Stable, scalable, decentralized P2P file sharing with non-altruistic peers

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Abstract—P2P systems provide a scalable solution for distributing large files in a network. The file is split into many chunks, and peers contact other peers to collect missing chunks to eventually complete the entire file. The so-called ‘rare chunk’ phenomenon, where a single chunk becomes rare and prevents peers from completing the file, is a threat to the stability of such systems. Practical systems such as BitTorrent overcome this issue by requiring a global search for the rare chunk, which necessitates a centralized mechanism. We demonstrate a new system based on an approximate rare-chunk rule, allowing for completely distributed file sharing while retaining scalability and stability. We assume non-altruistic peers and the seed is required to make only a minimal contribution.

I. INTRODUCTION

The marvel of peer-to-peer (P2P) networks is their scalability and robustness. Both of these attributes are due in turn to the distributed nature of such systems. In a P2P file sharing system such as BitTorrent [1], a large file is split into many chunks. A peer who downloads a chunk can immediately start uploading that chunk to other peers, contributing to the resource pool of the sharing network.

To ensure the availability of all chunks of the file at all times, at least 1 seed (who has the complete file) is assumed to stay in the network at all times. However, in an open system, where peers are arriving according to a random arrival process, the presence of a single seed does not guarantee stability. It has been observed and demonstrated through various analytical models ([2], [3], [4], [5]) that if the peers contact each other and download chunks in a purely random fashion, a single chunk might be driven to near extinction, causing peers to stay in the system for a long time and driving the number of peers in the system to infinity. In this scenario, the rare chunk is difficult to obtain, because there is a high probability that the randomly contacted peer does not have it, and peers who have the rare chunk tend to leave the system quickly since they probably already have every other chunk. Thus the rare chunk becomes progressively rarer as new peers accumulate.

It is known that the rare chunk issue can be avoided through altruistic behavior of the peers [5], [6]. In this model, peers who complete the file stay in the system for an additional random time to aid the remaining peers. It has recently been proven [7] that it is sufficient for peers to remain in the network for a time that is on average equal to the time it takes to download a single chunk. Unfortunately in real networks, the altruistic peer assumption may not hold.

A similar stabilizing effect is observed if the upload capacity of the seed is large enough to maintain a balanced chunk distribution in the system [8], [7]. However, in such scenarios, the demand on the seed scales with the number of peers in the system, reducing the scalability of the protocol.

BitTorrent addresses the ‘rare chunk’ issue by forcing peers to download the rarest chunk first. This rule necessitates a centralized search in the network to track the rarest chunk, and the peers who possess that chunk. The tracker is the only centralized piece in the BitTorrent protocol, and presents a single point of failure for the system. It is desirable to replace this mechanism by a distributed rule that approximates the ‘rarest chunk first’ rule for downloads.

In this paper, we present a new P2P file sharing protocol that is provably stable. Our protocol is completely distributed, and fully scalable, avoiding the pitfalls of a centralized tracker or a privileged seed. Moreover, we assume that peers who complete the download leave immediately. Stability depends on a probabilistic local rule that peers follow to approximate prioritizing the rare chunk.

We model an open system, where peers are arriving according to a Poisson process. In our model, the current chunk profiles of all the peers in the system defines the state for a Markov process. This is in line with the model described in [8]. In contrast with deterministic fluid models such as the one used in [6], we attempt to directly prove the stability of the dynamic system. This approach is more reassuring, as a well defined relationship between the stability of the dynamical system and that of the fluid models is yet to be formulated [3]. Our model and assumptions are detailed in section I.

The protocol is presented in section III. It is a modification of the ‘majority’ rule that was first proposed in [9], [10], where the authors used simulations and large system limits to argue that the rule leads to a stable system. We have since been able to formally prove stability for the special 2-chunk case [3] (see section V for a brief discussion), however stability for the general case remains a conjecture. Our proposal implements a stricter rule to keep the rare chunks in the system longer,
and allows us to prove stability in general for any number of chunks and any arrival rate. The proof, presented in section [V], employs an unconventional Lyapunov function, which is the main contribution of this paper together with the new protocol. The form of the Lyapunov function is quite novel and might be useful in proving the stability of similar algorithms.

