Bi-level Model Predictive Control of Network-Wide Signal Timing Using Link Transmission Model with Queue Transmission

Lei Wei[a] and Meng Wang[a*]

[a] Chair of Traffic Process Automation, Institute of Traffic Telematics, Technische Universität Dresden, Dresden, Germany
lei.wei@mailbox.tu-dresden.de, meng.wang@tu-dresden.de
[*] Corresponding author

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1 INTRODUCTION

Traffic congestion in large-scale urban road networks leads to excessive economic losses and emissions. Among many measures to deal with urban congestion, traffic (signal) control has been proven to be a cost-effective solution. Existing traffic control strategies differ in their architectures, control methods, the role of system dynamics models, and the controlled network size. Notably, centralized, distributed, and hierarchical architectures have been reported in the literature. Compared with centralized or distributed counterparts, a hierarchical architecture enables more flexible choices of network control by involving modular layered design.

Regarding control methods, Model Predictive Control (MPC), has gained increasing attention in network traffic control (Van de Weg *et al.*, 2019, Aboudolas *et al.*, 2010). MPC has a receding horizon scheme and hence can utilize real-time feedback on road network dynamic conditions to make the best control decision over an anticipation horizon. This avoids myopic decisions for road networks with uncertain demand and multiple performance requirements. A cluster of MPC-based traffic control studies relied on the Macroscopic Fundamental Diagram (MFD) model (Aboudolas & Geroliminis, 2013) that assumes a homogeneous traffic state within a (sub-)network. However, the fluctuations of flow operation caused by congestion propagation and real-time signal control affect the performance of MFD-based control strategies, and the homogeneity assumption is not always held in real networks. To capture queue propagation within a segment, several studies used Cell Transmission Models (CTMs) that divide a road segment (RS) into some spatial cells (Lo, 2001), but the computational complexity poses challenges in terms of scalability and real-time implementation of network control.

Link Transmission Models (LTMs) take the whole RS as a unit to describe the flow propagation, and hence eliminate the need to divide the road segment into small cells. Using LTMs for large-scale network control has been shown to be more efficient and accurate compared with using the CTMs (Yperman *et al.*, 2005, Van de Weg *et al.*, 2019). While the LTM has been used in network signal control, the reported study did not capture queue transmission at different turning directions. Consequently, the detailed queue dynamics in multiple turning directions cannot be captured, which may cause the underrepresentation of spillbacks. Moreover, the simplified objective function can lead to fluctuating signal control plans that are undesirable for traffic control (Van de Weg *et al.*, 2019).

We put forward a bi-level MPC-based network signal control strategy using LTMs to maximize throughput and minimize queue length under congested conditions with queue spillbacks. The proposed strategy employs a standard LTM at the network layer and an extended LTM with an additional queue inflow variable at the local (intersection) layer. Thanks to the extended LTM, the local layer can hence capture the queue length changes of each RS without the need for sophisticated spatiotemporal discretization as in CTMs. It can predict spillback with acceptable computational overheads. The network layer generates a reference signal and constraints for the local layer to track and respect. The proposed hierarchical MPC strategy (MPC-Q) is compared with a baseline (MPC-B) (Van de Weg *et al.*, 2019) in the literature.

2 METHODOLOGY

The proposed framework follows a hierarchical MPC structure with a network layer residing on top of a local layer as shown in Fig. 1. The network layer employs a LTM (Van de Weg *et al.*, 2019) to predict the flow propagation in the considered network over a long horizon T_n and decides the optimal green time fraction $\boldsymbol{b} = [b_1^{seg}, \ldots, b_m^{seg}]$ for each approaching RS. The control objective of the network layer is to maximize network throughput and minimize oscillations in the signal plan based on the quadratic programming. The LTM in this layer can capture flow dynamics without distinguishing the traffic states of different turning directions in a RS.

The optimal green time fraction is sent to the local layer as a reference point. The local layer uses an extended LTM (Wei *et al.*, 2023) to predict the queue transmission for different turning movements at a shorter horizon $T_l < T_n$ and tracks the reference point by optimally allocating the green time to different turning movements of a single intersection. The objectives of the local layer are minimizing the tracking error and queue length of all movements based on the nonlinear programming. The decisions of the network and local layers are updated at time intervals of T_s^N and T_s^L respectively. We set $T_s^N = T_s^L$ in this work but the framework allows asynchronous updates.

