Optimal Bandwidth Allocation in mesh-based Peer-to-Peer Streaming Networks

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Abstract The design of efficient protocols for mesh-based Peer-to-Peer (P2P) networks has many challenges, one of them is the bandwidth allocation. On one hand, users (called *peers*) demand high Quality of Experience and network traffic when they watch their streaming contents. On the other, Internet Service Providers (ISPs) support their business with the capacity of their international links. A recent strategy considered in order to meet both peers and ISPs requirements is the Proactive Provider Participation, shortly named P4P [10]. This approach allocates the maximum total traffic in the network, reducing at the same time the percentage use of the most congested links.
This paper addresses the bi-level P4P problem. We introduce a polytime solution which achieves any given accuracy when only one content is delivered in the network In addition, we design a greedy randomized technique when multiple contents are shared. Finally, we apply our algorithm to a real peer-to-peer live video-streaming platform, when a single content is delivered. The results highly outperform current strategies.

1 Introduction

An important amount of today's Internet traffic is due to live video streaming [2]. For this reason, several peer-to-peer streaming networks were developed in the last years. The most successful ones are PPlive, TVUnetwork, SopCast, with proprietary and unpublished mesh-based protocols [8]. Mesh-based P2P networks are virtual unstructured networks developed at the application layer, over the Internet infrastructure. Bittorrent is the best known mesh-based P2P protocol, developed for file sharing purposes [3]. The users, called *peers*, offer their resources(bandwidth in

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a streaming application) to others, basically because they share common interests. They can connect and disconnect freely. This makes P2P networks an attractive tool for them, but increases P2P's design challenges, because the resource availability depends on them.

In P2P, the cooperation is the key element in order to assure a certain quality of experience to end-users [8]. There are three main steps in all mesh-based P2P protocols for cooperation. First, when a peer enters the net it should discover other peers sharing the same content, which is called *swarm selection strategy*. Once a new peer knows other peers in his swarm, he must select the best ones to cooperate, what is called *peer selection strategy*. Once a new peer handshakes other peers, it should decide which pieces of the streaming content should be asked first, called the *piece selection strategy* [1]. This paper is focused on the swarm selection strategy and in the peer selection strategy. The main issue is to locate the largest amount of traffic in the network without bottlenecks, and keeping the quality of experience between peers. In Sect. 2 the mathematical P4P model, based on [9], [10], is explained. The reader can find related work on P4P in [11], [4], [5].

Following the related work, in order to represent the complexity and scale of a real scenario with millions of peers, the peers are grouped in nodes. Each node is a geographical subset of Internet (for example: an autonomous system or an ISP point-of-presence), and they are interconnected by real links. Inside each node could be several peers sharing contents. Section 3 contains a polytime resolution for one content and a greedy randomized algorithm [7] for the general P4P problem. In Sect. 4 we show the performance of the single content polytime algorithm in GoalBit, which is the first open source real platform that widely offers live video streaming to final users in Internet [2]. Finally, Sect. 5 contains the main conclusions of this work.

2 Mathematical Model

Our model is inspired in [9], [10], where the authors relax the model into a linear programming one. Consider a network with nodes set $V = \{v_1, \dots, v_n\}$ and two one-way links between each pair of nodes, whose respective capacities are represented by a non-negative matrix $C = (c_{i,j})_{1 \leq i,j \leq n}$. The upload and download bandwidths for each node $v_i \in V$ are u_i^k and $d_i^k, i = 1, \dots, n$ respectively, where $k \in \{1, \dots, K\}$ represents different contents (each node v_i has K possible contents to download). Each link (i, j) uses a certain percentage of its capacity due to other applications, which is denoted by $b_{i,j}$, called the background traffic. Be $\mathscr{P} = \mathscr{P}_1^{k_1}, \dots, \mathscr{P}_m^{k_m}$ a set of oriented paths in the network, where $\mathscr{P}_h^{k_h} = (x_h, \dots, y_h)$ (x_h is the uploader and y_h is the downloader). Be $t_1, \dots, t_m$ their respective traffic magnitudes. In words: x_h uploads a traffic magnitude t_h of content type k_h to y_h by the oriented path $\mathscr{P}_h^{k_h}$.

