Optimal Dynamic Green Time for Distributed Signal Control

Kai Yuan, Victor L. Knoop and Serge P. Hoogendoorn

***Abstract*— Traffic signals are not only useful facilities to ensure the safety at an intersection, but also an important traffic management tool to improve the urban traffic network performance. Many traffic signal strategies have been presented to increase the throughput of an urban network and reduce the total delay. The difficulty is that a successful local optimization does not mean a better global performance and that the high complexity makes centralized coordinated strategies usually not efficient for a large network. To overcome these drawbacks, some promising distributed strategies are presented, such as the back-pressure algorithm. Whereas the back-pressure algorithm overcomes the main fundamental problems, some practical issues are not considered. Firstly, the original back-pressure algorithm does not take the all red time into consideration. Secondly, the algorithm relies strongly on the loop detector, which decreases the robustness. Therefore, this paper shows a dynamic green time approach which overcomes these drawbacks of the back-pressure algorithm. In the approach, the green time length depends on two elements: the back-pressure at the intersection and the upstream queue length. Meanwhile the green time for each phase is restricted to durations between 15 seconds and 65 seconds to ensure the robustness. The method is tested in a simulation. This shows that optimal dynamic green time approach shows the best performance among other green time mechanisms, such as fixed green time approach. The green time approach not only makes the back-pressure more practical, but also keeps the good network performance of the original algorithm.**

I. INTRODUCTION

Although traffic signals are originally installed to ensure safety via managing conflict traffic streams at one intersection, researchers have realized that traffic signals with different control strategies can affect the network performances considerably. That is, an optimal traffic signal control strategy could maximize the network throughput and minimize the total time spent by all vehicles in the network. Hence, a variety of traffic signal control strategies for urban intersections have been presented for the network optimization. Those strategies generally operate the stage specification, split, cycle time and offset to achieve the optimization goal [1]. A variety of efforts have been made to address the problem of responding to actual and predicted traffic conditions [2], [3], [4], [5]. Some researchers attempt to coordinate dynamic traffic management on freeways with signal control in urban environment [6].

Signal control strategies usually can be separated into isolated strategies, which only aims at single intersection, and coordinated strategies, that consider a network [1]. Due to the fact that a successful local optimization strategy does not mean a better global performance [7], [8], coordinated strategies are presented to ensure the global optimization.

The structure of coordinated strategies can be centralized, distributed, or hierarchical. Centralized strategies search for the global optimization result for the whole network, distributed strategies distribute control targets to each local controller and coordinate them by exchanging information, and hierarchical strategies allocate control problem into different levels. Because of the high complexity in the centralized control strategies, distributed and hierarchical strategies are preferred in network optimization.

Recently a promising distributed traffic signal control algorithm which is back-pressure algorithm has been presented [9]. This control scheme is also called max pressure algorithm in [10], [11], [12]. In this paper we refer to this algorithm as back-pressure algorithm. In the back-pressure algorithm, all signals are determined by local controller independently and a maximum network throughput is claimed. Compared to other decentralized strategies such as [7], this back-pressure algorithm does not need arrival rates. This algorithm determines the phase to be activated based on the so-called back-pressure, i.e. the difference in the queue length between the upstream and the downstream queue for a movement. The back-pressure of a phase is a sum of back-pressure of movements in the phase. The phase with the highest back-pressure will be activated.

Several extensions of the back-pressure algorithms have been studies in recent years. Considering multi-destination cases, Zaidi et al. [13] propose a multi-commodity back-pressure scheme for traffic signal control. Taale et al. [6] integrate route guidance and signal control following the principles of the back-pressure control, applying the concept of the back-pressure to a route. Le et. al [14] adapt the back-pressure scheme into a cyclic one with fixed cycle time.

In this algorithm, two concepts are important: slot time and all red time. Slot time is defined as the duration of a control time step, during which the same phase is activated, and all red time, which is also referred to as red clearance or set up time, is defined as a period when all the signals for the intersection are red. The all red time occurs when the intersection switches the activated phase. Then, for safety reasons all directions have a red light, allowing all vehicles in incompatible movements to leave the conflict area. Usually the all red time ranges between 3 and 8 seconds [7].

