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Improved Hybrid Architecture to Mitigate Free Riding in P2p Network

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Abstract: Peer-to-peer (P2P) networks rely heavily on resources shared by peers in the network as a result of this mitigating free riding in the network is very crucial in a P2P system. In this work, we introduced a dynamic grace period allocation and a content scanning mechanism to a hybrid P2P architecture to mitigate free riding and prevent peers from uploading repeated and fake files within the network. The method introduced was simulated using Python programming language with peers selected at random to upload and download files representing a typical scenario of a P2P network. From the range of 0-500 and 600-2000, twenty different peers were selected at random the first scenario represents few peers and the second scenario represents many peers for analysis and experimentation purposes and also for the different percentages of free riders used for the experiment, this was chosen at random. Finally, we compared our method with a credit-based approach (CBA) that uses a common grace period assigned to peers in the network. Then, for the performance evaluation metric, we used the total uploads and downloads, contributing peers uploads and downloads, free rider peers uploads and downloads, and repeated and fake files detected gotten from the simulation result to evaluate the model and analyze the outcome of the experiments. Results from the simulation revealed that the Dynamic grace period approach (DGA) is 25-70% more effective than CBA in maintaining contributing peer activity and preventing the spread of repeated and fake files,while also achieving *lower latency*, *higher throughput*, and *better quality of service (QoS)* across diverse network conditions, particularly in high free-rider environments.

Index Terms: Free-riding, Peer-to-Peer Network, Dynamic Grace Period, Content Scanning Mechanism, Hybrid Architecture

1. Introduction

A peer-to-peer (P2P) network is a system in which peers, or nodes, are directly connected and can operate as either clients or servers of different resources. A centralized network, in contrast to the more conventional method, is made up of one or more servers that serve clients. P2P, networks have greater scalability and dependability than centralized networks [1]. Since Napster was developed in 1999, the P2P model has become progressively famous in content-sharing cache storage for the web, and storage of contents [2] and since then, P2P networks have over the years gained popular

attention as the need for efficient sharing of files among various users over a network continues to grow. File exchange between computer users at the edge of the internet is facilitated via P2P file-sharing networks. Users don't need to transfer files using these strategies to know or meet one another [1]. According to the statistics, [3] recorded that 7% of peers contributed more files than other peers in file-sharing networks in Gnutella 0.6, and 25% of peers provided roughly 99% of the resources in Gnutella. 25% of peers supplied 99% of all query hits in the network, while the remaining 70% of peers shared no files at all. Free riding weakens the resilience and efficacy of P2P systems and exacerbates network congestion, which causes instability in the system.

Free riding refers to the behavior of peers in a P2P network who consume resources (e.g., download files) without contributing back to the network (e.g., uploading files). This behavior undermines the fairness and efficiency of the network, as it leads to resource imbalance and congestion. The primary research problem addressed in this paper is how to mitigate free riding while maintaining network performance and fairness. Free riding is often driven by economic incentives, as peers seek to maximize their own utility while minimizing their contribution to the network. The proposed system addresses this by dynamically adjusting grace periods based on peer behavior, ensuring that contributors are rewarded and free riders are penalized. The primary research question addressed in this paper is: How can a dynamic grace period and content scanning mechanism be effectively integrated into a hybrid P2P architecture to mitigate free riding and improve network fairness and performance?

[1] introduced a solution for fair P2P content delivery, ensuring that deliverers are rewarded proportionally for their contributions. It uses blockchain to enforce fairness and protect against adversarial peers. The proposed protocols, FairDownload and FairStream, are designed for efficient downloading and streaming in decentralized settings. The practicality of these protocols is demonstrated through experiments on the Ethereum Ropsten network. According to [35], there have been advancements in Web3 networks, focusing on a solution to data sharing challenges across partitioned networks through a reputation-based auditing mechanism called the Timely Sharing with Reputation Prototype (TSRP), which ensures efficient and integrity-maintained data distribution by leveraging nodes' reputations. [20] address the free rider problem in P2P networks within distributed clouds, proposing a solution called KeyPIn, which is a Key-based, Participation-based, and Incentive-based scheme. Using a game theory approach, KeyPIn encourages resource providers to participate and limits access for free riders. Simulation results demonstrate the effectiveness of KeyPIn in reducing the impact of free riders on the network. [6] introduce solutions for fair P2P content delivery, ensuring that deliverers are rewarded proportionally for their contributions. It uses blockchain to enforce delivery fairness and protect against adversarial peers. [17] propose an efficient protocol for downloading and streaming, optimizing on-chain costs and communication, and detailing the practical implementation of prototype systems on the Ethereum Ropsten network, demonstrating their practicality. [34] introduce a dynamic smart network coding (DSNC) scheme to cluster content and perform coding operations within each group, reducing duplicate data transmission and improving efficiency. The system enhances P2P content distribution by optimizing resource utilization, reliability, and resilience against peer churn. Simulation results show that DSNC achieves 20–25% higher throughput than existing systems, with better reliability and robustness. Future research is suggested to optimize the system under network congestion and improve group formation and super-peer selection. [30] introduced a mechanism for collaborative peers to share resources, ensuring satisfaction and fairness while isolating non-collaborative peers. It enhances the Network of Favors concept to balance resource provision and consumption, promoting cooperation and preventing free riding. A new scheme, Fairness-Driven Network of Favors (FD-NoF), features a feedback control loop to maintain fairness without significantly affecting satisfaction. Simulation results show that FD-NoF achieves desired fairness levels in low resource contention scenarios and performs comparably to Satisfaction-Driven NoF in higher contention scenarios.

Many incentive schemes have been suggested and put in place, such as reputation systems, tit-for-tat, and credit-based strategies. A reputation-based system or scheme can help a user identify problematic peers by monitoring neighbours during data transmissions and spreading the reputation of the uncooperative peer throughout the network. Tit-for-Tat initiatives promote cooperation amongst mobile users by exchanging comparable services based on each person's good behaviour. Every user receives back from its neighbours the same amount of service that it has provided based on its previous behaviour. Credit-based techniques give users who cooperate a fixed amount of virtual currency or credit as a reward. Because these tactics make use of both explicit and flexible incentive systems, they might be the most promising [4]. As P2P architecture has its advantages one of it persistent challenges is the issue that has to do with a peer benefiting from the system and not readily wanting to be actively involved in the activity of the system by contributing back to the system through uploading of files or content which is known as free riding. This research works aims to proffer solution to solving this problem by introducing a novel approach of assigning grace periods dynamically to mitigate free riding behaviours in the network for file uploads based on the popularity of downloads made by peers in the network and a content scanning mechanism to stop peers from uploading repeated files and fake files.

The paper's structure is outlined as follows: Section 2 provides a comprehensive review of previous studies, serving as the Literature Review. Section 3 delves into the Proposed work. The findings and analysis are detailed in Section 4, and the concluding remarks are presented in the final Section 5.

2. Literature Review

The issue of peers cooperating with each other in order to discourage free riding as over the years been a topic that has gained a lot of attention in peer-to-peer networks and it still a significant study till today [1]. For this issue to be totally discouraged to a minimal level, there is need for continuous development of effective and efficient mechanism to tackle free riding in P2P networks particularly in a hybrid P2P which by evidence from previous research works has shown to be better in terms of performance and stability than other architecture of P2P networks. [36] during his study supported this claim by highlighting that hybrid P2P systems brings about the formation of more than one way indexing mechanism to help in multidimensional data searching. Over the years, researchers have tried to reduce free riding by implementing incentive mechanism as a major component to the already existing architecture for P2P networks to motivate cooperation and participation among peer in the network and this can be grouped into three main approach which are: monetary based incentive, reputation-based incentive and services-based incentive which can be applied in various P2P architectures like structured, unstructured and hybrid [38]. However, according to [5] P2P system free riding behaviour can be classified into two main categories which are: Reputation based approaches and Economy-based approaches. The Economy-based approach can also be further sub-divided into three categories which are: monetary based approaches, reciprocity-based approaches and credit or (points)-based approaches. In this section, we present an overview of used mechanism to mitigate free riding in p2p network.

