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AI-Based Channel Modeling and Prediction for 5G/6G Wireless Links

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Abstract

The increasing complexity of fifth-generation (5G) and emerging sixth-generation (6G) wireless systems has intensified the need for accurate and adaptive channel modeling and prediction techniques. Conventional model-driven approaches struggle to capture the highly dynamic, non-linear, and high-dimensional characteristics of modern propagation environments, particularly in millimeter-wave and terahertz frequency bands. This chapter presents a comprehensive exploration of artificial intelligence (AI)-driven methodologies for wireless channel modeling, emphasizing their capability to learn intricate spatial and temporal dependencies directly from data. Advanced machine learning and deep learning architectures, including convolutional, recurrent, and hybrid CNN–RNN models, are examined for their effectiveness in modeling complex channel behaviors and predicting channel state information with high precision. The discussion highlights the integration of spatio-temporal learning frameworks, ensemble techniques, and hybrid physics-informed models to enhance robustness, generalization, and interpretability. Critical applications in 5G and 6G systems, such as beamforming optimization, resource allocation, and high-mobility communication scenarios, are analyzed to demonstrate the practical significance of AI-based channel prediction. Key challenges, including data scarcity, computational complexity, and model reliability, are addressed alongside emerging research directions such as federated learning and intelligent reconfigurable environments. The chapter establishes AI-driven channel modeling as a transformative approach for enabling intelligent, scalable, and adaptive wireless communication systems in next-generation networks.

Keywords: AI-Based Channel Modeling, 5G/6G Wireless Systems, Channel Prediction, Deep Learning, Spatio-Temporal Modeling, Massive MIMO.

Introduction

The evolution of wireless communication systems toward fifth-generation (5G) and sixth-generation (6G) networks has introduced a paradigm shift in the design and operation of modern communication infrastructures [1]. Rapid growth in data demand, proliferation of connected devices, and the emergence of data-intensive applications such as augmented reality, autonomous systems, and smart cities have significantly increased the complexity of wireless environments [2]. Communication systems now operate across diverse frequency bands, including millimeter-wave and terahertz spectra, where propagation behavior differs fundamentally from conventional sub-6 GHz systems [3]. Signal attenuation, sensitivity to environmental obstructions, and limited diffraction characteristics create highly dynamic and unpredictable channel conditions [4]. These factors necessitate advanced modeling techniques capable of capturing intricate relationships between environmental parameters, transmission characteristics, and user mobility. Accurate channel modeling plays a crucial role in system design, performance evaluation, and optimization, as it directly influences link reliability, spectral efficiency, and overall network performance in next-generation wireless systems [5].

Traditional channel modeling approaches have long served as the foundation for analyzing wireless communication systems [6]. Empirical models, deterministic techniques such as ray tracing, and geometry-based stochastic frameworks provide simplified yet effective representations of signal propagation under specific conditions [7]. These models rely on assumptions regarding stationarity, uniform scattering, and predefined environmental parameters, which enable tractable mathematical formulations [8]. In legacy systems, such assumptions provided reasonable approximations for channel behavior, facilitating efficient simulation and system design. In contrast, emerging wireless environments exhibit non-linear, high-dimensional, and non-stationary characteristics that challenge these conventional assumptions [9]. Variations in user density, mobility patterns, and environmental complexity introduce significant uncertainty in channel behavior. Model-driven techniques often fail to generalize across diverse scenarios, limiting their effectiveness in real-world deployments. Increasing computational demands associated with deterministic approaches further restrict scalability, particularly in large-scale and real-time applications [10].

Artificial intelligence and machine learning have emerged as transformative technologies capable of addressing the limitations of traditional channel modeling techniques [11]. Data-driven approaches leverage large volumes of wireless measurements to learn complex relationships between input features and channel characteristics without relying on restrictive assumptions [12]. Machine learning algorithms enable adaptive modeling by continuously updating parameters based on observed data, allowing systems to respond effectively to changing environments [13]. Deep learning architectures, including convolutional neural networks and recurrent neural networks, provide powerful tools for extracting spatial and temporal patterns from high-dimensional channel data [14]. These models capture intricate dependencies that remain difficult to represent using analytical formulations. The ability to learn from heterogeneous datasets enhances model flexibility and improves prediction accuracy, making AI-based approaches highly suitable for next-generation wireless communication systems [15].