xTL: Reducing Communication Overhead with XAI-Guided, Semantic-Aware DRL for Urban Traffic Light Control

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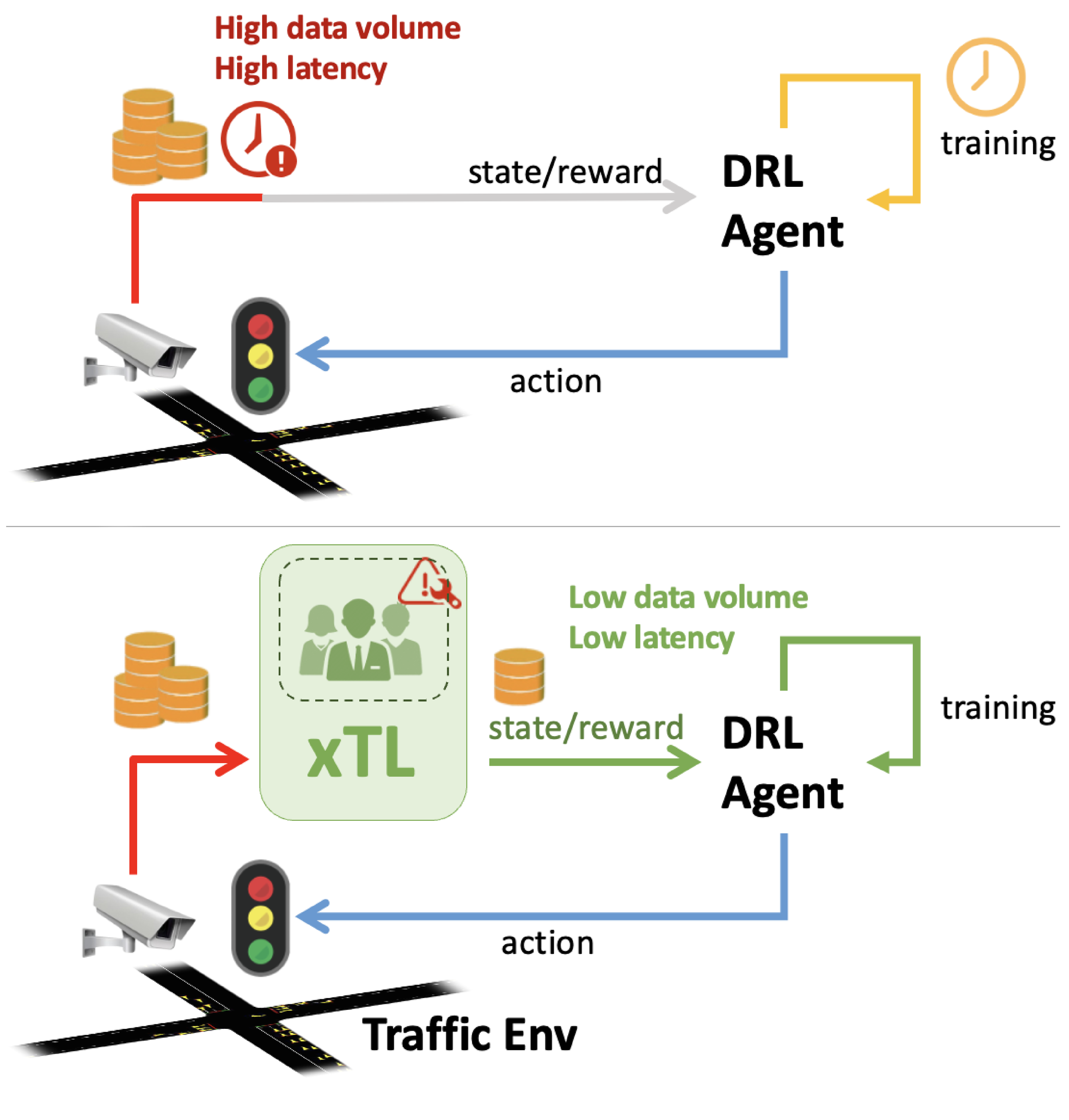
1. Introduction

Problem Background

- DRL-based traffic light controllers require real-time transmission of raw camera images, leading to high communication overhead and latency that hinder practical deployment.
- Manually engineered traffic features offer little interpretability of model decisions and result in repeated feature-design iterations.

