École Polytechnique Fédérale de Lausanne

Incentive Fairness in Peer-to-Peer Storage Networks

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Summer Internship Report

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1 Introduction

This summer I had the opportunity to be an intern in the Decentralized and distributed systems lab at EPFL. It was an extremely valuable learning experience and in this report I will try to summarize my work during those 8 weeks.

We will start in section 2 with some background on P2P storage networks with a focus on the SWARM network in subsection 2.2, in 2.2.3 we move on to cover the most important aspects of the SWARM incentive mechanisms necessary to analyze their fairness. In 2.3 we define the concept of fairness in these networks and how we will measure it. In section 3 we introduce and explain our Shuffling solution to the gateway unfairness effect observed in the Tit-for-Token paper [1]. Finally we switch directions in section 4 to cover Markov chain modelization of incentive mechanisms and give a road map to approach this idea.

2 Background

2.1 Peer-to-Peer storage networks

2.1.1 Definition

Peer-to-peer (P2P) storage networks are decentralized storage systems that rely on a network of interconnected nodes to store and retrieve data. In contrast to centralized storage systems, where data is stored on servers controlled by a single entity. Data distribution across multiple nodes makes the system more resilient, fault-tolerant, and potentially more secure.

2.1.2 Brief history and limits

The early 2000's has known the creation of multiple p2p storage networks for file sharing and storing such as Gnutella(2000), eDonkey(2000), Bittorent(2001)... But no matter the level of popularity that these systems attained, the fact that they weren't conceived with economics and game theory in mind made the collaboration between parties using these networks non-persistent over time ([2],[5]), evidently limiting their use.

2.1.3 Blockchain Contribution

When blockchain innovations hit the scene in the last decade, the incorporation of their numerous applications was inevitable. Their main contribution lies in providing a token based-economy that rewards active and contributing users, mitigating the free-riding problem and improving overall system availability and performance. This gave rise to more advanced and polished storage systems, with SWARM being the main system we focused on during my internship.

2.2 SWARM

2.2.1 Introduction

Swarm is a peer-to-peer network of nodes that provide a decentralized storage and communication solution. It operates using content addressable chunks: the atomic unit of data stored and shared in the network, Their addresses come from the same address space as the swarm peers. These chunks are stored within neighborhoods close to their specific addresses. In the following more mechanism details will be presented, most of which are directly taken from the SWARM book [5]

2.2.2 Topology Properties

To manage the network's routing, Swarm uses a variant of the traditional kademlia protocol : forwarding kademlia (figure 1), ensuring effective peer discovery and communication.Additionally Swarm was developed by the Etherium foundation, and so it leverages all the benefits of working on top of the Etherium blockchain which can range from using smart contracts to facilitate payments on the network to managing the content stored. Our interest lies however in the token-based incentive mechanisms facilitated by the infrastructure that tries to push favorable behavior network wide to provide an efficient and reliable service.

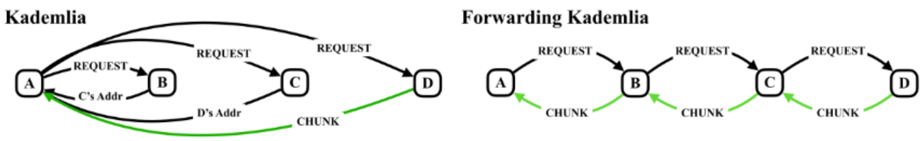

Figure 1: Forwarding kademlia DHT protocol

2.2.3 Storage Incentives in SWARM

In order to understand this type of incentives let's consider a short story of 2 nodes in the SWARM network : Alice and Bob. Alice wants to upload a file into the network, she will first proceed by splitting her file into chunks, then she would get a batch of postage stamps for these chunks : A postage stamp is a proof of payment associated with a chunk. they prevent frivolous uploads by imposing an advance cost. By giving a quantity of BZZ (The token used in SWARM) they signal a chunk's relative importance which storer nodes can then use to rank chunks when selecting which ones to retain and serve, and which ones to replace in the event of capacity shortage.