II. PROBLEM DEFINITION

A file is divided into \( k \) chunks, to be distributed in a P2P system. Peers enter the system at Poisson rate \( \lambda \) and leave immediately upon receiving all \( k \) chunks. We make the following assumptions:

- There is always exactly 1 seed in the system (denoted by \( s \)), who has all the chunks.
- At a Poisson rate of 1, each peer can sample randomly with replacement up to 3 peers from the current population \( U \cup \{ s \} \). (A peer is allowed to sample itself.)
- At the time of sampling, the peer can choose to download at most 1 chunk which it does not already have, but shows up in the sample. The download is assumed to happen instantaneously.
- A newly arriving peer arrives with no chunks.

Let \( S \) be the total number of peers in the system (including the seed). Note that each peer (including the seed) can be sampled, on average, at most by three other peers per unit time. Therefore the average upload bandwidth per peer is bounded, and does not scale with \( \lambda \) or \( S \).

We seek a rule by which a peer can decide which chunk (if any) to download at each time slot from the current sample. However the rule we propose will not depend on these. We require that the chosen rule stabilizes the stochastic system in the Lyapunov sense.

III. SOLUTION: COMMON CHUNK PROTOCOL

Let \( S_i = \# \) peers who have chunk \( i \) including the seed, \( i \in \{1, \ldots, k\} \).

- \( S_0 = \# \) peers who have no chunks.
- \( S_i = S - S_i \).
- \( T_i = \# \) peers who have only chunk \( i \) missing.

**Definition 3.1:** A chunk in a sample of 3 peers is rare if exactly 1 peer in the sample has that chunk. A chunk is called a match if it is contained in the sample but not in the sampling peer’s profile.

We define the rule as follows:

- Peers with no chunks sample 3 peers at random and choose to download a chunk that is a rare match. If there is more than 1, they pick randomly among them. If there are no rare matches, the peer skips this time slot without downloading.
- Peers who have more than zero, but less than \( k - 1 \) chunks sample only 1 peer at random, and download a chunk at random among those that match (no rare match required). Skip if there is no match.
- Peers who have \( k - 1 \) chunks sample 3 peers at random. Download only if every chunk that the peer has appears at least twice in the sample, and there is a match. Otherwise skip without downloading.

Roughly, the first item is meant to stop arriving peers from acquiring a common chunk as their first chunk. The last item attempts to keep rare chunks from leaving the system. This should balance out the chunk distribution in the system and provide stability.

Note that by sampling only 3 peers, we are requiring the bare minimum that allows a majority rule. By sampling more peers, one could clearly do better, however our main purpose here is to demonstrate that stability is possible even in this restricted setting. We discuss sampling more peers and other performance enhancing heuristics in section [V].

In this paper, we model the proposed system by a Markov process with state space \( \mathcal{X} \) described by the peers currently in the system and their chunk profiles. The description of the state space is essentially identical to that in [8]. Let \( q(x, x') \) denote the entries of the generator matrix of this Markov process. For any function on the state space,

**Definition 3.2:** The drift \( \Delta f(x) \) of a function \( f(x) \) is defined as

\[
\Delta f(x) = \sum_{x' \neq x} q(x, x')(f(x') - f(x)).
\]

We use the following well known tool for the proof:

**Theorem 3.3:** [Foster-Lyapunov] Let \( L \) be a function on the state space with drift \( \Delta L \). Let \( L \geq 0 \) and let \( \{ L \leq l \} \) be a finite set for any finite constant \( l \). If for any \( \epsilon > 0 \), \( \Delta L < -\epsilon \) on the set \( S > c \), for a suitably chosen constant \( c \), then the Markov process is positive recurrent.

