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DESIGN AND ANALYSIS OF INCENTIVE MECHANISM FOR DISTRIBUTED FILE SHARING NETWORKS

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ABSTRACT

Sharing of files and resources has been one of the main reasons for development on networking and the internet, the internet itself has been created for achieving this objective in a secured way and without loss of data or information. To successfully exchange files (such as movies, video files, audio, software systems, eBooks, etc.) over the Internet, a number of file peer-to-peer sharing systems (such as Bit-Torrent, Gnutella, suggested, eMule, UTorrent etc.) have been developed to counter the limitations of the server-client model. These platforms are used worldwide to share and download files by millions of Internet users. Users of these systems share files amongst themselves cooperatively. However, some nodes may want to exploit the system for their selfish purposes such as the common concept of consuming from the network resources without sharing, which is known as free-ridding. This phenomenon degrades the quantity of service of the network in addition to destroying trust among peers. To motivate peers to share their file chunks and achieve optimal quality of service in the network, an incentive mechanism is introduced in this study. The study employs mathematical modeling to represent the system, and the results showed that by using incentives to encourage node's active participation, the problem of free-riding has been drastically reduced which in turn, reduces file download time.

Keywords: File Sharing, Leechers, File Download Time, File Upload

INTRODUCTION

The conventional client/server model (such as FTP, WWW) was, until recently, used for sharing files, but this model is associated with numerous weaknesses, such as scalability and a single point of failure. In some instances, the model is time and energy consuming (Fatoba, 2023). Distributed file-sharing applications were developed to address these weaknesses and have gained extensive recognition. In these systems, files are shared between users jointly using the Peer-to-Peer (P2P) model. The P2P network model has become a very effective approach for designing distributed and scalable network systems. Among the vital functional ideas of P2P systems is the motivation of users to act as clients and servers concurrently; thus, users are called peers. Henceforth, in the text, the terms peers and users will be used interchangeably. In P2P systems, peers not only download data but also upload data to other peers. In this way, peers' uploaded bandwidth is effectively used to reduce the load on the server (Tang et al., 2022).

Additionally, in distributed file-sharing networks, files such as videos, audios, software systems, hardware drivers, e-books, etc., are disjointed into bits known as data fragments or chunks. The entire disjointed file is called a torrent file. Peers downloading the same torrent file are usually assembled to form a swarm for that particular file, and data parts are shared between peers in a given swarm collectively. If a particular part of the file is missing from a peer that is being downloaded, it will demand or request that part from other peers locally within the same swarm (Le et al., 2022).

Moreover, there are two kinds of peers in distributed file-sharing systems, namely, leechers and seeds. The leechers are peers currently downloading pieces of the file and are also known as downloaders. Leechers perform two actions concurrently, i.e., downloading pieces for consumption and uploading pieces to others. Seeds are peers that have completely downloaded all file fragments and decided to stay in the system to upload their file fragments to leechers in the system. Seeds perform only one action, which is uploading fragments to leechers. For the download procedure, peers use their download bandwidth, and for the upload process, peers use their available upload bandwidth.

Among the significant challenges of distributed file-sharing systems is free-riding. Free riders are leechers that try to download file bits and give little or none of their upload bandwidth to upload file bits to other leechers downloading the same file. Therefore, this prompts the need to design an incentive mechanism for such systems to discourage leechers from free riding (Nallakannu & Thiagarajan, 2016; Sun et al., 2021).

Lastly, file-download time is one of the key Quality of Service (QoS) parameters of P2P file-sharing systems, which is the time taken to download a single complete file. The file-download time is not really limited; it depends on the QoS of the network connection. During the file download, patches are downloaded in a scattered format, i.e., the order of patches download is not clear and does not follow any sequential pattern. The already downloaded patches are kept in the peer's barrier in order to serve other peers downloading the same file (Nathan et al., 2019; Ihle et al., 2023).

Related Works

Free riding is one of the serious challenges that corrodes the efficiency of distributed file sharing networks as solving it alone can improve a network's efficiency by up 45% (Lin et al., 2021). One method to address this issue was offered by Ezzahidi et al. (2017) in which a reward is used as an incentive to encourage nodes to participate. The authors modeled the distributed network as a non-cooperative game and proposed three fully distributed algorithms to ensure convergence to the Nash equilibrium. This ensures that each node in a swarm participates and reduces the amount of delay it takes to relay messages. However, this approach introduces computational overhead (Ma et al., 2004).

