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Distributed coordinated signal timing optimization in connected transportation networks

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ABSTRACT

This paper presents a Distributed-Coordinated methodology for signal timing optimization in connected urban street networks. The underlying assumption is that all vehicles and intersections are connected and intersections can share information with each other. The novelty of the work arises from reformulating the signal timing optimization problem from a central architecture, where all signal timing parameters are optimized in one mathematical program, to a decentralized approach, where a mathematical program controls the timing of only a single intersection. As a result of this distribution, the complexity of the problem is significantly reduced thus, the proposed approach is real-time and scalable. Furthermore, distributed mathematical programs continuously coordinate with each other to avoid finding locally optimal solutions and to move towards global optimality. We proposed a real-time and scalable solution technique to solve the problem and applied it to several case study networks under various demand patterns. The algorithm controlled queue length and maximized intersection throughput (between 1% and 5% increase compared to the actuated coordinated signals optimized in VISTRO) and reduced travel time (between 17% and 48% decrease compared to actuated coordinated signals) in all cases.

1. Introduction

Majority of signal timing optimization algorithms utilize a centralized formulation and architecture. As a result, they optimize various signal timing parameters (i.e., phase plan, cycle length, green times, and offsets) of all intersections at the same time in one mathematical program. However, network signal timing optimization is an NP-Complete problem (Wünsch, 2008; Hajbabaie, 2012) and a central optimization technique will not be scalable and applicable to large transportation networks.

Hierarchal approaches decompose the signal timing optimization problem to several interconnected sub-problems with a central control unit. The underlying concept of most hierarchal approaches is to handle slow-varying and wide-area-level decisions at upper levels and perform real-time and small-area computations in lower levels. As a result, the upper and lower levels may have objective functions that compete with each other. Therefore, designing signal control methods with a reasonable balance between these levels is challenging (Dion and Hellinga, 2001).

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There are also a number of studies that focused on decentralized signal control in urban settings. As a result of the decentralization, these approaches are scalable and can be real-time; however, rather than global optimization, they mostly locally control the signals and may find sub-optimal solutions.

This paper develops a Distributed-Coordinated (DC) approach for network-level signal control in a connected urban street environment. We propose a new distributed formulation for signal timing optimization problem, where a mathematical program finds the optimal timing of only a single intersection with the objective of maximizing its throughput while penalizing for long queue length on different approaches. However, each mathematical program is aware of other intersections' decisions and traffic flow conditions. As a result, the decisions at neighboring intersections are coordinated to ensure smooth traffic flow throughout the network and avoiding locally optimal solutions.

This study also proposes an innovative solution technique to solve the DC problem. The proposed rolling horizon solution technique gathers demand and queue length data at each intersection at each time step and optimizes the timing of signalized intersections for several time steps in the future (a.k.a. prediction period); however, only implements the decisions on terminating or extending the signals for the next time step (i.e., could be as short as one second). As a result, in addition to coordination between different intersections, the approach finds solutions that are expected to be near-optimal for the entire study period.

The proposed DC approach is real-time and scalable to networks of any size as long as enough computational power is available and the right duration of time step and prediction periods are selected. The underlying assumption is that the entire network (all vehicles and intersections) is connected. It also addresses the oversaturated conditions with selection of an appropriate objective function and inclusion of explicit constraints on maximum queue length. The proposed approach is dynamic and can react to abrupt changes in demand level and roadway capacity (e.g., lane closure due to a traffic accident).

The remainder of this paper is organized as follows. Next section presents a review of relevant literature on traffic signal timing methods and highlights the research gaps. Then, problem formulation and the proposed solution technique are introduced. Information on the study site and implementing the algorithm is detailed next. The method is applied to two case study networks under four different demand patterns and the results are discussed and compared with different traffic signal control methods. Finally, concluding remarks and trends for further research are presented.

2. Literature review

Much research is devoted to traffic signal control. This section provides a review of relevant studies and presents them in three different groups: central, hierarchal, and decentralized signal timing approaches. At the end of this section, the contributions of this paper will be highlighted.

2.1. Central signal timing approaches

Longley (1968), Abu-Lebdeh and Benekohal (1997), and Chang and Sun (2004) developed central methods to control traffic signals dynamically in oversaturated networks. Hajbabaie et al. (2011) proposed Genetic Algorithms and Approximate Dynamic Programming approaches for traffic signal coordination and queue management in oversaturated networks. These methods were compared (Medina et al., 2011) and used to evaluate the effects of prohibiting or allowing left turns at signalized intersections (Hajbabaie et al., 2010), using a common or variable cycle length in signal coordination (Hajbabaie and Benekohal, 2011a, 2011b), and metering traffic entering a congested network (Hajbabaie and Benekohal, 2011a, 2011b; Medina et al., 2013) on traffic operations. Putha et al. (2012) proposed a traffic signal coordination method under oversaturation flow conditions using ant colony optimization and compared it to simple genetic algorithms.

Cantarella et al. (1991) developed an iterative procedure for equilibrium network traffic signal setting and heuristics for optimizing signal setting and lane layout (Cantarella et al., 2006). Ceylan and Bell (2004) and Teklu et al. (2007) proposed methodologies for simultaneous signal timing optimization and traffic assignment using genetic algorithm. Beard and Ziliaskopoulos (2006) simultaneously optimized traffic signal timing and system optimal traffic assignment problems in a mixed integer linear programming model. Sun et al. (2006) combined signal control in oversaturated networks with stochastic route choice in a bi-level mathematical programming model and used a heuristic solution technique to solve it. Karoonsoontawong and Waller (2010) proposed a robust optimization formulation for network capacity expansion, traffic signal optimization, and dynamic traffic assignment. Ukkusuri et al. (2013) proposed a bi-level formulation to optimize the signal setting to minimize the system-level travel time at the upper level, and optimize travelers' routes to minimize their travel cost at the lower level.

He et al. (2012) developed a mixed-integer linear program to find future optimal signal status considering transit and passenger car modes in a connected vehicle environment. The computational complexity of their approach increased with traffic demand; thus, a real-time solution was not possible. He et al. (2014) proposed multi-modal priority control with the consideration of signal coordination for connected vehicles. The study includes emergency vehicles, transit buses, commercial trucks, and pedestrians. Their approach minimizes the actual travel time along the route to the destination. Hajbabaie and Benekohal (2015) developed a bi-level program for simultaneous signal timing optimization and traffic assignment for oversaturated transportation network. This study introduced a new objective function, maximization of the weighted number of completed trips, and explicit constraints on queue length. Feng et al. (2015) applied dynamic programming to optimize min-