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A group-based traffic signal control with adaptive learning ability

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A B S T R A C T

Group-based control is an advanced traffic signal strategy capable of dynamically generating phase sequences at intersections. Combined with the phasing scheme, vehicle actuated timing is often adopted to respond to the detected traffic. However, the parameters of a signal controller are often predetermined in practice, and the control performance may suffer from deterioration when dealing with highly fluctuating traffic demand. This study proposes a group-based signal control approach capable of making decisions based on its understanding of traffic conditions at the intersection level. In particular, the control problem is formulated using a framework of stochastic optimal control for multi-agent system in which each signal group is modeled as an intelligent agent. The agents learn how to react to traffic environment and make optimal timing decisions according to the perceived system states. Reinforcement learning, enhanced by multiple-step backups, is employed as the kernel of the intelligent control algorithm, where each agent updates its knowledge on-line based on a sequence of states during the process. In addition, the proposed system is designated to be compatible with the prevailing signal system. A case study was carried out in a simulation environment to compare the proposed control approach with a benchmark controller used in practice, group-based vehicle actuated (GBVA) controller, whose parameters were off-line optimized using a genetic algorithm. Simulation results show that the proposed adaptive group-based control system outperforms the optimized GBVA control system mainly because of its real-time adaptive learning capacity in response to the changes in traffic demand.

1. Introduction

The problem of traffic congestion in urban areas can be alleviated by optimally performing advanced control strategies at intersections. Traffic light system is an important road facility that can operate traffic flows efficiently through two different controls: signal timing and phasing. Whereas signal timing refers to the methods of determining durations of traffic light indications, compatible turning movements can be offered with the same traffic light indications through phasing control. Among different phasing control approaches, group-based traffic signal control is frequently used for traffic light system in many European countries. Such a control scheme owns its advantages in allocating green times, especially in the case that demands on different turning movements are unbalanced at an intersection (Tang and Nakamura, 2011). Unlike stage-based control whose phase sequence is predetermined, group-based control is capable of dynamically combining compatible turning movements into phases. Previous studies have compared the group-based controllers with stage-based controllers and showed the potential to improve the performance of traffic system in the aspects of traffic mobility, energy efficiency and emissions of pollutants (e.g., Jin and Ma, 2014).

The emerging methods in computer science and machine learning fields nowadays provide great opportunities in developing more efficient traffic controls and management strategies. Especially, reinforcement learning (RL), an advanced machine learning approach, has attracted lots of recent research interests when coping with signal control problems (e.g., Thorpe and Anderson, 1996; Wiering, 2000; El-Tantawy et al., 2013; Khamis and Gomaa, 2014). In the RL framework, intelligent agents are employed to model a signal control system, and they comply trials in light of their knowledge. The trials result in new observations from traffic system that each agent may learn and acquire new knowledge based on the learning framework. The signal controller hence carries out a knowledge creation process in various operational conditions and becomes smarter and smarter during the execution of control operations.

In the practice of traffic management, the cost of deploying a new signal control system is considered expensive, especially when both signal

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controller and detection system are required to be replaced. Therefore, it becomes of great importance to figure out a cost-effective solution for improving the existing signal control system. Although group-based controllers are widely deployed in the existing infrastructure, signal timing is normally on-line generated as a result of the control parameters set in advance. Indeed, the parameters could be either manually tuned by traffic engineers using their experience or determined by optimization studies carried out off-line using analytical tools. The pre-defined signal timing settings may, however, meet difficulties when handling sudden changes of live traffic demand. Therefore, an intelligent timing strategy becomes more important in the current signal control development, capable of adapting the control parameters with respect to live traffic conditions.

To this end, the objective of this study is to develop an intersection traffic signal control approach capable of making intelligent timing decisions based on machine learning. Particularly, the proposed control method should fit the context of the group-based traffic light system such that there is no need to replace the existing traffic infrastructure. The proposed signal control is enabled by a multi-agent modeling of the group-based traffic light system and reinforcement learning based intelligent control approach. The focus of this paper is on intersection traffic control, but the self-interested design makes the approach potentially extensible for road network control. The rest of this paper is organized as follows. The next section provides a literature review regarding the state of the art of traffic light systems, especially taking advantages of machine learning and artificial intelligence techniques. The methodology of the proposed signal control is illustrated in the following section. Section 4 elaborates the case study together with analyses and discussion of the results obtained from simulation experiments. The last section summarizes the paper with conclusions and future work.