Key Insights

- 6G Semantic Communication: Transmit only semantic information instead of full images, dramatically reducing bandwidth usage.
- XAI: Identify which image regions influence the DRL policy most, guiding the extraction of compact, informative semantic features.

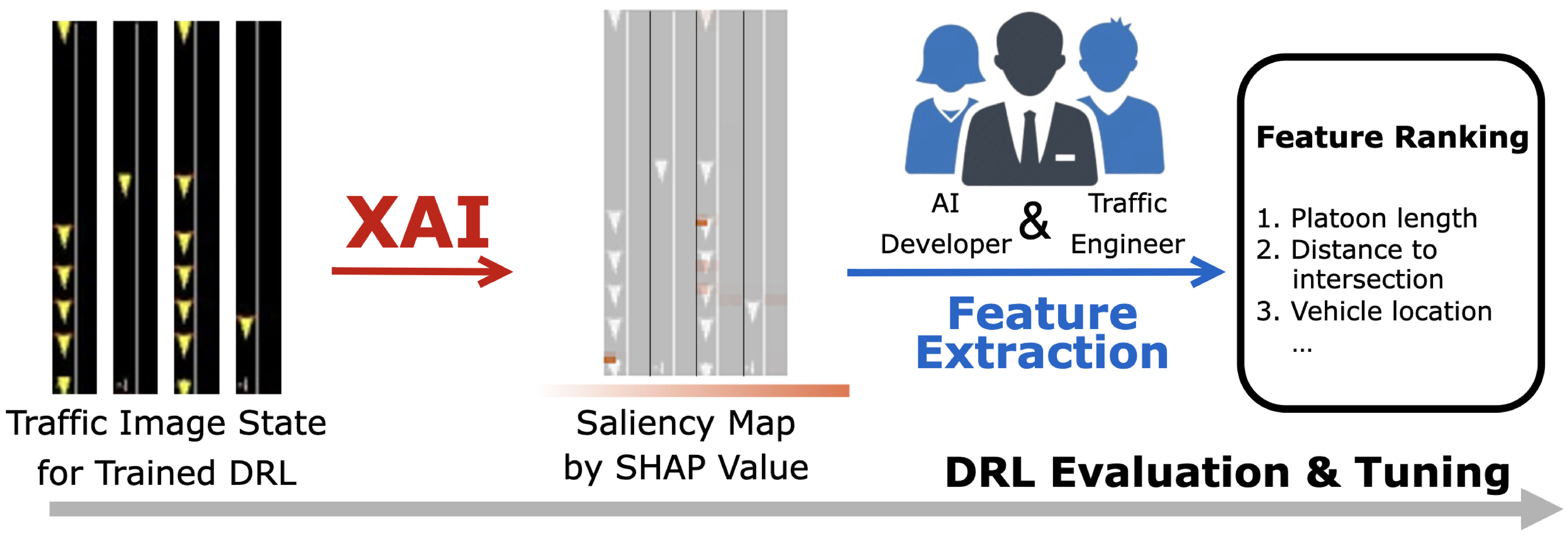


Traditional DRL control (top) v.s. xTL (bottom).

Core Objective

Propose **xTL**, a framework that leverages XAI-generated explanations to design semantic state representations, achieving major reductions in communication cost while preserving control performance.

2. xTL Approach



Overview of xTL.

