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Decentralized signal control for urban road networks

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ABSTRACT

We propose in this paper a decentralized traffic signal control policy for urban road networks. Our policy is an adaptation of a so-called BackPressure scheme which has been widely recognized in data network as an optimal throughput control policy. We have formally proved that our proposed BackPressure scheme, with fixed cycle time and cyclic phases, stabilizes the network for any feasible traffic demands. Simulation has been conducted to compare our BackPressure policy against other existing distributed control policies in various traffic and network scenarios. Numerical results suggest that the proposed policy can surpass other policies both in terms of network throughput and congestion.

1. Introduction

Traffic congestion is a major problem in modern societies due to increasing population and economic activity. This motivates the need for better utilizing the existing infrastructures and for efficiently controlling the traffic flow in order to minimize the impact of congestion.

One of the key tools for influencing the efficiency of traffic flow in urban networks is traffic signal control that enables conflicting traffic to flow through intersections via the timing of green/red light cycles. It has long been recognized that the challenge is to find optimal cycle timing over many intersections so as to reduce the overall congestion and to increase the throughput through the network.

There has been much work in the past both on designing and optimizing isolated or coordinated signals that reactively resolve congestion in the urban networks. Broadly, there are two types of control that have been used for signal control: static and vehicle-actuated controls; see Hamilton et al. (2013). Static control (sometimes called "fixed time plan") involves the optimization of the cycle time, the offset between nearby intersections, *and* the split of green times in different directions within a cycle. This can be optimized in isolation or in a coordinated manner, for instance to create a so-called green wave where vehicles always arrive at intersections during the green cycle time, e.g. Webster (1958), Gartner et al. (1975a,b), and Kraft (2009, 6th ed.). In contrast, vehicle-actuated controls use online measurements from on-road detectors (e.g. inductive loops) to optimize signal timings on a cycle-to-cycle basis in real time. Some examples of commonly used implementations are: SCOOT, see Hunt et al. (1981); UTOPIA, see Mauro and Taranto (1990); and the hierarchical scheme RHODES, see

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Mirchandani and Head (2001). Combinations of both the fixed time plan and vehicle-actuated control also exist; one widely used example is SCATS, see Lowrie (1982).

Given a choice of the control scheme, various approaches to optimize the signal plans have been proposed. Examples include Mixed-Integer Linear Programming problems, see Gartner et al. (1975a,b) and Dujardin et al. (2011); Linear Complementary Problem, see De Schutter and De Moor (1998); rolling horizon optimization using dynamic programming, see Gartner (1983), Henry et al. (1983), and Mirchandani and Head (2001), or its combination with online learning algorithms, see Cai et al. (2009); store-and-forward models based on Model Predictive Control (MPC) optimization, see Aboudolas et al. (2009), Aboudolas et al. (2010), Tettamanti et al. (2008, 2010), Tettamanti and Varga (2010), and Le et al. (2013), or MPC optimization with non-linear prediction, see Shu et al. (2011). Many of these approaches formulate the problem in a way that is centralized and thus are inherently not scalable. While the state of the art is the use of centralized techniques, improved scalability may be obtained using decentralized approaches. In this paper, we focus exclusively on decentralized schemes. Although such schemes are in their infancy, this research is one step along the path of improving such schemes to offer performance comparable with centralized schemes while retaining their scalability.

A scalable distributed approach is to solve a set of loosely coupled optimizations, one for each intersection, with coupling provided by traffic conditions. Two natural approaches are to control the traffic lights based on either (a) the expected number of vehicles to enter the intersection during the next cycle, or (b) the *difference* in traffic load on the road leading into the intersection and those leading out. These approaches are now deployable in practice thanks to emerging technologies, such as cameras and wireless communication enabling better access to real-time traffic data.

