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Dynamic dual adjustment of daily budgets and bids in sponsored search auctions

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ABSTRACT

As a form of targeted advertising, sponsored search auctions attract advertisers bidding for a limited number of slots in paid online listings. Sponsored search markets usually change rapidly over time, which requires advertisers to adjust their advertising strategies in a timely manner according to market dynamics. In this research, we argue that both the bid price and the advertiser (claimed) daily budget should be dynamically changed at a fine granularity (e.g., within a day) for an effective advertising strategy. By doing so, we can avoid wasting money on early ineffective clicks and seize better advertising opportunities in the future. We formulate the problem of dual adjusting (claimed) daily budget and bid price as a continuous state — discrete action decision process in the continuous reinforcement learning (CRL) framework. We fit the CRL approach to our decision scenarios by considering market dynamics and features of sponsored search auctions. We conduct experiments on a real-world dataset collected from campaigns conducted by an e-commerce advertiser on a major Chinese search engine to evaluate our dual adjustment strategy. Experimental results show that our strategy outperforms two state-of-the-art baseline strategies and illustrate the effect of adjusting either (claimed) daily budget or bid price in advertising.

1. Introduction

With the recent trend of "economics meets search" [16], there is a rapid growth of search engine-based advertisements. Such sponsored search is often managed through a form of auctions, where a bidding contract is triggered once a query of certain keywords is submitted. Advertisers need to carefully manage their advertising strategies through the parameters of the bidding setup in order to compete with other advertisers. The high volume of search demands makes bidding in sponsored search auctions a continuous and dynamic process. Once an advertiser adjusts her advertisements and/or advertising strategies, rankings of the sponsored links and cost-per-click will be changed accordingly. Thus, to achieve an effective campaign, advertisers should continuously monitor the auction market and adjust their strategies in response to market dynamics.

Among all factors to be managed, budget is one critical factor that is endogenous to the auction process [3]. Previous research usually assumes budget to be fixed and take it as a constraint in strategy development. For example, some research [18,24] studied the allocation of budget over keywords. This method cannot effectively deal with the dynamic sponsored search auctions provided by major search engines (e.g., Google). It is necessary to examine budget allocation at finer granularity, such as real-time adjustment within a day, for advertising. At this level, so far, most studies considered only bid price adjustment [13,22] and ignored budget control.

In the lifecycle of advertising campaigns in sponsored search, budget decisions occur at three levels [35]: allocate budget across search markets [34], distribute budget over a series of temporal slots (e.g. day) [36,37], and adjust the claimed budget within a temporal slot (to simplify the wording, this paper uses 'day' to replace 'temporal slot' hereafter). Note that after deciding each day's budget during a given promotional period, an advertiser can claim a daily budget (named daily budget in short) which is different from their actual internal budget (named daily budget limit in short). By changing the (claimed) daily budget, the advertiser can restrict the amount of clicks to be directed to their sponsored links by the search engine in a unit time. Thus, in a sponsored search auction, after an advertiser determines her daily budget limit for a campaign (or each keyword of the campaign), she should monitor the advertising performance and adjust the daily budget together with bid prices corresponding to market dynamics, until the end of the daily advertising schedule or when the day's remaining budget is zero. Thus she can avoid wasting money on ineffective clicks and save money for future opportunities.

In a previous work [35] we developed a hierarchical budget optimization framework (BOF), which considers all three levels of budget allocation in the entire lifecycle of advertising campaigns in sponsored search auctions. Following that, this work aims to tackle the advertising strategy optimization problem by dynamically adjusting daily budget and bid price within a day. To the best of our knowledge, our work might be the first effort in this direction.

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We address the dual adjustment problem as a continuous state — discrete action decision process in the continuous reinforcement learning (CRL) framework, since it can be viewed as a special multi-stage dynamic decision problem. Specifically, we employ continuous-time and continuous-state reinforcement learning [7] to capture the continuous state variables in the problem (such as the day's remaining budget, click dynamics, etc.). We adapt the CRL framework from two perspectives to meet the requirements of the advertising decision problem in sponsored search auctions. First, in classic CRL, behaviors of the environment were usually given as prior knowledge. However, we don't have information due to the complicated nature of sponsored search. Thus, we employ a Back Propagation Neural Network (BPNN) to approximate the parameters of the environment using historical data. Second, since some search engines (e.g., Google) only permit making a limited number of changes on (claimed) daily budget during a day, we employ step functions to represent the multiple discrete actions, which can occur at any time of the day. We provide an algorithm to solve our CRL-based dual adjustment model that iteratively optimizes the actions along the decision temporal points. In order to evaluate the effectiveness of our proposed approach, we conduct some experiments using a real-world dataset collected from search advertising campaigns conducted by an e-commerce advertiser on a major Chinese search engine. Experimental results illustrate that our strategy outperforms two state-of-the-art baseline strategies. They also show that budget adjustment plays a more important role in the dual adjustment strategy.