1. **Explanation Generation:** Apply SHAP to a trained DRL policy on SUMO-GUI intersection snapshots to produce temporal saliency maps.
2. **Semantic Feature Extraction:** Experts analyse SHAP saliency maps that highlight the image regions that most influence the agent's decisions, to identify and rank features for semantic communication.
3. **Semantic Communication for DRL:** Encode extracted features as the DRL state instead of raw images or large matrices.

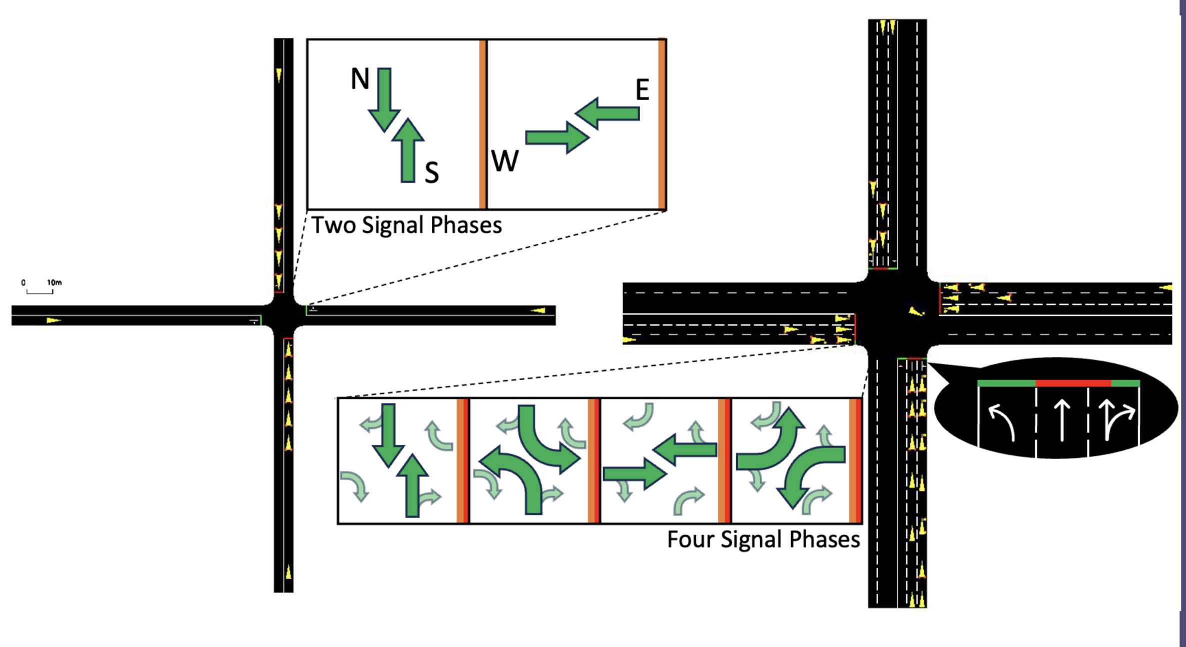
3. Evaluation Methodology

Simulation: SUMO & SUMO-GUI for testing scenarios

- Simple: 2-phase 4-way straight-through intersection
- Complex: 4-phase + left turns, 6-road intersection

