

Photon Splatting: Real-Time Wireless Propagation Modeling and 4D Channel Prediction

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For beyond 5G and 6G wireless systems, digital twins are expected to be one of the most promising technologies to meet the diverse performance requirements (extremely low latency, ultra-reliability, user-defined quality of physical experiences) for novel applications (autonomous driving, industry 4.0 and beyond, extended reality, immersive multimedia, Metaverses, etc.). A digital twin-empowered 5G and beyond wireless system will enable the analysis, design, real-time monitoring, and configuration of wireless devices for cost-effective and resource-optimized operation. Today, the wireless digital twin (WDT) for 6G networks has become part of the scope of 6G research and the subject of standardization activities.

Although the promise of WDTs is well recognized, several challenges need to be overcome before developing WDTs at scale. First, high-fidelity physical-layer modeling is required for the accurate capturing of complex wave interactions with propagation environments. Second, real-time response is crucial because WDTs should respond to dynamic conditions such as user mobility, channel variations, and time-varying beam patterns. Finally, scalability is very important to model large, densely populated urban areas without loss of speed or accuracy.

Motivated by recent advances in computer rendering and neural reconstruction, we aim to investigate a physics-informed neural surrogate capable of learning the interactions between electromagnetic (EM) waves and their propagation environment. After the learning process, the model can predict critical wireless channel properties in real-time for any new configuration within the scene.

The first ingredient draws inspiration from the photon mapping algorithm in computer graphics, which simulates the interaction of light with objects during rendering. Adapting this concept to our work, wave propagation is modeled as a swarm of photons traveling through an environment. The photons interact with surfaces via wave physics of reflection, diffraction, and scattering. Next, these interactions are captured through a splatting operation, which projects the wave signature onto a spherical rasterizer. To enhance the performance, we incorporate Fourier Neural Operators and spherical wavelets to efficiently process high-dimensional spatial data and encode angular dependencies. This combination allows the trained model to predict critical wireless channel properties, including time-of-flight, angles of arrival, and channel impulse response (CIR), with millisecond-level latency.