Notable among the first class is the work of Smith (1980), a so-called P_0 policy and its variants Clegg et al. (2000) and Smith (2011), followed by the work of Lämmer and Helbing, see Lämmer and Helbing (2008) where the switching cost between phases is taken into account. In this approach, each intersection estimates the amount of traffic that will arrive during the next complete cycle, and sets the split time such that each phase gets a time proportional to the number of cars expected to arrive on roads which have a green light during that phase. The lack of central control raises the possibility that intersections may interact in unexpected ways to cause instability. To limit this, a stabilization mechanism was proposed in Lämmer and Helbing (2010). However, beyond heuristic arguments, there remains no formal proof of stability of this approach. Indeed, when arrival rates are known, stability is achievable by a centralized optimization, cf. Proposition 1, and under known deterministic arrival rates further queue length optimization is possible. Here Pontryagin's maximum principle is the appropriate tool for verifying optimality of a proposed solution and optimal cycle policies can be derived, see Haddad et al. (2013). However, when decentralized control is required over multiple intersections and when arrival rates are unknown or fluctuate due to unknown and changing demands on the road network, Blackwell's Approachability Theorem, see Blackwell (1954, 1956), is the appropriate control framework and for this BackPressure is the corresponding policy.

Approach (b) including work by Varaiya (2013), Wongpiromsarn et al. (2012) and Zhang et al. (2012) was inspired by research developed for packet scheduling in wireless networks: a so-called max weight or back pressure (refer to as BackPressure in this paper) algorithm, see Tassiulas and Ephremides (1992) and McKeown et al. (1999). Like approach (a), BackPressure does not require any *a priori* knowledge of the traffic demand, but it has the added benefit of provable stability. To make that more precise, define a traffic load to a network as "feasible" if there exist splits at each intersection such that the queues do not build up indefinitely. Under certain simplifying assumptions, it can be shown that the queues under BackPressure do not build up indefinitely for any feasible traffic load. This will be made more formal in Section 3. In wireless networks, BackPressure can be computationally prohibitive, but in road networks, e.g. Wongpiromsarn et al. (2012), Varaiya (2013), and Zhang et al. (2012), it admits a simple distributed implementation, just like approach (a).

It is worth noting that all the above mentioned policies, see Smith (1980, 2011), Lämmer and Helbing (2008), Varaiya (2013), Wongpiromsarn et al. (2012), and Zhang et al. (2012), make decisions periodically bases on the evaluations of traffic over a fixed time interval. These are called *fixed cycle* policies. For example, the BackPressure policy in Wongpiromsarn et al. (2012) determines the phase to be activated at the beginning of each fixed time slot, while the policy in Lämmer and Helbing (2010) decides whether to keep serving the current flow or switch to other flow at a regular time interval which can be arbitrary small.

Given the possibility of a stability guarantee by the BackPressure scheme, our objective in this work is to fully adapt it to the traffic control scenarios. To this end, we propose in this paper a new signal control strategy that addresses two weaknesses in the prior application of BackPressure to road networks, see Wongpiromsarn et al. (2012), Varaiya (2013), and Zhang et al. (2012), while retain and prove the important stability property of the BackPressure-based algorithms.

The first weakness to be addressed is that phases can form an erratic, unpredictable order in the previously proposed BackPressure policy. This is acceptable in the context of communications systems but for urban road traffic this is undesirable since erratic ordering of phases brings frustration to drivers and potentially causes confusion leading to dangerous actions. Moveover, if one inbound road is particularly backlogged, then it is possible that other roads are "starved" by being assigned a red light for an extended period. To rectify this, we modify BackPressure to a "cyclic phase" policy where a policy is said to be cyclic phase policy if it allocates strictly positive service time to all phases in each control decision, and thus, it is possible to arrange the phases into a fixed ordered sequence.

The second weakness that we address is that prior applications have required each intersection to know the "turning fractions", that is, the fraction of traffic from each inbound road that will turn into each possible outbound road. We prove that the stability results still apply when these turning fractions are estimated using even very simple measurements; specifically, any unbiased estimator of the turning fractions suffices. Such stability proofs apply for a general network model