However, in the original presentation of the back-pressure algorithm [9], [10], [11], the all red time which is necessary in reality was not taken into account. This might considerably

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affect the traffic flow performance of the algorithm. In the back-pressure algorithm without considering the all red time, the shorter the slot time is, the better the network performance will be. Because in the original algorithm a shorter slot time can guarantee a quicker reaction, that is to determine which phase to be activated, to the local traffic situation. But after considering the all red time during which the traffic flow for all traffic directions should be zero veh/h, there would be a large waste of capacity if the traffic signal switched too often. That means there would be an optimal slot time for the algorithm.

Secondly, a potential thread of the algorithm is the possible large effect of a failing detector. Because the activated phase is only determined by the back-pressure, a failing detector might cause a wrong back-pressure continuously, so a wrong phase would be activated, which might have a long lasting effect on the green time.

Thirdly, as proposed in [14], in the original presentation of back-pressure algorithm, an erratic and unpredictable order of activated phase may lead to drivers dangerous actions due to frustration. Le et al. [14] propose a cyclic phase policy into the back-pressure algorithm to rectify this weakness.

Therefore, this paper tries to solve the above problems and maintain the maximal network throughput at the same time. This paper presents an optimal dynamic slot (green) time approach to overcome all of these issues, considering switching cost, robustness and fairness.

The outline of the paper is as follows. Section II describes some basic concepts in back-pressure algorithms, Section III describes some key concepts in the optimal dynamic slot (green) time approach, Section IV presents the optimal dynamic slot (green) time approach, Section V shows a case study and Section VI draws the conclusion.

II. ORIGINAL BACK-PRESSURE ALGORITHMS

Wongpiromsarn et al. [4] presents a distributed signal control approach which applies back-pressure routing to large-scale urban road network signal control. This algorithm, which we call the original back-pressure algorithm, uses only local information, being the number of vehicles in the links connected to an intersection. This strategy is used to determine the optimal phase sequence. The active phase for an intersection is determined independently from other junctions. Controllers in every intersection will set an active phase every slot time, so in this algorithm slot time is a control time step. During one slot time, the activated phase will not change, and the activated phase may remain the same for several successive slot time periods if the back-pressure in the phase continues being the highest. So the length of a green time (including all red time) can be a length of combined slot time periods. That is, in the original back-pressure algorithms there is no such a concept as cycle time or split plan.

The back-pressure algorithm works basically as follows. At the beginning of each slot time $T_{\text{slot}}(t)$, there is a weight $w_{ab}(t)$ associated with each movement from the upstream link a to the downstream link b. The weight is the difference in queue length (in vehicle), $Q_a(t)$ and $Q_b(t)$ between upstream and downstream link, i.e.,

$$w_{ab}(t) = Q_a(t) - Q_b(t) \tag{1}$$

For each movement, the weight $w_{ab}(t)$ times a demand $\xi_{ab}(t)$ of this movement is the movement back-pressure. The demand is calculated as real-time flow rate through one intersection. At one intersection, there are a set of links Φ_p in a phase p. For this phase, the back-pressure $B_p(t)$ is the sum of movement back-pressures in the phase, as shown in (2).

$$B_p(t) = \sum_{(a,b)\in\Phi_p} w_{ab}(t)\,\xi_{ab}(t) \tag{2}$$

Finally, the phase with the highest back-pressure will be activated, i.e., given the right of the way. Wongpiromsarn et al. [9] show that this algorithm leads to less delays than SCATS via simulations.

TABLE I
KEY CONCEPTS

Features	Concepts	Descriptions
Periodicity	Periodic control	Every phase have to and can only be activated once in a cycle time.
	Aperiodic control	The active phase is independent from the previous active phases.
Dynamicity	Static slot time	Slot time is fixed all the time.
	Dynamic slot time	Slot time is flexible.
Coordination	Global slot time	The entire network shares a same slot time.
	Local slot time	Each intersection determines its slot time independently.

III. KEY CONCEPTS

Section IV describes the dynamic optimal green time approach. In this approach there, there are several important concepts, i.e., the periodic and aperiodic control, static and dynamic slot time, as well as global or local slot time. All these concepts are summarized in TABLE I and described in this section. Note that for the sake of simplicity we give a description only for two-phase intersections.