IV. PROOF OF STABILITY

We will split the proof into two cases according to whether \( \lambda \leq \frac{1}{3\epsilon} \) or \( \lambda > \frac{1}{3\epsilon} \). In each case, we will show the stability of this system by demonstrating a Lyapunov function for it.

Let \( r \) be the total rate of downloads. \( dS^+ \) is the virtual rate (stochastic intensity) at which a peer with no chunks downloads chunk \( i \), and \( dS^- \) is the virtual rate at which a peer who is lacking only chunk \( i \) downloads and leaves the system. We will need the following lemmas:

**Lemma 4.1:** \( r \geq \frac{S_i^2}{S} \) where \( r_0 = \sum_j dS_j^+ \).

**Proof:** Write \( S_i = S_0 + B_i + T_i \) to define \( \bar{B}_i, \bar{B}_i \) is the number of peers who lack chunk \( i \) and have at least 1 and at most \( k - 2 \) chunks. We can write

\[
r \geq S_0 d(S_0) + T_i d(T_i) + B_i d(B_i)
\]

where \( d(\cdot) \) denotes the virtual rate of downloads for an individual peer in each group. By definition, \( d(S_0) = \sum_i dS_i^+ \geq dS^+_j \) for any \( j \). Also

\[
d(T_i) \geq \frac{3T_i^2}{S^3} S_i \geq \frac{T_i^2}{S_i^3} 3S_i^2 S_i S^3 \geq \frac{T_i^2}{S_i^3} dS_i^+
\]

where the last inequality follows because \( \frac{3S_i^2 S_i}{S^3} \) is the probability of a rare match, but \( dS_i^+ \) might be smaller due to
the possibility of multiple rare matches. It is left to note that $d(B_i) \geq \frac{dS^+_{i}}{3}$. To argue this, note that $d(B_i)$ is the total virtual rate of downloads per peer for peers in $B_i$, and a sample of chunk $i$ is sufficient to result in a download (even if chunk $i$ is not chosen to be downloaded). The probability of sampling chunk $i$ in 1 go is at least $\frac{1}{3}$ the probability of sampling chunk $i$ in 3 tries, which in turn at least as large as $dS^+_i$. We can now write

$$r \geq (S_0 + \frac{1}{3}B_i + dS^+_{i} + \frac{T_3 i}{S^+_i}) \geq \frac{S_i}{6}dS^+_i.$$ 

Here we argue that $x + y + z = 1 \implies x + \frac{y}{3} + z^3 \geq \frac{1}{6}$. Therefore

$$r \geq \max_i \frac{S(dS^+_i)^2}{6} \geq \frac{r^2 S}{6k^2}. \tag{4.2}$$

**Lemma 4.2:**

$$r \geq \min_i \frac{S_i}{2k^3}, \text{ if } S \geq 12.$$

**Proof:** Argue as in the previous lemma that for $S_0$, a rare match of $i$ is sufficient for a download. For $B_i$, a simple match is sufficient and $\frac{S_i}{S^3} \geq \frac{S^2 S^{-1}}{S^3}$. Therefore

$$r \geq (3S_0 + B_i + \frac{T_3 i}{S^3}) \geq 3\frac{S_i}{S^3} \geq \frac{2S^3 S_i}{3S^3}, \text{ for any } i.$$ 

Here we argue that $x + y + z = 1 \implies x + \frac{y}{3} + z^3 \geq \frac{2}{3}$. Since $\max_i \frac{S_i}{S^3} \geq \frac{S^{-1}}{k^3}$, we have the result when $S \geq 12$. We consider first the case $\frac{S_i}{S^3} \geq \frac{1}{3\epsilon}$.