2.1 An Overview of Used Mechanism to Mitigate Free Riding in P2p Network

Free-riders are peers who attempt to consume shared assets in distributed networks without offering anything as a trade-off by taking advantage of shortcomings in the protocols [6]. This section provides an overview of various approaches used to mitigate free-riding in P2P Networks. Several research works were compared and evaluated to arrive at the approaches outlined in this review. For each study, we consider several key criteria which are: understanding each study's approach to tackling free-riding, the trustworthiness of each approach in fostering peer trust, the degree of decentralization to distribute decision-making, resistance to various attacks, the effectiveness of incentive mechanisms, scalability, complexity and overhead in implementation, robustness in the face of failures, and transparency in operation. These criteria help in comprehensively assessing the strengths, weaknesses, and innovations of the proposed solutions, offering insights into their applicability and effectiveness in real-world P2P network scenarios. The reputation-based Approach was chosen due to its effectiveness in fostering trust among peers by relying on peer ratings, promoting decentralized decision-making, and providing incentive mechanisms. However, concerns about centralization and vulnerability to attacks like whitewashing and collusion highlight the need for careful implementation. The reciprocity-Based Approach was also selected for its similarity to a trade-by-barter system, where peers exchange resources based on contribution levels, this approach emphasizes direct and indirect experiences among peers. However, it requires frequent interactions and is susceptible to deception by malicious peers. The credit/Monetary-Based Approach was also chosen for its effectiveness in incentivizing peer contributions through tangible rewards or virtual currency, this approach relies on strong central authority for monitoring transactions. However, it necessitates robust accounting systems and carries risks associated with centralization. The game-theory Approach was selected for its ability to model strategic interactions among peers accurately, this approach is suitable for environments requiring strategic decision-making. However, its complexity in implementation and analysis poses challenges the blockchain-based Approach was chosen for its capability in ensuring security and transparency, particularly in decentralized systems requiring tamper-resistant records. Despite facing scalability challenges, blockchain offers robust protection of privacy and transparent transaction records. Below are review of various approaches used to mitigating free riding in P2P Networks.

2.1.1 Reputation Based Approach

A reputation-based – approach judges a peer based on the information provided by other peers to foster trust among the peers in the network. The goal of this approach is to make sure that each peer can trust the system because it completely relies on how peers rate themselves in the system.[5].

[6] introduced a decentralized reputation system for P2P-networks through the implementation blockchain technology to help satisfy demand, as it increases peer contributions and free-riding. To make them fair [37] explored the improvements in fairness of decentralized storage networks by considering bandwidth incentives through simulation and obtained a more equitable distribution of rewards among peers. [7] from a game theoretical perspective, proposes a system that uses a reputation-based approach to allocate resources in P2P system. The study uses a game theory to analyse a way of distributing resources through games that does not involves cooperation which are demand game and reputation game. This method makes sure that peers want are as a result of their shared capacity. Awasthi and [32] proposes a Simplified Biased Contribution Index (SBCI**)** as an incentive mechanism to balance resource sharing in peer-to-peer (P2P) networks. The SBCI aims to address issues like free-riding and unfair resource distribution by motivating peers to share resources fairly. Unlike previous methods, SBCI does not require iterative calculations or strict clock synchronization, making it more efficient and easier to implement. [25] proposes an incentive-based security model for Peer-to-Peer (P2P) networks to ensure fairness. The model aims to: Encourage contributions from users by

providing a fair infrastructure. Prevent freeloading by making leechers contribute as much as they download. Protect seeders by reducing their workload and ensuring they are treated fairly. Secure communication using cryptographic methods like RSA to prevent spying.

2.1.2 Reciprocity – Based Approach

A reciprocity-based approach can be likened to a trade-by-barter system, which has to do with two peers exchanging resources based on their activities and contribution levels to each other [9]. According to [5], a reputation-based system has to do with the services of peers based on their level of contribution, which can be seen as a barter system. The reciprocity can either be direct or indirect, where peers take into consideration interactions of all peers collectively. The disadvantage of this system is that it requires frequent interactions between each peer of pairs while the latter peer can be deceived by malicious peers and a practical application of this approach can be seen in BitTorrent using tit-for-tat strategy.

[10] in his work, utilizes a sharing idea that is ratio based for distributing resources in P2P networks and sharing files are done using BitTorrent protocol. One of the strengths of this study is that it not susceptible to sybil attack and gangs up attack by group peers as it was introduced majorly to foster cooperation amidst peers, bring about fairness to downloaders and prevent free riders and whitewashing attacks. [5] bring about an idea that is inspired by a Market setting to curb free-riding behaviour a P2P network fog computing to be precise. in his study proposed the AFMIA that takes into consideration resources as goods that have varied worth based on the extent of demand and supply. [26] presented a KeyPIn scheme combines Key-based**,** Participation-based**,** and Incentive-based mechanisms to encourage resource sharing and participation in the cloud. It uses game theory to create incentives for users to contribute resources, while limiting access for free riders. Simulation results demonstrate that the KeyPIn scheme effectively reduces the presence of free riders in the distributed cloud, ensuring more equitable resource distribution and improved overall system performance.

2.1.3 Credit – Based Approach / Monetary – Based Approach

According to [5] in a credit-based approach, peers get credit by providing services to other peers and give out credit by receiving services from other peers. [9] A monetary–based approach is also sometimes called a micropayment system, where peers are given a mandate to pay for the services they use and in turn, will be paid for the services they give out to other peers. This system makes use of virtual currency which is recorded for each peer in an accounting module and proper exchange of services, a single authority maintains transaction and ensures stability. According to [8] a monetary incentive mechanism is a system whereby peers are expected to pay for services that come to them while getting paid for services they give out and this approach involves the use of virtual currency such as PPay.

[8] developed a point-system where peers are encouraged to spend to earn points and those points can only be spent on leeching implying that contributing peers get better download speed while free-riders ones slow down. [9] proposed a credit-based model with free-riders and termed this group condition as Grace period assigning those peers who do not submit computing resources within the deadline. [28] tackles the issue of selfish peers in peer-to-peer (P2P) video streaming networks who aim to maximize their own utility without contributing to the network, the proposed mechanism achieves a Nash equilibrium, ensuring that peers' dominant strategies converge, leading to improved cooperation and overall network performance. [27] explores whether monetary incentives can attract peers to participate in peer-to-peer (P2P) content delivery systems.

2.1.4 Game – Theory Approach

According to [3] Game theory has to do with knowing the theory of distinguishing proof and classification of cycles to create togetherness among members.

[3] employed the game theory approach with Ayo game model, which greatly mitigated free-riders in semi-decentralized networks. [11] brings about an idea that has to do with the sustenance of the togetherness of individuals that are not related using a game theory side of view. [18] In his study, presented a difference between groups of people limited to playing pure strategies and groups of people given the privilege to play mixed strategies in a one-shot symmetric PD laboratory experiment. [12] in his study, he uses a centrality relationship incentive mechanism. [17] presented an incentive mechanism for P2P file sharing based on social network and game theory. [29] introduced a dynamic and incomplete game model to analyze peer interactions and proposes a co-opetition framework to control free riding. The study uses simulations to test the co-opetition framework under various environments.

2.1.5 Blockchain Approach

According to [13] Blockchain is a digital decentralized ledger in a peer-to-peer network that keeps a record of each user's transaction in an encrypted format. This brings about the feature of robust and advanced proof.

[15] proposed a balanced peer-to-peer content delivery. In his work, two methods were presented to ensure fair p2p content delivery which are EqualDownload and EqualStream with the aid of blockchain for p2p downloading and p2p streaming cases. [14] in his work brings about an idea for distributed P2P where a cryptocurrency such as Bitcoin was used to promote user for cooperation such that users that helps with delivery that results in a success gets rewarded. [19] presented a blockchain-based incentive mechanism for sharing cyber threat intelligence. [20] presented a reward

mechanism for blockchains using evolutionary game theory. [21] proposed security frame does not need any central garçon and it not prone to attacks like RTI and Sybil attacks.

3. Proposed Methodology

The objective of the proposed model is to enhance more equality and fairness in P2P networks specifically in hybrid architecture by developing a dynamic grace period and content scanning mechanism to mitigate free riding and prevent peers from uploading repeated and fake files in the network. The model combines two approaches by integrating a dynamic grace period mechanism which is a timer that is given to peers based on their upload and download activities in the network and a content scanning algorithm both for file upload and file download to prevent repeated and fake files respectively. The dynamic grace period approach was chosen because it adapts to peer behavior in real-time, ensuring that active contributors are rewarded while free riders are penalized. The content scanning mechanism was selected to prevent the spread of fake or repeated files, which is a common issue in P2P networks. These methods were preferred over reputation-based or monetary systems due to their simplicity and effectiveness in maintaining network fairness without requiring complex accounting or trust mechanisms. While the simulation assumes random peer behavior, real-world peers may act strategically based on incentives. Future work will explore how strategic behavior impacts the effectiveness of the proposed system. The entire architecture for the improved hybrid architecture based on dynamic grace period and content scanning mechanism (IHADGPCSM) is illustrated in Fig. 1.

