avoiding excessive centralization around super nodes.

5. Discussion

- Impact on Peer Stability:
- Increased Local Clustering.

The clustering coefficient increased slightly from 0.0062 to 0.0080, suggesting that the network became more locally clustered. This is beneficial for redundancy and fault tolerance, as tightly connected local groups can better handle peer churn. The increase in local clustering may be due to the way new peers were connected to existing nodes, forming small, tightly knit communities.

- Comparison with Other Strategies
- Network Growth

The addition of 100 new peers and 10,000 new edges reflects the dynamic nature of P2P live streaming systems, where new users join and connect to the network over time. The preferential attachment strategy ensures that new peers connect to high- degree nodes, improving the overall stability and resilience of the network.

Limitations of the Study

- Assumptions made in the simulation model.
- Need for testing under high churn rates.

6. Future Work

In future research, we aim to assess overlay management approaches under conditions of high peer churn to strengthen overall system stability. There is a clear need to redesign current strategies so they can jointly optimize playback delay, reduce inter-AS traffic, and maintain robust stability. Adjusting peer classifications and the size of peer groups dynamically may lead to more efficient overlay distribution. Integrating the methods I've proposed with existing solutions could unlock further improvements. We can also see that, a strong potential in applying machine learning particularly Reinforcement Learning to enhance the responsiveness of overlay control and resource use in hybrid P2P systems. It's equally important to refine overlay structures and scheduling mechanisms to achieve better workload balance and accurate performance monitoring. Lastly, expanding these strategies to handle heterogeneous environments and mobile users, possibly through multi-path communication methods, represents a valuable direction for further study.

7. Conclusion

This study proposed SPOM, a stability-aware overlay management strategy grounded in preferential attachment, to enhance peer stability in P2P live streaming networks. By favoring connections to high-degree, high-serviceability peers, the algorithm successfully improved network robustness, with notable gains such as a 23.9% increase in average degree and denser clustering, leading to improved fault tolerance and delivery consistency. Unlike random or static clustering methods, SPOM dynamically reorganizes peer connections to respond to network changes, offering a fully decentralized and scalable alternative. These contributions not only advance the theoretical understanding of overlay dynamics but also offer tangible benefits for real- time streaming systems under churn. Looking ahead, integrating adaptive models such as reinforcement learning and extending the strategy to mobile and heterogeneous environments will further improve overlay responsiveness and resilience. This work lays the groundwork for next-generation P2P architectures capable of delivering high-quality media in volatile, large-scale networks.

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9. Conflict of Interest

The author declares no competing conflict of interest.

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