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CDL vs TDL in 5G-NR mmWave: A 3GPP-Compliant Performance Evaluation

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Abstract

The use of millimeter-wave (mmWave) frequency bands in Fifth-Generation New Radio (5G-NR) promises unprecedented data rates and spectral efficiency, but their highly variable propagation characteristics make accurate performance evaluation a critical challenge. Among the standardized 3GPP models, the Clustered Delay Line (CDL) and the Tapped Delay Line (TDL) are widely used, yet their comparative impact on mmWave system reliability has not been thoroughly quantified. This paper presents a detailed evaluation of CDL and TDL models under realistic deployment conditions, including both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) scenarios. Simulations are performed with 3GPP-defined parameters, accounting for delay profiles, delay spreads, Doppler effects, carrier frequency, and antenna configurations. Performance is assessed through Signal-to-Noise Ratio (SNR) and Block Error Rate (BLER) metrics. Results indicate that CDL models exhibit superior robustness in NLOS environments, achieving a BLER of 0.02% at 25 dB SNR for CDL-C versus 0.3% or TDL-C, while in LOS conditions CDL-D achieves 0.06% BLER compared to TDL-E's 6.495×10−5%. These outcomes demonstrate that the choice of channel model significantly influences system-level evaluations and provide insights into optimizing 5G-NR mmWave deployments through appropriate channel modeling and signal processing strategies

Keywords: 5G-NR mmWave, 3GPP Channel Models, CDL/TDL, Block Error Rate (BLER), Performance Evaluation

1. Introduction

The advent of fifth-generation (5G) mobile networks, particularly in the millimeter-wave (mmWave) spectrum, represents a major milestone in wireless communications. Leveraging wide bandwidth availability, 5G-NR promises ultra-high data rates, enhanced spectral efficiency, and massive connectivity, enabling applications ranging from the Internet of Things (IoT) to immersive virtual and augmented reality. However, mmWave frequencies also introduce unique challenges due to their propagation characteristics, including severe path loss, high susceptibility to blockage, complex multipath effects, and pronounced Doppler spread [1]. To capture these effects in system evaluation, the 3rd Generation Partnership Project (3GPP) has standardized two main channel models: the Clustered Delay Line (CDL) and the Tapped Delay Line (TDL) [2]. The CDL model accounts for spatial richness by grouping multipath components into clusters with defined angular and power distributions, making it well-suited for urban and spatially diverse deployments. The TDL model, by contrast, specifies deterministic taps with predefined delays and gains, offering reduced complexity and faster simulation at the expense of spatial accuracy [3].

Although these models are extensively used in standardization and simulation frameworks, their comparative impact on system-level performanceÚparticularly on metrics such as Block Error Rate (BLER) and Signal-to-Noise Ratio (SNR)Úremains underexplored. Prior works often adopt either CDL or TDL in isolation, with-out systematically analyzing their relative strengths and limitations across LOS and NLOS scenarios. A focused comparison is therefore essential to guide the appropriate selection of channel models, especially as 5G deployments expand into heterogeneous environments where channel behavior directly influences reliability and efficiency.

Contributions of this work: This paper addresses this gap through a comprehensive, 3GPP-compliant evaluation of CDL and TDL models for 5G-NR mmWave systems. Our main contributions are:

- A systematic performance comparison of CDL and TDL models across LOS and NLOS scenarios with standardized 3GPP parameters.
- Quantification of BLER and SNR differences under varying antenna configurations (NRx = 2 and 4).
- Demonstration that CDL models provide superior reliability in NLOS conditions due to cluster-based spatial representation.
- Practical insights for engineers and researchers in selecting appropriate channel models for 5G-NR mmWave deployments.

The remainder of this paper is organized as follows. Section 2 reviews related work and identifies open challenges. Section 4 details the simulation methodology, including model parameters and evaluation setup. Section 5 presents the results and discusses key observations. Finally, Section 6 summarizes the findings and outlines directions for future research.

2. Background and Related Work

This section reviews the key concepts of 5G mmWave communication, summarizes existing channel models, and highlights relevant studies addressing performance limitations and proposed solutions.