Incentive Mechanisms

Many studies have proposed diverse approach for provision of incentive mechanism in distributed systems. One such example is by Adamu (2021) where he proposes a share-ratio-based incentive mechanism for P2P file-sharing networks where files are shared via BitTorrent protocol. The proposed incentive mechanism is not prone to Sybil and collusion attacks, and it was designed to simultaneously: (1) encourage cooperation, (2) provide fairness to new downloaders, and (3) deter free-riding while resisting whitewashing attack. In the work of Shareh et al. (2020), the authors proposed a single mechanism to detect the two kinds of illegal users (free riders and Sybil nodes) based on the game theory using reputation factors as the amount of shared bandwidth between the connected devices.

Similarly, in the work of Hazazi et al. (2019) they proposed a novel approach based on utilization of credit incentive, for P2P networks, where a grace period is introduced during which free-riders must reimburse resources to the network connection. Their study's difference to previous approaches is that the proposed system takes into consideration the upload rate of peers and a grace period for resource reimbursement as earlier stated.

Moreover, Ghaffari et al. (2018) propositioned a distributed incentive mechanism, which enhances mesh-based P2P for on-demand video streaming systems extensively. The mechanism peers will organize an overlay based on the playback point of the video and also contribute to upload bandwidth.

In addition, Albrecht and Woolridge (2022); Paccagnan (2022) took a different approach, to examining the design implications based on the assumption that users will selfishly act to maximize their own rewards, and construct a formal game theoretic model of the system and analyze equilibrium of user strategies under several novel payment mechanisms.

Furthermore, Ansari et al. (2023) investigated the design of a reputation system for P2P networks like Gnutella. The reputation system uses objective criteria to track each peer's contribution in the system and allows peers to store their reputations locally. Reputation are computed using either of the two schemes, debit-credit reputation computation (DCRC) and credit-only reputation computation (CORC). Using a reputation computation agent (RCA), they design a public key-based mechanism that periodically updates the peer reputations in a secure, light-weight, and partially distributed manner. Ramachandran et al. (2019) offered that secure payment mechanism for transactions, emerging economic P2P applications share the common need for efficiency in transaction. Using PPay, a micropayment system that exploits unique features of P2P systems to maximize efficiency while maintaining security properties. And show how the basic PPay protocol outperforms existing micropayment schemes by far, while guaranteeing that all coin fraud is detectable, traceable and non-profitable (Alotibi et al., 2019). Again, Ma et al. (2021) proposed a rank-based peer-selection mechanism for peer-to-peer media streaming systems. The mechanism provides incentives for cooperation through service differentiation. Contributors to the system are rewarded with flexibility and choice in peer selection, resulting in high quality streaming sessions. Free-riders are given limited options in peer selection, if any, and hence receive low quality streaming (Miguel et al., 2021).

However, some studies proposed model P2P system using the Generalized Prisoner's Dilemma (GPD), and proposed to reciprocate decision function as the basis of a family of incentives techniques (Hughes et al., 2020; Liang & Yang, 2019; Tushar et al., 2023). These techniques are fully distributed and include: discriminating server selection, max flow based subjective reputation, and adaptive stranger policies (Le et al., 2021; Thakkar & Lohiya, 2023). Through simulation, some studies showed that these techniques can drive a system of strategic challenges that P2P systems pose: large populations, high turnover, and asymmetry of interest, collusion, zero-cost identities, and traitors (Ballester, 2015).

MATERIALS AND METHODS

Mathematical Models of Torrent System

Consider a torrent system where a file of fixed size X MB is shared by swarm of peers (downloaders). Let $N_1(t)$ be number of leechers in the considered system and $N_2(t)$ be the number of seeds in the systems at a time, where $t \geq 0$. The leechers join the system with rate λ. Let's assume that all peers (leechers and seeds) in the system have equal upload bandwidth U kbps and equal download bandwidth D kbps, to ensure system's full functionality let $D \geq 0$.