The objective function is to reduce the maximum link utilization ρ in the network. Constraint 1 imposes that the total traffic generated in the network must be maximized. Constraints 2 and 3 assure that each node does not upload (respectively download) more traffic than its capacity (for each content). Constraint 4 states that edge capacities must not be exceeded. Finally, constraint 5 classifies nodes as uploader or either downloader for each content.

$$\min_{\mathscr{P}} \max_{(i,j):i\neq j} \rho(\mathscr{P}) = b_{i,j} + \frac{\sum_{h:(i,j)\in\mathscr{P}_h^{k_h}} t_h}{c_{i,j}}, \qquad s.t.$$

P4P Model

$$\begin{cases} \max_{\mathscr{P}} \sum_{h=1}^{m} t_h & (1) \\ \sum_{h:x_h=i,k_h=k} t_h \leq u_i^k, \forall i \in V, k \in \{1,\dots,K\} & (2) \\ \sum_{h:y_h=j,k_h=k} t_h \leq d_j^k, \forall j \in V, k \in \{1,\dots,K\} & (3) \\ b_{i,j}c_{i,j} + \sum_{h:(i,j)\in\mathscr{P}_h}^{k_h} t_h \leq c_{i,j}, \forall i \neq j \in V & (4) \\ u_i^k.d_i^k = 0 \quad \forall i \in V, k \in K & (5) \end{cases}$$

In a real world scenario, the objective function has an economic interpretation: reduce the bottleneck of the most expensive edges in Internet at the same time fulfilling the peers demands (Constraint 1) according with the available resources in the network (Constraints 2, 3 and 4). In practice, once we have a set of oriented paths $\mathscr{P}$ and their respective magnitudes, it is possible to converge probabilistically to that traffic distribution in a real network. The swarm (list of peers) for a peer located at node v_i that asks for content k, is populated with the following probability of peers from node v_j:

$$w_{ji}^k = \frac{\sum_{h:(j,i)\in\mathscr{P}_h^k} t_h}{\sum_{x\in V}\sum_{h:(x,i)\in\mathscr{P}_h^k} t_h}. \qquad (6)$$

Note that the numerator of w_{ji}^k represents, for content k, the traffic coming from node v_j to v_i, while the denominator adds all incoming traffics for the same content to node v_i. Equation 6 defines how to swarm must be created(i.e. the swarm selection strategy), where the peers in the swarm must be chosen randomly, according with the empirical probabilities w_{ji}^k.

Moreover, the peer statistically takes in consideration these weights also in his peer selection strategy in order to have a faster converge. See [6] for details.

3 A Polytime Resolution and its Generalization

Although the high complexity of the general P4P formulation, we show there is a Fully Polynomial Time Approximation Scheme (FPTAS) when one content is distributed in the network:

Theorem 1. *There is a FPTAS for the P4P Problem when* $K = 1$.

Proof. Connect two ideal nodes s and t (one transmitter and the other receiver) to every node v_i with corresponding capacities u_i and d_i. Find the mincut-maxflow ϕ_{max} via the classical Ford-Fulkerson [6] (FF) algorithm. Finally, reduce all capacities c_{ij} by a certain factor ρ. The minimum factor ρ_{min} that preserves ϕ_{max} can be found iteratively with a bipartition scheme in the closed interval $[\max_{1\leq i,j \leq n} b_{i,j}, 1]$ and calling FF. □

To the best of our knowledge, there is not an exact resolution in polytime for multiple contents [6]. A possible heuristic approach is detailed next.

Algorithm 1 $\mathscr{P} = RandomList(U, D, C, B, p)$

$\mathscr{P} = \emptyset$
while $(length(p) > 0$ AND $C \geq 0)$ **do**
  $k = ChooseContent(p)$
  $\mathscr{P} = \mathscr{P} \cup FF(U^k, D^k, C, B)$
  $Update(U, D, C, B, p)$
end while
return $\mathscr{P}$

Algorithm *RandomList* is very simple, and proposes a Greedy Randomized generalization for multiple contents. It receives the bandwidth matrices $U = (u_i^k)$ and $D = (d_i^k)$ (that store the bandwidth of every node for each content), the capacity and background matrices C and B respectively and a probability vector $(p_k)_{1\leq k\leq K}$, that measures the priority to the content type k. In each iteration, a content is chosen randomly according with the priority vector p. Immediately, FF is called in order to find the best bandwidth allocation for that content. The flows obtained so are added and the bandwidth and capacities updated (the entry $p_k = 0$). This process is repeated until there is no more capacity or after all contents were delivered.

