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SDI^2 - Software-Defined Intelligent Intersections for Smart Mobility

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Abstract

Intelligent Intersection Management (IIM) approaches aim to optimize urban traffic flow but face inherent limitations depending on their operational mode. Sequential approaches suffer from inefficiencies under high traffic demand, rigid cyclic operations, and poor scalability. Parallel approaches struggle with turning conflicts, unbalanced traffic flows, and strict lane discipline requirements. Synchronous approaches depend heavily on precise timing, reducing their flexibility. To address these challenges, we propose the Software-Defined Intelligent Intersections (SDI^2) framework, an SDN-based IIM solution that intelligently orchestrates intersection management through centralized control. The SDI^2 framework dynamically switches between sequential, parallel, and synchronous modes based on real-time traffic patterns, effectively accommodating both individual vehicles and groups. This adaptive strategy optimizes traffic flow by reducing reaction times to green signals, minimizing unnecessary stopped delays by up to 89.5%, and significantly reducing energy waste by 63.3% and associated emissions by 76.9% compared to conventional approaches.

Keywords: Software-defined networking, adaptive intersection management, stopped delays, and fuel efficiency;

1. Motivation

The increasing disparity between limited physical road infrastructure and rapid vehicle growth has led to traffic congestion, environmental pollution, and economic and health issues (Afrin and Yodo, 2020; Reddy et al., 2024a; Samal et al., 2021). The global fleet of light-duty commercial and passenger vehicles is projected to grow from approximately 1.31 billion in 2020 to 2.21 billion by 2050, further exacerbating these problems and demanding intelligent solutions. Intelligent Intersection Management (IIM) protocols, powered by advanced Information and Communication Technologies (ICT), autonomous vehicles (AVs), and software-defined networking (SDN) paradigms, offer promising approaches to addressing these challenges (Yang et al., 2020). These protocols can be broadly classified based on how vehicles access intersections: sequentially, parallelly, or synchronously (Reddy et al., 2024b).

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Sequential approaches allow vehicles on one road to proceed during a green phase before switching cyclically in a clockwise or counterclockwise direction. Parallel approaches enable vehicles from opposite road lanes to move simultaneously before switching to the next pair of opposite lanes. Synchronous approaches coordinate vehicle movements by aligning arrival and departure times with traffic signals. Despite their advantages, these approaches have limitations (Reddy et al., 2024b). Sequential approaches, for instance, suffer from inefficiencies under high traffic demand, rigid cyclic operations, and poor scalability. Parallel approaches face challenges in managing turning conflicts, adapting to unbalanced traffic flows, and requiring strict lane discipline. Synchronous approaches depend heavily on precise timing. These challenges highlight the necessity of hybrid models and adaptive systems to enhance traffic efficiency and address the evolving demands of modern transportation.

To overcome these challenges, we propose the Software-Defined Intelligent Intersections (SDI^2) framework, an SDN-based IIM solution capable of dynamically adapting its operational mode in response to real-time traffic patterns. When traffic consists of lone vehicles, the framework relies on the Synchronous Intersection Management Protocol (SIMP) (Reddy et al., 2022, 2024a). Conversely, when multiple vehicles need to cross in the same direction, the Adaptive Intersection Management Protocol (AIMP) coordinates their movement, thereby maximizing traffic efficiency, minimizing stopped delays, and reducing energy waste and associated emissions. Through this hybrid approach, this paper makes two key contributions. First, the SDI^2 framework integrates multiple IIM approaches and dynamically adjusts its operational mode based on real-time traffic conditions, efficiently managing both lone vehicles and vehicle groups. Second, to optimize traffic flow for vehicle groups, AIMP dynamically allocates green phases and their durations based on vehicle crossing directions. The following section provides a detailed discussion of the SDI^2 framework.

2. Software-defined intelligent intersections framework

Figure 1 illustrates the architecture of the SDI^2 framework, designed for a small road network with four signalized intersections. Each intersection is equipped with roadside sensors, such as induction loop detectors and cameras, to monitor traffic conditions. This data is transmitted via roadside units (RSUs) and processed at local edge nodes. The system extracts key information, including vehicle presence, count, and intended crossing directions (left/straight/right).

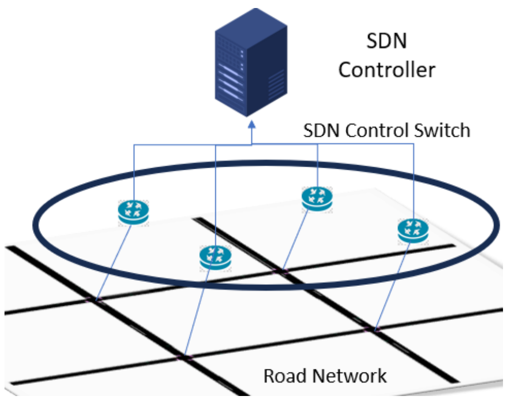


Fig. 1: SDN-based intelligent road network.