2.1. 5G mmWave Technology

Fifth-generation (5G) mobile networks are designed to operate across three primary spectrum ranges: low-band frequencies (below 1 GHz), mid-band frequencies (1–6 GHz), and high-band frequencies (above 24 GHz), which include millimeter-wave (mmWave) bands [2,4]. Among these, mmWave technology has emerged as a cornerstone for enabling 5G's ambitious performance targets. With abundant spectrum resources and contiguous bandwidths reaching several GHz, mmWave frequencies offer the potential to deliver multi-gigabit-per-second data rates and unprecedented spectrum efficiency [5]. These characteristics make mmWave indispensable for data-intensive and latency-sensitive applications such as virtual reality (VR), augmented reality (AR), high-definition video streaming, autonomous driving, and advanced industrial automation. However, the adoption of mmWave frequencies is not without significant challenges. Unlike sub-6 GHz bands, mmWave signals experience severe propagation impairments due to their short wavelengths, which result in high path loss, limited diffraction, and poor penetration through obstacles such as buildings, foliage, and even the human body. The increased Doppler sensitivity in high-mobility scenarios further complicates system reliability. These limitations imply that mmWave systems require dense deployments, advanced beamforming, and robust channel estimation techniques to ensure acceptable coverage and performance.

Table 1 summarizes the key advantages and limitations of mmWave technology in 5G networks. The benefits primarily stem from its ability to unlock massive bandwidth for ultra-high data rates, low latency, and support for massive device connectivity. Conversely, challenges such as restricted coverage, vulnerability to environmental blockages, and Doppler effects impose constraints on its standalone applicability, often necessitating integration with low- and mid-band frequencies in a heterogeneous network architecture. Beyond technical enablers, mmWave technology also plays a strategic role in extending 5G services to new domains. Figure 1 illustrates its wide range of applications, including mobile backhaul, small-cell fronthaul and backhaul, fixed broadband access, video surveil-lance, and government broadband initiatives. These use cases highlight the versatility of mmWave technology, not only as a driver for end-user applications but also as an essential component for infrastructure densification and network scalability. In particular, mmWave-based small-cell backhaul solutions provide operators with cost-effective and high-capacity alternatives to fiber deployment, while fixed broadband access over mmWave supports rapid digital inclusion in under-served areas.

2.2. Characteristics of CDL/TDL Models

The CDL/TDL channel models are two fundamental approaches used to model the propagation characteristics in wireless communication systems, particularly in 5G mmWave networks [2,3]. These models enable the representation of complex interactions between multipath components while adapting to a variety of scenarios, ranging from stationary to highly dynamic and high-mobility environments.

Category	Details
Advantages of mmWave Technology	
High data rates	Supports multi-Gbps peak rates, enabling ultra-HD video streaming, AR/VR, and immersive applications [1,5].
Low latency	Facilitates ultra-reliable low-latency communications (URLLC) for mission-critical applications such as autonomous driving and industrial automation [6,7].
Massive connectivity	Provides high spatial reuse and spectrum efficiency, supporting dense IoT deployments and massive machine-type communications (mMTC) [4].
Limitations and Challenges	

Limited coverage range	Severe free-space path loss restricts effective coverage to a few hundred meters, necessitating dense cell deployments [8].
Susceptibility to blockages	Strongly attenuated by obstacles such as buildings, trees, and human bodies, leading to frequent link outages [6].
Mobility and Doppler effects	High carrier frequencies exacerbate Doppler shifts, degrading link stability in vehicular and high-speed scenarios [7].

Table 1: Advantages and Challenges of mmWave Technology in 5G Networks

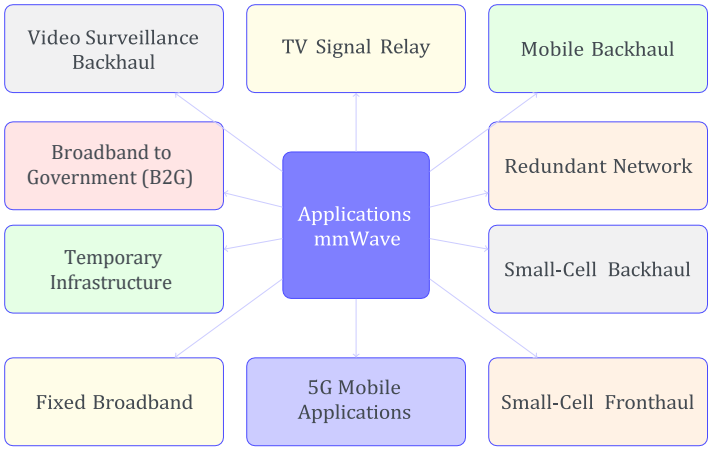


Figure 1: 5G mmWave applications across different sectors, ranging from consumer services to critical infrastructure

The TDL (Tapped Delay Line) model represents multipath propagation environments using a set of paths (taps) characterized by specific delays, powers, and Doppler shifts. This model is mainly used for fast and straightforward network performance evaluations, particularly in non-MIMO scenarios. The TDL profiles include:

- TDL-A, TDL-B, TDL-C: Designed for NLOS scenarios.
- TDL-D, TDL-E: Suitable for LOS scenarios, considering specific fading distributions [2,3].

