Electronic Commerce Research and Applications 11 (2012) 537–547

Contents lists available at SciVerse ScienceDirect

Electronic Commerce Research and Applications

journal homepage: www.elsevier.com/locate/ecra

Co-evolution-based mechanism design for sponsored search advertising

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ARTICLE INFO

Article history:
Available online 25 April 2012

Keywords:
Sponsored search advertising
Mechanism design
Co-evolutionary simulation
Niche-based evolution

ABSTRACT

Sponsored search advertising (SSA), the primary revenue source of Web search engine companies, has become the dominant form of online advertising. Search engine companies, such as Google and Baidu, are naturally interested in SSA mechanism design with the aim to improve the overall effectiveness and profitability of SSA ecosystems. Due to model intractability, however, traditional game theory and mechanism design frameworks provide only limited help as to the design and evaluation of practical SSA mechanisms. In this paper, we propose a niche-based co-evolutionary simulation approach, aiming at computationally evaluating SSA auction mechanisms based on advertisers' equilibrium bidding behavior generated through co-evolution of their bidding strategies. Using this approach, we evaluate and compare key performance measures of several practical SSA auction mechanisms, including the generalized first and second price auction, the Vickrey–Clarke–Groves mechanism, and a novel hybrid mechanism adopted by sogou.com, a major search engine in China.

1. Introduction

In sponsored search advertising (SSA), online advertisers bid for keyword-specific advertisements to appear alongside the organic search results on Web search result pages. With the promise of precise and in-context customer targeting, SSA provides an effective way of monetizing Web search queries. Within a decade, it has evolved into the dominant form of online advertising and becomes an industry on its own. In 2010, SSA constituted the largest category share (46%) of the $26 billion online advertisement spending in the U.S. markets, far exceeding the share of display advertisement, the second largest category, 24%.[1] SSA is also the primary revenue source of Web search engine companies. In recent years, it accounted for more than 96% and 99.9% of Google and Baidu's international revenues, respectively.[2]

The basic economic institution behind most SSA platforms, such as Google's AdWords and Baidu's Phoenix Nest, is keyword-based position auction. In this type of auction, advertisers selling similar products or services bid for the same keywords on an SSA platform. Once a relevant search query arrives, an auction will be conducted to determine the rank position and the associated payment of winning advertisements. When a user clicks on an advertisement, she will be sent to the landing page on the website of the corresponding advertiser, who in turn pays the search engine.

From search engine companies' point of view, SSA auction mechanism design, i.e., the choice of auction mechanism or format with the ranking and pricing schemes at its core, is of paramount importance. Different auction mechanisms induce different types of advertiser bidding behavior, which in turn determine advertisers' revenues and search engine companies' profitability. In the long run, the stability and sustainability of the SSA ecosystem, to a large degree, hinges on SSA auction mechanism design as well.

A variety of auction mechanisms have emerged during the evolution of SSA since its appearance in 1998. The pioneer of SSA, GoTo.com (then Overture, now part of Yahoo!), used the generalized first-price (GFP) auction, in which advertisers were ranked by and pay their own bids. In 2002, Google started to use the generalized second-price (GSP) auction, which ranks advertisers by their bids but charges them, if their advertisements are clicked by Web users, by the next highest bids. Currently, most major search engines around the world have adopted a variant of the GSP mechanism, in which advertisers are ranked by the product of their own bids and search engine-assigned quality scores. In the meanwhile, other auction formats have been experimented and used as well. A prominent example is a hybrid auction format adopted by sogou.com, China's third largest search engine. In this auction, advertisers are ranked by their bids but allowed to select to pay following either the first or second pricing scheme. In this

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[1] http://www.iab.net/insights_research/947883/adrevenuereport#tabs-10.
[2] http://investor.google.com/financial/tables.html, and http://ir.baidu.com/phoenix.zhtml?c=188488&p=irol-reportsAnnual.

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http://dx.doi.org/10.1016/j.elerap.2012.03.002

paper, we refer to this auction format as the First–Second-Price (FSP) auction.

In the literature, the Vickrey–Clarke–Groves (VCG) and laddered auctions have also been studied (Aggarwal et al. 2006). These auction formats offer nice properties such as incentive compatibility, typically aimed at optimizing the profitability of search engines, and at reducing the possibility of advertisers trying to "game the system." As a result, market efficiency can be achieved, i.e., advertisers with higher per-click values are more likely to win better advertisement slots.

Due to its practical significance, SSA auction mechanism design has attracted a lot of attention from the research community in recent years. Most existing work evaluates auction mechanisms using frameworks and tools from game theory and, in particular, mechanism design theory. As SSA platforms evolve and associated auction rules undergo changes in dynamic online business settings, formal mathematical analysis based on mechanism design theory quickly becomes inadequate in dealing with design and evaluation of practical SSA auction mechanisms. It has become a major challenge for search engines to understand advertisers' bidding behavior and assess the outcome of complex SSA auctions. As a result, these companies can only rely on ad hoc anecdotal evidence or limited scenario-based comparisons to make major decisions concerning auction rules, increasing the risk and hindering innovation in the SSA space.