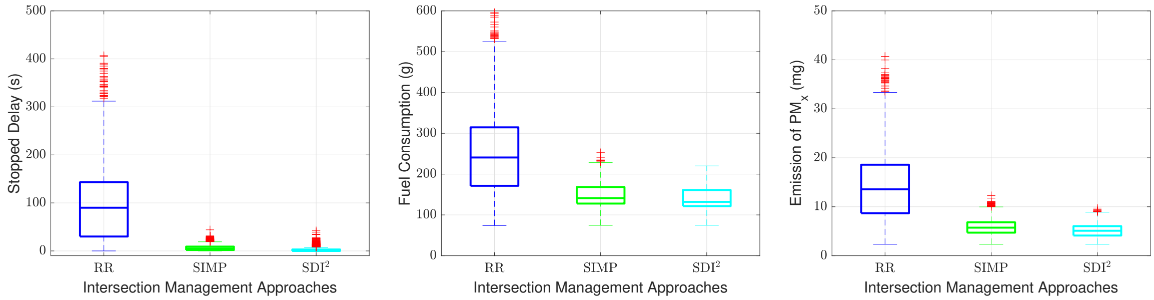
Based on this information, the SDN controller dynamically selects the appropriate IIM protocol. The SIMP protocol is invoked if a vehicle is isolated, meaning no subsequent vehicle intends to cross in the same direction. Conversely, if multiple vehicles want to cross in the same direction, the AIMP protocol is activated. When invoking AIMP, the SDN controller schedules traffic light control phases (green, yellow, red) and adjusts phase durations. In contrast, under SIMP, phase durations remain predefined.

The SIMP protocol operates in cycles, serving one vehicle per non-conflicting road lane. These non-conflicting lanes are determined using the Conflicting Directions Matrix (CDM) (Reddy et al., 2022, 2024a), which regulates vehicle permissions at intersections. A vehicle at the intersection entrance triggers SIMP's traffic signal control phases. Similar to SIMP, AIMP also utilizes road infrastructure but differs in its adaptive phase timing. By analyzing the number of consecutive vehicles intending to cross in the same direction from all inflow lanes, AIMP optimizes green phase durations accordingly, improving traffic flow efficiency.

3. Evaluation

The SDI^2 framework was implemented and tested using the Simulation of Urban Mobility (SUMO) (Lopez et al., 2018), demonstrating its potential to enhance traffic efficiency and sustainability compared to the conventional Round-Robin (RR) (Chaudhuri et al., 2022) and synchronous SIMP approaches (Reddy et al., 2022). To simulate the three approaches, we injected traffic at a rate of 0.1 veh$/s$ for 3600s on all eight inflow roads, following the same setup as scenario-1 in Reddy et al. (2024b). The remaining simulation parameters and values were adopted from Reddy et al.

(2024b), with a maximum vehicle speed of $30 km/h$. A total of 2846 vehicles completed their journey, and we recorded stopped delay, fuel consumption, and PM_x emissions, as shown in Figure 2.



(a) Stopped delay (s). (b) Fuel consumption (g). (c) PM_x emissions (mg).

Fig. 2: Comparing the results of various IM approaches at $30 km/h$.

The results highlight the overall inefficiency of the RR approach, which exhibited the highest stopped delay (just over 400s), fuel consumption (approximately 600g), and PM_x emissions (slightly above 40mg). In contrast, the IIM approaches, SIMP and SDI^2, demonstrated strong performance, with SDI^2 emerging as the best and SIMP as the second-best. The highest recorded values for SIMP were 44s, 252.6g, and 12.3mg, whereas for SDI^2, these were 42s, 220g, and 9.7mg, respectively.

These results indicate that SDI^2 significantly outperforms the conventional RR approach, reducing stopped delay by 89.5%, fuel consumption by 63.3%, and PM_x emissions by 76.9%. Furthermore, SDI^2 improves upon synchronous SIMP by 5% in stopped delay, 15% in fuel consumption, and 27% in PMx emissions. This performance gain stems from SDI^2's efficient invocation of the SIMP and AIMP protocols, which effectively serve both isolated vehicles and groups of vehicles. In contrast, the RR approach serves only groups of vehicles from one road at a time while blocking other roads, whereas SIMP serves one vehicle from each non-conflicting lane.

The full paper will provide a detailed discussion of the SDI^2 framework, including its components and functionality. Future work will explore different simulation scenarios to assess the SDI^2 applicability under varied traffic conditions, including platoons. Additionally, we plan to evaluate the energy efficiency of electric vehicles under the SDI^2 framework.

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References

Afrin T., Yodo N., A Survey of Road Traffic Congestion Measures towards a Sustainable and Resilient Transportation System. Sustainability. 2020, 12(11), pp.4660.

Reddy, R., Almeida, L., Santos, P.M., Kurunathan, H. and Tovar, E., 2024. Energy savings and emissions reduction of BEVs at an isolated complex intersection. Transportation Research Part D: Transport and Environment, 136, p.104403.

Samal, S.R., Mohanty, M. Santhakumar, S.M., Adverse effect of congestion on economy, health and environment under mixed traffic scenario. Transportation in Developing Economies, 2021, 7(2), pp.15.

Yang, J., Zhang, J. and Wang, H., 2020. Urban traffic control in software defined internet of things via a multi-agent deep reinforcement learning approach. IEEE Transactions on Intelligent Transportation Systems, 22(6), pp.3742-3754.

Reddy, R., Almeida, L., Santos, P. and Tovar, E., 2024. Advantages of synchronizing vehicles intersection access. Transportation research procedia, 78, pp.475-482.

Reddy, R., Almeida, L., Gaitán, M.G., Santos, P.M. and Tovar, E., 2023. Synchronous Management of Mixed Traffic at Signalized Intersections Toward Sustainable Road Transportation. IEEE Access, 11, pp.64928-64940.

Chaudhuri, H., Masti, V., Veerendranath, V. and Natarajan, S., 2022. A Comparative Study of Algorithms for Intelligent Traffic Signal Control. In Machine Learning and Autonomous Systems, springer, pp.271-287.

Lopez, P.A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flötteröd, Y.P., Hilbrich, R., Lücken, L., Rummel, J., Wagner, P. and Wießner, E., 2018, November. Microscopic traffic simulation using sumo. In 2018 21st IEEE international conference on intelligent transportation systems (ITSC), pp.2575-2582.