Developing Cooperative Traffic Signal Control Systems

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Description

Mobility services and infrastructure must enable people to move conveniently, transport goods, and maintain their social contacts (CBS, 2022). Since the mobility demand has increased in recent years, improving transport infrastructure efficiency has become a top research topic (Sun & Lang, 2015). One of the biggest challenges in multi-modal networks is to efficiently distribute the limited capacity of urban road infrastructure among different transport modes and road users, such as passenger cars, freights, public transport, bikes, and pedestrians, without seriously degrading the level of service (LOS) and safety for individual road users. The challenge is even more subtle at intersections where traffic signals manage conflicting traffic flows (Kabir et al., 2021; Majstorović et al., 2023). Frequent congestion occurs at intersections, leading to excessive delays and more fuel consumption, emissions, and noise pollution. Moreover, conflicting movements and lack of proper operation at signalized intersections can impose significant safety hazards for road users (Kabir et al., 2021). In 2021 alone, 29% of fatal crashes in the Netherlands occurred at intersections, mainly on municipal roads (Swov, 2022). The problem becomes more immense with the presence of an augmented number of heavy-duty vehicles on the roads, leading to more safety hazards and environmental pollution. Since building new infrastructure is costly or infeasible in some urban areas, the better solution is to efficiently utilize the existing infrastructure (Khamis & Gomaa, 2014).

One way to improve urban infrastructure efficiency and safety as well as reduce emissions is by improving the performance of traffic signals (Mahmod & Mahmod, 2011). Generally, there are three types of traffic signal control (TSC) systems, namely fixed-time, vehicle-actuated, and adaptive control. For fixed-time TSC systems, the preprogrammed cycle lengths are optimized offline based on the historical data (van Katwijk et al., 2008). Vehicle-actuated traffic signals, on the other hand, respond to approaching traffic detected by, e.g., inductive loop/magnetic detectors, cameras, or radars. In practice, vehicle-actual control systems are widely used in many countries (e.g., about 91% of signalized intersections in the Netherlands (Willekens, 2016)), where signal phases depend on the presence of vehicles, cyclists, and pedestrians at the approaching lanes (Zamanipour et al., 2014). Adaptive traffic signal control (ATSC) systems are also used in some cities, where the cycle lengths of traffic signals are dynamically adjusted depending on the fluctuation of daily traffic flows in order to increase intersection throughput and minimize delays (Mahmod & Mahmod, 2011; Pavleski et al., 2018). SCOOT (Bretherton, 1990), SCATS (Sims & Dobinson, 1980), RHODES (Mirchandani & Fei-Yue, 2005), and UTOPIA (Pavleski et al., 2017) are examples of the ATSC systems. Recent ATSC systems are based on machine learning and predictive models that can forecast future traffic states and adjust the signal timings accordingly (Miletić et al., 2022). Such systems learn how traffic conditions change over time and dynamically calculate effective control strategies to achieve certain objectives (e.g., minimize delays) (El-Tantawy et al., 2013; Qadri et al., 2020).

ATSC systems are generally categorized into centralized and decentralized systems. In centralized systems, a traffic control center manages the entire signal controls in a network, optimizing for system-wide objectives. This is only feasible if traffic signals and the control center can seamlessly communicate (Yang et al., 2019). Therefore, the centralized systems are not robust, expandable, and flexible enough for large networks with sophisticated structures due to interdependencies and communication complexity (El-Tantawy et al., 2013). While in decentralized systems, each signal controller runs separately and autonomously and therefore can be locally optimized (Yang et al., 2019). In other words, the system is decomposed into multiple agents and each agent tries to optimize its own behavior (Vilarinho et al., 2016). Cooperative Traffic Signal Controls (C-TSC) system is a type of decentralized system, in which the optimal joint action of locally optimized agents can be achieved through coordination between connected signal controls (Yang et al., 2019). The term 'cooperative' means that the optimal signal timing of an intersection depends on not only its approaching traffic but also the signal timings of its neighboring intersections (Liu et al., 2017). Thus, the final decision of an agent is usually a trade-off between the agent's own objectives and of other adjacent ones (Vilarinho et al., 2016). Moreover, C-TSC systems could also receive real-time information and/or send the signal status to approaching vehicles that are equipped with vehicle-to-infrastructure (V2I) and infrastructure-to-vehicle (I2V) communication technologies. The continuous exchange of information and data will allow better coordination between signal controls and approaching vehicles and therefore improve infrastructure efficiency (Rondinone et al., 2013).