The TDL model is widely used for its simplicity and flexibility, as it allows realistic channel simulations under various conditions [1–3]. It is defined by the following equations [9]:

- Channel Impulse Response:

$$h(t,\tau) = \sum_{m=1}^{M} \alpha_m e^{j\psi_m} \delta(\tau - \tau_m) e^{j2\pi f_{D_m} t}, \qquad (1)$$

where:
M: Number of *taps* or multipath components.
α_m: Complex amplitude of tap m.
ψ_m: Phase of tap m.
τ_m: Delay of tap m.
fD_m : Doppler shift of tap m.

- Doppler Spectrum per Tap:

$$S(f) \propto \frac{1}{\sqrt{1-\left(\frac{f}{f_{D_m}}\right)^2}}, \quad \text{for } |f| \le f_{D_m}, \qquad (2)$$

where fD_m is the maximum Doppler frequency.

- Tap Power:

$$P_m = P_0 e^{-\frac{\tau_m}{\tau_{\text{rms}}}}, \qquad (3)$$

where:
– P_0: Total channel power.
– τ_m: Delay of tap m.
– τ_{rms}: RMS delay spread.

- Ricean or Rayleigh Fading (for LOS or NLOS):

$$f(\alpha) = \begin{cases} \frac{\alpha}{\sigma^2} e^{-\frac{\alpha^2}{2\sigma^2}}, & \text{(Rayleigh, NLOS)} \\ \frac{\alpha}{\sigma^2} e^{-\frac{\alpha^2+K}{2\sigma^2}} I_0\left(\frac{\alpha\sqrt{2K}}{\sigma^2}\right), & \text{(Ricean, LOS)} \end{cases} \qquad (4)$$

– σ2: Fading variance.
– K: Rice factor (LOS).

– I0: Modified Bessel function of the first kind and order zero.

The CDL (Clustered Delay Line) model, an advanced 3D extension of TDL, organizes paths into clusters and incorporates angular information (AoA, AoD, ZoA, and ZoD), making it ideal for Massive MIMO and dynamic environments [1]. CDL-A through CDL-C target various indoor and suburban scenarios, while CDL-D and CDL-E are suited for high-mobility, complex settings. The CDL model is defined by the following general expression [9]:

$$h(t,\tau,\theta,\phi) = \sum_{n=1}^{N}\sum_{m=1}^{M} \alpha_{n,m} e^{j\psi_{n,m}} \delta(\tau - \tau_{n,m}) e^{j2\pi f_{D_{n,m}} t}, \quad (5)$$

where N is the number of clusters, M is the number of sub-paths per cluster, and the angular parameters $\theta_{n,m}$ and $\varphi_{n,m}$ follow Gaussian distributions centered on cluster means.

2.3. Channel Modeling for 5G mmWave and Related Work

Channel modeling plays a crucial role in the design and performance evaluation of 5G mmWave networks. An accurate channel model allows for the simulation of realistic propagation conditions, enabling the development and optimization of key technologies such as beamforming, MIMO, and equalization [2,3]. Table 2 summarizes the key differences between CDL/TDL models.

3. Prior Research and Motivation

This section reviews prior research efforts organized into three primary domains: (i) channel modeling and performance, (ii) phase noise estimation and compensation, and (iii) deep learning approaches. The objective is to highlight gaps that motivate a more systematic comparative analysis of standardized 3GPP channel models.

(i) Channel Modeling and Performance in 5G mmWave Networks: The effectiveness of 5G-NR systems is strongly dependent on the accuracy of channel models that capture real-world propagation characteristics, including multipath fading, delay spread, and Doppler effects. Naqvi et al. explored indoor coverage using massive MIMO arrays, emphasizing the role of accurate delay profiles and antenna configurations [7]. Barb and Otesteanu compared CDL and TDL models in downlink MIMO scenarios, showing how delay spreads directly affect BLER and throughput [3]. Tsoulos et al. con-ducted large-scale field trials, focusing on interference management and antenna alignment [5]. Xu et al. examined operational 5G deployments, highlighting trade-offs between coverage, throughput, and energy efficiency [10]. Alkhateeb et al. introduced hybrid precoding and channel estimation, mitigating mmWave vulnerabilities to interference [11]. Kim et al. studied side link V2X reliability, demonstrating the effect of channel impairments on vehicular safety systems [6]. Moltchanov et al. advanced measurement-driven channel sounding techniques for realistic mmWave propagation characterization [1].