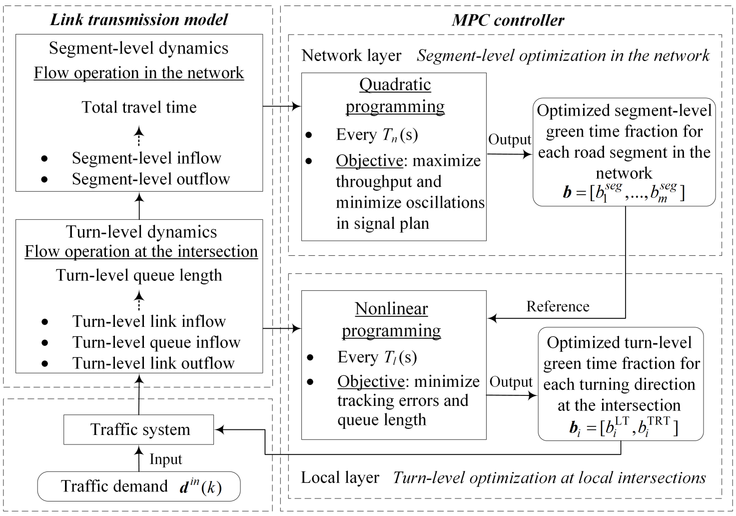


Figure 1 – *Hierarchical framework of the proposed MPC-Q.* $\boldsymbol{b} = [b_1^{seg}, \ldots, b_m^{seg}]$ *is the set of segment-level effective fractions of green time for all RSs in network;* $\boldsymbol{b}_i = [b_i^{\mathrm{LT}}, b_i^{\mathrm{TRT}}]$ *is the set of turn-level effective fractions of green time for RS i; k is the time step.*

The extended LTM employed by the local layer assumes that the through and right-turn directions share the same lane, an RS i of length L_i, combined with the adjacent upstream and downstream intersections, thus can be divided into two links with left-turn (LT) and through/right-turn (TRT) directions, as shown in Fig. 2. In the extended LTM, the state of a link i with turning direction μ is described by the cumulative link inflow $N_{i,\mu}^{in}$, cumulative queue inflow

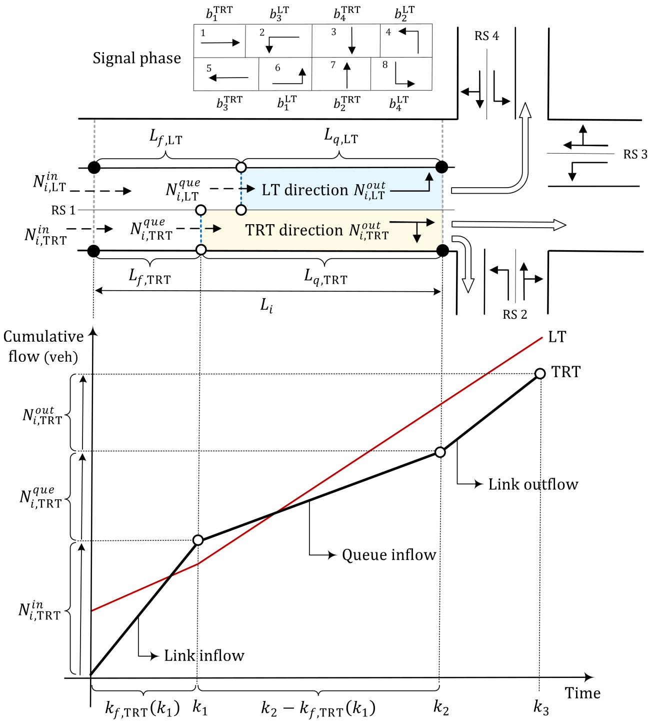


Figure 2 – *Illustration of flow dynamics determined by the LTM with queue transmission. An RS with length L_i is divided into the frow-flow and moving parts with lengths $L_{f,\mu}$ and $L_{q,\mu}$, respectively; $k_{f,\mu}(k)$ represents the free-flow travel time in μ at k.*