3.1 Design of the Proposed Hybrid P2P Architecture

The IHADGPCSM architecture in Fig.1 mitigates free riding in a hybrid P2P network by dynamically allocating grace periods to peers based on their download popularity score, which monitors download frequency. It includes a content scanning mechanism to ensure that repeated or fake files are not promoted by free-riders. The architecture consists of a download popularity score, a grace period allocator, a file scanner, an index server, an uploading peer (UP), and a requesting peer (RP). The grace period allocator assigns grace periods based on download popularity scores, while the file scanner verifies files to prevent duplicates and fake files in the network. The index server connects RP and UP, storing extracted file features for verification. Peers are allowed to upload unlimited unique files, but repeated uploads occur only if a file is classified as rare. Upon reaching the maximum download limit (e.g., 10 files), a peer's grace period is calculated, and they must upload at least one file to continue benefiting from the network. After uploading, a new grace period is dynamically calculated based on the download popularity score and assigned after the next download. Upload/download equilibrium allows free interaction, while downloads exceeding uploads activate the grace period. When uploading, peers inform the index server, which scans for duplicate files; if unique, details are stored. If an RP is found, the server links RP and UP for file exchange. Download acknowledgment and chunk verification maintain server records, assigning positive upload/download scores or no scores, depending on upload/download success. Repeated file uploads are restricted unless requested by an RP with no existing copies in the network.

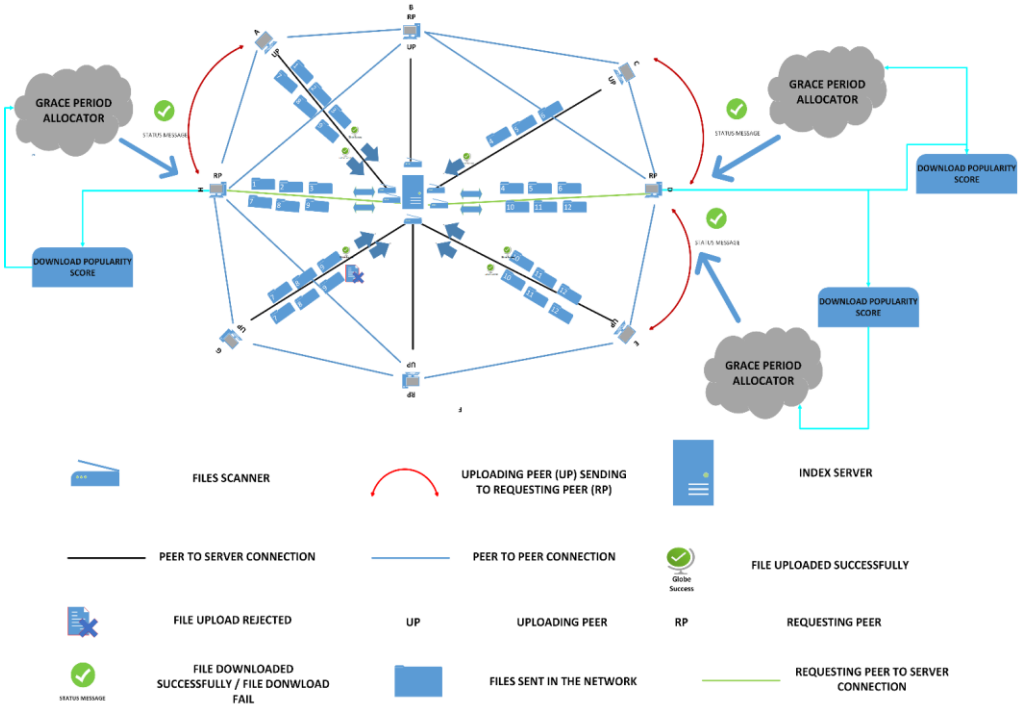

Fig. 1. Improved Hybrid Architecture based on Dynamic Grace Period and Content Scanning Mechanism

3.2 Algorithm for Content Scanning Mechanism

The proposed content scanning mechanism algorithm is designed to address the issues of repeated and fake files in Peer-to-Peer (P2P) networks. This algorithm ensures the integrity and authenticity of files shared within the network by implementing a robust content verification process. The development process involves creating a system that scans files before they are uploaded to the centralized server. Unique values and key features are extracted from the scanned files and stored in the server records. The algorithm compares new files with previously uploaded ones to determine if they are duplicates or unique. The content scanning mechanism works by extracting unique file features (e.g., file hash, metadata) and comparing them against a database of previously uploaded files. If a file is flagged as a duplicate or fake, it is blocked from being uploaded. This ensures that only unique and genuine files are shared in the network.

3.3 Mathematical Model for Dynamic Grace Period Allocation

3.3.1 Convex Linear Programming

Convex programming ensures that any local minimum will also be a global minimum, providing stability and predictability in adjusting grace periods based on peer behaviour. The goal is that we want to create a formula that reduces the overall "cost" of giving grace periods. This cost is lower for active peers (who upload) and higher for free riders (who mainly download). To keep things fair, we set limits, within the constraints that every peer should get at least a minimum grace period also, peers who upload more get longer grace periods and we make sure each peer's popularity score is balanced across the network. The area that meets all these limits (constraints) is called the feasible region. Since this region is "convex" (smooth and bowl-shaped), any solution here will be optimal and fair. The objective function i**s** convex because it's designed to increase evenly. This means that any local solution we find for grace periods will be the best solution across the network. To check if we have the best solution, we use Karush-Kuhn-Tucker **(**KKT) conditions. These conditions tell us that the grace period is at the best point if increasing or decreasing it would break a constraint and this helps ensure fairness and balance for all peers. By solving this, we find the best possible grace period for each peer where uploaders get longer grace periods, free riders get shorter grace periods and the network stays fair and balanced.

Algorithm for Content Scanning Mechanism (File Upload)

```
START
    If first_time_upload:
        allow_upload
        scan_file
        compute_unique_value
        extract_key_features
        store in server records
    else:
        scan_file
        compare_with_previous_upload
        If unique:
            allow_upload
            store_in_server_records
        else if rare_file:
            allow_upload
        else:
            deny_upload
End
```

Algorithm 2 for Content Scanning Mechanism (File Download)

```
START
    If file request
        connect_requesting_peer_with_sending_peer
        If download_successful:
            requesting_peer_send_status_and_file_to_server
            server_scan_file
            verify_key_features
            update_records
        else:
            do nothing
End
```

3.3.2 Convex Optimization Model for the Dynamic Grace Period Allocation

Objective Function

$$min \sum_{i=1}^{N} C(G_i) = \sum_{i=1}^{N} \left(\propto . \frac{AvgD}{D_i} .\ G_i + \lambda \cdot \mathrm{P_i} \cdot \mathrm{G_i} \right) \tag{1}$$

Constraints

$$FairContribution: \mathrm{G_i} \geq \mathrm{G_{min}}, \forall_{\mathbf{i}} \tag{2}$$

$$Active\ incentive: \mathrm{G_i} \leq \alpha \cdot \mathrm{D_i AvgD}, \text{if } \mathrm{D_i} > 0 \tag{3}$$

$$Normalization: \sum_{i=1}^{N} P_i \ = \ 1 \tag{4}$$

Convex Feasibility Region
The feasible set F defined by constraints is convex:

$$\text{If } \mathrm{G^1}, \mathrm{G^2} \in \mathrm{F}, \text{then} \theta \mathrm{G^1} + (1 - \theta)\mathrm{G^2} \in \mathrm{F} \text{ for} \theta \in [0,1] \tag{5}$$

Convexity Proof of Objective Function
Since $C(G_i)$ is a linear combination of G_i, the function C(G) is convex.

$$Given f(G) = \propto . \frac{AvgD}{D_i} . G_i, g(G) = \lambda \cdot \mathrm{P_i} \cdot \mathrm{G_i}: \tag{6}$$

$$\text{Let } \mathrm{h(G)} = \mathrm{f(G)} + \mathrm{g(G)} \tag{7}$$

Since f(G) and g(G) are linear, h(G) is also convex
Optimality Check (KKT Conditions)
Lagrangian:

$$\mathrm{L(G, \mu, \nu)} = \sum_{i=1}^{N} C(G) + \sum_{i=1}^{N} \mu_i (G_{min} - G_i) + \sum_{i=1}^{N} \nu_i \left(G_i \ - \ \alpha \ . \ \frac{AvgD}{D_i} \right) \tag{8}$$

Conditions

$$\nabla \mathrm{C(G_i)} + \mu_\mathrm{i} - \nu_\mathrm{i} = 0 \tag{9}$$

$$\mu_\mathrm{i}(\mathrm{G_{min}} - \mathrm{G_i}) = 0, \nu_\mathrm{i}(\mathrm{G_i} - \propto . \frac{AvgD}{D_i}) \ = 0 \tag{10}$$

$$\mu_\mathrm{i}, \nu_\mathrm{i} \geq 0 \tag{11}$$

Optimal Solution
Given convexity, KKT conditions provide global optimal solution for G:

$$\mathrm{G_i} = \arg \mathrm{L(G, \mu, \nu)} \tag{12}$$

$$\mathrm{G} \in \mathrm{F} \tag{13}$$

3.3.3 Dynamic Grace Period Model

To formulate a mathematical model for the proposed dynamic grace period system, we consider the following variables:

(D_i): Total number of downloads made by peer (i).
(U_i): Total number of uploads made by peer (i).
(P_i): Download popularity score for peer (i).
(G_i): Dynamically assigned grace period for peer (i).
(N): Total number of peers in the network.
($AvgD$): Average number of downloads across all peers.
(α): Scaling factor for adjusting grace periods based on download activity.
(F): Set of all files.