(i) Phase Noise Estimation and Compensation: Phase noise, exacerbated at high carrier frequencies, degrades signal integrity and reduces spectral efficiency in mmWave transmissions. Dikarev et al. developed PT-RS (Phase Tracking Reference Signal)-based algorithms for uplink robustness [12]. Guel et al. assessed ZF and MMSE phase noise mitigation methods, achieving notable improvements in quality of service [13]. Park et al. proposed MMSE-based Com-mon Phase Error (CPE) estimation to enhance reliability in challenging noise conditions [14]. Collectively, these works show that robust estimation algorithms are essential for practical mmWave deployments.

Criteria	CDL	TDL
Main Usage	High-resolution spatial MIMO scenarios	Simple, non-MIMO evaluations
Simulated Environments	Dense urban, indoor, Massive MIMO	LOS and NLOS
Parameters	Angle of Arrival (AoA), Angle of Departure (AoD), cross-polarization	Multipath delays (*taps*), Doppler spectrum
Available Profiles	CDL-A, CDL-B, CDL-C, CDL-D, CDL-E	TDL-A, TDL-B, TDL-C, TDL-D, TDL-E
Typical Applications	Massive MIMO and smart antenna analysis	Fast network performance evaluation
Spatial Accuracy	High (due to 3D modeling of angles)	Low (no modeling of AoA/AoD angles)
Computational Complexity	High (multiple complex parameters to model)	Low (simplified model for fast calculations)
Propagation Type	Accounts for multipath characteristics with advanced 3D structure	Simplified model based on delays and amplitudes
Massive MIMO Compatibility	Optimized for Massive MIMO and antenna polarization	Not optimized, mainly used for simple evaluations
Covered Frequencies	mmWave bands (above 24 GHz) and sub-6 GHz bands	Wide frequency range, from 0.5 GHz to 100 GHz

Table 2: Comparison of CDL/TDL models in the context of 5G mmWave

(iii) Machine Learning and Deep Learning Approaches: Machine learning has gained momentum for addressing complex propagation environments and interference management. Zehra et al. used supervised learning for PRACH preamble detection, significantly improving reliability in noisy channels [8]. Dahal and Vaezi demonstrated the effectiveness of multi-agent reinforcement learning for interference management in dense mmWave cells [15]. Weragama et al. introduced CNN-based interference detection for 6G MIMO networks, achieving high accuracy with low computational overhead [16]. Robinson et al. applied CNN-based RF interference detection in dense wireless systems [17]. These works suggest that ML and DL are promising complements to traditional physical-layer modeling approaches.

Gaps in Existing Research: Despite significant advances in channel modeling, noise compensation, and intelligent optimization, there remains a lack of direct comparative analyses of standardized CDL and TDL models under diverse operating conditions, particularly with respect to their impact on BLER across LOS and NLOS scenarios with varying antenna configurations. This paper addresses this gap.

4. Methodology and Implementation

This section outlines the methodological framework and simulation protocol used to evaluate the performance of 5G-NR mmWave networks under CDL and TDL channel models. It details the key processing stages, simulation parameters, and performance evaluation metrics, highlighting the impact of channel and phase noise characteristics on system performance.

4.1. Simulation Framework Overview

The modeling of 5G-NR mmWave systems requires a complex processing chain that integrates several key stages, from channel coding to signal reception. This section describes the methodological framework used to simulate CDL/TDL channel models, estimate phase noise, and assess network performance. Figure 2 illustrates the processing chain for evaluating CDL and TDL channel models in 5G-NR mmWave systems. The various stages for NR-PDSCH (Physical Downlink Shared Channel) transmission and reception are:

(a) NR-PDSCH Encoding: Data is encoded using Low-Density Parity-Check (LDPC) codes. The goal of channel coding is to introduce redundancy to enhance error resistance and ensure reliable communication.

