A Digital Twin Simulator for Physics-Inspired AI in 6G Wireless Networks

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***Abstract*—Future 6G networks will operate in dense urban environments where accurate modeling of wireless propagation is essential. We construct a digital twin of the Seoul metropolitan area, with buildings and streets represented in full 3D. Radio propagation is simulated using the NVIDIA Sionna channel model, providing a realistic representation of the urban wireless channel. Within this environment, communication scenarios are represented as interacting entities whose dynamics are approximated by a neural solver trained to emulate the underlying physical processes. The proposed simulator offers a practical platform for evaluating and optimizing association strategies in future networks.**

I. Introduction

6G networks are envisioned to support a wide range of services, which leads to a rapid increase in the number of network entities, such as user equipments (UEs), base stations (BSs), and beams [1]. Timely association among these entities becomes essential for reliable operation. In this context, efficient association plays a critical role, for example, in managing links between UEs and BSs and aligning transmission and reception through beam selection. However, conventional optimization techniques, including the Hungarian algorithm, are computationally prohibitive for real-time implementation. Moreover, existing AI-based approaches handle constraints by introducing them as penalty terms in the objective, so strict feasibility is not guaranteed. This limitation may lead to network service failures.

To overcome these challenges, we propose a physics-inspired approach in which the association problem is represented as a system of interacting nodes. Rather than relying on iterative information exchange among nodes, the system dynamics are emulated by a neural solver trained in an unsupervised manner. This design naturally embeds the underlying constraints, enabling the derivation of robust solutions without the need for labeled data. Recent advances in digital twin technology have enabled site-specific and physically realistic evaluation of wireless networks by integrating detailed 3D city models with accurate channel simulations. Such environments provide a rigorous basis for evaluating algorithms that must satisfy stringent latency and reliability requirements under complex urban propagation conditions [2].

Based on this approach, we develop a high-fidelity simulator that integrates a Unity-based digital twin of Korea University with the NVIDIA Sionna channel model for ray-tracing propagation [3]. The resulting system provides a practical platform for the evaluation of association strategies in realistic urban wireless environments.

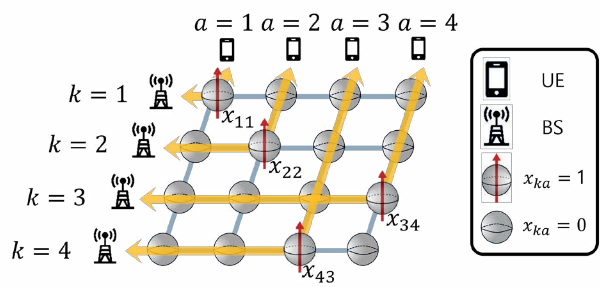

Fig. 1: Physics-inspired reformulation of the BS–UE association problem as an interacting particle system.

II. 6G Simulator with Physics-Inspired AI

The method is motivated by first examining the association problem in the conventional optimization setting. In the simulator, ray-tracing propagation provides signal-to-interference-plus-noise ratio (SINR) values for each link, which are converted into achievable rates w_{ka}. This process defines the optimization problem that serves as the basis for validating the physics-inspired solver within the simulation environment.

A. System Model

We consider a downlink system consisting of K BSs and N UEs. The objective is to determine an association between BSs and UEs so as to maximize the aggregate network sum-rate. To this end, let $x_{ka} \in \{0,1\}$ denote the binary association variable, where $x_{ka}=1$ indicates that BS k is associated with UE a, and $x_{ka}=0$ otherwise. The corresponding optimization problem can be formulated as:

$$\mathbf{P1}: \max_{\mathbf{X}} \sum_{k=1}^{K}\sum_{a=1}^{N} w_{ka}x_{ka},$$

$$\text{subject to} \sum_{a=1}^{N} x_{ka} \le 1, \quad \forall k, \in \mathcal{K}, \tag{1a}$$

$$\sum_{k=1}^{K} x_{ka} = 1, \quad \forall a \in \mathcal{N}, \tag{1b}$$

where the weight w_{ka} characterizes the instantaneous achievable rate of the link (k,a).

B. Physics-inspired AI Solver

The combinatorial optimization in **P1** is intractable for large network sizes. To address this challenge, we reformulate the association task from a statistical physics perspective. In this view, each BS–UE link (k, a) is regarded as an interacting element of a particle system, and the optimal allocation corresponds to the minimum-energy ground state, as shown in Fig. 1.