The chunks are then uploaded into the network until they find the neighborhood where they will reside. Let's suppose now that Bob is part of the neighborhood responsible for one of those chunks. In a given period storage rent taken from the batches of postage stamps all aroud the network will constitute the reward pot for the "Lottery game" that will take place. This game is managed by a suite of smart contracts on the blockchain that redistribute to storage providers the BZZ tokens that uploaders deposited within the postage contract.

Nodes earn the right to play through participation in storing and syncing chunks. The winners claim their reward by sending a transaction to the game contract. When Bob participates in the lottery game he has to first stake a certain amount of BZZ tokens relative to what he is currently storing.

The game then starts with it's first part, The commit phase : where the smart contract receiving the transaction verifies that Bob is staked. the game then goes to the reveal phase where each node reveals it's commitment. Finally in the claim phase, the winner node of the game (in our case Bob) out of all the participating ones must submit a claim transaction to the game contract to receive it's token reward, we should also note that stakes are used as weights by the contract to determine the winner among the nodes.

2.2.4 Bandwidth Incentives in SWARM

The bandwidth incentives are handled by the SWAP mechanism. It is a tit-for-tat accounting scheme that enables direct peers to exchange payments or commitments. The SWAP name actually represents the acronym for every single aspect of the mechanism:

1. Service Wanted And Provided : Service for service exchange.
2. Settle With Automated Payments : Automatically send cheque when payment threshold is reached.
3. Send Waiver As Payment : Waive debt using uncashed cheques
4. Start Without A Penny and Send With A Peer : Supports zero-cash entry via unidirectional swap.

Service for Service and Automatic cheque
The best way to illustrate these two features is by taking the figure 2 given in the swarm book :

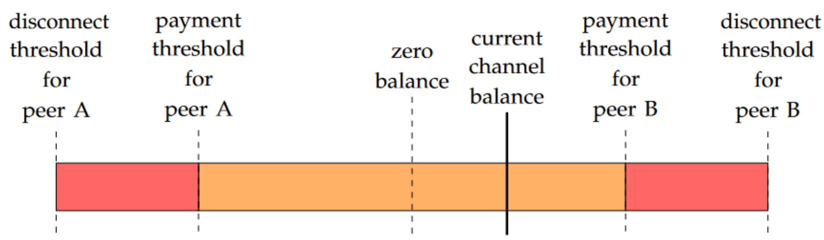

Figure 2: Service for Service thresholds

Swap facilitates service exchange among connected peers. In cases where connected parties ask the same amount of services from each other, these services can be reconciled without the need for payments (The channel balance remains in the middle). Additionally, In a connection each pear has a payment threshold, if the channel balance goes beyond it they will require a cheque from the other party for a service, the disconnect threshold plays the role of a safety net to ensure the peer in debt is disconnected if more services are provided to it with no retribution.

Waivers

Consider the situation where peer A issued cheques to B in order to bring back the balance of the channel to 0. Later on A goes a bit in debt to B by some amount, What node A can do in that case instead of paying the amount is to "cancel" the previous cheques if they weren't cashed in yet. Essentially paying cheques off of each other in order to reduce the cost of transactions.

Zero cash start

When a newcomer joins the system without any available funds it connects with an insider node who has previously accumulated resources, it can then offer services without utilizing any and accumulate a positive Swap balance. The send with a peer stands for the fact that newcomers can ask a peer to send their first cashing transactions since that require gas that the newcomers might not have.

2.3 Incentive Fairness

2.3.1 Motivation

During my time with the Decentralized and Distributed Systems lab, I mostly engaged with the Incentive Fairness research that Dr. Vero Estrada was leading (analyzing and improving the fairness of P2P storage systems).

Even though the incentive infrastructure is well established in systems such as SWARM, pushing forward network favorable behavior and slashing adversarial ones. their fairness remains yet under-explored especially from the bandwidth point of view.

Intuitively in an economic setting, 2 parties providing the same effort which in our case corresponds to nodes offering bandwidth resources to the network should receive the same token rewards. This plays an important role in network behavior as nodes are much more prone to stay and participate the more they feel that their efforts are fairly compensated, making the analysis of fairness pivotal in such systems.

