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Variegated competing peer-to-peer systems with selfish peers

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ABSTRACT

Thanks to years of research and development, current peer-to-peer (P2P) networks are anything but a homogeneous system from a protocol perspective. Specifically, even for the same P2P system (e.g., BitTorrent), a large number of protocol variants have been designed based on game theoretic considerations with the objective to gain performance advantages. We envision that such variants could be deployed by selfish participants and interact with the original prescribed protocol as well as among them. Consequently, a meta-strategic situation—judicious selection of different protocol variants—will emerge. In this work, we propose the usage of population games, evolutionary and learning dynamics in the study of node coevolution for selfish protocol selection, and, most importantly, its impact on system performance. We apply our models and algorithms to P2P systems and draw on extensive simulations to characterize the dynamics of selfish protocol selection. In particular, our proposed distributed algorithms outperform others in terms of download rate. We believe that evolution patterns identified in our study will shed light on both further theoretical study and the design of next generation distributed systems.

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1. Introduction

The effectiveness of a peer-to-peer (P2P) network is contingent on the cooperation of autonomous participants. Such cooperation, or the lack of it, manifests as the result of aggregated actions taken by rational and strategic peers. Indeed, based on game theoretic considerations [1,2], a plethora of protocol variants have emerged, aiming to take some unfair advantages in a P2P network. The most notable example is the BitTorrent file sharing networks. Apart from the original prescribed protocol [3], participating peers can choose to deploy protocol variants such as BitThief [4], BitTyrant [5], PropShare [6], BitMate [7], and Birds [2]. In particular, BitThief is designed to exploit other clients and free-ride without any contribution, while BitTyrant is a strategic protocol to contribute the minimum while downloading from others. Consequently, a typical P2P network is anything but a homogeneous system from a protocol perspective.

Peers are rational for their own utility maximization, strategic with the capacity to adjust actions, and adaptive to align strategic decisions to environmental changes. They learn, adapt and evolve by adjusting their adopted protocols. With the continual emergence of various protocol variants, we thus envision a *variegated environment*, where peers interact and coevolve with each other to obtain competitive advantages by dynamically making protocol selection decisions. In such a variegated environment, a number of untackled yet critical issues arise:

- Which protocol(s) is(are) more preferable in order to gain an edge in performance? Will benevolent protocols such as BitTorrent, or malevolent protocols like BitThief, succeed? Is there a protocol universally preferred by all peers?

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- How does a selfish node evolve and select protocols distributively, and thus obtain performance benefits? Most importantly, what is the impact of meta-strategic behaviors—dynamic protocol selection—on the entire system performance?
- How to analytically model the evolutionary stability of the system and quantitatively measure the success of a specific protocol? Will a polymorphic equilibrium be achieved? If not, will the system become unstable or even chaotic?

Unfortunately, existing research does not provide insightful answers to these challenging questions. In this paper, we meet this research challenge by investigating strategic autonomous protocol selection in a variegated environment. Specifically, even with diverse design choices, normal-form games are still being used for modeling pairwise encounters of peers [1,8]. As such, general conclusions for systems with protocol diversity are largely unknown. *Population coevolution* is employed to describe the evolution of protocols taken by interacting strategic clients. In summary, our major contributions are threefold:

- *A framework for population coevolution.* We first present a general model, in which the entire population in P2P networks is classified into different groups, each of which consists of peers taking the same protocol. Out of self-interests, peers dynamically migrate among diverse groups. In population coevolution, we study the dynamics and impact of such migration patterns. Population games are adopted to build tractable models. We formally demonstrate that both BitTorrent file sharing and P2P live streaming are population games, in stark contrast to traditional adoption of normal-form games.
- *Dynamics for population coevolution.* Replicator dynamics [9,10] are used for centralized population coevolution with the global knowledge of peer utility. To strive for a decentralized mechanism, we advocate the adoption of learning dynamics on graphs. Fixation probability borrowed from evolutionary graph theory is proposed to quantitatively measure and analyze the success of a protocol. Also, we propose a novel metric, invasion probability, for more accurate quantification. In addition, we analytically adopt such measures to evaluate BitTorrent and BitThief protocols with insightful observations.
- *Tractable equilibrium analysis.* Equilibrium analysis is critical to build tractable models and analytically understand gaming interactions among nodes. We take the coexistence of BitTorrent and BitThief protocols as an example, and quantitatively analyze evolutionary stability. In particular, we first derive Nash equilibria and evolutionarily stable strategies, and then show the existence of a unique evolutionarily stable state in the network. Such analysis validates our proposal of population games to model protocol diversity. We also study strategic protocol selection with the consideration of the connection topology among nodes.

We validate our global and distributed solutions in both BitTorrent file sharing and P2P live streaming networks. In this paper, replicator dynamics reveal insightful patterns for dynamic protocol selection. We also propose lightweight and distributed coevolution algorithms for nodes to evolve on an evolutionary graph. These algorithms only utilize local information among neighbors for strategy update, and thus implicitly consider network topology. In particular, our distributed algorithms can achieve higher system performance and node utility.

The remainder of this paper begins with modeling a variegated environment in Section 2. We formally model P2P systems as population games in Section 3. Evolutionary dynamics and learning dynamics on graphs together with analysis of evolutionary stability, fixation probability, and invasion probability are presented in Section 4. Section 5 considers important implementation issues and presents extensive simulation results on BitTorrent file sharing and P2P live streaming networks. Recent advances in incentives in P2P systems are stated in Section 6. Section 7 provides concluding remarks.

2. Modeling a variegated environment

In this section, we first introduce a basic model to investigate the coexistence of peers with the choices of diverse protocol variants. We then use the number of adopting nodes to evaluate the success of a particular protocol, followed by a formal model of population dynamics based on a continuous time Markov process.

2.1. Basic model

We study autonomous systems without any central authority, in which ordinary clients have the free choice to adopt whichever protocols they like. With the evolution of distributed systems, diverse protocol variants are usually proposed and implemented. Due to the selfish nature, distributed clients potentially compete and thereby coevolve with each other. We refer to such a system with protocol diversity as a variegated environment. A population is the set of clients taking the same protocol. Coevolution means that a population interacts with and affects the fitness of other populations and itself [11]. For example, BitTyrant is a strategic protocol to game against BitTorrent. The downloading performance of clients taking the vanilla BitTorrent protocol is thus influenced by others' adoption of BitTyrant. This in turn affects the fitness of BitTyrant clients themselves.

Population biologists use the population growth of a species as a measure of its success [9]. Indeed, individuals can always adopt the strategy achieving highest expected fitness. We also adopt this concept to evaluate the success of a protocol in a variegated environment. To this end, we study the population growth of clients taking different protocols, which is referred to as population dynamics. Note that such population dynamics do not involve variation operators such as mutation and recombination [12], which is covered in another undergoing study in our research

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