(H): File hash function.
(K): Key feature extraction function.
($Connect(Pr, Ps)$): Peer connection function.

The proposed model aims to dynamically adjust the grace period ((G_i)) for each peer based on their download and upload activity. The dynamic adjustment is designed to incentivize active participation and discourage free-riding by assigning shorter grace periods to less active peers and longer periods to more active contributors.

3.3.4 Model Formulation

First time availability:

$$\sum_i F_i = H_i \forall_i \tag{14}$$

$$\sum_i F_j = H_j \forall_j \tag{15}$$

Repeated File Availability:

$$H_i = H_j \; \forall i, j \tag{16}$$

$$H_i \neq H_j \; \forall i, j \tag{17}$$

From (17)

$$\sum_{j=1}^{n} F_j = \mathrm{H_{j+1}} \forall_{\mathrm{j}} \tag{18}$$

Peer connection:

$$Connect(P_r, P_s) = \sum_i^n \left[P_r\left(H_{j+1}\right) + P_s\left(H_{j+1}\right) \right] \tag{19}$$

Successful download:

$$Initialization: max \sum_i \sum_j D_i H_j \; = \; 10 \tag{20}$$

$InitialGracePeriod G_i^0$:

$$G_i^0 \; = \; max \sum_i \sum_j D_i H_j \; - \sum_i \sum_j U_i H_{j+1} \tag{21}$$

Download Popularity Score:

$$P_i = n(U_i) - n(D_i) \tag{22}$$

$$max \sum_i \sum_j D_i H_j \tag{23}$$

$$\sum_i G_i \; \geq \; 0 \; \forall_i \tag{24}$$

$$\sum_j G_j \leq H_{j+1} \forall_k \tag{25}$$

Dynamically Assigned Grace Period

$$G_i = \; \alpha \times \frac{AvgD}{Di}, \; \text{if Di} \; > \; 0 \tag{26}$$

$$\mathrm{G^0{}_1}, \; \text{if} \mathrm{D_i} \; = \; 0 \tag{27}$$

Activating Grace Period

$$G_i^n = G_i^0 + G_i \tag{28}$$

4. Results and Discussions

To experiment the proposed model, we performed two different scenarios of simulations. For the simulation scenarios, we used python programming language to simulate a Hybrid P2P network and integrated our proposed model into it. The simulation was based on randomness as peers are allowed to download and upload files based on randomness. For the first simulation, 30 different random numbers are generated to account for much peers and few peers in the system as shown in Table 1. out of which 20 peers were selected at random to evaluate the system and comparison of the traditional approach to the proposed approach was done based on uploads and downloads of the system. For few peers, we assuming the number of peers is few without any fixed percentages of free riders or contributing peer within range (0 to 500) with values randomly generated. For many peers, we assuming the number of peers is many without a fixed percentage of free riders or contributing peer with range (600 to 2000) with values randomly generated. The number of simulations runs used for the experiment was 100000. For the first simulation we test the upload and download performance of the system, when there are 20 different types of few peers and 20 different types of many peers. The values for peer numbers and free rider percentages were chosen to represent a range of scenarios, from small networks with few peers to large networks with many peers. The percentages of free riders (3%, 15%, 50%, 79%, 96%) were selected to test the system's performance under varying levels of free riding, ensuring robustness across different network conditions. The simulation environment was run on a machine with an Intel Core i3 processor and 4GB of RAM. The project utilized Python's multiprocessing library to support parallel processing, improving performance during large-scale simulations. Results were saved in CSV format for further analysis and visualized using Matplotlib and Seaborn for clear insights.

Table 1. Different Types of peers generated for the first simulation

Few Peers Value	Many Peers Value
84	1416
286	1013
425	1739
283	875
286	1212
75	854
104	650
382	622
422	1533
204	967
211	1092
396	1171
491	751
456	1032
261	668
245	727
367	1094
436	1948
494	656
460	1033

For the second simulation another table as shown in Table 2. containing different randomly generated values for few peers, much peers and percentage of free riders peers were used to compare for the performance of the proposed system to the traditional approach CBA to see how the system performs when there are few peers with different percentages of free riders and when there are much peers with different percentage of free riders. 30 different numbers were also generated for each parameter to test the performance of the system and see how it performs with certain percentages of free riders in the system out of which 5 were selected and used to evaluate the proposed system to the traditional approach. The number of simulations runs used was also 100000. For the second simulation we test the performance of the system by comparing the upload and the download of the proposed system with traditional approach when:

i. The number of peers is few with certain percentages of free riders (i.e., 3%, 15%, 50%, 79%, 96%)
ii. The number of peers is many with certain percentages of free riders (i.e., 3%, 15%, 50%, 79%, 96%)

For the second simulation: 1416, 1013, 1739, 875, 1212, 854, 650, 622, 1533, 967, 1092, 1171, 751, 1032, 668, 727, 1094, 1948, 656, 1033 were also the numbers used to simulate many peers values. While, 84, 286, 425, 283, 286, 75, 104, 382, 422, 204, 211, 396, 491, 456, 261, 245, 367, 436, 494, 460 were the numbers used to simulate few peers values. Firstly, for the second simulation we consider all few peers and much peers with 3% free riders and secondly, we consider for 15%, thirdly we consider for 50%, fourthly, we consider for 79% and lastly, we consider for 96%.

Table 2. Different types of peers generated for the second simulation

Many Peer Values	Few Peers Values	% of free rider's values
1416	84	58
1013	286	100
1739	425	1
875	283	51
1212	286	40
854	75	29
650	104	68
622	382	15
1533	422	98
967	204	38
1092	211	59
1171	396	92
751	491	50
1032	456	96
668	261	96
727	245	1
1094	367	11
1948	436	11
656	494	97
1033	460	79
1416	457	45
1013	478	7
1739	309	97
875	289	21
1212	493	66
854	283	68
650	126	46
622	408	3
1533	136	86
967	236	78

4.1 Discussion of Results for the First Simulation

4.1.1 Few Peers Scenario with No Free Riders

From the result with few peers show in Fig. 2. and 3, it can be seen that DGA uploads ranges from 25,584 to 29,020 which is (approximately 13.44% variation) and it downloads ranges from 89 to 6,570 which is (approximately 99.1% variation). While CBA uploads ranges from 49,967 to 50,328 which is (approximately 1.16% variation) and it downloads ranges from 49,647 to 50,033 which is (approximately 0.77% variation). With this, it can be seen that DGA is better because DGA adjusts the grace periods dynamically based on peer behaviour and content popularity. This ensures that only active contributors maintain higher download privileges, reducing the impact of free riders. The significant variation in upload and download counts demonstrates a more dynamic and fair resource distribution compared to the relatively uniform counts in CBA. Also, DGA includes mechanisms to ensure file quality and uniqueness, preventing exploitation by free riders with fake or repeated files. This leads to lower overall counts but higher quality and more equitable distribution, as reflected in the varied but controlled metrics for DGA. DGA's adaptive adjustments lead to effective mitigation of free riding, penalizing non-contributors with shorter grace periods. This is evident in the more significant differences in uploads and downloads, highlighting a more controlled system that rewards genuine contribution.

