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Steady-State Traffic Signal Control With Variable Phase Combinations and Sequences

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Abstract: The space distribution of traffic flows is often unbalanced, resulting in regional congestion, and even oversaturation of the network. In this paper, the steady-state traffic signal control design approach, with consensus-based control objective of network states, is proposed. A traffic flow model is first introduced based on store-and-forward modeling procedures. Furthermore, a link-based distributed signal control law is proposed with the consensus of link occupancies as control objective, and moreover control approach for phase combinations and sequences is introduced, especially in case of higher network demands. At last, simulation investigations for a topological network in Beijing are conducted in VISSIM software, which shows that the proposed approaches can improve performance indices of the network and then reduce local traffic congestion.

Keywords: Urban traffic networks; traffic control; steady-state control; consensus; phase combinations and sequences

1. INTRODUCTION

With social and economic development of cities and increasing levels of urbanization, especially in developing countries, the number of motor vehicles increases rapidly, resulting in serious traffic congestion in some urban central regions and local bottleneck links at peak hours almost every day, which indirectly induces the pollution of environment. At present, intelligent transportation system (ITS) strategies have been carried out in most of countries, and traffic signal control system, as an important part of ITS, plays a critical role for governing traffic flows in the network. Currently, most of traffic control systems are mainly designed for the under-saturation conditions and thus traffic control for the oversaturation network is still a challenging problem, (Papageorgiou et al., 2003). Thus, different modeling and optimization approaches for urban traffic networks have been proposed, such as CTM-based generic algorithm, (Lo et al., 2001), MPC based approaches, (Aboudolas et al., 2010), and (Lin et al., 2011), optimal control approaches, (Aboudolas et al., 2009), (Diakaki et al., 2002), and (Ioslovich et al., 2011), hybrid system modeling and control approaches, (Haddad et al., 2010, 2014), (He et al., 2013a), (De Schutter, 2002), (Wang et al., 2015), etc.

Usually, minimum of total delay or travel time is taken as the control objective for the design of traffic signal plans, such as (Ioslovich et al., 2011), (Lin et al., 2011), (Lo et al., 2001), (De Schutter, 2002). In urban traffic networks, especially with higher saturation levels, a typical scenario is often observed, where local congestion occurs in some network links, but there may be enough space being not sufficiently utilized in other network links, demonstrating that the space distribution of traffic flows is unbalanced. Then, the balance of network flows in some sense is the adequate and reasonable control objective for enhancing the utilization efficiency of network capacity. The steady-state control approach for isolated signalized intersections was proposed in (Haddad et al., 2010, 2014), the ideas behind which is that solving the optimal red-green switching sequence by off-line way, ensuring the queues can reach the expected state, which may indicate the queues can reach the balance in some sense. Clearing policy and its extensions proposed in (He et al., 2013a) and (Wang et al., 2015) were on-line feedback control strategies for the under-saturation intersections, which can realize the balance of saturation levels in different flow directions. However, the results above need to be further extended to the network-wide signal control. The traffic-responsive urban control (TUC) strategy in (Aboudolas et al., 2009, 2010) and (Diakaki et al., 2002) is one of successful applications of control theory approaches in traffic control, where the linear-quadratic optimal control approach is applied for the real-time splits control. The TUC strategy has been sufficiently validated in real-world networks, and reported the perfect performance, especially for the oversaturation networks, (Kosmatopoulos et al., 2006) and (Kraus et al., 2011). Specifically, the TUC strategy is implemented in the centralized way, in which the balance of network flows is adequately embodied in the performance index.

In recent years, the distributed coordination control of multi-agent networks has attracted extensive attention because of abundant application fields, (Ren et al., 2011). Many coordination control problems of multi-agent networks can be reduced to the consensus problem, meaning that states of network agents asymptotically converge to a common value by local or global communication. Abundant theoretical approaches in consensus problem may provide new insights on traffic control. If the evolution of adequately defined

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traffic states in network links can reach consensus, the balance of network flows can be realized in some sense, and then local congestion can be reduced. The consensus-based approach in (He et al., 2013b) was developed for traffic control, and a centralized splits feedback control law was proposed by using partial stability method. If the set of network agents is partitioned into finite number of subsets, and agents in each subset reach consensus, the cluster consensus of multi-agent networks is realized, (Xia et al., 2010). The idea of cluster consensus was introduced in the signal control design, and a distributed splits feedback control law was proposed in (Wang et al., 2013, 2014), where adjustable parameters in splits control law assumed a constant, need to be chosen by trail-and-error way. The cluster-consensus based approach admits consideration of the dynamic/static diversities of network links, e.g., the consensus values of states in longer and shorter links respectively may be chosen to be different, or for protecting some busy links, in which the consensus values of states should be smaller. The consensus or cluster consensus approach in traffic control further extends ideas in (Haddad et al., 2010, 2014), (He et al., 2013a), and (Wang et al., 2015) to the network-wide signal control.