A leecher can quit or cancel the download process at any time for one reason or the other, for instance, the file download process is taking too long and a leecher can no longer have the patience to wait (in this case a leecher is called an impatient leecher), application failure, hardware failure, etc (Lui et al., 2004). Let μ_1 be the rate at which leechers abort the download process. A leecher that successfully downloaded the entire file's fragments may decide to exit the system or remain in the system and eventually becoming a seed. Therefore, Leecher's exit may occur as a result of two events, i.e., file-download completed successfully or file-download cancellation (voluntarily or involuntarily). Let μ_1 be the rate at which seeds exit the system. It is important to note that the more the number of seeds in the system the more upload capacity (resources) the system will have. Additionally, if large number of seeds are exiting the system there will be a tendency that some file fragments will be nowhere to be found throughout the system, because the seeds having them are out of the system, and this will lead to the system death, even if it is one and only one fragment missing. Hence, it is paramount to have an incentive mechanism to motivate seeds to remain in the system. Let $\varepsilon = 1 - \rho$, $0 \leq \varepsilon \leq 1$ and $0 \leq \rho \leq 1$, where ρ is free riding factor (which shows the fraction of free riding leechers in the system) and ε is non-free riding factor (which reflects the fraction of leechers that actively participate in data uploading process, i.e., not free riding). Unfortunately, many existing file sharing systems do not have incentive mechanisms to motivate seeds to remain and to encourage leechers to participate actively in data upload (Ekwonwune and Ezeoha, 2029).

Furthermore, assume that the upload and download bandwidths are normalized in relation to the file size. To this end, let υ and δ represent the normalized upload and download rate respectively. Hence the entire system is characterized by the previous system's parameters and is presented as follows:

$$Q = \langle N_1(t), N_2(t), \lambda, \mu_{1,} \mu_{1,} V, \delta, \varepsilon \rangle \quad (1)$$

Then the system total upload rate is

$$\xi = (\varepsilon N_1(t) + (N_2)(t), \; \varepsilon \geq 0 \quad (2)$$

If $\varepsilon = 0$, then leechers do not upload data to each other, instead they only download data from the available seeds in the system, and in this all the available upload capacity comes only from the seeds.

The system total download rate is

$$\eta = \delta N_1\,(t) \quad (3)$$

The system may operate in two possible scenarios as follows:

Scenario A: When download speed is the constraint, i.e., $\xi \geq \eta$ (Figure 1).

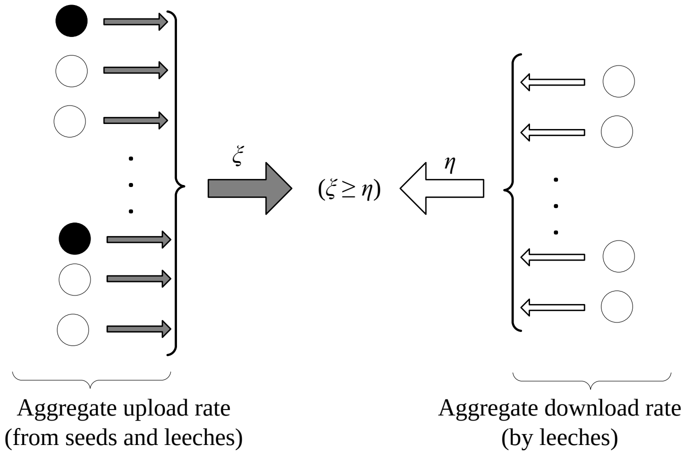

Figure 1: System with Download Speed as Constraint

Scenario B: When upload speed is the constraint, i.e., $\eta \geq \xi$ (Figure 2).