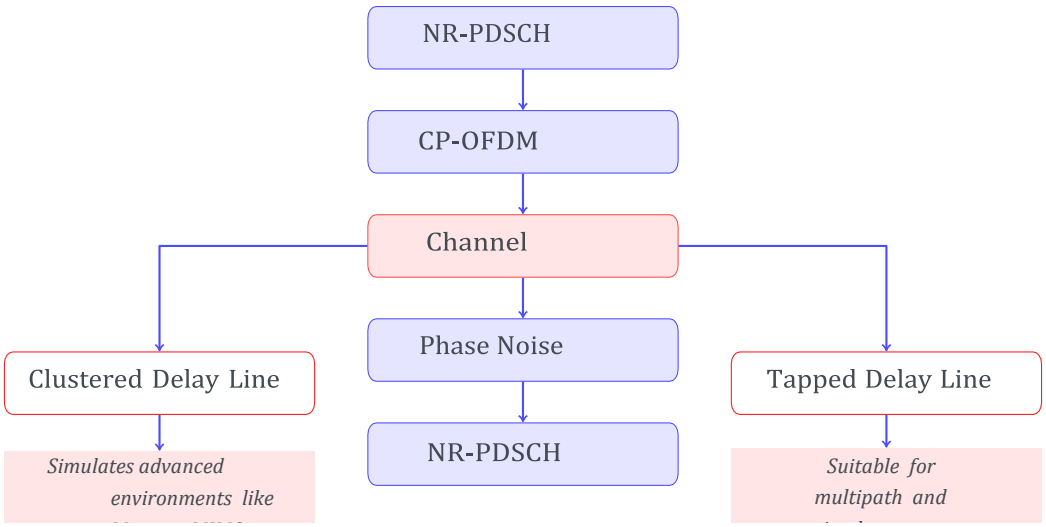


Figure 2: NR-PDSCH processing chain including CDL/TDL channel models. The receiver employs MMSE equalization with PT-RS-based Common Phase Error compensation

(b) **CP-OFDM Modulation:** After encoding, modulated symbols (64-QAM) are mapped onto resource elements (REs) in allocated resource blocks. CP-OFDM (Cyclic Prefix Orthogonal Frequency Division Multiplexing) is applied via Inverse Fast Fourier Transform (IFFT), followed by cyclic prefix insertion to mitigate inter-symbol interference (ISI) caused by multipath propagation.

(c) **Phase Noise Modeling:** Phase noise based on 3GPP Model A is inserted to represent transceiver local oscillator imperfections [18].

(d) **Channel (CDL/TDL):** The modulated signal passes through a wireless channel modeled using either a CDL or TDL model.

(e) **AWGN and Receiver Synchronization:** Thermal noise (AWGN) is added at the receiver according to the target SNR. Receiver-side timing and frequency synchronization are performed.

(f) **NR-PDSCH Receiver:** At the receiver, CP-OFDM demodulation extracts transmitted NR-PDSCH information. MMSE channel estimation and equalization are applied to mitigate multipath fading. Common Phase Error (CPE) estimation and correction based on Phase Tracking Reference Signal (PT-RS) are applied to mitigate phase noise before NR-

PDSCH decoding.

4.2. Simulation Parameters

The simulation considers the following key parameters to evaluate the impact of propagation channels on the performance of 5G-NR mmWave networks.

Key Notes on Simulation Parameters:

- **Phase Noise Model:** The simulation uses 3GPP Phase Noise Model A, corresponding to f_c = 30 GHz. Similar conclusions are expected for Models B and C.
- **MIMO Architecture:** The configuration uses N_{Tx} = 2 transmit antennas and $\{N^{Rx}\}$ 2, 4 receive antennas to evaluate spatial diversity gains.
- **SNR Range and BLER Measurement:** The simulation iterates over an SNR range of -5 to 25 dB with 2.5 dB steps. For each SNR level, BLER is computed as the ratio of blocks with errors to total transmitted blocks. A minimum of 100 block errors per SNR point is targeted for statistical significance.
- **Receiver Implementation:** The receiver employs (1) MMSE channel estimation, (2) MMSE equalization with PT-RS-based CPE correction, and (3) NR-PDSCH decoding with LDPC turbo iteration limits.

4.3. BLER Computation and Reproducibility

The Block Error Rate (BLER) is computed as:

$$\text{BLER} = \frac{\text{Number of erroneous blocks}}{\text{Total number of transmitted blocks}}. \quad (6)$$

For this study, the simulation runs a single 5G-NR frame (10 ms) per SNR point, encompassing 14 OFDM symbols with 66 resource blocks. The BLER is evaluated after NR-PDSCH decoding with CPE compensation enabled.

Reproducibility Note: The simulation framework is implemented in MATLAB R2023b 5G Toolbox using standard functions (nrPDSCHIndices, nrChannelEsti-mate, nrEqualizeMMSE). The CDL and TDL models conform to 3GPP TR 38.901 specifications. All random seeds are fixed to enable deterministic reproducibility. Interested readers can contact the corresponding author for simulation code.