The contributions of this work can be summarized as follows:

(1) We frame the dual adjustment problem (on changing daily budget and bid price within a day) for advertising strategy development in sponsored search auctions.
(2) We build a continuous-time, continuous-state, and discrete action model under a CRL framework that fits the decision scenarios of the dual adjustment problem in sponsored search auctions.
(3) We develop an iterative numerical approach that can efficiently solve our proposed model for online applications.

The rest of this paper is organized as follows. The next section briefly reviews some relevant literature. In Section 3, we describe budget decision scenarios in sponsored search auctions and state the research problem under consideration. Section 4 presents our dual adjustment model based on CRL. Section 5 provides a numerical solution to our proposed model. Sections 6 and 7 report the experiments to evaluate our dual adjustment model and discuss the implications of results. Section 8 concludes this work.

2. Literature review

Effective advertising strategy is an important problem in marketing. In the middle of the last century, [33] proposed the concept of advertising effectiveness and equations on sales response dynamics. They provided an optimal solution for the allocation of limited budgets considering sales dynamics. [23] introduced the concept of advertising goodwill to reflect the flow of current advertising expenditures. They considered that aggregated advertising effectiveness would influence future budget decisions and built a dynamic adjustment framework to optimize advertising strategies and price policies. The framework was later generalized by [28] into the case with limited budgets.

In recent years, many researchers have attention on the impact of market dynamics on advertisers' decision, such as budget allocation and adjustment [12,19,26,27,30]. Some studies recognized that the shape of the advertising response function plays an important role in advertising strategies [20,21,29,32]. Particularly, the S-shaped response function was carefully examined [10,14] since its convexity at low expenditure levels makes it easy to obtain the periodic optima in practice. Krishnan and Jain [17] investigated the optimal advertising policy for new products considering the influence of information diffusion and concluded that optimal advertising strategies are determined by the advertising effectiveness, discount rate, and the ratio of advertisement to profits.

The increase in sponsored search auctions has lead to advertising competitions in this unique auction market environment [15]. In such environments, various mathematic programming algorithms have been developed to improve advertising strategies. Integer programming and nonlinear programming were used to find optimal solutions for budget allocation over sponsored keywords [18,24]. OZluk and Cholette [24] showed that price elasticities of the click-through rate and response functions were key factors for budget decisions, and investing in more keywords under a certain threshold could help improve advertisers' profits. Fruchter and Dou [11] established an optimal control model to study the optimal budget allocation problem among web portals, and used dynamic programming to derive the analytical solution to the problem.

Considering the dynamic nature of sponsored search auction markets [36], it is natural to formulate the budget optimization problem as a Markov decision process [8] or an optimal control model [1,11]. Archak et al. [1] showed that under a reasonable assumption, online advertising has positive carryover effects on the propensity and form of user interactions with the same advertiser in the future. Based on the Nerlove–Arrow advertising framework [23], Rutz and Bucklin [25] proposed a dynamic linear model to capture the potential spillover from generic to branded paid search. The budget optimization problem can also be established as an online (multiple-choice) knapsack problem [4,5], from which advertisers can achieve a provably optimal competitive ratio. By considering bid dynamics and rankings of advertisers, a cyclical bid adjustment model in a two-player competition game was studied by Zhang and Feng [38], where an equilibrium bidding price for two advertisers can be obtained. Some researches have explored periodical budget allocation strategies by considering temporal features, such as weekday, weekends, and months of a year [9]. However, this exploration is not detailed enough for real-time strategy adjustment.

3. Budget decisions in sponsored search auctions

3.1. Budget decision scenarios

Three different budget decision scenarios occur during the lifecycle of sponsored search advertising campaigns. Fig. 1 describes budget decision scenarios according to temporal granularity, with two dimensions: over time (the horizontal axis) and across markets (the vertical axis). The interested reader is referred to see article [35] for more details of budget decision scenarios in sponsored search auctions.

Suppose the advertiser intends to conduct a sponsored search marketing campaign. First, at a long-term level, an advertiser needs to decide how to allocate her search advertising budget across multiple markets, given a predetermined total budget. Second, at a medium-term level, the advertiser needs to distribute her advertising budget across a series of temporal slots/days (named daily budget limit). Here, if necessary, the advertiser can optimize one day's budget limit based on historical advertising performance. However, once determined, the advertiser would expect to use up all budget in that temporal slot. Third, in each temporal slot of an ongoing advertising campaigns, an advertiser can also adjust some factors, such as (claimed) daily budget and bid price, in real-time to affect the ranking of the advertiser's sponsored links in response to advertising dynamics.

Budget strategies at these three levels complement each other and form an integrated budget optimization problem chain. That is, results of higher-level decisions constrain lower-level decisions, and operational results at lower levels create feedback for decisions at higher levels. Moreover, budget operations at these three levels all interact with outside environments, which contain great uncertainties ranging from advertising resources to advertising performance.