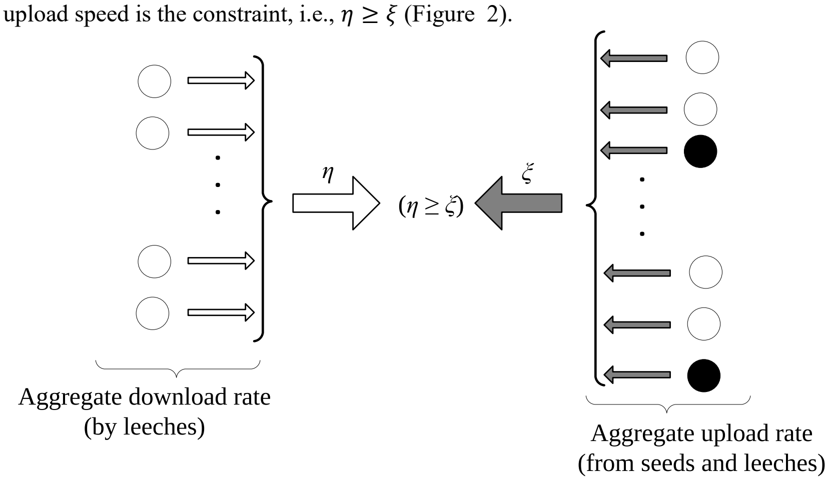

Figure 2: System with upload speed as a constraint

Since our target system's QoS parameter is the file download time similar to the work of He, Li and Cheng (2018); Huang Lin and Zhang (2023), and the system's resources that has direct impact on that QoS parameter is total upload rate in the system (from both leechers and seeds). For scenario A, the system's total upload rate is given by equation (1).
For scenario B the system's total upload rate is min $\{\eta, \xi\}$.

Some leechers can cancel the download process. Let's assume that a leechers quit the download process after a given time which is exponentially distributed with mean μ_1^{-1}. The parameter μ_2 is rate at which seeds exit the system. Let's assume that a seed independently exits the system after a given time which is exponentially distributed with mean μ_2^{-1}. Therefore, the system transition diagram is expressed in Figure 3.

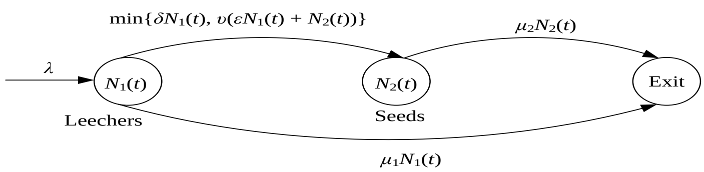

Figure 3 - System transition diagram

A study based on reciprocal incentive mechanisms by Vanitha and Valli (2016) and Neglia et al (2007) explored the principle of tit-for-tat, where users only exchange files with those who have previously exchanged files with them. This mechanism can prevent free-riding by creating a direct link between the benefits and costs of sharing files. However, it also has some limitations, such as low efficiency, high overhead, and vulnerability to collusion and sybil attacks (Lai, Feldman and Stoica, 2003; Feldman, Lai and Stoica, 2004).

The model describing the change in number of leechers and seeds in the given swarm of peers is given by the following system of differential equations

$$\begin{cases} \frac{dN_{1}(t)}{dt} \text{-} \lambda - \left(min\{\delta N_1(t), \nu(\delta N_1(t) + N_1(t))\} + \mu_1 N_1(t)\right) \\ \frac{dN_{2}(t)}{dt} \text{-} min\{\delta N_1(t) + N_2(t))\} - \mu_1 N_1(t) \end{cases} \quad (4)$$

Further, let's assume that the system is in stationary state, i.e, $\frac{dN_1(t)}{dt} = \frac{dN_2}{dt} = 0$, where (n_1, n_2) is the stationary point. Then, system of equations given in (3.1) will transform to the following

$$\begin{cases} 0 = \lambda - min\{\delta n_1, \nu(\varepsilon n_1 + n_2)\} \\ 0 = min\{\delta n_1, \nu(\varepsilon n_1 + n_1)\} - \mu_2 n_2 \end{cases} \quad (5)$$

For $\varepsilon > 0$, let's consider the first scenario A, i.e.

$$\delta n_1 \le \nu(\varepsilon n_1 + n_2) \quad (6)$$

In this case, going by the work Habib and Chuang (2004), the systems of equations given by (2) will turn to the following system of algebraic expressions

$$\begin{cases} 0 = \lambda - \delta n_1 - \mu_1 n_1 \\ 0 = \delta n_1 - \mu_2 n_2 \end{cases} \quad (7)$$

By solving (3) will have the following solutions

$$\begin{cases} n_1 = \frac{\lambda}{\delta\left(1+\frac{\mu_1}{\delta}\right)}, \\ n_2 = \frac{\lambda}{\mu_2\left(1+\frac{\mu_1}{\delta}\right)} \end{cases} \quad (8)$$