We propose:

$$L_1 = \sum_i S_i$$

The drift of $L$ is

$$\Delta L_1 = k\lambda - r \leq \frac{1}{3} - r.$$ 

From **Lemma 4.2** we know

$$r > \frac{S^3 S_i}{2S^3}, \text{ for any } i.$$ 

Picking $i$ to be the rarest chunk, we observe that $r > \frac{1}{3} + \epsilon$ whenever $S > 3k^3$.

Now assume $\lambda \geq \frac{1}{3\epsilon}$.

We propose:

$$L = C \sum_i S_i + \sum_i \frac{S}{e^{S_i}} + \frac{S}{e^{S_0}}$$

where $C$ is a constant to be chosen later.

We will calculate the drift of $L$ in two parts. A download of chunk $i$ decreases $S_i$ by one and leaves all other $S_j$ unchanged. A new arrival increases each $S_i$ by one. Therefore

$$\Delta L_1 = k\lambda - r.$$ 

Also

$$\Delta L_2 \leq \sum_i \frac{\lambda}{e^{S_i}} - \lambda \left( \frac{S}{e^{S_0}} - \frac{S + 1}{e^{S_0 + 1}} \right) \leq \sum_i \frac{S_0 S_0 S_0}{e^{S_0}} \left[ \frac{1}{e^{S_0}} - \frac{1}{e^{S_1 + 1}} + \frac{1}{e^{S_0}} - \frac{1}{e^{S_0 - 1}} \right]$$

$$+ \sum_i \frac{T_1 dS^+_i}{S_{i}^3} \left( \frac{S - 1}{e^{S_0}} - \frac{S}{e^{S_0}} \right)$$

The first two terms correspond to the the arrival of a new peer. The second term is the drift due to a peer with no chunks downloading chunk $i$. The last term corresponds to the event where a peer leaves the system after having downloaded chunk $i$.

The inequality is due to the fact that we omitted terms corresponding to transitions which keep $S$ and $S_0$ constant, and in the last set of terms, for each individual $i$ we ignored the terms corresponding to $S_1$ and $S_0$. These transactions can only decrease $L_2$.

Since $dS^-_i \leq \min_{j \neq i} \frac{3S_i}{S^3}$ and $T_i \leq S_j, \forall j \neq i$, the last term satisfies

$$\sum_j \left( \frac{S - 1}{e^{S_j - 1}} - \frac{S}{e^{S_j}} \right) \sum_{i \neq j} T_i dS^-_j$$

$$\leq \sum_j 3(e - 1)(k - 1) \frac{S_3 S}{S^3} < \frac{8k^2}{S}. \tag{4.3}$$ 

We get

$$\Delta L_2 < \sum_i \frac{\lambda}{e^{S_i}} + \frac{\lambda}{e^{S_0}} - \lambda(e - 1)S$$

$$+ \sum_i \frac{(e - 1)S_0 S_0 S_0}{e^{S_0}} \left[ \frac{1}{e^{S_0}} - \frac{1}{e^{S_1}} \right] + \frac{8k^2}{S}$$

Since $\sum \frac{1}{e^{S_0}} + \frac{1}{e^{S_0}} < (k + 1)\lambda$, we may write

$$\Delta L < \frac{8k^2}{S} + \lambda + (C + 1)k\lambda - Cr - \lambda(e - 1)S$$

$$+ \sum_i \frac{(e - 1)S_0 S_0 S_0}{e^{S_0}} \left[ \frac{1}{e^{S_0}} - \frac{1}{e^{S_1}} \right]$$

Now we are ready to show **Theorem 4.3:**

$$\Delta L \leq -\epsilon$$

with $\epsilon > 0$ and $C = 108e^{k^3}$ whenever $S > 4Ce^{3k^3} e^{6e^{4k^3}}$.