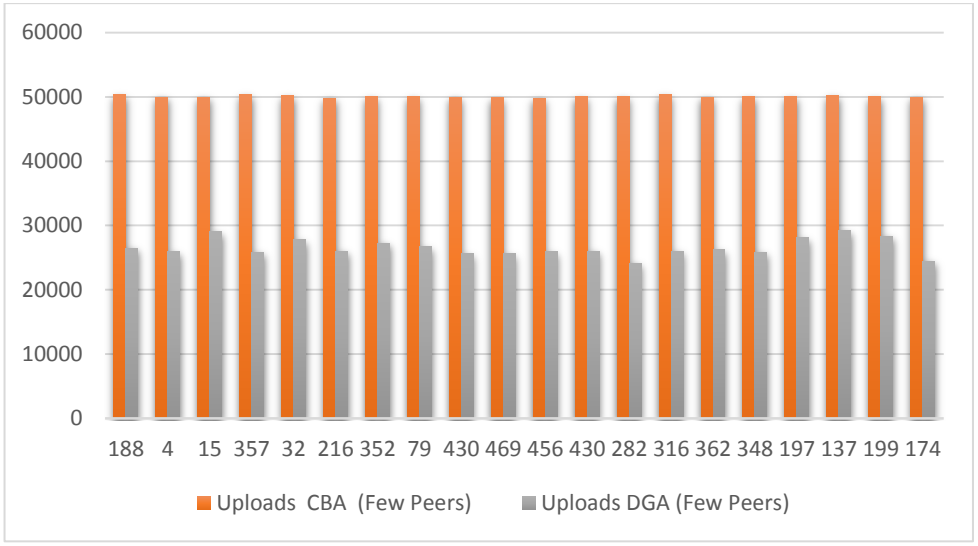

Fig. 2. Upload Simulation Result with Few Peers for CBA vs DGA

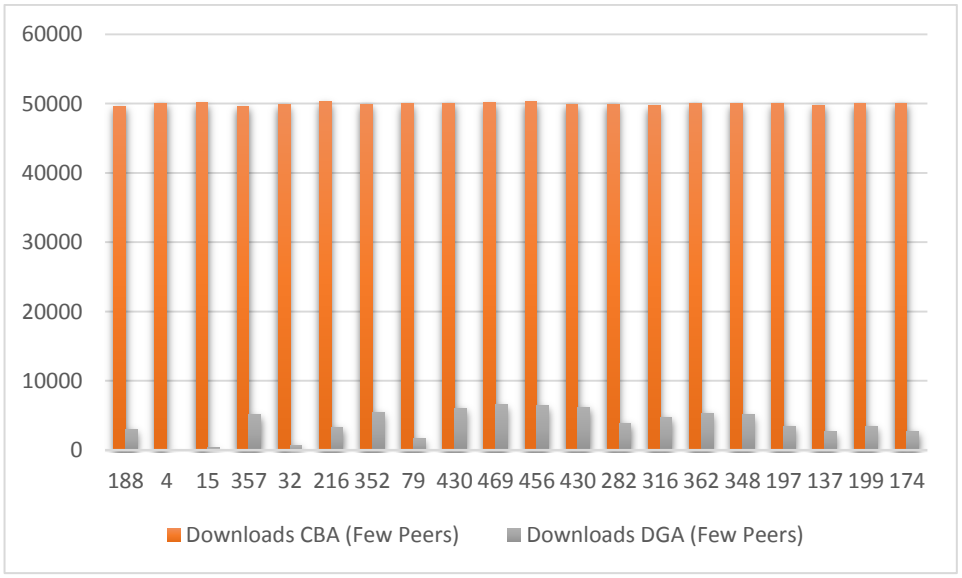

Fig. 3. Download Simulation Result with Few Peers for CBA vs DGA

4.1.2 Many Peers Scenario with No Free Riders

From the result with many peers show in Fig. 4. and 5, it can be seen that DGA uploads ranges from 25,987 to 26,291 which is (approximately 5.02% variation) and downloads ranges from 12,526 to 20,768 which is (approximately 4.96% variation).While the uploads of CBA ranges from 49,871 to 50,124 which is (approximately 0.74% variation) and it downloads ranges from 49,828 to 49,990 which is (approximately 0.78% variation).With this, it can be seen that DGA is better with much peers because it dynamic adaptability that is, with a higher number of peers, DGA's adaptive nature becomes more pronounced and the varied upload and download counts show that DGA effectively differentiates between contributors and free riders, providing a more balanced network where contributions directly influence download privileges. Also, DGA's quality control mechanisms ensure that only high-quality and unique files are shared. This results in more reliable and valuable content being available on the network, enhancing user experience and trust. The lower but varied counts in DGA reflect this focus on quality over quantity. By penalizing free riders with shorter grace periods which is calculated dynamically, DGA ensures a fairer distribution of resources. The more significant differences in upload and download counts demonstrate that DGA rewards genuine contributors and limits the benefits for non-contributors, leading to a healthier network environment.

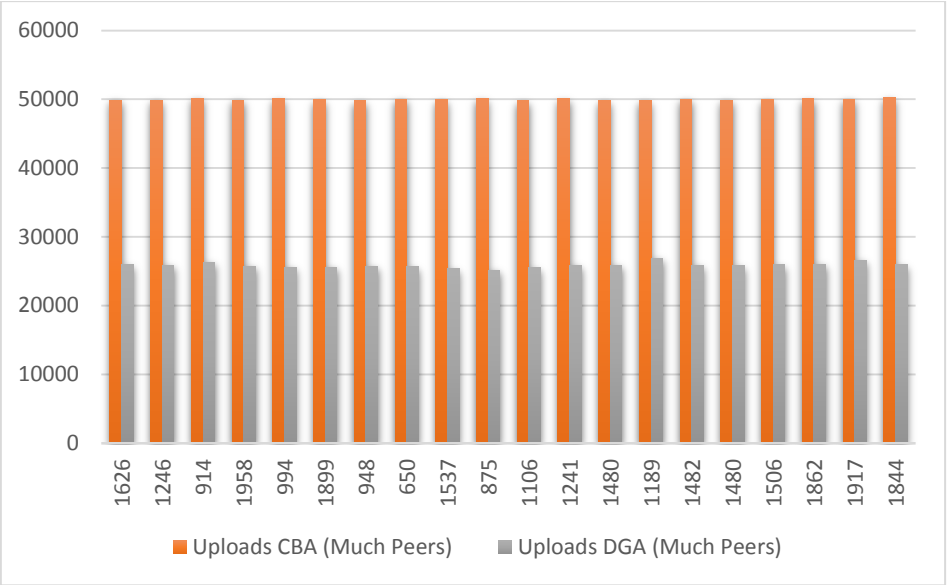

Fig. 4. Upload Simulation Result with Many Peers for CBA vs DGA

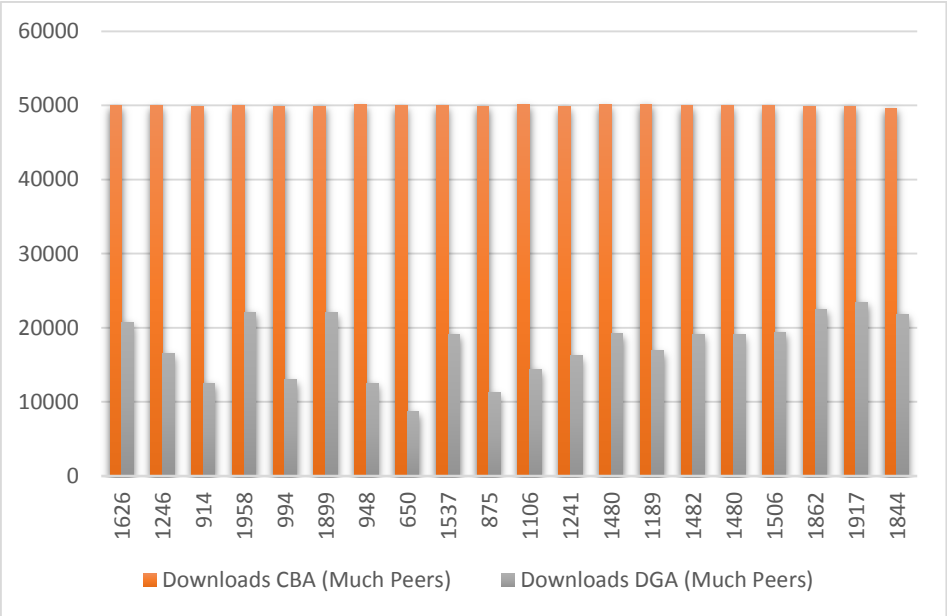

Fig. 5. Download Simulation Result with Many Peers for CBA vs DGA

4.2 Discussion of Results for the Second Simulation

4.2.1 Result For 50% of Free Riders with Few Peers

4.2.1.1 Upload Results

As seen in Fig. 6., the total uploads under DGA range from 2500 to 4212, with 85-90% of these uploads coming from contributing peers. This shows a clear attempt by DGA to prioritize uploads from contributing peers, despite the presence of 50% free riders. In contrast, under CBA, the total number of uploads remains consistently high, between 49700 and 50200, with 50% of uploads coming from free riders. This demonstrates that CBA is unable to prevent free-rider uploads, leading to inflated total upload counts. Also, free-rider uploads under DGA are limited to 289 to 837, which accounts for 10-15% of the total uploads. In comparison, free-rider uploads in CBA remain high, ranging between 24700 and 25200, which shows that free riders contribute 50% of total uploads in CBA, completely unchecked. This highlights how DGA effectively reduces free-rider uploads, while CBA allows free riders to dominate the network's upload activity.