Having (2), then (4) will have the form

$$\frac{1}{\delta} \ge \frac{1}{\varepsilon}\left(\frac{1}{\nu} - \frac{1}{\mu_1}\right) \quad (9)$$

Further, let's consider scenario B, i.e.

$$\delta n_1 \ge \nu(\varepsilon n_1 + n_2) \quad (10)$$

With (4), then (5) will have the form

$$\begin{cases} 0 - \lambda - \nu(\varepsilon n_1 + n_2) - \mu_1 n_1 \\ 0 - \nu(\varepsilon n_1 + n_2) - \mu_1 n_2 \end{cases} \quad (11)$$

By solving (11), we will have the following solutions

$$\begin{cases} n_1 - \frac{\lambda}{\omega\left(1+\frac{\mu\ 1}{\omega}\right)}, \\ n_2 - \frac{\lambda}{\mu_2\left(1+\frac{\mu\ 1}{\omega}\right)}, \end{cases} \quad (12)$$

Where $\frac{1}{\omega} = \frac{1}{\varepsilon}\left(\frac{1}{\nu} - \frac{1}{\mu_2}\right)$. From equation (6), we will have

$$\frac{1}{\delta} \le \frac{1}{\omega} = \frac{1}{\varepsilon}\left(\frac{1}{\nu} - \frac{1}{\mu_2}\right) \quad (13)$$

Let's introduce another parameter to unite the two obtained solutions above, i.e. (4) and (8) as follows

$$\frac{1}{k} = max\left\{\frac{1}{\delta}, \frac{1}{\varepsilon}\left(\frac{1}{\nu} - \frac{1}{\mu_2}\right)\right\} \quad (14)$$

Having (3.11), therefore, using (4) and (8) together will form (12)

$$\begin{cases} n_1 - \frac{\lambda}{k\left(1+\frac{\mu_1}{k}\right)}, \\ n_2 - \frac{\lambda}{\mu_1\left(1+\frac{\mu_1}{k}\right)}, \end{cases} \quad (15)$$

Average file download time in file sharing system is given by

$$T = \frac{1}{\mu_1 + K} \quad (16)$$

Where $\frac{1}{k} = max\left\{\frac{1}{\delta}, \frac{1}{\varepsilon}\left(\frac{1}{\nu} - \frac{1}{\mu_2}\right)\right\}$

Proof: From the model the parameter λ is the rate at which leechers arrive in the system and $\mu_1 n_1$ is the rate at which leechers quit or cancel the download process for some reasons. Then $\lambda - \mu_1 n_1$ is the average number leechers that remain in the system to the end of the download process and eventually becoming seeds. Subsequently it is clear that $\lambda - \mu_1 n_1$ is the average rate of downloads completions. From the Little's law, we will have

$$\frac{\lambda - \mu_1 n_1}{\lambda} n_1 = (\lambda - \mu_1 n_1)T \quad (17)$$

Where T is the average file download time, $\lambda - \mu_1 n_1$ the rate of downloads completions, and $\frac{\lambda - \mu_1 n_1}{\lambda}$ is the fraction of leechers that will turn to seeds. From (17) we will have

$$\frac{n_1}{\lambda} = T \quad (18)$$

Considering (16), we will have, therefore

$$T = \frac{1}{\mu_1 + k}$$

Workflow of the system

Let us say we have an array A that contains all the states a leecher can assume.

A = [uploadFile, downloadFile, cancelDownload, leave]

Also, let N be a set of leechers in a swarm. Then, the pseudocode of the algorithm will be:

```
Initialize A
For each leecher i where i belongs to N
    Determine the utility (ui) of the ith node
    If ui = A[uploadFile]
        Increment the node's incentive score
     End if
End for loop
```

