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A versatile digital twin framework for maritime communications with off-the-shelf components

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Maritime communication is in increasing demand as oceanic activities surge in recent years [1]. However, maritime networks face challenges such as rapidly changing sea conditions and sparse users. Unlike terrestrial networks, maritime infrastructures often require capital-intensive hybrid satellite-terrestrial architectures, where a direct transplantation of terrestrial-oriented technologies is inefficient [2]. Consequently, validating these specialized designs typically involves high-stakes sea trials that are economically burdensome and operationally risky, creating a substantial barrier to entry for agile research. Digital twin networks (DTNs) offer a promising solution by providing a synchronized virtual counterpart that enables interactive scenario configuration, rapid iteration, and real-time monitoring, thus reducing dependence on costly sea trials [3].

Existing DTNs have been widely applied to communication networks, satellite networks, autonomous systems, and wireless positioning [4]. For maritime communications, Wang et al. [5] proposed a DT-enabled maritime networking architecture for smart-ocean information dissemination and quality of service (QoS) provisioning. However, this work mainly focuses on theoretical networking architecture and QoS provisioning, while practical implementation aspects, such as data collection and real-time data interaction, are less discussed. Qian et al. [6] developed a federated learning-assisted digital twin framework for marine networks to reduce the communication energy consumption during the DT construction phase. Nevertheless, this study focuses on data aggregation and model training to build the virtual replica, while the interaction mechanisms are less discussed, leaving the compatibility between the dynamic network design and the DT model to be further explored.

To address these challenges, we propose a versatile DTN framework for maritime communications, built using off-the-shelf components.

Our main contributions can be summarized as follows.

(1) We design a modular digital-twin co-simulation architecture that separates interaction-oriented control from real-world/simulation data. The control plane provides an interactive 3D twin for scenario construction, parameter configuration, and analytics, while the data plane offers a timestamped, unified interface to fusion states, metrics, action streams, and heterogeneous data sources across diverse backends. This architecture allows for independent evolution of the heterogeneous modules.

(2) We build a flexible DTN prototype using off-the-shelf components, consisting of three modular layers: visualization layer, network emulation layer and intelligent decision layer. These layers are glued together through a database-assisted interface. The validity of the framework is demonstrated through two demo cases that share the same core architecture but differ in system composition and objectives: (i) a maritime coverage design scenario using shipborne base stations, and (ii) a multi-UAV assisted maritime communication scenario.

Framework architecture. The proposed framework is referred to as an intelligent digital twin architecture (IDTA). The architecture is designed for easy assembly using off-the-shelf components, as illustrated in Figure 1(a).

(1) Visualization layer: this layer is responsible for (i) constructing highly realistic simulation environments with dynamic elements and scenes, (ii) executing system kinematics and updating environmental conditions at each simulation step, and (iii) visualizing system states and performance metrics in near real-time. In practice, the layer can be implemented with a 3D scene engine such as Unity 3D to provide an immersive and interactive front-end.

(2) Network emulation layer: given the time-varying topology and mobility states from the visualization layer, this layer models communication channel models and protocol behaviors, and outputs QoS metrics (e.g., throughput, end-to-end packet delay) for performance evaluation under dynamics. In practice, it can be implemented with a protocol-level simulator such as NS-3 or OMNET++ to provide packet-level communication fidelity.

(3) Intelligent decision layer: this layer aggregates heterogeneous inputs to compute control/configuration decisions via optimization and/or machine learning algorithms. The resulting actions are then issued back to the other two layers, enabling closed-loop co-simulation. In practice, it can be implemented with any numerical software for optimization/learning, e.g., Python-based