2.3.2 Fairness Metric

Income fairness in the network is assessed by calculating the Gini coefficient, which quantifies income distribution among peers. It is derived by :

1. Summing up the net income accumulated over time for every peer (difference between incoming and outgoing payments)

2. computing the Lorenz curve : a graphical representation of income or wealth distribution. On the x-axis, you plot the cumulative percentage of the population from the poorest to the

richest (0% to 100%), and on the y-axis, you plot the cumulative percentage of income or wealth that they possess.

3. Compute the area difference between the Lorenz curve and the 45 degree line that corresponds to a perfect distribution (grey area in the illustration below 3), The Gini coefficient ranges from 0 (equal income distribution) to 1 (high income inequality).

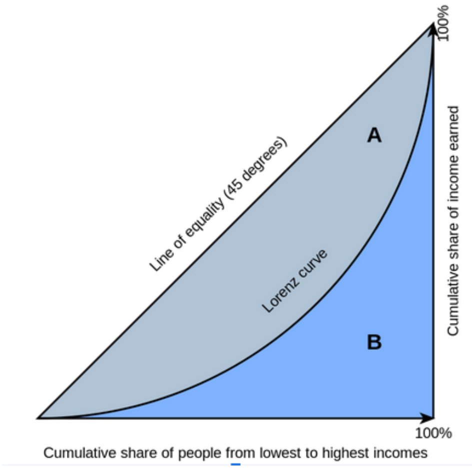

Figure 3: Lorenz curve in Gini coefficient computation

2.3.3 Tit-for-token paper

My internship coincided with the finalization of the Tit-for-token paper ([1]) in the bandwidth incentive fairness context, to which Dr.Estrada-Galiñanes was a co-author. It explores three key reward mechanisms: distance-based payments, reciprocity and time-limited free service. Using the Swarm network as a base model for comparison, it introduces the Tit-for-Token model, offering insights into those mechanisms and proposing improvements for fairness and Swarm network enhancements.

The paper offered many insights into what factors and parameters affect income fairness the most, including the effect of the random addressing of peers, reciprocity and free-service. However, the observation that peeked the interest of my colleague Arman Babaei and I was the major effect of gateways on income fairness, The figure 4 below shows how independently of the specific model parameters, the small percentage of gateways compared to the entire network size causes a high inequality of income in simulation.

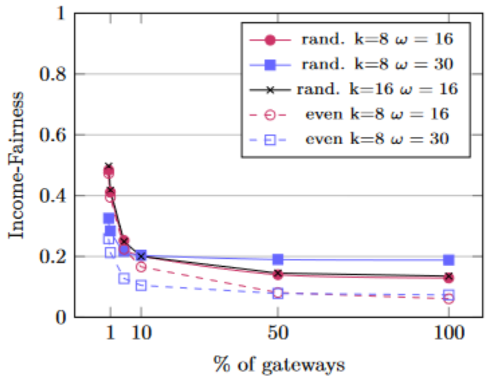

Figure 4: Gateway number increase improves fairness independently of model parameters

Unfortunately, increasing the percentage of gateways in a network is quite hard (one solution can be enforcing that each gateway has to have multiple nodes in the network depending on it's size and request rate), with a fixed number of gateways an income fairness bottleneck arises. It is also observable that the closer a node is to a gateway the greater it's income at the end of the simulation compared to nodes further away in the network . Given these observations we thought of a way to "emulate" the beneficial increase in gateways without changing their number : Shuffling.

3 Shuffling of Gateways

3.1 The Idea

As we just previously mentioned. With a fixed number of gateways, we can still evenly distribute their resources around the network by periodically changing their addresses and therefore changing the nodes in their neighborhood. In the following we present a model to compute the minimal frequency required to achieve a given level of shuffling, we then provide shuffling simulation results that prove it's effectiveness and end with discussing the limits of such an approach.

3.2 Theoretical Model

3.2.1 Model assumptions

This model is founded on the idea that ensuring fairness for first hop nodes of a gateway will lead to general fairness with respect to gateway effect on the network. We can consider this since all nodes will get a chance (in expectation) to be direct neighbors of the gateway, this however abstracts away whether some nodes find themselves more often on the second hop for example compared to others which in practice gives them more rewards in order to simplify the analysis and fairness condition.