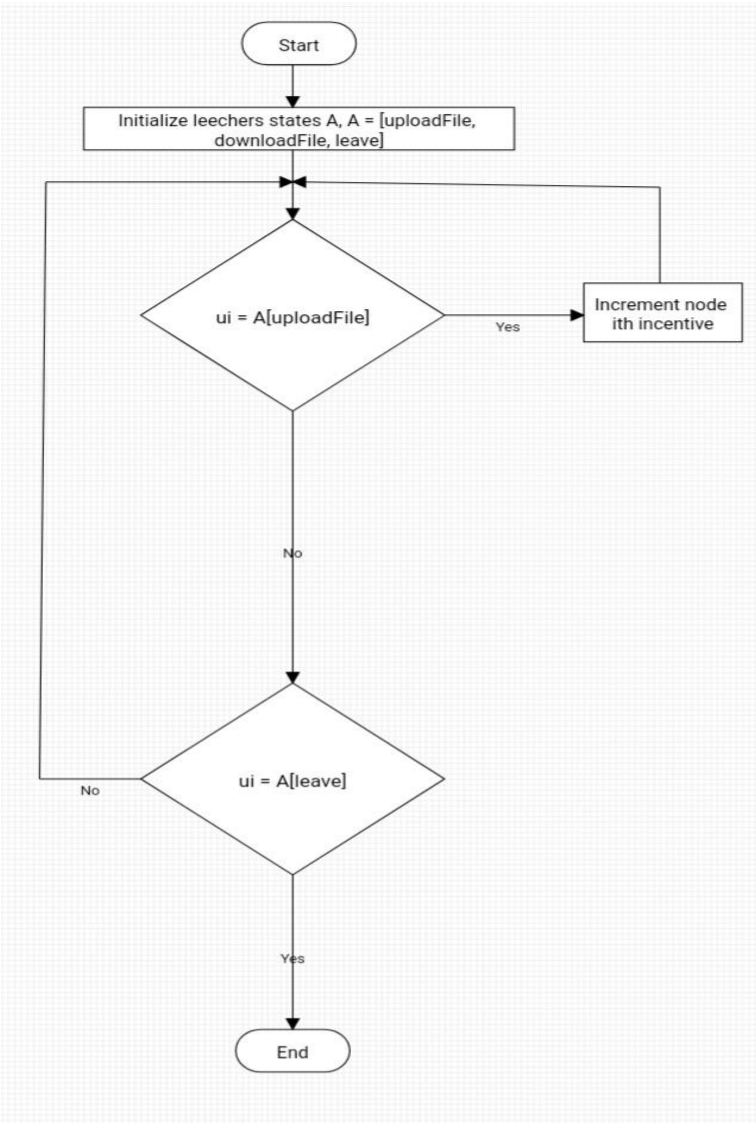

Figure 4: Flowchart of the proposed scheme

RESULTS AND DISCUSSION

To determine the effectiveness of the proposed scheme, three metrics: free-riding factor, average file download time and rate at which leechers exit the network were considered to measure its performance against its counterpart, which is non-incentive file sharing scheme. Graphs where created using MATLAB

Free-riding factor

This factor determines the adverse effect of free-ridding and how it would improve the performance of the system. As in the work of Hernandez-Oregon et al (2023) and Zhao et al. (2008), to measure the free-ridding factor, average file download time is used against the coefficient of leechers participation.

