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Hybrid fluid modeling approach for performance analysis of P2P live video streaming systems

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Abstract In this paper a hybrid modeling approach with different modeling formalisms and solution methods is employed in order to analyze the performance of peer to peer live video streaming systems. We conjointly use queuing networks and Fluid Stochastic Petri Nets, developing several performance models to analyze the behavior of rather complex systems. The models account for: network topology, peer churn, scalability, peer average group size, peer upload bandwidth heterogeneity and video buffering, while introducing several features unconsidered in previous performance models, such as: admission control for lower contributing peers, control traffic overhead and internet traffic packet loss. Our analytical and simulation results disclose the optimum number of peers in a neighborhood, the minimum required server upload bandwidth, the optimal buffer size and the influence of control traffic overhead. The analysis reveals the existence of a performance switch-point (i.e. threshold) up to which system scaling is beneficial, whereas performance steeply decreases thereafter. Several degrees of degraded service are introduced to explore performance with arbitrary percentage of lost video frames and provide support for protocols that use scalable video coding techniques. We also find that implementation of admission control does not improve performance and may discourage new peers if waiting times for joining the system increase.

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1 Introduction

The use of Internet video streaming services is spreading rapidly and web technologies for live video broadcast increasingly attract more and more visitors. In the classical client/server system architecture, the increase in number of clients requires more resources like high bandwidth transmission channels (TCs) with large upload rates. Since these TCs are extremely expensive, the usual outcome is a limited number of Unicast connections that a Streaming Server (SS) can support at a given time. In the early nineties, it was expected that IP Multicast [1] will be the natural technology to satisfy the requirements of large scale streaming with lower cost. However, the lack of support for higher level functionality, scalability issues and requirements for hardware Internet technology changes, have prevented its wider deployment. This motivated the science community to work in the field of new approach for Internet Live Video Streaming (LVS) by the use of Peer to Peer (P2P) networking technologies.

In essence, P2P LVS systems are data dissemination logical networks formed on top of the physical network. Basically, they form two different types of logical topologies: tree and/or mesh [2]. While the tree topology forms structured network of a single tree such as Nearcast [3], or multiple multicast trees as in [4], mesh topology is unstructured and does not form any firm logical construction, i.e. it organizes peers in swarming or gossiping-like environments, such as Chainsaw [5] or CoolStreaming [6]. Some protocols use a combination of these two aspects, forming a hybrid network topology, such as [7–11]. In mesh systems peers are organized in groups or neighborhoods and every peer maintains connections with all the peers from its group. The video data is divided in small pieces called chunks that are streamed by the source (SS) to the peers. Each peer acts as a server as well as a client, forwarding received video chunks after some short buffering. Chunk requesting and forwarding is controlled by a chunk scheduling algorithm, which is responsible for on-time chunk acquisition and delivery among the neighboring peers. The peers join and leave the network at free will (peer churn) which has a negative effect on system's performance. Another complication is added by the peers' Upload Bandwidth (UB) heterogeneity.

Hence, in the last decade, a number of such protocols were developed. In this manner, CoolStreaming [6] have reported a number of 4,000 concurrent users and Gridmedia [12] reported more than 15,000. Recent measurement study of PPLive [13] reported a peek of even 200,000 simultaneous users (when on January 28, 2006, PPLive broadcasted the annual Spring Festival Gala on Chinese New Year), with bitrates in range of 400–800 kbps, which corresponds to an aggregate bitrate of ~100 gbps. Clearly, these P2P LVS networks offer huge economic benefit in deploying and managing IP video streaming, but these systems are still in their early stages and bring a lot of open issues and research challenges that need to be explored. Therefore, prior to creating a P2P LVS system, it is necessary to analyze its behavior via representative model that provides deeper insight into system's performance, gathering valuable information for design and development of such systems.

Modeling and performance analysis of P2P LVS systems is a challenging task which requires addressing many properties and issues of P2P systems that create complex combinatorial problem. Following a number of approaches in which different modeling formalisms and solution methods are combined in order to exploit their complementary strengths, in this paper, a hybrid modeling approach with different modeling formalisms and solution methods is employed, in order to analyze the performance of P2P LVS systems. We conjointly use queuing networks (QNs) and Fluid Stochastic Petri Nets (FSPNs) [14–16], developing several performance models to analyze rather complex peer to peer streaming systems. What needs to be mentioned is that, in FSPNs, the fluid variables are represented by fluid places, which can hold fluid rather than discrete tokens. Transition firings are determined by both discrete and fluid places, and fluid flow is permitted through the enabled timed transitions in the Petri Net. By associating exponentially distributed or zero firing time with transitions [15], the differential equations for the underlying stochastic process can be derived.

In our study, a QN model is used to obtain a comparable analytical solution for a bufferless system, while for the FSPN model of both bufferless and buffered system, only simulation solution method appeared to be feasible. The models unite numerous features of P2P LVS systems, such as network topology, peer churn, scalability, peer average Group Size (*GS*), peer UB heterogeneity and video buffering, as well as several features unconsidered in previous performance models such as Admission Control (AC) for lower contributing peers, control traffic overhead and internet traffic packet loss.

The rest of this paper is organized as follows. Section 2 presents our main motivation and gives an adequate review of related work. In section 3 the model definition is presented, starting with a general overview of the modeling idea. Following is a description of peer churn along with the transfer of bits as a fluid stream through the network. Later, the stream function is derived and closed form expressions for QN model of bufferless system are obtained. Next, the FSPN models for a system with buffering and a system that accounts for AC are described. In section 4, performance evaluation results and analyses are presented accompanied with brief discussions regarding a handful of key elements. Section 5 provides concluding remarks and summary of contribution.