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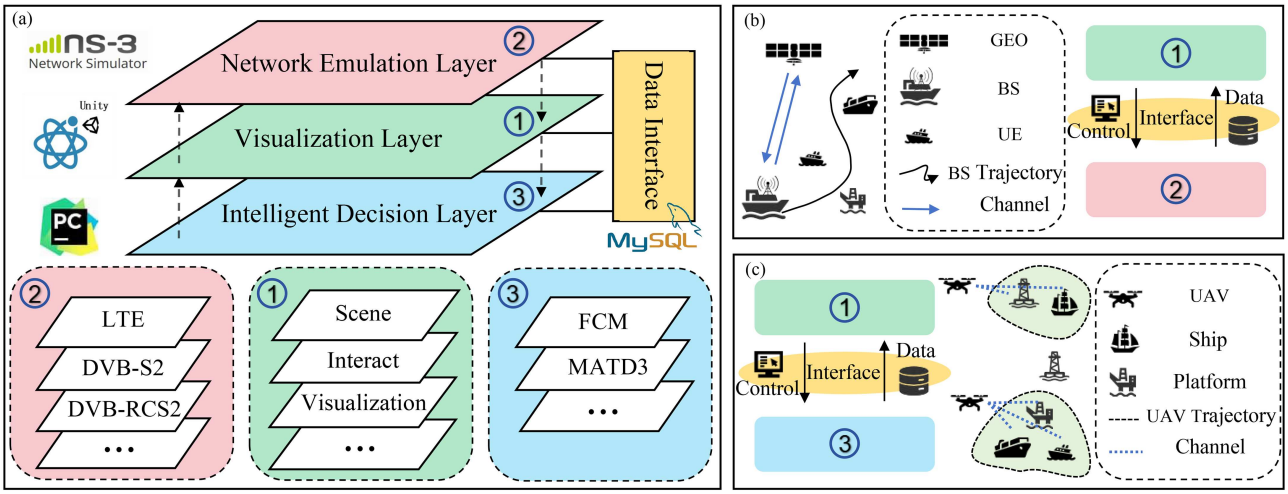

Figure 1 (Color online) (a) A versatile DTN framework for maritime communications; (b) Demo case 1; (c) Demo case 2.

toolchains.

Execution workflow. In the proposed architecture, the visualization layer (e.g., Unity 3D) constructs the physical scenario and triggers the cloud-deployed NS-3 via lightweight HTTP requests. To resolve the synchronization bottleneck among heterogeneous modules, the framework employs a timestamp-aligned, database-mediated asynchronous mechanism. Rather than enforcing rigid lock-step execution, a MySQL database acts as a shared global state buffer. Here, continuous frame-driven states from Unity 3D and discrete event-driven logs—continuously updated by NS-3—are tagged with unified timestamps. This ensures temporal coherence, real-time visualization, and smooth cross-layer data fusion without throttling individual module performance. The intelligent decision layer (e.g., Python packages) may then be integrated with this visualization-simulation cycle by fetching on-scene data from the database, performing computations, and issuing control commands back to Unity 3D for system adjustments.

In the following, we provide two concrete examples based on the proposed framework.

Demo case 1: maritime coverage enhancement with shipborne base stations. This demonstration highlights the framework's reliability, high-fidelity simulation, and low-latency performance, which are essential for dynamic maritime environments. The scenario implements a digital twin system for maritime area coverage enhancement problem based on shipborne base stations and satellite backhaul. The demo illustrates how the proposed framework executes an end-to-end co-simulation loop that couples (i) physics-driven scene evolution, (ii) packet-level network evaluation, and (iii) database-mediated cross-domain fusion. The case vividly illustrates how the DTN may help to plan ship trajectory (Figure 1(b)).

The construction of the DTN starts with drag-and-connect of pre-configured 3D modules in Unity 3D to specify the position and movement of the objects. To accurately twin the maritime scenario, we can model wave-induced vessel motions by decomposing the hull geometry. Specifically, the hull buoyancy is approximated by a set of primitive volumes (e.g., spheres) whose submerged areas can be efficiently computed and aggregated. The buoyancy force on a primitive is modeled as

$$\boldsymbol{F}_{\mathrm{f}} = \begin{cases} \boldsymbol{0}, & \xi(p) \leqslant p_y, \\ Sg\rho\big(\xi(p) - p_y\big) n_y \boldsymbol{y}, & \xi(p) > p_y, \end{cases} \tag{1}$$

where $\boldsymbol{F}_{\mathrm{f}}$ denotes the buoyancy force vector, $\xi(p)$ denotes the water level at position p, p is the centroid position of the submerged sphere, S is the submerged area, ρ is the fluid density, g is the acceleration of gravity, n is the centroid vector, n_y is its y-component, and $\boldsymbol{y}$ is the unit vector along the vertical direction.