4 Empirical Results

In this work we implemented Algorithm FF when one content is delivered to converge empirically to the optimum P4P bandwidth allocation in a real P2P video streaming platform, called GoalBit [2]. GoalBit maintains the BitTorrent's philosophy, trying to extend its success to video streaming. The P4P-based strategy we propose acts exactly in the moment of the peer list conformation, applying FF algorithm to skew routing to converge to the theoretical P4P solution. Emulations were carried out with information provided by The Uruguayan National Telephony Operator ANTEL[1] from their GoalBit deployment live service. We contrast the swarm and peer selection strategy using our P4P algorithm(i.e. FF algorithm) versus the

[1] This paper was supported by The National Telephony Operator ANTEL (www.antel.com.uy)

Classical GoalBit strategy (based on BitTorrent). For all emulations we evaluate the quality of experience of final users (buffering time), the total amount of exchanged traffic and the one which crosses international links. In particular, we show the results of two emulations for the cases of 60 and 100 simultaneous peers connected in average. Tables 1 and 2 show, for both strategies; the total traffic, incoming and outgoing international links[2] traffic. Also, shows the percentage growth of incoming and outgoing traffic $P_{G_{in}}$ and $P_{G_{out}}$ when the P4P model is applied, in relation with a Classical strategy. Specifically:

$$P_{G_{in}} = 100 \times (\frac{In_{P4P}}{In_{Classic}} - 1), P_{G_{out}} = 100 \times (\frac{Out_{P4P}}{Out_{Classic}} - 1),$$

where In_{P4P}, $In_{Classic}$ and Out_{P4P} and $Out_{Classic}$ represent the total incoming and outgoing traffic for P4P and Classic respectively. It is desirable to obtain negative percentage growth, interpreted as a reduction in the international links, and consequently, an improvement in relation with the Classical strategy.

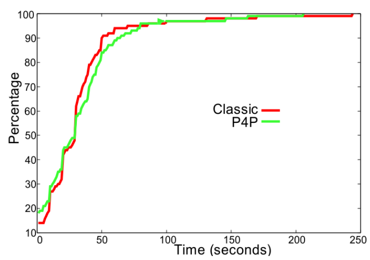

Fig. 1 Buffering time for 60 peers

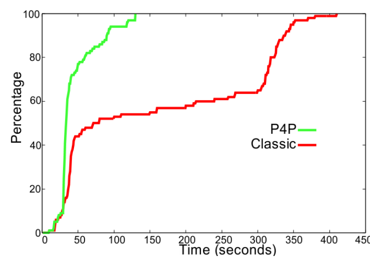

Fig. 2 Buffering time for 100 peers

Table 1 Link utilization for 60 peers

Model	Incoming	Outgoing	Total
Classic	31656	31366	183069
P4P	7927	16446	183067
% grow traffic	-47.57	-74.96	0.0

Table 2 Link utilization for 100 peers

Model	Incoming	Outgoing	Total
Classic	5681	10253	55078
P4P	3657	4451	58893
% grow traffic	-56.59	-35.63	6.93

It can be appreciated from Table 1 that the incoming reduction is 47.57%, while the outgoing reaches 74.96%, keeping the total traffic achieved by the Classical strategy. Also, Table 2 shows important reductions for the 100 simultaneous peers case, and an increasing in total traffic is perceived. Fig. 1 shows that the buffering time distributions are quite similar for both techniques. In both cases, the 85% of peers perceived a buffering time lower than 55 seconds. In contrast, for the 100 simultaneous peers case, P4P present much lower buffering times when compared with the Classical strategy (see Fig. 2). A 68% of peers wait no more than 38 seconds to start playing when P4P is applied, but only a 27% of peers can start playing the

[2] As we can only measure the traffic through the outgoing and incoming links to and from Uruguay, this will be our reference node.

video during the same time. Many emulations were carried out for different inputs showing similar bandwidth savings, close to 30% in average [6].

5 Conclusions

In this work, the Proactive Participation Provider (P4P) performance was analyzed, and contrasted with the Classical GoalBit strategy. In a theoretical aspect, the P4P mathematical model can be solved with the desired precision when only one content is distributed in the network. However, when multiple contents are distributed the problem has not been solved exactly so far. Emulations of a real system indicate a 30% link utilization reduction in average with our P4P application, and at the same time the quality of experience seems to improve. Qualitatively, this highlights the competitiveness of the P4P optimum bandwidth allocation.

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