We consider therefore in our model that direct neighbors are the only ones to receive rewards. We say that a node is "touched" by a gateway if it finds itself among it's first hop nodes. Given these constraints ensuring the fairness of the rewards is equivalent to making the "touches" as fair as possible, over all nodes.

Our goal is to find a minimal frequency that ensures a random node will be touched with a high enough probability, depending on model parameters. We considered some additional assumptions for that :

1. Single bucket per gateway : in Kademlia, nodes have multiple buckets, each one stores a certain number of nodes at a XOR distance range from the current node, this means that nodes in different buckets have different probabilities of usage. In order to simplify our analysis, we consider that gateway neighbors have the same probability of usage which doesn't conform exactly to kademlia. This approach can be generalized to multiple buckets with an additional condition that each bucket has a different probability of usage, we however don't consider that in our analysis.

2. Request Based Frequency: our frequency of shuffling is going to be expressed in terms of requests, not as a function of time. This approach has the advantage of abstracting away request fluctuations that gateways might experience overtime.

3. Static nodes in neighborhoods : We suppose that once a node is in a gateway's neighborhood it doesn't leave until the gateway is shuffled again, we are therefore not modeling churn or any dynamic behavior of nodes in between shuffling actions.

The shuffling happens right after a transaction (a request) in what we call a Shuffling action, We denote T the number of requests in a certain time frame (a day for example). F the frequency of shuffling. The following figure 5 shows illustrates an example of shuffling with frequency 1/2 during T transactions.

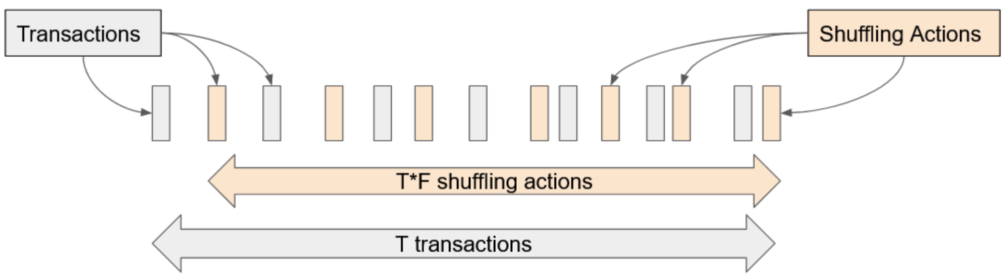

Figure 5: Shuffling actions and normal transactions

3.2.2 The model

Given the forementioned assumptions, From a node's perspective, every shuffling action represents an independent trial where the probability of success (getting a gateway touch) is

$$p = \frac{Bucket\ Size}{Network\ Size} \tag{1}$$

The number of trials until a touch is therefore expressed as a discrete exponential random variable with probability of success p.

To ensure that a random node experiences a touch with probability α, we need a number of trials superior to the α-quantile denoted k_α whose expression is :

$$k_\alpha = \left\lceil \frac{\log(1-\alpha)}{\log(1-p)} \right\rceil \tag{2}$$

Given that the trials in our model are simply the shuffling actions, we can deduce the minimal frequency bound :

$$Number\ of\ Trials \geq k_\alpha \tag{3}$$

$$\Rightarrow T \times F \geq \left\lceil \frac{\log(1-\alpha)}{\log(1-p)} \right\rceil \tag{4}$$

$$\Rightarrow F \geq \frac{1}{T} \times \left\lceil \frac{\log(1-\alpha)}{\log(1-p)} \right\rceil \tag{5}$$

Such a frequency ensures reaching a random node with probability α, taking α in the range 97%-99% gave us a frequency that achieved good shuffling in simulation observations.

3.3 Simulation and results

My colleague Arman was in charge of the simulation aspect of the shuffling analysis, therefore I'm not really familiar with details of the implementation he added on top of the simulator that Vahid Heidaripour developed for the paper [1]. I can however show the results he had in these simulations 3.3.