Furthermore, C-TSC systems can have additional functions, such as Green Light Optimized Speed Advisory (GLOSA), *green waves* along arterials, and signal priority for certain transport modes or user groups. GLOSA was among the first applications of C-TSC systems using I2V communication technology. Here, information about the signal status and speed recommendations are provided to the approaching vehicles in the vicinity of an intersection to prevent unnecessary stops and acceleration/deceleration maneuvers (Stahlmann et al., 2018). Generating *green waves* along arterials based on real-time or predicted traffic conditions is another function of C-TSC systems. The goal is to reduce stop-and-go frequencies and, thus, improve intersections' capacity. Vehicles along the *green waves* will continuously receive green lights and pass through a sequence of consecutive intersections without stopping (Zhou et al., 2020). Fewer stops at intersections will reduce traffic incidents and fuel consumption (energy consumption for electric vehicles), which will positively impact traffic safety and the environment (Majstorović et al., 2023). Traffic signal priority is also an operational function of C-TSC systems. In such a system, the signal timings are adjusted to favor one or multiple priority vehicles (e.g., public and freight transport) or user groups (e.g., cyclists and pedestrians) (Zamanipour et al., 2016). Priority controls (green light extension, early green, and phase insertion) are employed to facilitate a smooth progression of prioritized transport modes/user groups at signalized intersections (Park & Ahn, 2019). It is expected to reduce vehicle/person delay and negative externalities (He et al., 2014; Kaisar & Ardalan, 2020). Signal priority can be granted based on absolute or conditional priority (e.g., emergency vehicle. Nonetheless, there are pros and cons to signal prioritization. Since there is a limited infrastructure capacity, 'signal prioritization' typically means trade-offs between prioritized vehicles/user groups and the rest of the traffic. Several studies reported the positive benefits of signal priority for prioritized vehicles/road users. Others demonstrated negative side effects such as increases in network-wide delays and emissions, and loss of signal coordination (Ahn et al., 2016; Park & Ahn, 2019; Zamanipour et al., 2016).

Though C-TSC systems provide new opportunities to improve traffic efficiency and safety through signal coordination and dynamic exchange of information between vehicles and signal controls, they also introduce new challenges. Traffic signal control optimization considering the stochastic behavior of traffic flows is an inherently complex task (Vilarinho et al., 2016). When solving the problem in real-time with multiple (conflicting) objectives and simultaneously coordinating many intersections in a large-scale network, it gets even more complex. With the increase in the number of signalized intersections, the curse of dimensionality grows exponentially, and so does the computation cost

(Rondinone et al., 2013). There have been several approaches proposed in the literature for C-TSC systems, such as mixed integer non-linear program (Mohebifard et al., 2019), fuzzy logic (Gokulan & Srinivasan, 2010; Heung & Ho, 1998), genetic algorithms (Ghanim & Abu-Lebdeh, 2015), evolutionary algorithms (de Oliveira Boschetti & Bazzan, 2006), artificial neural networks (Ghanim & Abu-Lebdeh, 2015), and, more recently deep reinforcement learning (RL) (Khamis & Gomaa, 2014; Liu et al., 2017; Wang et al., 2021; Yang et al., 2019). However, most of these approaches suffer from the same problems of offline optimization, scalability to large-scale networks, and computational costs. Furthermore, little attention has been paid to cooperation between signal controls and approaching traffic equipped with V2I and I2V communication technologies.

To fill the gaps mentioned earlier, this PhD project aims at real-time optimization and coordination of C-TSC systems along urban arterials with the following characteristics. (1) A decentralized multi-agent system in which signal controls (active computing agents) are locally optimized considering the real-time traffic information collected from roadside sensors, vehicle agents (passive agents) equipped with V2I, and adjacent signal controls (I2I communication). (2) Real-time optimization and coordination of a sequence of cooperative signals where decisions are taken based on multiple objectives (e.g., minimizing waiting time, incident risks, and emissions) to benefit the system as a whole. (3) Adaptive system that can respond to traffic dynamics (variations in traffic demand, vehicle compositions, etc.). (4) Embedded GLOSA and conditional signal priority for one or multiple transport modes/user groups (freight, buses, cyclists, and pedestrians) in a mixed-traffic environment while ensuring an acceptable LOS and safety for all road users.

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