From a research perspective, with the end goal of helping the SSA ecosystem maintain its overall effectiveness, profitability, and stability, there is a critical need to develop new research methodologies for SSA mechanism design. However, to the best of our knowledge, research in this area is severely lacking. Our research is targeted at filling in this important gap. We propose a niche-based co-evolutionary approach, aiming at automatically searching for equilibrium bidding behavior of rational advertisers in SSA auctions, and in turn evaluating and designing alternative SSA auction mechanisms. Niche plays a central role in evolutionary divergence during the ecological speciation process, and can be used in co-evolutionary simulations to construct the equilibrium continuum of SSA auctions by forming and maintaining stable sub-populations, each converging at a single equilibrium. Compared with the analytical mechanism design approach, co-evolutionary simulation offers the following advantages. First, it evaluates the macro-scope properties of SSA auctions by simulating long-term co-evolution and co-adaptation of advertisers' micro-scope bidding behavior. As such, the simulation process is robust to input mechanisms, and can be adapted to assess various kinds of SSA mechanisms with only minor modifications. Second, co-evolutionary simulation can be used to optimize advertisers' bidding strategies via searching through the entire strategy space. This can help search engines better understand advertisers' behavior in a specific SSA mechanism.

This paper makes the following contributions. Methodologically, the reported work is the first attempt to apply the co-evolutionary simulation approach to auction mechanism design in SSA contexts. We also propose a novel niche-based co-evolutionary algorithm to help design and evaluate SSA auction mechanisms. Practically, our research can help Web search engines better understand advertisers' complex bidding dynamics in SSA auctions, and computationally evaluate SSA auctions' performance. From the perspective of competing advertisers, our research and algorithm can help them discover all kinds of possible equilibrium bidding strategies, and analyze their marketing effectiveness. As a result, a variety of observed bidding behavior to "game the system" (Zhou and Lukose 2006), as well as irrational or even malicious bidding behavior (Iyengar et al. 2007), may be recognized and reduced in SSA practice.

The remainder of this paper is organized as follows. Section 2 provides a brief review of the SSA auction mechanism design literature. In Section 3, we discuss performance measures concerning SSA auction mechanisms and the rationale behind co-evolutionary auction simulation. We then present in detail our proposed niche-based co-evolutionary mechanism design. Several typical SSA auction mechanisms are evaluated through co-evolutionary simulations in Section 4. In Section 5, we summarize our research findings and discuss future research possibilities.

2. Literature review

Mechanism design has long been an active topic in auction research. Here we are mainly concerned with the mechanism design work in the SSA context. Two research streams, analytical and computational mechanism design, have been developed in the literature. Below we present a brief survey of these two lines of thoughts.

2.1. Analytical mechanism design

The classical mechanism design framework has been used to formally characterize the key properties of various SSA auction mechanisms. For instance, the early GFP mechanism has been proved to be unstable with price cycles in bids (Zhang and Feng 2005). In contrast, the prevailing GSP mechanism has a symmetric Nash equilibrium (SNE) continuum, and the bids of revenue-maximizing advertisers will converge to the lowest-price Nash equilibrium (LPNE) in SNE (Edelman et al. 2007). However, GSP is not a truthful mechanism, and its Nash equilibria (NE) beyond the SNE continuum is not yet fully explored. For theoretical analysis, researchers have investigated truthful SSA mechanisms such as the VCG and laddered auctions (Aggarwal et al. 2006), in which advertisers are motivated to truthfully bid their private per-click values. Moreover, an optimal mechanism has been proposed to maximize search engines' expected revenue while achieving Bayesian incentive compatibility and individual rationality of advertisers (Garg and Narahari 2009).

Recent analytical research focuses mainly on mechanism design for emerging SSA formats. For instance, an execution-contingent VCG mechanism was proposed for SSA platforms operating on federated search engines (Ceppi et al. 2011). Multi-slot SSA auctions have been studied, in which an advertiser can bid for multiple advertisement slots simultaneously (Deng et al. 2010). Several extended forms of advertisers' utility functions, e.g., a linear form with identical slopes and a single discontinuity, a piece-wise linear form with non-identical slopes and multi-discontinuities, have also been developed to improve the expressiveness of SSA mechanisms (Aggarwal et al. 2009, Duting et al. 2011).

In general, analytical mechanism design has the following limitations. First, due to inherent analytical complexity, it is difficult to mathematically evaluate complex SSA mechanisms in dynamic online environments. Second, the analytical approach is usually highly sensitive to auction mechanisms. Even a minor modification to the mechanism can lead to totally different analyses and solutions. For instance, if advertisers aim to maximize their revenues and the rivals' payments in competitive SSA markets, their bids in a GSP auction will converge to the highest-price equilibrium in the SNE continuum, instead of the LPNE (Yuan et al. 2011). Third, the standard game-theoretic analysis cannot reveal such dynamic properties as stability and robustness of equilibrium bidding strategies, and thus sheds limited light on which kind of equilibrium outcome is more likely to be observed in SSA auctions with a specific mechanism over the long run. These limitations have motivated research in computational mechanism design.