A. Periodic and Aperiodic

The original back-pressure algorithm presents an aperiodic control strategy in which the one phase can be activated for several successive slot times. This aperiodic strategy can offer a long green time to a long queue and lead to a rather large throughput. Contrary to aperiodic control, there is periodic control where in a certain time (or cycle time) every phase has to and can only be activated for one time. The cycle time is not necessarily fixed. Because this paper only studies the two-phase intersection, the periodic mechanism indicates a fixed active phase sequence.

On one hand, aperiodic control can provide long enough green time to one phase to increase the intersection throughput, on the other hand, it degrades the network robustness, i.e., failed loop detectors could affect the whole network performance. Therefore, it is argued that making the signal strategy periodic is a way to increase the robustness.

B. Static and dynamic slot time

In the back-pressure algorithm, slot time gives the green time. Static slot time means the slot time is fixed for all the control period while the dynamic slot time means the slot time is flexible and depends on the local traffic situation.

Compared to the static slot time strategy, a dynamic slot time strategy can make a better use of junction capacity. We believe there are two reasons for the dynamic slot time strategy. First, a dynamic slot time strategy allows signal control to be traffic-responsive, especially when the periodic control setting is believed can increase the robustness as argued in Section III-A. A combination of a periodic control and a static slot time will lead to a fixed traffic signal control, so a dynamic slot time is believed to be necessary for the periodic control to ensure the sensitivity of a controller to the local traffic condition. Second, even with aperiodic setting, the dynamic slot time can control the green time length more flexibly than the static one. That is, the static slot time strategy can only give a green time length which is a integer multiple of the static slot time, while the dynamic slot time strategy can give more options of green time length.

C. Global and local slot time

Global slot time and local slot time are two specific ways of determining the slot time in a large signal network. A global slot time means the entire network will share a same slot time all the time while a local slot time means each intersection will choose its own slot time independently.

In some previous control strategies for an urban road signal network, e.g. SACTS, there is one critical junction which determines a shared cycle time in a controller signal group. Similarly, in the global slot time strategy in this paper a critical junction was defined to synchronize the slot time for a network, i.e. in a network a critical junction will be used to determine a slot time which is global for the entire network. A global slot time coordinates junctions in a network without increasing complexity. Note that the global slot time does not mean the control strategy is not a distributed control, because distributed structure is also one of coordinated structures.

The critical junction should be picked by a criticality parameter. In the approach here, the junction with the highest back-pressure or with the largest back-pressure difference among phases will be chosen as the critical junction. Section 5 will test results with different criticality parameters.

IV. DYNAMIC OPTIMAL SLOT TIME APPROACH

To solve above problems, an optimal dynamic slot time approach is presented. This approach extends the basic back-pressure strategy by calculating an optimal dynamic slot time and making a slot time synchronization mechanism.

Moreover, to overcome the low robustness, it is proposed that the same phase cannot be activated in two successive slot times. Because this paper only takes two-phase intersections into account, this is also called periodic in this paper. Therefore, this periodic strategy has determined the activated phase sequence at the beginning. The calculation of slot time is activated after the next activated phase has been determined.

According to the back-pressure algorithm, the dynamic slot time (T_{slot}) for the periodic strategy is related to two variables: back-pressure difference between phases and up-stream queue length in the next activated phase.

Let's firstly consider the difference between the back-pressure (B) of the active phase (B_{act}) and the non-active phase (B_{non}). If the difference between the two is large, a long green time is required to reduce this large difference, and hence a long slot time is suitable.

Secondly, even if the back-pressure difference is small, but the back-pressure for each direction is high, the queues for each direction are long. In this case, no intersection capacity should be wasted by the all red time. So also then, long green time, and hence long slot time is chosen.

Therefore, we propose to calculate the slot time based on a minimum slot time (τ) and add a dynamic part τ_A to that. In line with the above reasoning, the dynamic part is proportional to the back-pressure difference and proportional to the maximum queue length, and bounded by minimum and maximum values. For this paper, we take 0 and 50 seconds respectively for these bounds. In equations, we hence propose the following:

$$T_{\text{slot}}(t) = \tau + \max\left(0, \min\left(50, \tau_{\text{A}}(\text{t})\right)\right) \tag{3a}$$

$$\tau_A(t) = \alpha\left(\text{B}_{\text{act}}(\text{t}) - \text{B}_{\text{non}}(\text{t})\right) Q_{\text{up}}^{\max*}(t) \tag{3b}$$

In this equation, $Q_{\text{up}}^{\max*}(t)$ is the maximum upstream queue length in the to be activated phase at time t. Note that for periodic control, the back-pressure now only determines the duration of the green time (via the slot time), rather than the activated phase, since these alternate.