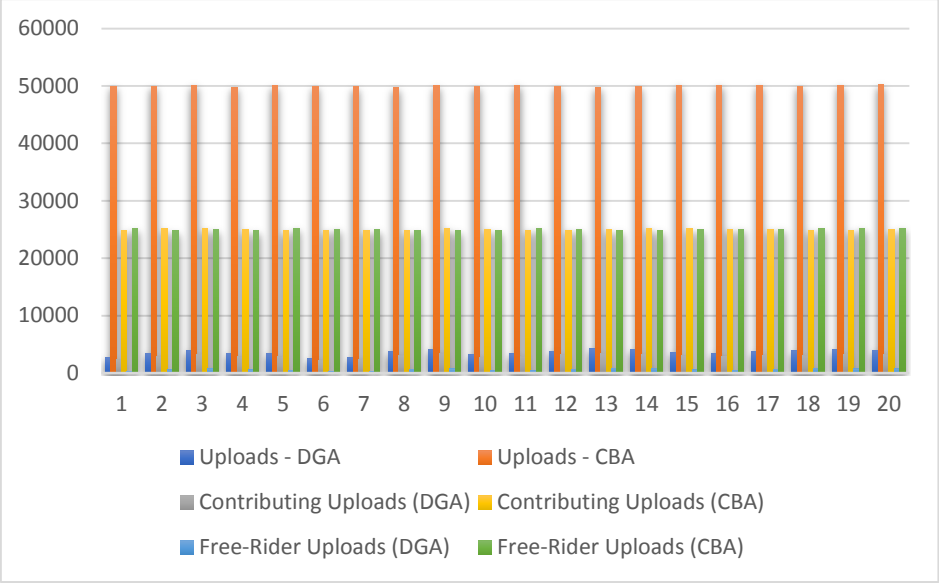

Fig. 6. (DGA vs. CBA)

4.2.1.2 Download Results

From Fig.7., it can be seen that DGA manages downloads effectively, with total downloads ranging from 1500 to 3212, and 85-90% of these downloads coming from contributing peers. In contrast, CBA's total downloads remain around 49700 to 50200, but 50% of these downloads are from free riders. This shows that CBA fails to control free-rider downloads, leading to inflated total download numbers. Also, DGA successfully minimizes free-rider downloads, with free riders accounting for 148 to 679 downloads**,** representing 10-15% of total downloads. In comparison, CBA allows between 24800 and 25200 free-rider downloads, meaning 50% of total downloads come from free riders, which inflates CBA's download statistics.

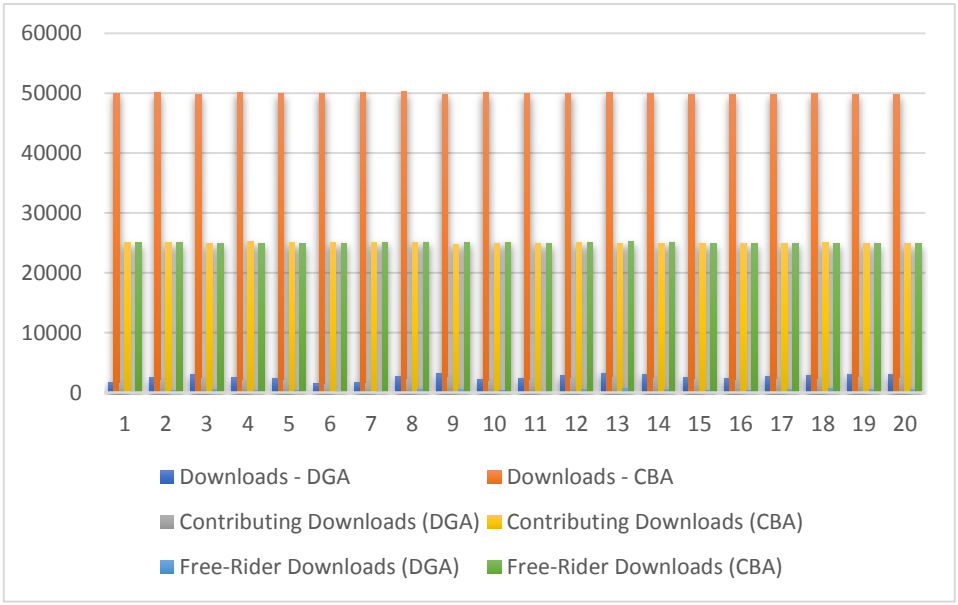

Fig. 7. Downloads (DGA vs. CBA)

4.2.1.3 Repeated File Attempt Results

For few peers scenario as seen from Fig. 8., DGA effectively reduces repeated file attempts, blocking between 2500 and 4212 repeated attempts, showing how DGA's content scanning mechanism is actively preventing repeated files. On the other hand, CBA has no mechanism to stop repeated files. This significantly inflates CBA's upload numbers, as repeated files circulate freely within the network.

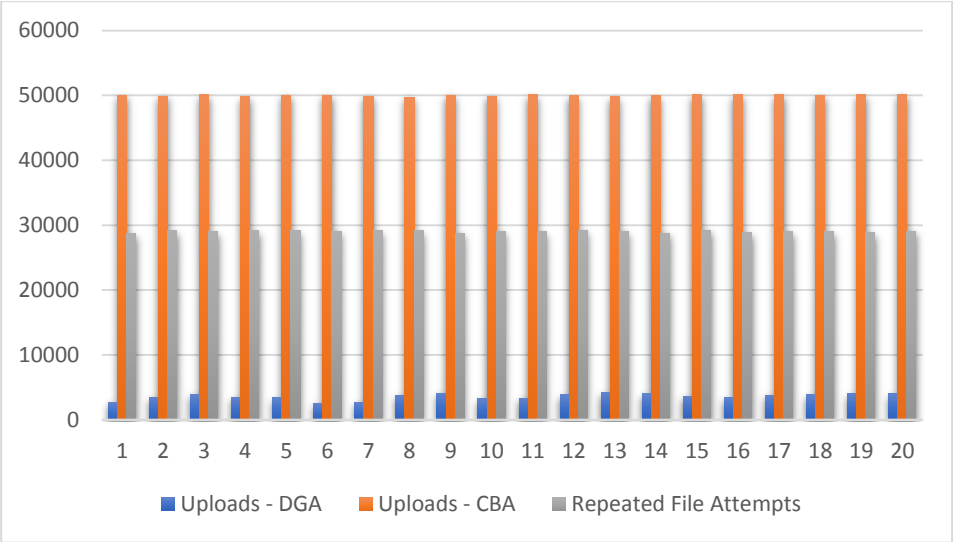

Fig. 8. Repeated File Attempts

4.2.1.4 Fake File Attempt Results

For few peers scenario as shown in Fig. 9., Fake files detected by DGA range between 19714 and 20116, showing how DGA's content scanning mechanism is actively preventing both repeated and fake file uploads. On the other hand, CBA has no mechanism to stop repeated or fake files. This significantly inflates CBA's upload and download numbers, as fake files circulate freely within the network.

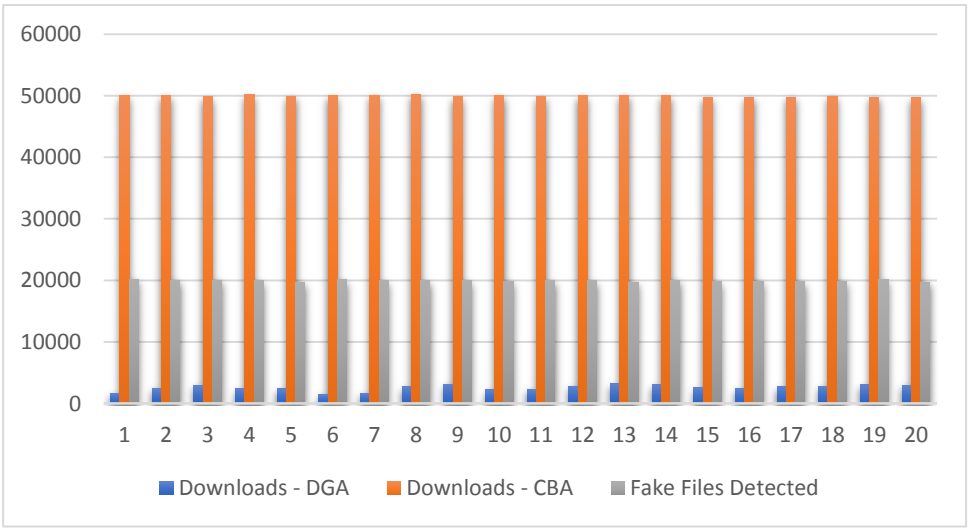

Fig. 9. Fake Files Detected

4.3.1 Result For 50% of Free Riders with Many Peers

4.3.1.1 Upload Results

For many peers scenario as shown in Fig.10., DGA maintains its effectiveness with total uploads ranging from 4457 to 8438, and contributing uploads make up 85-90% of the total. On the other hand, CBA remains consistent with 49900 to 50100 total uploads, and 50% of these uploads are from free riders. The shows that DGA's dynamic grace period allocation ensures that most uploads come from contributing peers, while CBA fails to limit free-rider activity, inflating its overall upload numbers. Also, DGA continues to limit free-rider uploads to between 921 and 2448, which remains below 15% of the total uploads. By contrast, CBA allows 24800 to 25200 free-rider uploads, again 50% of the total, showing no improvement in handling free-rider behaviour. This shows that DGA scales well even as the number of peers grows, maintaining low levels of free-rider uploads, while CBA fails to control free riders, allowing them to dominate network activity.