$N^{que}_{i,\mu}$ and cumulative link outflow $N^{out}_{i,\mu}$. For the network layer, the turn-level flow dynamics will be aggregated into segment levels including total cumulative link inflow $N^{in}_{i,\Sigma}$ and outflow $N^{out}_{i,\Sigma}$. Therefore, the decision variable at the network layer is the segment-level green time fraction b^{seg}_i that is given by:

$$b^{seg}_i(k) = b^{\text{LT}}_i(k) + b^{\text{TRT}}_i(k). \tag{1}$$

The decision variable at the local layer is the green time fraction b^{μ}_i for each turning movement (Van de Weg *et al.*, 2019):

$$b^{\mu}_i(k) = q^r_{i,\mu}(k)/q^s_{i,\mu}, \tag{2}$$

where $i \in \Pi$; $q^r_{i,\mu}(k)$ is the realized outflow of turning direction μ in RS i; $q^s_{i,\mu}$ is the corresponding saturation flow rate; $b^{\mu}_i(k) \in [0,1]$. It should be noted that we limited the scope of decision variables at intersections to include the green time fractions for various turning movements. The optimization of offsets and phase sequences is not involved in the proposed method.

3 SIMULATION RESULTS

The simulated arterial consists of 14 RSs and 6 origin-destination pairs as shown in Fig. 3. To demonstrate the superiority of the proposed MPC-Q, the MPC-based control with the basic LTM is chosen as the baseline (MPC-B) (Van de Weg *et al.*, 2019). The simulation results are shown in Fig. 4, where the sampling interval of LTM is set to 1 s; the network-layer prediction horizon T_n and local-layer update interval T_l are set to 600 s and 60 s, respectively. It is clear that the proposed MPC-Q eliminates the spillbacks caused by the bottleneck on RS 14. However, the compared MPC-B cannot achieve that since it determines the aggregated inflow and outflow of the RS to make the total number of vehicles on the link restrained rather than the actual queue lengths restrained, therefore fails to allow for predicting the explicit queues and spillback.

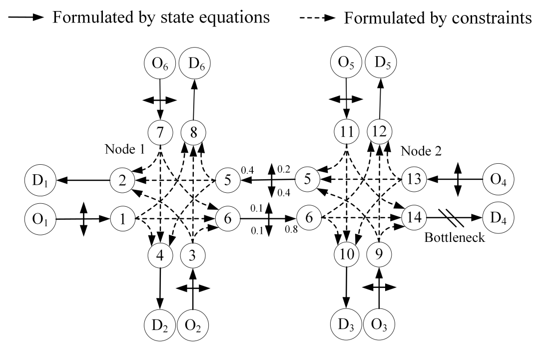
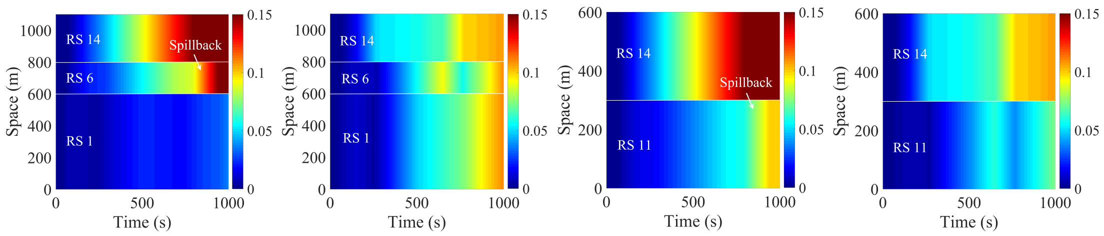


Figure 3 – *Illustration of the arterial with successive intersections.*



(a) *Path 1 by MPC-B* (b) *Path 1 by MPC-Q* (c) *Path 2 by MPC-B* (d) *Path 2 by MPC-Q*

Figure 4 – *Evolution of space-time average density (veh/m) at different paths with MPC-B and MPC-Q. The presented two travel paths are related to the bottleneck on RS 14*

4 CONCLUSION

This study proposed a novel MPC approach that uses LTMs with queue transmission to optimize the traffic signals in urban road networks. In the network layer, a quadratic programming-based controller with inputs of signal timing variations was formulated to improve the network-wide throughput. By converting the generally used time-step independent signal timing into signal timing variations, the proposed MPC-Q framework is capable of considering signal control stability. In the local layer, a nonlinear programming-based controller with reference tracking was developed to track and refine the segment-level effective fractions of green time output by the network layer to the turn level. Thus, the proposed MPC-Q can be performed without assuming that flow operations in different turning directions are homogeneous.

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