2. Literature review

Vehicle actuated (VA) signal control is one of the most conventional approaches in traffic light system. But it has a limitation in coping with the fluctuation of traffic demands within short periods. In order to address this issue, adaptive traffic control systems were proposed by adjusting control parameters in accordance with the predicted traffic patterns. In the 1980s, SCOOT and SCATS began pioneering the development of adaptive signal control system (Hunt et al., 1982; Sims and Dobinson, 1980). The ideas of the two systems are rather similar, by selecting the most appropriate signal plan from a look-up table according to the traffic being detected in real time. Along with the development of detection technologies, some adaptive signal control systems have been proposed and even deployed in the field, e.g., RHODES (Mirchandani and Head, 2001) and TUC (Boillot et al., 2006). However, most adaptive signal control systems work with stage-based phasing rather than group-based phasing.

In the past decade, some techniques from machine learning (ML) and artificial intelligence (AI) fields were applied to the development of adaptive signal control systems. For example, Srinivasan et al. (2006) presented a neural networks-based multi-agent system approach to developing distributed traffic-responsive signal control models. Signal controllers using fuzzy logic approaches have been proposed by researchers all over the world (e.g., Balaji and Srinivasan, 2011; Jin et al., 2017). The general idea of fuzzy logic-based signal controllers is to use a set of rules to determine the control operations based on the inputs from traffic system. Reinforcement learning is another technique that has been employed for signal control. Intelligent agents are used to model traffic light system while agents can learn from traffic environment and react with corresponding decisions (e.g., Thorpe and Anderson, 1996; Wiering, 2000).

Among all the adaptive signal controllers using ML and AI approaches, reinforcement learning (RL) has been considered as a promising control method for traffic light system. This is mainly because of the convenience of formulating signal control as a sequential decision-making problem. Thorpe and Anderson (1996) firstly applied an RL algorithm to control an isolated intersection. The simulation results showed that the adaptive signal control outperformed a fixed time controller by reducing the average waiting time of the vehicles traversed. On the other hand, Wiering (2000) launched another approach for adaptive signal control using RL. In the study, the knowledge of an agent is updated on the basis of vehicle-level performance measures during the learning process.

Since the first applications of RL in traffic signal control, the proposed framework becomes more general and increasingly advanced. For example, Cai et al. (2009) formulated signal control problem using a Markov process modeling framework. The simulation result showed that the RL based controller could achieve a substantial reduction in travel delay for vehicles compared to an optimized stage-based fixed-time control. Recently, much effort has been devoted to controlling traffic lights of large networks using RL methodologies. For instance, Bazzan et al. (2010) introduced a supervised multi-agent signal control system for a group of signal controllers in a large network. Abdoos et al. (2013) applied an organization-based multi-agent system (so-called holonic multi-agent system) to reduce the complexity of the control problem for large-scale systems. Besides, El-Tantawy et al. (2013) implemented a decentralized design for an RL-based signal control system with large-scale applications. Khamis and Gomaa (2014) proposed a cooperative multi-agent framework for network-wide traffic signal controls using a multi-objective reinforcement learning algorithm.

In summary, many adaptive signal control systems proposed assume the availability of individual vehicle information in their system designs (e.g., Wiering, 2000; Khamis and Gomaa, 2014). But such systems have difficulties to deal with reality since they require vehicles sending their travel information to the controller at a high frequency. In the current traffic system, advanced signal control is mostly implemented based on information from vehicle-actuated detectors, such as loop detectors. While the latest studies in adaptive signal control put lots of effort on the control strategies at the network level, the intersection control is mostly assumed fixed-time and stage-based. To the best of the authors' knowledge, few of the adaptive traffic light systems ever proposed are suited for different phasing strategies, especially for group-based phasing. Consequently, there is a gap between the research on adaptive signal control systems and traffic engineering practice. This paper proposes an intelligent agent-based signal control that is suited for group-based phasing. Although the study focuses on intersection control, there is a potential to apply the approach for a large road network due to its local design and adaptive learning properties.

3. Methodology

3.1. Traffic signal modeling

In a group-based signal control system, a fundamental unit is a signal group. A signal group is usually defined to govern a turning movement or a collection of several turning movements. All compatible signal groups are possible to form a phase. During the operation of group-based phasing, if a signal group in the current phase is ordered to terminate, the system automatically searches for another signal group as the substitution. The substitute signal group is chosen from a set of candidate signal groups. For a certain signal group in the current phase, its candidate signal groups cannot have conflicts with the rest of the signal groups. Meanwhile, they should not have been activated in the current cycle. If no candidate signal group exists, the ordered-to-terminate signal group has to wait until all signal groups in the current phase are ordered to terminate. During the waiting time, the ordered-to-terminate signal group shows a green indication, but detection information for the signal group is no longer registered to determine signal timings. This green period is named as "passive green time" in traffic engineering.

Signal groups can only be activated once in a cycle such that a cycle ends when all of the signal groups have been ever activated.