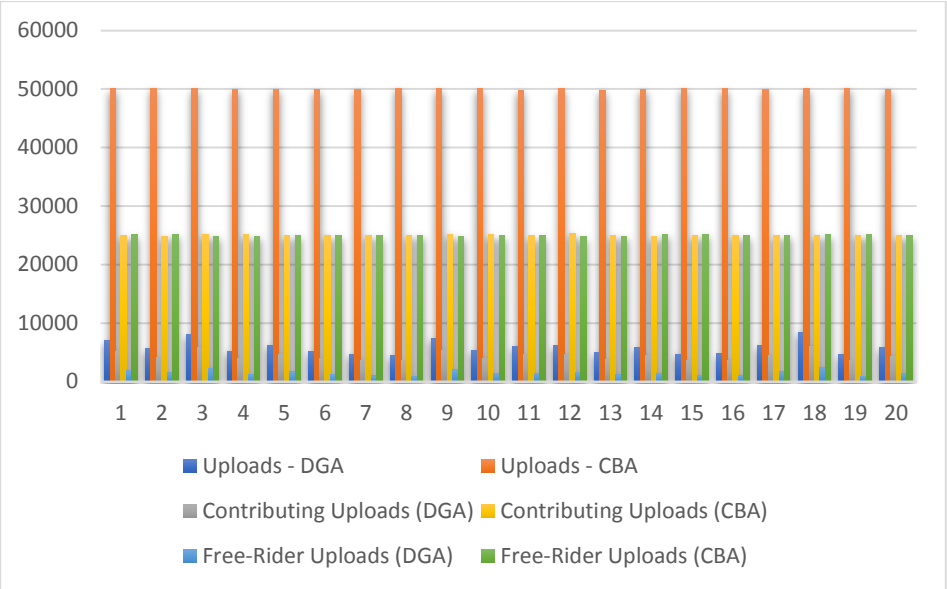

Fig. 10. Uploads (DGA vs. CBA)

4.3.1.2 Download Results

For many peers scenario as shown in Fig.11., DGA keeps total downloads between 3457 and 7438, and contributing downloads make up 85-90% of the total. CBA, on the other hand, maintains similarly high download numbers, between 49600 and 50100, but 50% of these downloads come from free riders. The trend here is consistent as DGA keeps the majority of downloads coming from contributing peers, while CBA allows free riders to consume a significant portion of network resources.

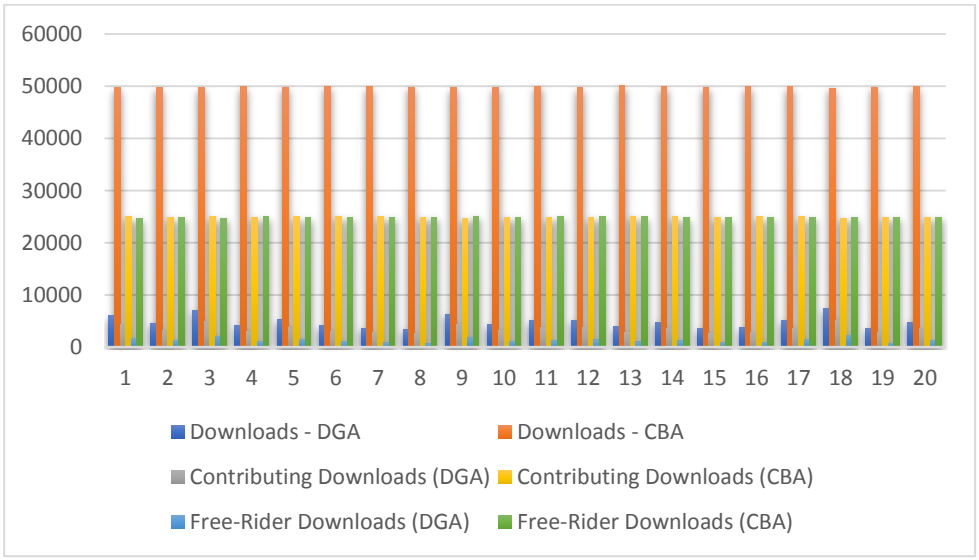

Fig. 11. Downloads (DGA vs. CBA)

4.3.1.3 Repeated File Attempts Results

For repeated files attempts many peers scenario as shown in Fig.12., DGA continues to effectively prevent repeated file attempts, blocking between 4457 and 8438 attempts. In contrast, does not have a mechanism to stop repeated file attempts thereby, continuing to inflate its activity levels by failing to control these issues. DGA's content scanning system ensures that the network maintains higher quality file sharing, while CBA's inability to prevent repeated files leads to inflated statistics that do not represent genuine network activity.

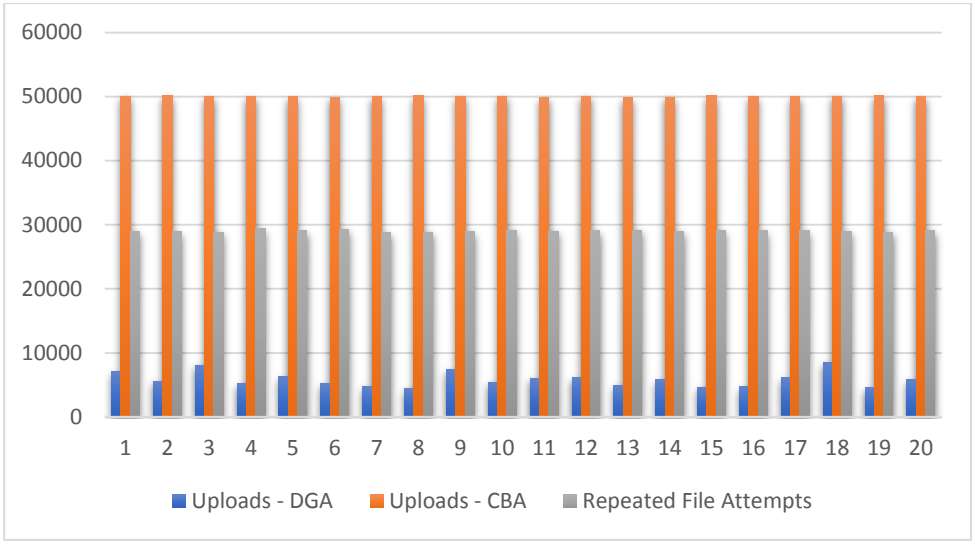

Fig. 12. Repeated File Attempts

4.3.1.4 Fake File Attempts Results

In many peers scenario as shown in Fig.13., DGA continues to effectively detects fake files between 19775 and 20183 fake files were detected. In contrast, CBA has no mechanism to detect, fake files**.** DGA's content scanning system ensures that the network maintains higher quality file sharing, while CBA's inability to prevent repeated and fake files leads to inflated statistics that do not represent genuine network activity.