To describe this interaction, we introduce two messages for each link: the BS-to-UE message α_{ka}, representing the preference of BS k for UE a, and the UE-to-BS message ρ_{ka}, representing the reciprocal preference of UE a for BS k. These messages are updated iteratively as

$$\rho_{ka}^{(t+1)} = f(\alpha_{ka}^{(t)}, \mathbf{W}), \quad \alpha_{ka}^{(t+1)} = g(\rho_{ka}^{(t)}, \mathbf{W}), \tag{2}$$

where $\mathbf{W} = [w_{ka}]$ is the weight matrix, and $f(\cdot)$ and $g(\cdot)$ denote the update functions. When the iterations converge, the messages α_{ka} and ρ_{ka} become mutually consistent, yielding a stable association between BSs and UEs [4].

Although message passing converges reliably, its iterative nature introduces significant latency in real-time operation. To address this, we adopt a deep neural network (DNN) as a non-iterative solver that maps the SINR-based weight matrix $\mathbf{W}$ directly to the converged representation. The DNN predicts (α, ρ), and the association for each UE a is obtained as $k^* = \arg\max_k \rho_{ka}$, with tie-breaking to satisfy the per-BS constraint $\sum_a x_{ka} \leq 1$.

Training is unsupervised and enforces self-consistency by minimizing the residuals of (2) under the Frobenius norm, i.e., $\mathcal{L} = \|\rho - f(\alpha, \mathbf{W})\|_F^2 + \|\alpha - g(\rho, \mathbf{W})\|_F^2$. This enables low-latency inference while preserving constraint satisfaction, making the solver suitable for real-time 6G operation.

C. Digital Twin Simulator

To validate the proposed method, a digital twin of Korea University is constructed using the Unity 3D engine, where buildings and terrain are modeled in full 3D. Wireless propagation is simulated with the NVIDIA Sionna ray-tracing channel model, which accounts for reflections, diffractions, and blockages to provide physically accurate SINR values. By integrating a digital twin with ray tracing, the simulator efficiently captures the complex interactions of wireless propagation in realistic environments.

In this environment, users are randomly placed and move along pedestrian pathways between buildings, inducing realistic channel variations. The resulting SINR values are converted into instantaneous achievable rates, forming the weight matrix $\mathbf{W}$ that serves as input to the proposed solver. As shown in Fig. 2, a graphical user interface (GUI) allows the operator to set the number of users, configure their mobility speeds, and select the neural network model. Changes take effect in real time during the simulation. In addition, the simulator provides real-time visualization of coverage and interference distributions and continuously computes and displays the aggregate network sum-rate based on the solver's decisions. This digital twin platform thus serves as a high-fidelity testbed for evaluating association strategies under dynamic urban conditions.

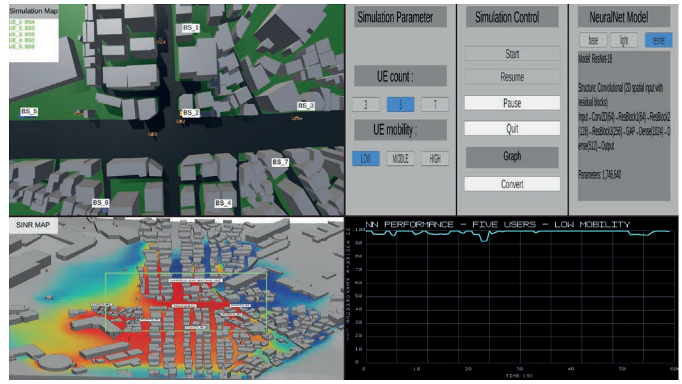

Fig. 2: Digital twin-based 6G simulator with physics-inspired AI models

III. Simulation Results

A total of $K = 7$ base stations are deployed, and three user configurations are considered with $N \in \{3, 5, 7\}$. The neural solver consistently achieved at least 93% of the performance of the optimal algorithm, while operating with a single forward pass instead of multiple iterations. This confirms its suitability for real-time operation in dynamic environments.

IV. Conclusion

A high-fidelity digital twin simulator integrating Unity and NVIDIA Sionna is developed to validate the proposed physics-inspired neural solver. Beyond serving as a testbed for user association, the simulator provides realistic 3D urban modeling, accurate ray-tracing–based propagation, and configurable user mobility, enabling comprehensive evaluation under dynamic conditions. This work highlights the potential of digital twin–based simulation platforms as practical tools for real-time algorithm design and performance assessment in future 6G networks.

Acknowledgement

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