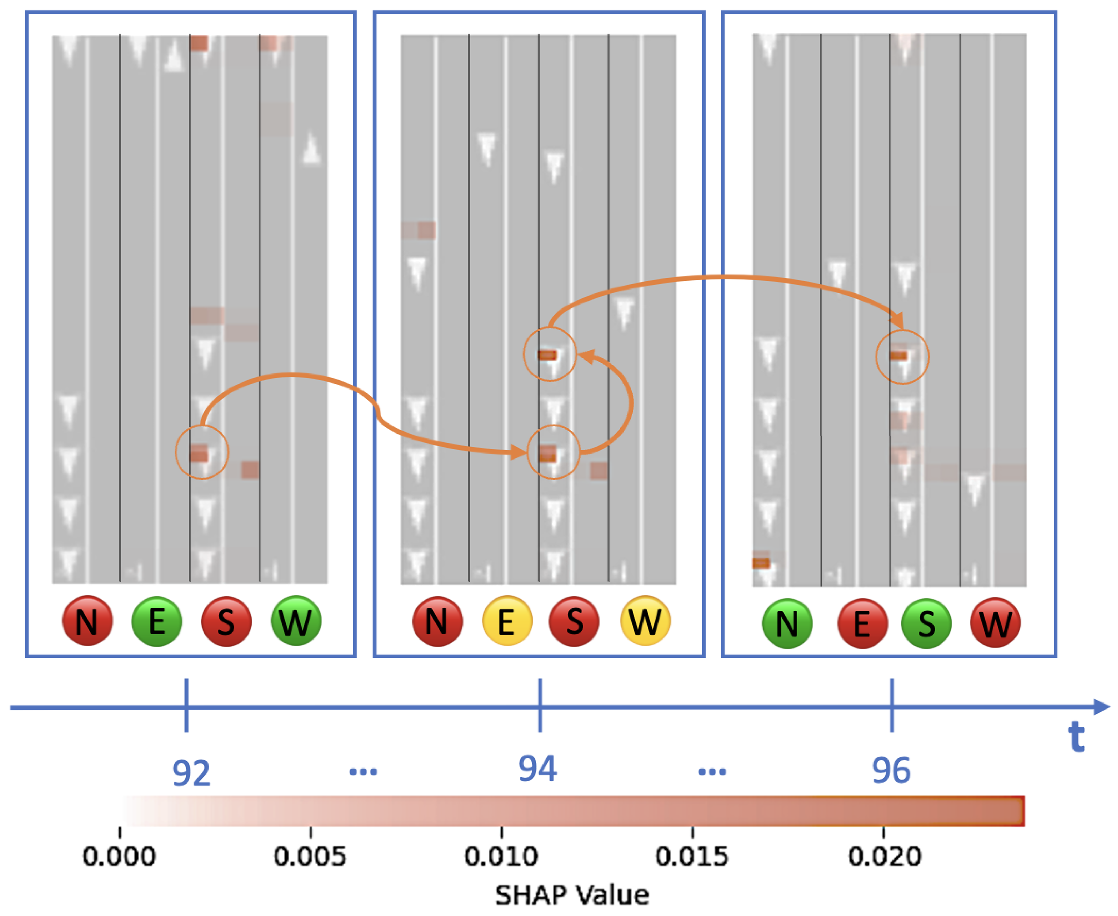
Compared Methods

- Static: a preset traffic signal plan
- IntelliLight: a DRL-based method with states consisting of a simplified image matrix and hand-engineered features



Testing urban intersection scenarios.

4. Evaluation Results



A new critical feature identified via xTL.

Estimated Comm.Cost

xTL: *Location of the last vehicle in the leading platoon* on each of 4 approaches, and the current signal phase.

$$(4 + 1) \times 4 \; bytes = 20 \; bytes$$

IntelliLight: 1) a 2D matrix of (36, 36) indicating vehicle locations and intersection's layout; 2) queue length, vehicle count, and waiting time of all incoming roads; 3) the index numbers of the current signal phase and the next.

$$(36 \times 36 + 3 \times 4 + 2) \times 4 \; bytes = 5240 \; bytes$$

Performance in the Simple Scenario.

	Travel Time	Train. Time	Comm. Cost
Static	32.95	–	–
IntelliLight	22.20	13.39	5240
xTL	**21.09**	**11.65**	**20**

Performance summary:

- Communication cost: > 90% reduction (Complex: 8252 bytes v.s. 52 bytes)
- DRL training: 13% (Simple) and 21% (Complex) faster than IntelliLight
- Without compromising traffic efficiency

5. Future Work

- Conduct more realistic, real-world traffic scenario testing
- Explore extraction of additional, previously unknown semantic features

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