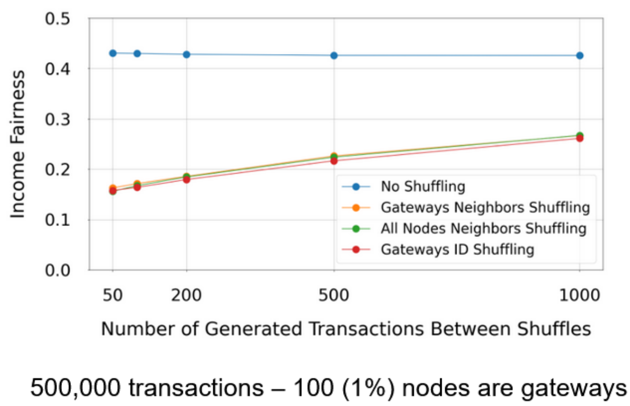

Figure 6: Shuffling results

These results show that even a once in every 1000 transactions frequency reduces the unfairness nearly by half. This is a considerable improvement that shows the importance of solving the gateway problem to improve fairness and the effectiveness of the shuffling procedure to do so.

3.4 Limits

The shuffling approach still presents some limits that need to be tackled in order to make it viable, mainly :

1. Protocol modifications needed to incentivize shuffling. Taxing mechanisms can be used on transactions with a tax value increasing with request count, and resetting it once the gateway changes addresses, this will incentivize shuffling and also benefit network nodes by giving the collected tax to the lottery game in order to be redistributed once more to the storers.

2. Global efficiency impact in retrieval speed : the delay caused by shuffling and it's potential consequences need to be analyzed.

3. The performance difference in changing neighbors for a gateway, if it's too important and unpredictable gateways wouldn't want to conform to a protocol that could affect the quality of service it provides for clients.

4 Markov Chain modeling

4.1 Motivation

In the beginning of our internship and before shifting our focus to the Tit-for-Token paper [1], Arman and I were engaged in the very interesting idea proposed to us by our supervisor Dr. Vero Estrada-Galiñanes consisting of unifying incentive analysis using markov chain models. These models could then be used not only on SWARM but other P2P storage networks as a comparison basis for incentive mechanism fairness in addition to other behaviors such as churn and failures, essentially a single point of reference that solves the problem of relying on specific simulations on the analysis of such networks. We started by looking through the literature related to this approach in p2p storage networks to then create our model, unfortunatly we were unable to find satisfying results before switching our interest to the paper. I do think however that what we looked into can serve as a road map if anyone would want to further explore this idea. In the following I will go through the papers whose insights proved useful to us in tackling this problem, in hopes that efforts will continue in order to solve it.

4.2 Related work

4.2.1 Step 1 -IPFS and Friends: A Qualitative Comparison of Next Generation Peer-to-Peer Data Networks by Daniel Erik et. al

We think that starting with this paper is the best way to get familiar with the new generation of P2P storage networks such as IPFS, SWARM, Storj, etc. It investigates the common technological building blocks of these systems while quickly going through the specificities of each one of them, giving the reader a broad and interesting view on how each one of these systems operate, with an enumeration of the incentive mechanisms used by each one of them. The following figure 7 provided in the paper summarizes the incentives categories in each system :