**Proof:** Since we assume that $\frac{8k^2}{S} < 1$, we are left with 5 terms which can be written as

$$\Delta L < [1 + \lambda + (C + 1)k\lambda] - Cr - \lambda(e - 1)S$$

$$+ \sum_i \frac{(e - 1)S_0 S_0 S_0}{e^{S_0}} - \sum_i \frac{(e - 1)S_0 S_0 S_0}{e^{S_1}}$$

- If $r \geq 2k\lambda$;
- If $(e - 1)S_0 S_0 S_0 \geq \frac{Cr}{3}$. Then $r_0 \leq \frac{S_0}{6e^{k\lambda}}$ by lemma 4.1 and $r_0 S_0 \leq \frac{S_0}{6e^{k\lambda}} < \frac{1}{5k}$. The third and
fourth terms give at most \(-\frac{(e-1)(\lambda-1/k)S}{e^e}\), which is negative. Since \(r \geq 2k\lambda\), we’re done.

- If \(\frac{(e-1)S_0 r_0}{e^e} < C_1\), we have

\[
\Delta L < 1 + \lambda + (C + 1)k\lambda - \frac{4}{3}CkL < -\epsilon.
\]

- If \(r < 2k\lambda\), then by lemma 4.2, \(\exists J \subseteq \mathbb{R}^r\) such that \(dS_i^+ > \frac{2\delta^2}{k^2}\), the last term is at most \(-\frac{3}{e^{3/2}}\). Here we used the bound \(\frac{3(e-1)S_i^2}{e^e} > 1\).

- If \(\frac{(e-1)S_0 r_0}{e^e} \geq \frac{C_1}{3}\); then \(r_0 S_0 \leq \frac{S_0^3}{6e^e e^e} < \frac{C_3}{3}\). The third and fourth terms give at most \(-\frac{(e-1)(\lambda-1/k)S}{e^e}\), which is negative. If \(S_0 \geq 3C\lambda^2e^{6k\lambda}\), the last term is less than \(-\frac{1}{2}Ck\lambda\), and

\[
\Delta L < 1 + \lambda + (C + 1)k\lambda - \frac{3}{2}Ck\lambda < -\epsilon.
\]

Else \(S_0 < \frac{3C\lambda^2e^{6k\lambda}}{2e^e e^e}\), so we would have

\[
\Delta L < 1 + \lambda + (C + 1)k\lambda - \frac{2(e-1)}{e}Ck\lambda < -\epsilon
\]

since \(\frac{2(e-1)}{e} > \frac{5}{4}\).

- If \(\frac{(e-1)S_0 r_0}{e^e} < \frac{C_1}{3}\), we can omit the second and fourth terms which add up to \(\frac{(e-1)S_0 r_0}{e^e} - C\epsilon < 0\). Again by the reasoning as above, if \(S_0 \geq 3C\lambda^2e^{6k\lambda}\), the last term is less than \(-\frac{1}{2}Ck\lambda\), and

\[
\Delta L < 1 + \lambda + (C + 1)k\lambda - \frac{3}{2}Ck\lambda < -\epsilon.
\]

Else \(S_0 < \frac{3C\lambda^2e^{6k\lambda}}{e^e e^e}\), so we would have

\[
\Delta L < 1 + \lambda + (C + 1)k\lambda - \frac{2(e-1)}{e}Ck\lambda < -\epsilon
\]

since \(\frac{2(e-1)}{e} > \frac{5}{4}\).

It is clear that both Lyapunov functions that are used satisfy the properties of theorem 3.3. We conclude that the proposed system is positive recurrent for any value of \(\lambda\).

V. PERFORMANCE

From a performance point of view, some aspects of the protocol may strike the reader as inefficient. In particular, the rule for leaving the system is quite strict, and may cause substantial delay for the peers that have all but one chunk. Consider a state where most of the peers have a few or no chunks. A sample of 3 peers needs to contain at least \(2k - 1\) chunks (1 for the missing chunk, 2 each for the rest) for apeer to be able to leave the system. Therefore a peer with \(k - 1\) chunks will need to wait in the system, until the system becomes more saturated.