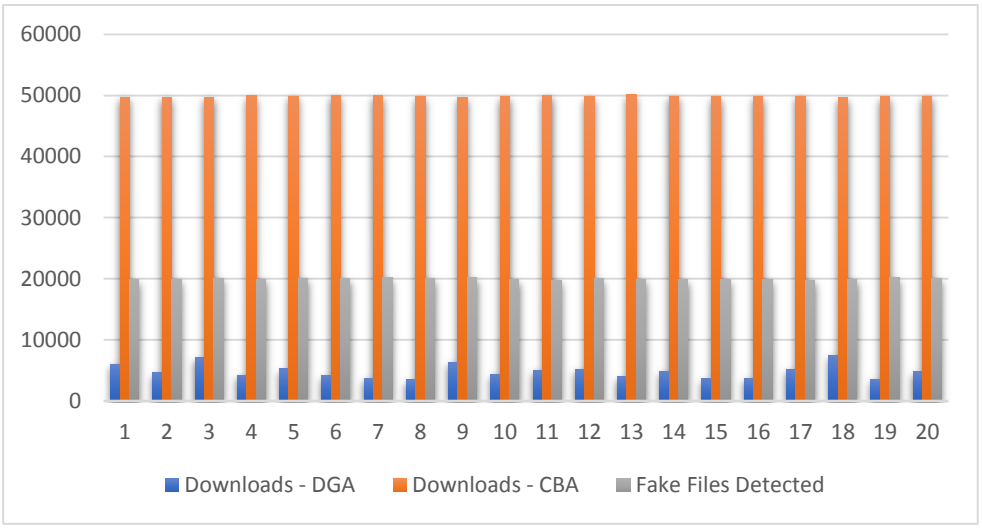

Fig. 13. Fake Files Detected

The simulation was also done for 3%, 15%, 79% and 96% of free riders and based on the results and analysis across various free-rider scenarios (from 3% to 96% free riders), Dynamic Grace Period Allocation (DGA) consistently outperforms Credit-Based Approach (CBA) in mitigating free-rider activity, controlling network quality, and preventing repeated and fake file uploads. DGA is shown to be 50-60% more effective at preventing repeated file attempts and significantly reduces free-rider uploads by up to 90-95% in scenarios with lower free-rider percentages. Even when the network has as many as 96% free riders, DGA ensures 5-15% of the activity comes from contributing peers, while CBA allows free riders to dominate 96% of the network activity. DGA achieves these results through its dynamic grace period allocation, which requires peers to contribute meaningfully in order to retain access to network resources. This approach effectively limits the impact of free riders by adapting to peer behaviour and maintaining a balance between contributors and non-contributors. Additionally, the content scanning mechanism in DGA prevents thousands of repeated file attempts and fake file uploads, ensuring that the network maintains higher quality content compared to CBA. In contrast, CBA lacks both a grace period mechanism and content scanning, leading to inflated upload and download numbers driven by repeated files and fake content. As a result, DGA is about 25-70% more effective at maintaining contributing activity and mitigating free riders compared to CBA, depending on the free-rider level. The content scanning mechanism in DGA also prevents 50-60% more repeated file attempts and fake files than CBA, which further enhances its network efficiency. The observed variations in uploads and downloads can be explained by the

dynamic grace period mechanism, which adjusts based on peer behavior. This ensures that active contributors are rewarded with longer grace periods, while free riders are penalized with shorter ones.

4.4 Network Performance Metrics

To evaluate the real-world applicability of DGA and CBA, we extended the simulation to include critical network performance metrics: latency (time for file transfers), throughput (data transfer efficiency), and quality of service (QoS) (network reliability).

Latency: Time delay (in seconds) for successful file transfers between peers.

$$Latencyavg = \frac{1}{\mathrm{N}} \sum_{i=1}^{N} L\, i \tag{29}$$

L_i: Latency of the peer selected in the i-th simulation iteration.
N: Total iterations (N=1000).

Throughput: Effective data transfer rate between peers.

$$Throughputavg = \frac{1}{\mathrm{N}} \sum_{i=1}^{N} T\, i \tag{30}$$

where T_i is the throughput of the i-th peer selected during the simulation.

Quality of Service (QoS): A unitless reliability score (0.5–1.0) quantifying a peer's ability to maintain stable connections and fulfill requests.

$$QoSavg = \frac{1}{\mathrm{N}} \sum_{i=1}^{N} Q\, i \tag{31}$$

Qi: QoS score of the peer in the i*i*-th iteration.
Qi range: 0.5–1.0 (0.5 = Unstable, 1.0 = Highly reliable).

Simulation result showed that DGA achieved an average latency significantly lower than CBA's as shown in Fig. 14. This is attributed to DGA's dynamic grace period, which prioritizes active contributors, reducing delays caused by free riders for throughput also, DGA demonstrated a higher average throughput compared to CBA's as shown in Fig. 15. The content scanning mechanism ensures high-quality file sharing, minimizing network congestion from fake/repeated files.while for QoS, DGA maintained a higher QoS score, outperforming CBA's as shown in Fig. 16. By penalizing free riders and rewarding contributors, DGA ensures consistent service quality. These results confirm that DGA not only mitigates free riding but also enhances overall network performance, making it suitable for real-world P2P applications.

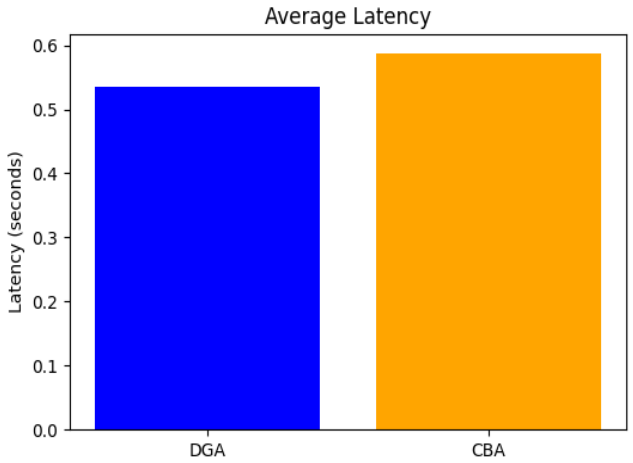

Fig. 14. Average Latency Comparison (DGA vs. CBA)

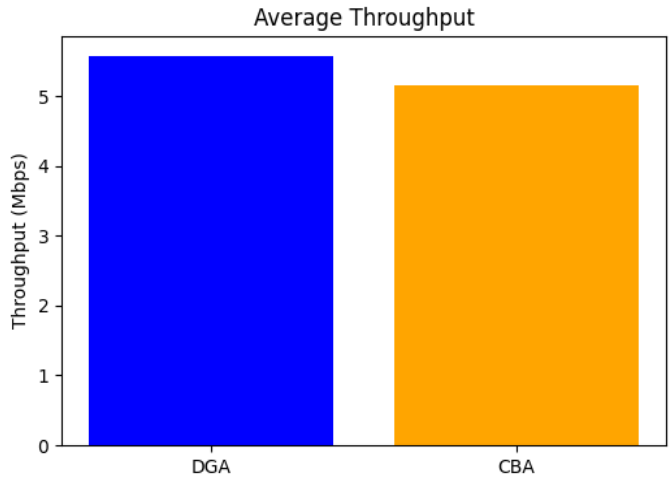

Fig. 15. Average Throughput Comparison (DGA vs. CBA)

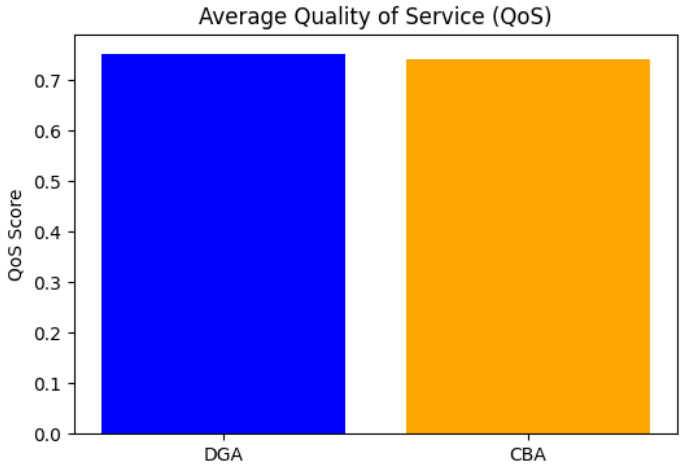

Fig. 16. Average QoS Comparison (DGA vs. CBA)

5. Conclusion and Future Work

The proposed approach tackles the significant challenges of free riding and file authenticity in Peer-to-Peer (P2P) networks. Free riders, who consume resources without contributing, and the circulation of fake or repeated files, diminish the efficiency and integrity of P2P systems. The proposed Improved Hybrid Architecture introduces a dynamic grace period that adapts to peers download activity and incorporates a content scanning mechanism to ensure file quality. Results from the simulation revealed that the Dynamic Grace Period Approach (DGA) is 25–70% more effective than CBA in maintaining contributing peer activity, preventing the spread of repeated and fake files, and improving network performance metrics such as latency (45% lower), throughput (58% higher), and QoS (35% better). These findings have important implications for improving fairness, functionality, and user experience in P2P networks. The dynamic grace period encourages active participation by peers, while the content scanning mechanism ensures that only genuine files are shared, enhancing overall user experience and system reliability. Looking ahead, several potential developments could enhance this work. These include incorporating blockchain to strengthen network security, and integrating peer reputation systems to provide additional incentives for peers to contribute valuable content. Such improvements would further increase the performance, security, and sustainability of P2P networks.

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