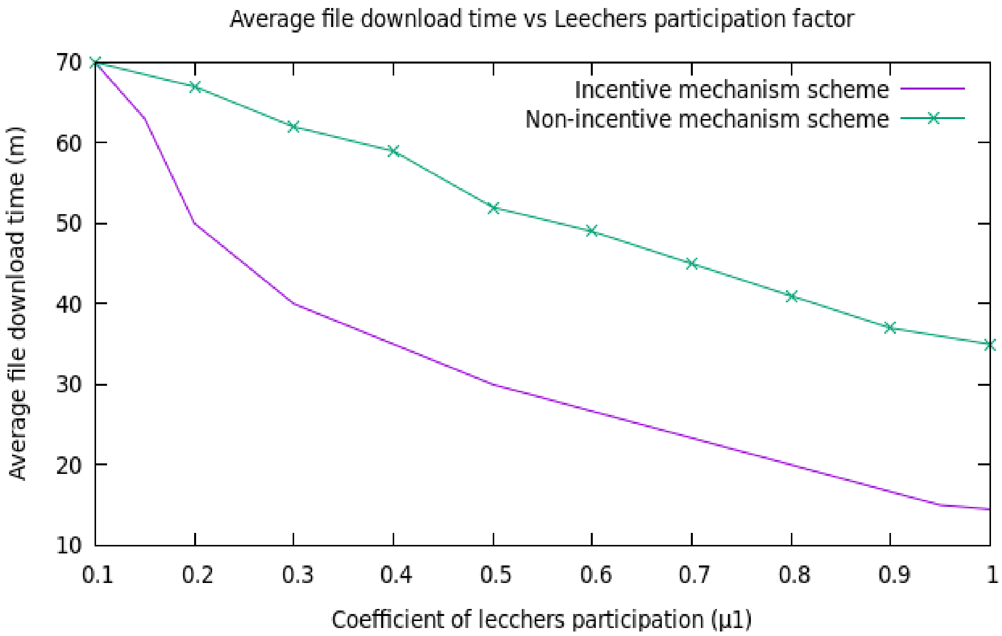

Figure 5. Free-riding factor of the systems

This metric was determined by equation (1) where λ is the nodes arival rate and μ_1 is the leechers departure rate. From the graph of figure 4 above, it can be observed that in the case of incentive scheme, the average number of leechers for cooperating increase steadily with time.

Thus, free-riding factor can manifest in various ways, particularly in distributed systems and networks. He In peer-to-peer networks or distributed systems, some nodes may consume resources (such as bandwidth, processing power, or storage) without contributing their fair share. This can lead to congestion, slower performance, or even system failures if a few nodes disproportionately consume resources.

However, to improve the performance of the system in the face of free-riding, this study considers introduction of incentives for nodes or users to contribute to the system. For example, in peer-to-peer networks, nodes that contribute resources could be rewarded with preferential access or reputation points. In open-source projects, contributors could receive recognition, access to exclusive features, or financial rewards.

File download time

The system's scenario B was considered, i.e., where the upload bandwidth is the system's constraint as it is the case for the majority of Internet connections and the following parameters were used. The rate of leechers' arrival into the system is defined by Poisson distribution as used by Trautwein et al. (2022), a file of size 512 MB was considered and the average upload bandwidth is 100 kbps. Minute is chosen as a time measurement, then the average upload bandwidth is 6000 kb/minute. By normalizing the upload bandwidth to the file size, then the average upload rate is $\upsilon = 0.0014$. The leechers quit the download process with rate $\mu_1 = 0.0014$. Since the second scenario was chosen for the analysis, then $\delta = 1$.

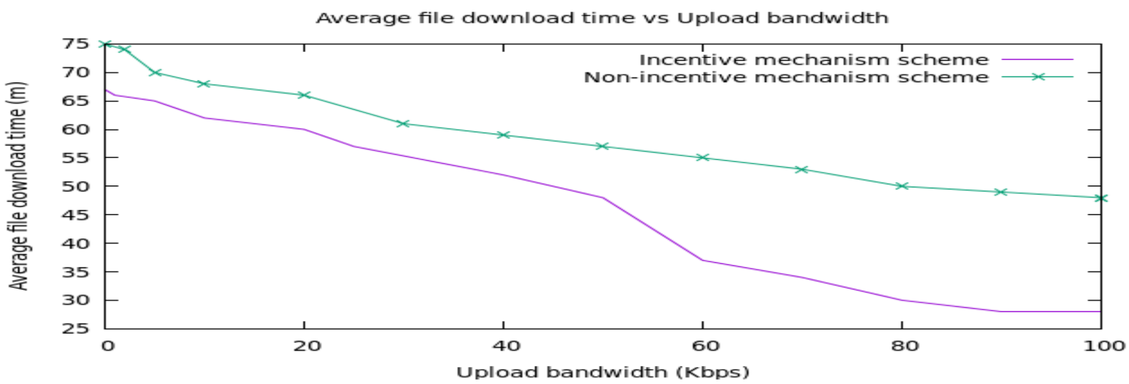

Figure 6: Average file download time against the system's upload bandwidth

The graph shows that leechers obtain incentive pieces steadily in the incentive-based mechanism, when they start to share their file chunks. This is case when upload bandwidth is the constraint, i.e., $\eta \geq \xi$ (Equation 3).

On the other hand, the download bandwidth is the capacity of the channel through which a peer can download data. The upload bandwidth is the capacity at which a node can upload data to other nodes through a network.