$$\boldsymbol{F}_{\mathrm{lift}} = \frac{1}{2}\rho C_L |S_{\mathrm{face}}||\boldsymbol{U}| \left(\boldsymbol{U} \times \frac{\boldsymbol{n} \times \boldsymbol{U}}{|\boldsymbol{n} \times \boldsymbol{U}|}\right), \tag{2}$$

$$\boldsymbol{F}_{\mathrm{drag}} = -\frac{1}{2}\rho C_D |S_{\mathrm{face}}||\boldsymbol{U}|\,\boldsymbol{U}, \tag{3}$$

where C_L and C_D are the lift/drag coefficients, $\boldsymbol{U}$ is the relative velocity between the primitive and the fluid, $\boldsymbol{n}$ is the surface normal, and S_{face} is the effective projected area. These models can be conveniently implemented in the visualization layer (e.g., Unity 3D in this particular case), enabling the scene to update vessel pose (position/attitude) at each simulation tick while remaining computationally tractable.

To ensure the fidelity of the DTN, the framework also inherently permits dynamic environment to be driven by real-time meteorological data and incorporate real-world historical AIS trajectories (from open sources or certain maritime administration entities). Specifically, we may acquire time-series radar grayscale images of the target sea area. Let $\boldsymbol{I}_t \in \mathbb{R}^{H\times W}$ denote the grayscale image matrix at time t. We extract the pixel value at a fixed observation coordinate $p(u, v) = (153, 240)$ to generate the echo intensity vector $\boldsymbol{E}$, defined as

$$\boldsymbol{E}(t) = \boldsymbol{I}_t(153, 240) \times \gamma, \tag{4}$$

where $\gamma = 10$ is the scaling factor. This vector $\boldsymbol{E}$ encapsulates the temporal variation of wind speed and precipitation.

These extracted intensities are injected into the DTN via the WindMySQL interface to drive the hydrodynamic models in Unity 3D. Real-time wind intensity can then be twinned with a wave mapping function $\mathcal{M}(\cdot)$ with constrained coefficients. Such parameterization allows the visualization layer to render diverse sea conditions accordingly, ranging from calm to rough waters.

Thanks to the built-in 3D modeling capability provided by Unity 3D, the weather effects on the ships can be seamlessly integrated. Their effects on the communication channel gain fluctuations can also be accurately evaluated given certain models (e.g., two-ray tracing model).

The communication performance of the system based on shipborne base stations and satellite backhaul can be conveniently simulated in the network emulation layer with NS-3. Given the constructed scenario in the visualization layer, JSON-based configuration and parameters are passed to NS-3, where automatic

scripts would instantiate the simulation scenario and start running. The logging data is exchanged with the visualization layer to be displayed.

In this case, the network emulation layer outputs throughput, latency, and packet loss rate as network-side communication KPIs, which are periodically written into the database and synchronized with the visualization layer for performance monitoring.

This complete workflow provides a means to evaluate base-station ship trajectory given real-world maritime users distribution under real-time weather conditions, establishing a closed-loop co-simulation workflow for subsequent analysis and decision making.

Demo case 2: multi-UAV assisted maritime communication. This demonstration investigates the scalability of the proposed framework and its capability to integrate with intelligent algorithms in a plug-and-play manner under large-scale and dynamic settings. The scenario of Demo case 1 is extended to accommodate a larger number of communication entities and more complex interactions, but follows a similar execution flow. Here we introduce the integration of a Fuzzy C-Means clustering and multi-agent twin delayed deep deterministic policy gradient (FCM-MATD3)-based UAV maritime communication collaborative optimization algorithm in the intelligent decision layer. As the system scale increases, the framework preserves the original closed-loop execution process, including state synchronization, network evaluation, and database-mediated data exchange (Figure 1(c)).