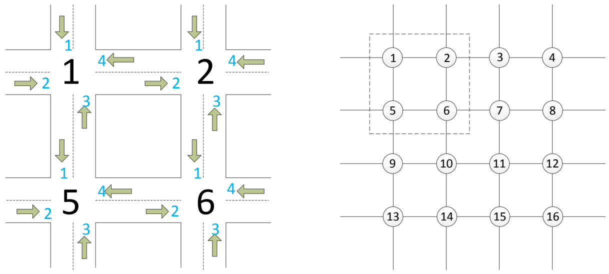
Finally, the slot times are either determined for each junction separately (referred to as Local) or synchronized for the whole network, determined by one critical junction (labelled as Global). All above approaches are tested with simulations.

V. CASE STUDY

A. Traffic simulations

In this simulation, a 4×4 urban road signal network was considered, as in Figure 1. For each junction there are two phases, i.e., phase 1 (movement 1, 3) and phase 2 (movement 2, 4), as shown in Figure 1(a). For each movement, the saturation flow is set 2400 (veh/h). For each entering point, the demand is different but they share the similar profile as in Figure 2. All traffic will go straight. Figure 2 takes demands for two links as an example to show the typical demand for the whole network. It is assumed that the all red time is 5 seconds, and we set $\alpha = 0.5$. As measures of performance, the total travel time and maximum queue length are used.

The simulation uses the same queue models. (4), (5) and (6), as in [9] where there queue models are based on [15],



(a) Two phases and four movements in each junction

(b) Network structure with sixteen junctions

Fig. 1. Network structure with sixteen 2-phase junctions. a) shows the 2 phases and 4 movements in each junction, b) the whole network structure.

[16]. These models are simple enough to be simulated and can provide sufficient inputs for the algorithm. The number of vehicles in link a at time $t+1$ is calculated by using the number of vehicles in link a at time t to plus the entering vehicles $I_a(t)$ and minus the exiting vehicles $O_a(t)$, as in (4).

$$Q_a(t+1) = Q_a(t) + I_a(t) - O_a(t) \tag{4}$$

$O_a(t)$, the number of exiting vehicles should increase as the number of vehicles in the link rises. So it can be calculated according to:

$$O_a(t) = R_a(t)\left(1 - e^{(-(Q_a(t)+I_a(t))/R_a(t)}\right) \tag{5}$$

where $S_a(t)$ is the saturation flow and $g_a(t)$ is the green time for link a. $R_a(t)$ is the maximum of exiting vehicles from a:

$$R_a(t) = S_a(t)\, g_a(t) \tag{6}$$

In the simulation here, we use (5) and (6) to simulate a traffic situation which was an input to the controller. The simulation time step $t_{\text{step}} = 1$ s. The slot time should be a multiple of the simulation step, so we round it to the nearest simulation step time:

$$T_{\text{slot}}(t) = \text{round}\left(\tau + \max\left(0, \min\left(50, \tau_{\text{A}}(\text{t})\right)\right)\right) \tag{7}$$

When calculating a back-pressure of each movement, we assume the following value for the flow $\xi_{ab}(t)$:

$$\xi_{ab}(t) = \min\left(\xi_{\text{saturation}}, \text{Q}_\text{a}(\text{t})/\text{T}_{\text{slot}}(\text{t})\right) \tag{8}$$

In this equation $\xi_{saturation}$ is the saturation flow rate and $Q_a(t)$ is the queue length in the upstream link a.

It is necessary to know that in this approach, there is a sequence: determining activated phase and then calculating slot time length, that is, those above equations are used only after the next active phase has been determined.

