Modeling and Optimization of Content Networks

By

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My Ph.D. work was in the general area of *Internet content distribution* and its related technologies like *Peer-to-Peer Networks* (P2P), *Content Distribution Networks* (CDN) and *Web-caching Networks*. The work and the results considered mainly the fundamental abstract problems that underlie and unite the various different approaches that have been proposed in the above-mentioned domains. The commitment of the work towards the fundamental open problems is evident from the titles of the main sections of the dissertation, which include: *"The storage capacity allocation problem for Internet content distribution"*, *"Selfish replication of objects in distributed replication groups"*, *"Interconnection algorithms for caching hierarchies"*, *"Scheduling algorithms for optimal video playout in Internet video streaming applications"*. In the following I briefly highlight some of the major contributions of the dissertation. (the relevant research articles are freely available from my web-site at http://www.cnl.di.uoa.gr/~laoutaris/laoutaris.html).

Under the "*The storage capacity allocation problem for Internet content distribution"* we presented a unified treatment of all the relevant sub-problems that arise in the dimensioning of a general content network. We showed that an optimal allocation of an available storage budget requires the joint optimal solution of three interrelated sub-problems which, in the past, had been considered only in isolation to each other and, therefore, had led to only partial solutions (which in most cases were sub-optimal in the context of an overall dimensioning). The three constituent sub-problems were: (i) the content-node placement problem, (ii) the content-node dimensioning problem, and (iii) the object placement problem. Our main contribution was casting the above overall dimensioning problem as a *multi-commodity k-median* problem that is an important generalization of the well know (single-commodity) *k-median* problem of facility location theory. We developed a general solution to the multi-commodity k-median by reducing it into a series of single commodity k-medians, which when combined with a *multi-commodity 0/1 Knapsack packing* problem synthesize the optimal solution to the original multi-commodity k-median problem.

Studying the *"Selfish replication of objects in distributed replication groups"* was motivated mainly by the prevalence of P2P networks. Such networks operate under multiple independent authorities (one per-node), which are self-aware and in many cases self-motivated and, therefore, do not necessarily have to abide to the object placement solutions that were previously developed for optimizing the social utility of a content network (such solutions are better suited to networks that operate under a single authority, e.g., a CDN). To model the contention between the different content nodes we employed game theoretic concepts and combined them with the standard facility location tools that are employed in studying the object placement problem. Our main contribution was the derivation of *Nash equilibrium object placement strategies* that: (i) can guarantee improved local utilities for all nodes concurrently as compared to the corresponding local utilities under greedy local object placement, (ii) do not suffer from potential mistreatment problems, inherent to centralized strategies that aim at optimizing the social utility, (iii) do not require the existence of complete information at all nodes. We developed a baseline computationally efficient algorithm for obtaining the aforementioned equilibrium strategies and then extended it to improve its performance with respect to fairness. Both algorithms are realizable in practice through a distributed protocol that employs Bloom filters and therefore consumes much less bandwidth for the exchange of information.

The *"Interconnection algorithms for caching hierarchies"* were developed in an attempt to use caching (i.e., request-driven temporary storage of objects combined with replacement) for approximating the high performance of off-line optimized object placement algorithms that employ replication (permanent storage of objects). Our main result was a simple interconnection algorithm for coordinating the caching decisions among the different nodes of a multi-level hierarchical cache. The new algorithm is more selective in choosing the caches that get to keep a copy of the same object that is missing from the hierarchy upon a request. It therefore creates fewer copies of the same object than the de facto interconnection algorithm that creates copies in all the caches that lay in the path between the requesting client and the closest cache that currently keeps a copy of the missing object. Our algorithm has the advantages of *avoiding the amplification of replacement errors* and of *exclusive caching* (different caches storing disjoint sets of objects) and, therefore, achieves a significantly better performance than the de facto one without adding new complexity. We have quantified the performance gains under the proposed interconnection through synthetic and trace-driven simulations and have developed an analytic model based on LRU caching for explaining the improved performance. The analytic model is in itself a substantial contribution to the modeling of interconnected caching systems (which are notoriously hard to model analytically due to the combinatorial hardness of analyzing the LRU replacement and the interdependencies (coupling) of the states of the different nodes).

In *"Scheduling algorithms for optimal video playout in Internet video streaming applications"* we analyzed and designed playout adaptation policies for packet video receivers (PVR) that operate in delay jitter inducing best-effort network, like the current Internet. We modeled a PVR as an Ek/Di/1/N phase-type queue, which has the ability to capture key system parameters, such as: the level of delay jitter (modeled through the parameter k), the performance metrics and the employed playout policy. We derived the optimal playout policy under k-Erlang frame inter-arrivals by formulating and solving a *Markov decision problem*. We then transformed the (theoretical) optimal playout policy into an implementable approximately optimal one that utilizes only observable information. Finally, we proposed a PVR that adapts to varying network delay jitter by trying to induce a performance that approximates the theoretical optimal one. By employing the developed playout policy, a PVR may avoid long lasting playout disruptions (frame freeze, frame overflow), and instead experience only short playout disruptions that, however, may be unnoticed due to human limitations in the perception of motion.