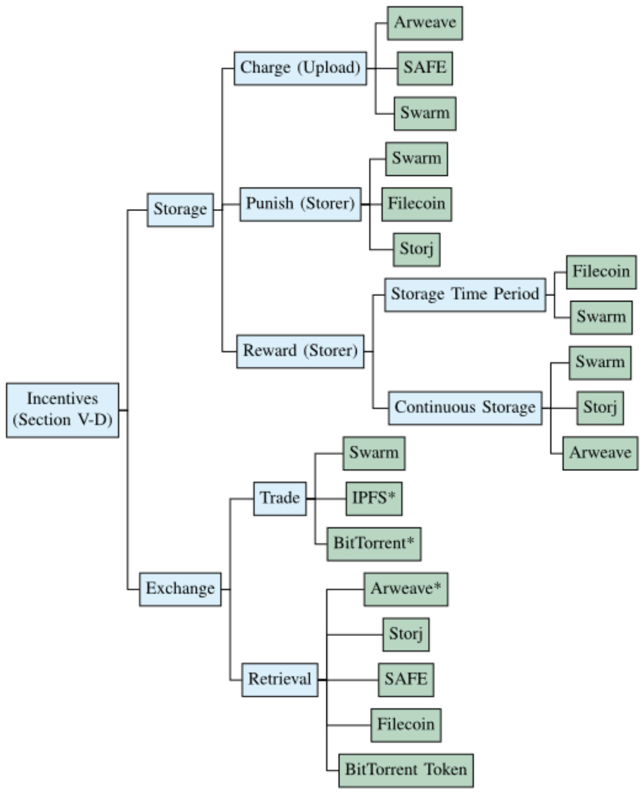

Figure 7: classification of incentives in modern P2P storage networks

4.2.2 Step 2 -Analyzing and enhancing the resilience of structured peer-to-peer systems by Wang et. al

This paper [6] from 2004 represents one of the first efforts we found for a markov chain model to analyze the resilience of p2p storage networks under failures. It studies the effect on resilience that different network features have and proposes improvements to the CAN network. The figure below shows the state diagram of the Markov model they used to calculate interesting values such as the hit ratio and average path length for a given message :

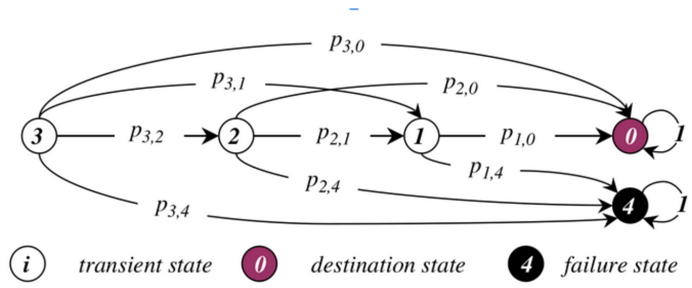

Figure 8: Message position Markov model

The analysis in this paper was encouraging since it showed that the Markov approach could be effectively used in the analysis of p2p networks.

4.2.3 Step 3 -Determining the Hop Count in Kademlia-type Systems by Roos et al.

This more recent paper [4] from 2015 uses Markov chains to compute the average hop count in Kademlia type systems. It also tests the performance of the proposed model against simulations of both the BitTorrent Mainline DHT and eMule's KAD implementation to validate it. In addition it gives a way to integrate paralellism in their model which we thought could be very useful in the model we were working on.

4.2.4 Step 4 -Incentive Mechanisms in Peer-to-Peer Networks — A Systematic Literature Review by Ihle et al.

Now that we've seen Markov chains in action, it is important to understand the different incentive mechanisms in multiple p2p storage networks. This recent study [3] provides a comprehensive review of incentive mechanisms taking into consideration many factors to differentiate them. The importance of this study lies in the enumeration of mechanisms and the framework they propose to classify incentive mechanisms in p2p networks consisting of the following properties :

1. Reward Type
2. Attack Resistance
3. Data Management approach
4. Contribution Mode

Finally they recommend considering the framework when proposing new incentive mechanisms in order to increase comparability between them.

5 Conclusion

During this internship I had the opportunity to get an in depth look on how incentive mechanisms work in modern p2p storage systems with a focus on the SWARM network. We tackled the problem of gateway distribution and proposed a solution that shuffles them around the network with a theoretical and practical approach to analyze it. We additionally provide a road map to approach Markov chain modeling of p2p incentive mechanisms that we hope would be of help when further exploring this idea.

6 Final Thoughts

Coming into this previous summer i didn't know what to expect from the program as it was my first internship in research. Now i can safely say that it has been by far one the most valuable learning experiences in my journey. Engaging with people in the field and seeing how passionate they are about tackling important problems day in and day out has been very eye opening to me.

Finally i want to specifically thank my supervisor Dr. Vero Estrada-Galiñanes for her continuous help and guidance during my internship, my colleague Arman Babaei for his collaboration, debates and insights, and more generally the Dedis lab and the summer in the lab program for this opportunity !

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