In this paper, the steady-state traffic signal control approach unifying the consensus and cluster consensus ideas is proposed for any topological network, and the link-based signal control law is suggested with the distributed implementation, admitting local coordination among adjacent links. Furthermore, the control approach for combination and sequence of phases in signalized intersections is presented for further reducing the possibility of occurrence of overflows. A topological network in Beijing is investigated for validating our results.

The paper is organized as follows. Section 1 provides the background of the paper; A signal control design model and the steady-state signal control approach are detailed in Section 2; Furthermore, the control approach for phase combination and sequence is introduced in Section 3; After simulation investigations for a topological network in Section 4, conclusions and further research problems are given in Section 5.

2. STEADY-STATE SIGNAL CONTROL FOR THE NETWORKS

2.1 Control Structure of the Network

We denote by J the set of signalized intersections in the network; by V={1,2,…} the set of links in the network; by V^S and V^D respectively the set of input and output links on boundaries of the network; and by V^I the set of internal links in the network. Furthermore, a signalized network is represented by a diagraph with network links as vertices and vehicle-flow directions as directed edges. The control structure of the network is illustrated in Fig. 1, where each link is equipped with three modules (i.e., communication, control, and coordination respectively), where the communication module communicates with adjacent links for acquisition of necessary information of traffic states; the control module generates local control law of the link; and the coordination module in real-time outputs final control plans of signalized intersections with necessary constraints.

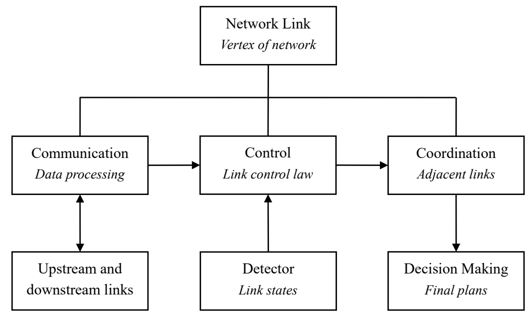

Fig. 1. Control structure of the network.

2.2 Traffic Flow Model

Based on the conservation principle of network flows, the update of traffic states in link $j\in V^I$ (Fig. 2) is given by:

$$N_j(t+1)=N_j(t)+Q_{j,in}(t)-Q_{j,out}(t), \tag{1}$$

where $t\in\mathbb{N}$ is the discrete-time variable; $N_j(t)$ is the number of vehicles in link j at time t; Both $Q_{j,in}(t)$ and $Q_{j,out}(t)$ are the total number of vehicles, respectively entering and leaving link j in sampled period T; and both $Q_{j,in}(t)$ and $Q_{j,out}(t)$ are respectively determined by:

$$Q_{j,in}(t)=\sum\nolimits_{i_q\in V_j^I}\alpha_{i_q j}\eta_{i_q}(t)N_{i_q}(t)+\sum\nolimits_{i_q\in V_j^S}\alpha_{i_q j}Q_{i_q}(t), \tag{2}$$

$$Q_{j,out}(t)=\sum\nolimits_{k_q\in V_j^D}\alpha_{jk_q}\eta_j(t)N_j(t), \tag{3}$$

where V_j^S, V_j^I and V_j^D are respectively the set of upstream input links, of upstream internal links, and of downstream links of link j; $Q_i(t)$, $i\in V^S$ is the number of vehicles entering the network from input link i in sampled period T; $\alpha_{ij}\ge 0$, $i\in V^S\cup V^I$, assumed to be constant, is the distributing proportion of traffic flows from link i to downstream link j, and satisfies: $\sum_{j\in V_i^D}\alpha_{ij}=1$; and $\eta_i(t)\triangleq Q_{i,out}(t)/N_i(t)$, $i\in V^I$ is the discharging proportion of traffic flows in link i in sampled period T, and is the control variables in the model. Then, (1) is the simulation model of the network, describing the evolution of network flows.

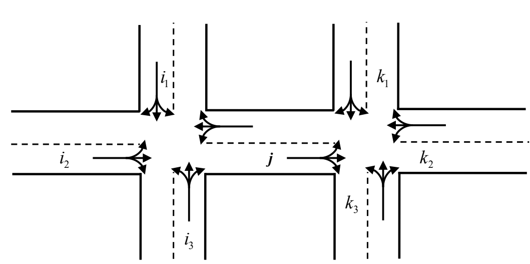

Fig. 2. Topology of an internal link of the network.