B. Results

The performances of the fixed and dynamic slot time strategy in simulations are shown in TABLE II and TABLE III, respectively. If a critical junction is used to synchronize the slot time for the whole network the maximum network

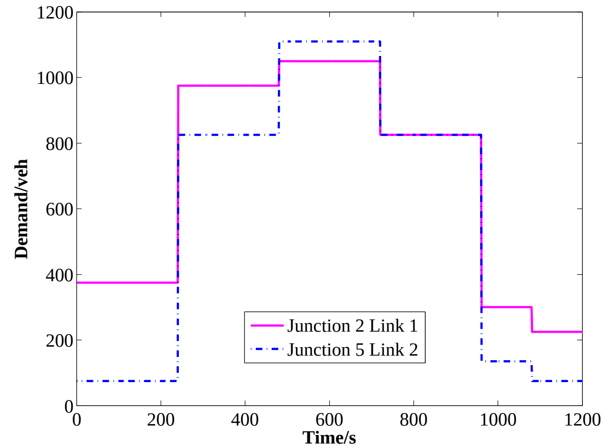


Fig. 2. Demand profile. Blue line is the demand to junction 5 link 2 and the red one is to junction 2 link 1.

TABLE II
FIXED SLOT TIME STRATEGY PERFORMANCE

	Slot time (s)	TTS_{lowest} (veh·h)	max queue$_{\text{lowest}}$ (veh)
Aperiodic	25	2.9×10^5	21.07
Periodic	45	1.2×10^5	21.02

throughput is achieved ($TTS = 1.1217\times10^5$ veh·h). According to these two tables, it is concluded that a dynamic periodic slot time calculation is preferred. This might be caused by the fact that the active phase sequence in aperiodic control only depends on the instantaneous local traffic situation, which would change after an all red time.

In TABLE II, it is shown that the best periodic fixed slot time strategy is better than the aperiodic one. Note first that the slot time where the least delay is achieved differs for the periodic and aperiodic strategy. Because an aperiodic strategy can choose to keep the same green phase, so sometimes traffic performances can benefit from a short slot time. The periodic strategy will always encounter an all red phase at the end of the slot time, and therefore short slot times will reduce performance considerably. Therefore, the best slot time for the aperiodic fixed slot time strategy is shorter than the best slot time for the periodic one in our case study. Note moreover that the aperiodic strategy outperforms the periodic one. One might think that the periodic strategy is one possible realization of the aperiodic one, and an optimization will find the best case (the periodic one) if that is in the set of possibilities. However, this does not happen because there is no optimization for the traffic flow in the following slot time; instead, there is one decision point in time. In other words, there is no prediction of the traffic state for the next slot time. So it happens that during the slot time following the decision point, traffic conditions change, leading to a worse traffic situation. In a periodic strategy, the green phase always changes, hence the negative influence is limited.

In TABLE III, the TTS in dynamic slot time control is

TABLE III

DYNAMIC SLOT TIME STRATEGY PERFORMANCE

Simulation scenarios		Critical pamaneter	TTS (veh·h)
Aperiodic	Global	Back-pressure	5.6×10^5
		Back-pressure difference	5.6×10^5
	Local	Not applicable	1.1×10^6
Periodic	Global	Back-pressure	1.1×10^5
		Back-pressure difference	1.1×10^5
	Local	Not applicable	9.6×10^5

not considerably lower than that in fixed slot time control strategy. In dynamic slot time control, only the periodic control with global slot time saves around 6.5% TTS while the others show higher TTS when comparing the best performance of fixed slot time control. However, it does not mean the dynamic control is not as good as predicted.

Firstly, the periodic control with dynamic global slot time saves more travel time. Secondly, please note that the best performance of fixed slot time strategy is based on the knowledge of OD matrix which is difficult and complex to predict precisely right now, which means the best performance of fixed slot time can hardly be reached. Therefore, firstly the dynamic slot time approach indicates a save of approximately 6.5% compared to the best performance of periodic fixed strategy. Secondly, this approach shows a higher practical possibility since it is not required to predict the optimal fixed slot time. Thirdly it is more robust against loop detector failures. In short, this dynamic periodic global green time approach keeps and makes use of the advantage of the back-pressure algorithm and even makes the strategy more realistic, optimal and practical.

VI. CONCLUSIONS

Based on simulations, we conclude a slot time calculation approach to extend the basic back-pressure signal control strategy. This approach takes the all red time into consideration and overcomes the low robustness of the original one. At the same time a maximum throughput is achieved. Besides, the dynamic slot time approach is more practical than the fixed one. The extended back-pressure strategy presented in this paper performs for the case study better than the original one.

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