# A Four-Dimensional Spatiotemporal Bin-packing Problem in the Cyber-Physical Internet: A Deep Reinforcement Learning

YI YOU and MING LI

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THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

## Introduction

Bin-packing problem is a combinatorial optimization problem of loading smaller items into larger bins that have to satisfy geometric constraints. It is categorized into three dimensions: One-Dimensional(1D), Two-Dimensional(2D) and Three-Dimensional(3D). In the field of logistics, the 3D bin-packing problem is also commonly referred to as the Container Loading Problem(CLP). With the establishment of Physical Internet (PI), goods are packaged in smart containers of modular dimensions that are reusable or recyclable, i.e., PI(Π) containers. It standardizes containers and promotes the research on weakly heterogeneous 3D loading problems.

Monitoring through PI identifiers facilitates tracking and tracing, akin to internet data packets, thereby digitizing the physical bin packing process. The emergence of Cyber Physical Internet (CPI) provides real-time information to the network layer, propelling the transition from 3D spatial packing problems to four-dimensional spatiotemporal packing problems. In contrast to PI, CPI further demands rapid alignment between freight demand and logistics resources, necessitating real-time decision-making within large-scale PI network. Rather than planning for the future, decisions are made at the moment of data acquisition. However, when dealing with extensive datasets, executing pre-forecasted packing scenarios according to a predetermined plan becomes challenging, leading to resource wastage and reduced network efficiency.

## Objectives

This paper employs the out of order execution approach to address the impact of uncertainty on loading problems. Based on four-dimensional spatiotemporal data, we construct a packing model to tackle spatial filling under the time dimension. The optimization objectives are twofold: minimizing the overall packing cost for goods destined to various locations and maximizing the space utilization within each container. However, these two objectives are not always positively correlated.

$$max \sum_{j=1}^{N}\sum_{i=1}^{Q} e_i \cdot f_i \cdot g_i \cdot D_{ij}$$

$$min \sum_{j=1}^{N} C_j$$

$$\Downarrow$$

$$min\ \alpha \sum_{d=1}^{\theta}\sum_{i=1}^{I}\sum_{c=1}^{m_j}\sum_{j=1}^{J} C_c\, O_{di} \cdot (1 - D_{dicj}) + \beta \sum_{c=1}^{m_j}\sum_{j=1}^{J} C_c \cdot n_{jc}$$

## Methodology

### CPI Network Interface Card Framework

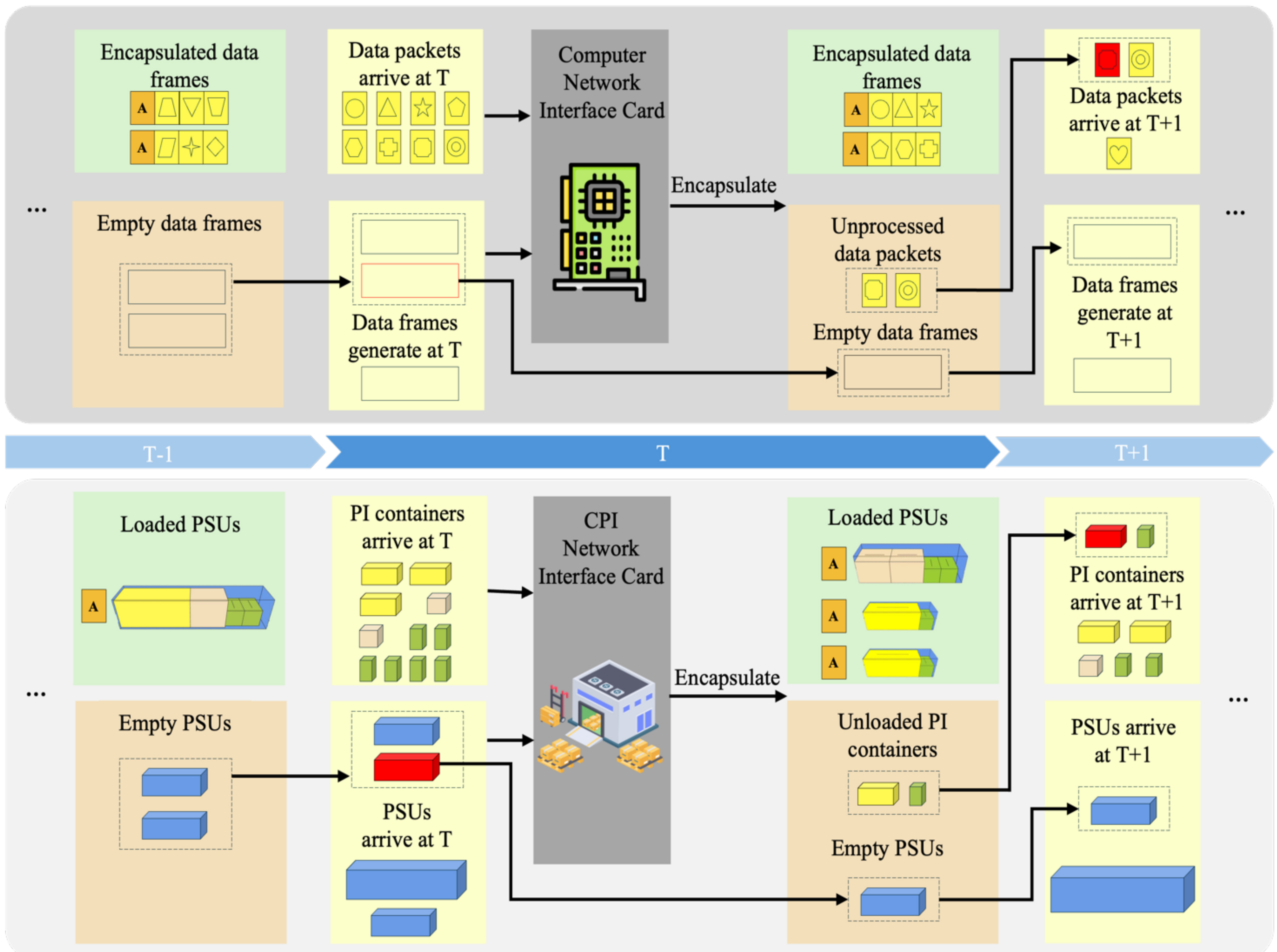


Figure 1 CPI Network Interface Card Framework

In this paper, the four-dimensional Spatiotemporal bin-packing problem is split into two phases: box-splitting and bin-packing. The box-splitting stage deals with the problem in the time dimension, and bin-packing solves the problem in the three-dimensional space.

## Conclusion

We employ deep reinforcement learning (DRL) to obtain an optimal loading scheme, enabling real-time matching of large-scale freight vehicle resources with customer order demands under dynamic and stochastic conditions. Furthermore, we investigate the computational advantages of different solution methods across varying time windows. In comparison to existing heuristic algorithms such as Hybrid Adaptive Large Neighborhood Search (HALNS), Genetic Algorithm (GA) combined with Differential Evolution (DE) and Best-Match-First (BMF), DE + BMF, and Particle Swarm Optimization (PSO) combined with Deepest-Bottom-Left Fill (DBLF), DRL demonstrates faster solution times and greater "real-time" capability.

## Future Work

The experimental data presented in this paper are specific to three different sizes of PI containers and three different sizes of trucks. Further research should be conducted using actual data from logistics sites. Sensitivity analysis has demonstrated that the proposed model in this paper exhibits a certain level of stability. However, further exploration of the model's generalisation capabilities is required. In the future, we plan to introduce additional constraints to enhance the suitability of the Deep Reinforcement Learning model for CPI scenarios.

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