In this use case, an FCM clustering algorithm will be applied to partition the maritime environment into regions according to their communication demand, which are modeled according to real-life AIS data and assumed traffic models for each vessel. Once these regions are defined, the MATD3 algorithm optimizes UAV trajectories and communication resource allocation to maximize system energy efficiency, while ensuring rate and power constraints are respected. This two-step process allows UAVs to prioritize resource allocation based on user density, improving both communication coverage and energy efficiency.

At each decision cycle, the decision layer aggregates system states and network metrics, which are continuously updated in the database. A clustering step first partitions users into C groups. Given user feature vectors $\{\boldsymbol{x}_i\}_{i=1}^{N}$ (e.g., positions and link-related attributes), cluster centroids are computed as

$$\boldsymbol{c}_j = \frac{\sum_{i=1}^{N} u_{ij}^{m} \boldsymbol{x}_i}{\sum_{i=1}^{N} u_{ij}^{m}}, \quad j = 1, \ldots, C, \tag{5}$$

where $u_{ij} \in [0, 1]$ denotes the membership of user i to cluster j and $m > 1$ is the fuzzifier. This step decomposes a large-scale system into structured subgroups, improving scalability.

Conditioned on the grouping structure, a multi-agent learning module outputs abstract control actions

$$\boldsymbol{a}_t = \pi_\theta(\boldsymbol{s}_t)\,, \tag{6}$$

where $\boldsymbol{s}_t$ denotes the aggregated state (including group descriptors and network KPIs) and $\pi_\theta(\cdot)$ is a parameterized policy. The actions are fed back to the execution layers through standardized interfaces, while the internal learning details remain encapsulated.

The energy efficiency (EE) is adopted as a representative system-level metric, defined as

$$\mathrm{EE} = \frac{\sum_{t=1}^{T} \sum_{u=1}^{N_U} R_{u,ms,t}\, \lambda_t}{\sum_{t=1}^{T} \sum_{u=1}^{N_U} E_u(t)}, \tag{7}$$

where $R_{u,ms,t}$ is the data rate for UAV u and vessel ms at time t, $E_u(t)$ is the energy consumption of UAV u, and λ_t is the slot duration.

In implementation, the composite FCM-MATD3 workflow is encapsulated as a single decision module. At each decision cycle, it produces (1) trajectory-related outputs for aerial nodes and (2) the corresponding system-level energy efficiency. These outputs are written as time-stamped records through the unified interface and then consumed by the visual-physical layer. Unity 3D updates the aerial-node motion accordingly and renders the resulting trajectories, while simultaneously visualizing and other key indicators on the UI in near real time. This closed-loop visualization-and-execution process allows users to observe how high-level decisions translate into physical motion and communication outcomes as the system scale grows.

Note that the framework treats intelligent algorithms as replaceable modules. Alternative grouping strategies or learning-based optimizers can be incorporated by substituting the decision module alone, without affecting the simulation or network layers. This demonstration confirms that the proposed architecture supports scalable operation and algorithm plug-and-play integration, providing a flexible foundation for embedding diverse intelligent strategies in large-scale digital twin systems.

Conclusion and future work. In the study, we present a modular DTN framework. By integrating visualization, network emulation, and decision-making into a unified closed-loop system, the proposed framework provides a versatile and cost-effective baseline for maritime digital twin validations. **Demo case 1** confirms system effectiveness in a shipborne base station scenario. **Demo case 2** demonstrates the framework's scalability, supporting the plug-and-play integration of intelligent algorithms.

Furthermore, the proposed architecture is not confined to the current selection of components. The visualization layer can be implemented with alternative 3D engines, such as Unreal Engine or Gazebo; the network emulation layer can adopt OMNET++ or other network simulators; and the decision layer can be developed with MATLAB, TensorFlow, or PyTorch.

It is important to note that the current implementation is primarily optimized for localized environments, such as vessel-based or air-based maritime communications. Extending it to ultra-large-scale heterogeneous networks currently poses substantial synchronization and computational challenges. To overcome this, building upon our preliminary cloud-based deployment, future work will focus on cloud-native scalable simulations. By integrating broader resources, we aim to expand the framework's application scenarios to include maritime emergency rescue, and even extend its reach from maritime domains to cross-domain systems, such as satellite communications and vehicular networks.

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