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Characterization of network traffic processes under adaptive traffic control systems

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Abstract

We present a compact characterization of network-level traffic processes for a dense urban area operating under an adaptive traffic control system. The characterization is based on a state classification scheme that is employed at a detector level, and a state transition model that works with combinations of detectors that are topologically dependent. Jointly, the two models provide a concise but rich representation of traffic processes at the network level. The key insight is the identification of transient states, termed *under-utilized (U)* states, where network effects such as insufficient downstream capacity are captured. In such states the green time is not fully used. The approach provides the space-time evolution of states across the network, conditional probabilities of upstream traffic states that drive state propagation in the near term, and probabilistic information on congested paths on the network, where paths are described as a sequence of detectors. The paper presents empirical evidence based on the SCATS adaptive control system in Dublin, the insights provided by the proposed approach, and the importance of *under-utilized* states, which represent as much as 20% of unused capacity along certain corridors in peak periods. The results provide a basis for future network control procedures.

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1. Introduction

Adaptive traffic control systems work by adjusting supply conditions to match locally observed traffic. Supply considerations, typically though of as green time provided to a particular intersection approach, include a host of factors that influence vehicle throughput. In urban networks and major corridors, throughput can be increased significantly if groups of traffic lights are coordinated to serve major directional flows. Such systems are deployed in many cities across the world and include SCATS (Sims and Dobinson, 1980) and SCOOT (Hunt, Robertson, Bretherton and Royle, 1982), two of several systems proposed in the literature and available in practice.

While control mechanisms used by adaptive systems perform well for under-saturated conditions, over-saturated conditions remain challenging. This is especially the case in general urban networks where small perturbations at

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critical locations, such as incomplete dissipation of a queue, can quickly move the system towards gridlock. While the role of *network-effects*, the influence of one intersection on its topologically dependent neighbors, has been identified as being critical, traffic dynamics of real-world systems in these regimes have not been well understood. When the intersections are adaptively regulated, supply-side actions introduced further complexity to establish network-level understanding of a traffic system.

This paper aims to provide empirical evidence of traffic dynamics of networks under adaptive control using real-world data from Dublin where the SCATS system is deployed. The system is characterized by a novel three state classification scheme that describes free-flow, congested, and transient states which are driven by network effects. In over-saturated conditions, such network states are critical as strategies to increase supply (via increased green time) are ineffective, since this cannot be effectively utilized. The classification scheme relies jointly on the *degree of saturation*, a unit-less measure computed for each approach and *flow* in vehicles per hour. Since data from adaptive control systems represents both supply and demand side of traffic processes, classical state variables of flow, density, and speed are not directly applicable and cannot be interpreted in a coherent manner due to discrete changes in supply and feedback mechanisms. The state of the control system is employed to further establish the penalty for coordination, a loss in throughput at a particular location that can be solely attributed to a (sub-optimal) control decision to favour other approaches within the coordinated subsystem.

Additionally, a network-level state transition model to capture dynamics of the three states based on a dynamic Bayesian network (DBN) is developed (Friedman, Murphy and Russell, 1998; Neapolitan, 2003; Murphy, 2002). BNs have been previously applied in the literature for traffic state prediction and estimation (Sun, Zhang and Yu, 2006; Pascale and Nicoli, 2011; Castillo, Menéndez and Sánchez-Cambronero, 2008) although not in the specific context studied herein, that of identification of relevant spatio-temporal patterns of traffic states. The DBN is calibrated based on the classified data obtaining a compact model which represents important traffic patterns over the network. With the compact DBN model, inferences such as evaluation of congestion propagation likelihood along any path in the network and acquisition of conditional distribution of the states at upstream and downstream detectors, can be made. Empirical results with a dataset in the Dublin city show that interesting state transient patterns can be revealed by querying the learned DBN.

At the macroscopic level, the major thrust in the literature has been towards establishing relationships between key traffic quantities of flow and density at the city-wide level. Such relationships that capture network-wide physics are powerful and pave the way for better network operations. The theory postulates that independent of demand, network topology and control mechanisms define a *macroscopic fundamental diagram* (MFD) which systematically relates the average network-wide densities and flow (Ardekani and Herman, 1987; Mahmassani, Williams and Herman, 1987; Daganzo, 2007; Geroliminis and Daganzo, 2008; Helbing, 2009). (Daganzo, 2007) argues for the use of MFD and neighborhood models in adaptive control.

Studies on key properties that would make the MFD applicable (Geroliminis and Sun, 2011; Buisson and Ladier, 2009) have found that spatial variability of density to be a critical factor. (Mazloumian, Geroliminis and Helbing, 2010) asserts that spatial inhomogeneity is critical in understanding poor network capacity. Network capacity is non-deterministic and highly variable. Similar conclusions on flux being dependent on topological features were reached by (Mendes, Da Silva and Herrmann, 2012). Studies that address the problem of homogeneously partitioning cities into neighborhoods such that MFDs are valid have been conducted (Ji and Geroliminis, 2012; Pascale, Mavroeidis and Lam, in review). (Helbing, 2009) analytically derive macroscopic relations based on kinematic wave theory. Assuming cyclical phases, relationships for three regimes are shown. Recently, (Mahmassani, Saberi et al., 2013) conclude, via simulation experiments in Chicago, that networks tend to gridlock in many ways and network capacity is highly influenced by demand considerations, such as adaptability of drivers and route choice.

Several studies have looked at network processes from the perspective of control engineering (**?**, see)for reviews]papageorgiou2003review,papageorgiou2007its. These works aim to provide optimal control at the network level and devise specialized traffic control strategies that mitigate gridlock. (Keyvan-Ekbatani, Papageorgiou and Papamichail, 2013) demonstrate the use of the MFD within a feedback control mechanism for gating. Gating refers to a strategy whereby traffic is carefully metered into a *protected area*, so as to disperse density as insights from the MFD suggests. They further advance this to remote gating using fewer observations (Keyvan-Ekbatani, Papageorgiou and Papamichail, 2014) for a perimeter control strategy and show an improvement in throughput. Traffic responsive urban control (TUC) (Dinopoulou, Diakaki and Papageorgiou, 2000) is a strategy that aims to ‘minimize and balance the