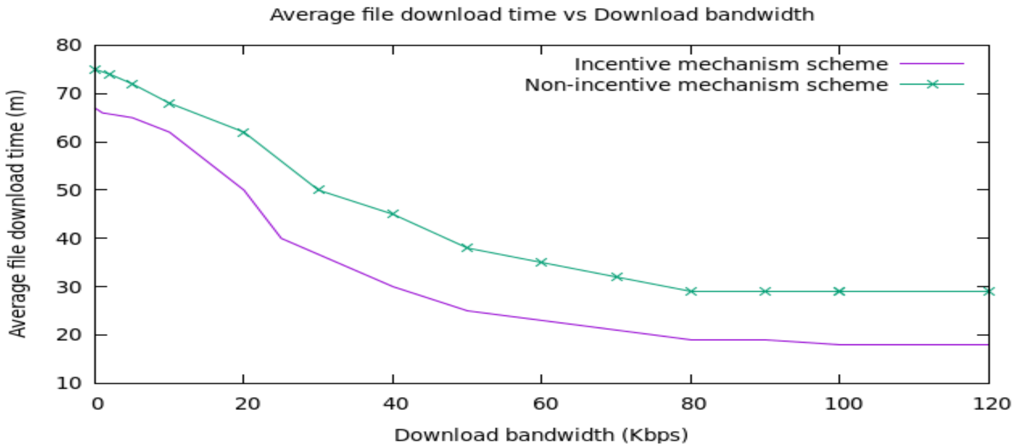

Figure 7: Average file download time against the system's upload bandwidth

The above result was derived from equation 3 the system total download rate is $\eta = \delta N_1(t)$ when download speed is the constraint, i.e. $\xi \geq \eta$. The result in Figure 4. Above shows that as leechers gain in more incentives and continue to share their file chunks, the bandwidth (δ) increases which consequently decreases the download time.

Rate at which leechers are converted to seeds
As found in the work of Lin et al. (2021), this metric is measured in download time against rate at which leechers exit the system without becoming seeds.

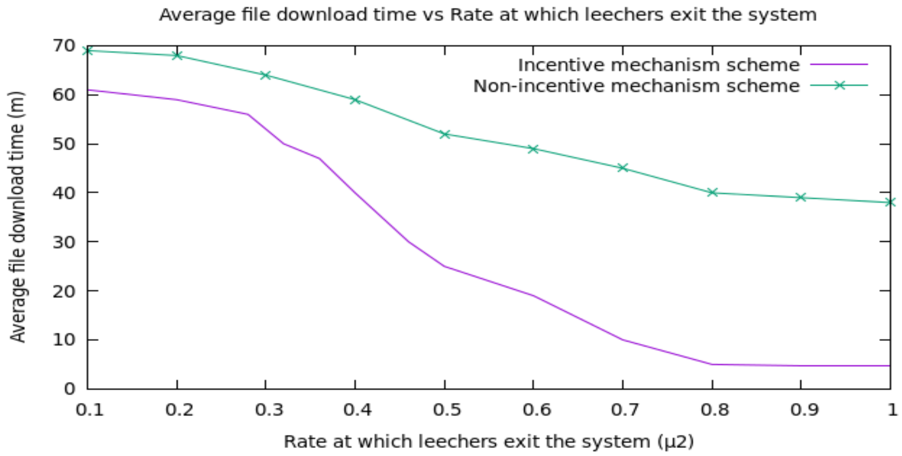

Figure 8: Average file download time against the rate at which leechers exit the system

Since it is assumed in equation 3.1 that $N_1(t)$ is number of leechers in the system and $N_2(t)$ the number of seeds in the systems at a time $t \geq 0$ and leechers join the system with rate $t \geq 0$. Then equation 3.2 is used to model the transformation of leechers to seeds in a given swarm.

CONCLUSION

A major finding of this study is that the implementation of incentives results in a greater level of participation among leechers. Furthermore, increased leecher participation and data dissemination correlate with a reduction in file download time. Additionally, when the upload bandwidth (δ) is augmented, the file download time decreases. However, once δ reaches a threshold as defined by equation 3.13, further increases in δ do not lead to a decrease in file download time; instead, the download time remains constant, indicating that δ is no longer a limiting factor.

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