On the other hand, this ensures availability of all chunks to other peers, and reduces starvation in the network. This rule can be interpreted as forcing a degree of altruistic behavior and has a similar effect in terms of stability.

A. m-sampling

The rule for the peers that have all but one chunk can be eased as follows. A peer in \(T_i\) samples \(m\) peers at random with replacement instead of 3. Allow a download only if each chunk other than \(i\) is observed at least twice in the sample of \(m\) peers. This would ensure none of the chunks which leave are rare. Sampling more peers increases the complexity of the system (decreases locality), but allows for a more efficient search (peers could leave earlier). One could pick \(m\) to strike a good trade-off between complexity and performance.

The proof of stability generalizes to this case with little modification. In (1), note that \(dS_i^- \leq \min_j \left( \frac{m}{2}S_j^2 \right)\), Therefore the last term would be bounded by \(\frac{m}{2}S_j^2\), which can be bounded by 1, provided we modify the bound on \(S\) in theorem 4.3 with \(\frac{m}{2}\). The rest of the proof goes through unaltered.

B. Rare chunk rule

The original rule proposed in \([9, 10]\) was as follows: All peers sample 3 other peers with replacement, and download only if there is a rare match. As noted before, this is a minimalist approach to approximation by a majority rule. The difficulty that arises in trying to prove the stability of this system is that the majority rule does not in general favor the rare chunk, but rather inhibits the common chunk. These two goals turn out to be identical in the special 2-chunk case, for which it has been possible to find a Lyapunov function:

**Theorem 5.1:**

\[
L = 2(S_0 + S_1 + S_2) + (S_1 - S_2)^2, \quad S > 30\lambda(20\lambda + 1)^2
\]

is a valid Lyapunov function for the 2-chunk system with the rare chunk rule described above.

In the interest of keeping our focus, we omit the proof of this result. We will only remark that the first term will be decreasing whenever there is sufficient balance in the system, and the second term turns out to be always decreasing due to the rare chunk rule, and makes up for the increase in the first term when the system is in severe imbalance.

C. Simulations

We compare our proposed algorithm with the parameter \(m\) taking the values \(\{3, 5, 10\}\), \(m = 3\) is the original protocol proposed in section III with the rare chunk rule.

Figure 1 shows a system with 20 chunks and \(\lambda = 10\). At time 0, only the seed is present. We can see all four systems reaching a stable state. The total number of peers for \(m = 5\) and \(m = 10\) behave roughly similar to the simple rare chunk algorithm, where \(m = 3\) hovers slightly above the others due to the stricter rule keeping peers in the system for a longer time. The same behaviour is observed in figure 2 where all systems relax in a similar manner from an initial population of 1000 peers, all of which lack the same chunk.

As reported in \([3, 9]\), the rare chunk rule seems to provide stability despite the lack of a conclusive proof in this direction. On the other hand, the newly proposed protocol performs competitively (and even more so with a suitably
VI. CONCLUSIONS

Peer-to-peer schemes such as BitTorrent have been remarkably successful in revolutionizing the way files are spread in a network. Still, it is desirable to completely decentralize such protocols to avoid the pitfall of a single tracker. Naive attempts at such schemes have been plagued with the ‘rare chunk’ syndrome, which causes instability. While it has recently been shown that relatively minor altruistic behavior or a powerful seed can stabilize such systems, these properties are usually a luxury in real world networks.

In this paper we have demonstrated that a completely decentralized, stable peer-to-peer network is possible, even with completely non-altruistic peers and a single seed with minimal upload capacity. While earlier work has hinted at this result with heuristics and simulations, it had proved difficult to come up with a provably stable scheme. Although our original algorithm has drawbacks in terms of performance, we have suggested an improvement that allows trading locality for performance. Our proof was easily adapted to this case, which suggests that the methods presented here might allow for stability guarantees for other algorithms.

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