2 Motivation and related work

Several related articles use fluid models for performance analysis of file sharing P2P systems. Qiu D. et al. [17] modeled mesh based, file sharing P2P system, developing simple deterministic fluid model that provides some insights in the system's performance. Yue Y. et al. [18] developed a general fluid model to study the performance and fairness of BitTorrent-like networks. In its basics, this model is an extension of [17], taking in consideration the diversity of peers' bandwidth capacities. Perronnin FC. et al. [19] proposed a stochastic fluid model for performance analysis of Squirrel, a P2P cooperative Web cache, where under the assumption that all objects are equally popular, they provide closed form expressions to model file sharing system where peer churn is modeled as an $M/M/\infty$ Poisson process. The model is extended to include unequal popularity by grouping the documents into classes and implementing the same steady state solution.

Similar approach is used to model P2P Video on Demand (VoD) systems. Tu YC. et al. [20] presented an analytical framework to quantitatively study the features of a hybrid VoD streaming model that involves Content Delivery Network (CDN) and P2P technologies. Yazici MA. et al. [21] introduce Markov chain based model to study mesh based, multi-stream, P2P VoD systems. The model accounts for peer churn, and query and setup times for a new connection with exponential probability distribution, while Lu Y. et al. [22] presented an analytical fluid model for mesh based P2P VoD system.

The models in [17–20, 22] are described by sets of differential equations, solved in steady state, and the accuracy of the models in [19, 20] is validated by a comparison to discrete event simulations (DESs).

Concerning the live video streaming, inspired by [17], Tewari S. et al. [23] proposed an analytical model for BitTorrent based P2P LVS system that concentrates on the number of fragments available for sharing, fragment size and optimal *GS*. Zhou Y. et al. [24] developed a simple stochastic model for comparing different data driven downloading strategies for P2P LVS systems in symmetric network settings. The model is defined by differential equations in discrete and continuous case that are solved numerically and evaluated by simulations. Wu D. et al. [25] developed infinite-server queuing network models to analytically study the performance of P2P LVS systems. Their analytic models capture the essentials of multi-channel video streaming systems taking into account: channel switching, peer churn, peer UB heterogeneity and channel popularity. Liu F. et al. [26] developed mathematical model to study the inherent relationship between time and scale in P2P LVS systems during a flash crowd. The model shows that system scaling behavior and peer startup delay are strongly affected by different peer arrival patterns and peer churn. Kumar R. et al. [27] developed stochastic fluid theory for mesh based P2P LVS systems. It represents general base for modeling such systems while interpreting peer churn as multiple levels $M/G/\infty$ Poisson processes and adopting fluid flow model for video streaming. The analyses include modeling a churnless bufferless system, bufferless system with churn, and P2P LVS system model with peer churn and buffering, while its analytical expressions bring insights in service degradation in all these cases. The performance of the P2P system, as the joining rate of new peers becomes very large, is studied and explicit expressions for the probability of degraded service for large systems are obtained. Wu J. et al. [28] proposed an extension of [27] focusing on the problem of maximizing Universal Streaming (US) rate in P2P LVS systems with a difference in taking in consideration neighborhood constraints. The model is restricted by assumptions of a churnless, bufferless system and peers with homogeneous UBs.

Even though works in [17–22] represent inspiration to model such systems, since they deal with file sharing or VoD, their models are not applicable to P2P LVS systems. Although in [27] multiple features of these systems are considered, such as peer churn, buffering and heterogeneity of peers' UB, peer *GS* is not taken into account. The other models concentrate on a very limited number of system characteristics. The models in [23, 24, 28] do not consider peer churn which is one of the most important aspects of P2P LVS systems, and [25, 26, 28] consider only bufferless systems. However, beside the existing deficiencies, none of the presented models account for control traffic overhead and Internet traffic packet loss, and their influence on system performance. They also do not provide information about service degradation, the minimum required SS UB, the optimum video stream rate for a given scenario, the performance boost gained if AC for low contributing peers is used, nor the average waiting time for admission controlled peers.

In this paper we combine multiple features of P2P LVS systems in a hybrid approach using QNs, and FSPNs developing fluid models that provide an in-depth insight into the system's performance in a variety of scenarios. We base our model on [27] and extend it to include features that are not considered in previous researches. For the solution of the QN model a closed form expression is derived, and for the FSPN models the solution is provided by DESs.

Hence, we can summarize our contribution as follows:

1. This is the first modeling approach for performance analysis of P2P LVS systems that, at the same time, accounts for so many features of these systems, including: i) network topology, ii) peer churn, iii) scalability, iv) peer average *GS*, v) peer UB heterogeneity and vi) video buffering, while, for the first time, accounting for vii) control traffic overhead, viii) internet traffic packet loss and ix) AC for lower contributing peers.
2. The analysis discloses: i) optimal peer *GS*, ii) optimal buffer size, iii) system's performance with respect to scaling and iv) influence of the control traffic overhead, while introducing several new output parameters, such as: v) minimum required SS UB, vi) several degrees of Quality of Service degradation (Δ) to explore system's performance with an arbitrary percentage of lost video frames, vii) optimal video rate for known peers' average UB and viii) performance evaluation of a system that implements AC, where the average number and the average waiting time for admission-controlled peers are presented, as well.
3. To the best of our knowledge, this is the first effort that uses FSPNs for modeling such systems, while at the same time introduces a novel DES approach for simulating FSPNs using process-based discrete-event simulation language.

3 General model definitions

The art of modeling and performance analysis covers two simple aspects. First, the model should always be simple,