Category	Parameters	Values
Modulation	Modulation Scheme Subcarrier Spacing Number of Resource Blocks (RBs) Number of OFDM Symbols per Slot Bandwidth	64-QAM 60 kHz 66 14 50 MHz
Channel Configuration		
Channel	Models Used Delay Spread Maximum Doppler Shift Carrier Frequency (f_c)	CDL/TDL 300 ns 5 Hz 30 GHz
MIMO Antenna Configuration		
Antennas	Transmit Antennas (N_{Tx}) Receive Antennas (N_{Rx})	2 2, 4
Phase Noise		
Phase Noise	Model Carrier Frequency	3GPP Model A 30 GHz
SNR and Noise		
Signal-to-Noise Ratio	SNR Range Thermal Noise	-5 dB to 25 dB (step 2.5 dB) AWGN
Phase Error Compensation		
CPE Compensation	Method Equalization	PT-RS (Phase Tracking Reference Signal) MMSE (Minimum Mean Square Error)
Simulation Configuration		
Simulation	Duration Tool Channel Estimation	1 frame (10 ms) MATLAB 5G Toolbox (R2023b or later) LS (Least Squares) with linear interpolation

Table 3: Simulation parameters for CDL/TDL channel analysis in 5G-NR mmWave systems

5. Results and Discussion

This section presents the simulation results and performance analysis of NR-PDSCH under different CDL/TDL channel models. The analysis focuses on the impact of the number of reception antennas (NRx = 2 and 4) on the Block Error Rate (BLER) as a function of the Signal-to-Noise Ratio (SNR), highlighting key differences between CDL and TDL models in terms of propagation characteristics and performance outcomes.

5.1. Results Analysis

CDL Channel Family Performance. Figures 3 and 4 illustrate the impact of different CDL channel models on BLER performance for reception antenna configurations of NRx = 2 and NRx = 4.

Figure 3 shows that CDL-C and CDL-D consistently outperform CDL-E across the SNR range. Indeed, CDL-C and CDL-D benefit from optimized delay profiles and lower delay spread, while CDL-E exhibits high inter-antenna correlation, reducing spatial diversity. CDL-C/D are preferred for NLOS scenarios in practical deployments. Increased antenna diversity improves BLER across all CDL profiles as showed in Figure 4. Four receive antennas provide better combining gains and mitigation of fading nulls. MIMO diversity is most beneficial in CDL scenarios with moderate spatial correlation.

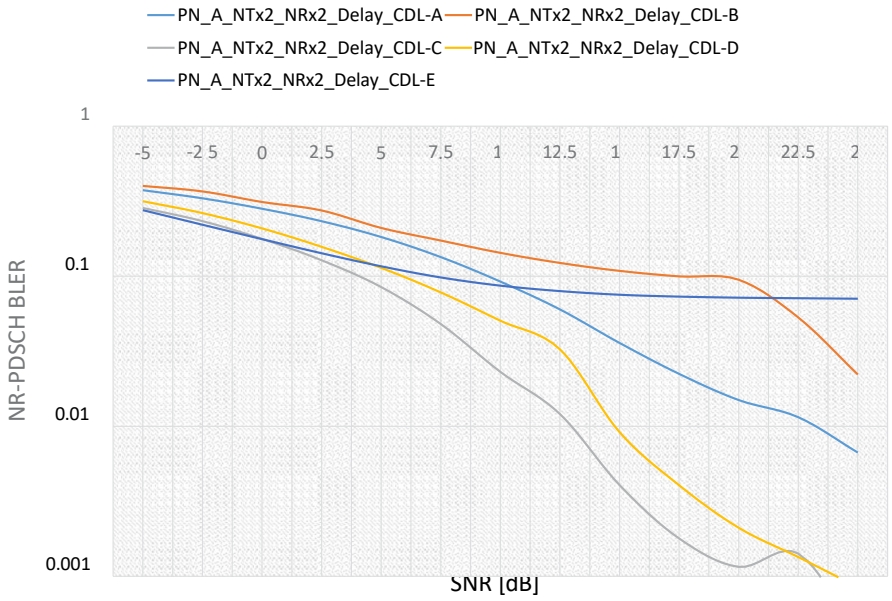


Figure 3: Impact of CDL channels (CDL-A through CDL-E) on NR-PDSCH BLER performance for N_{Rx} = 2 antennas.

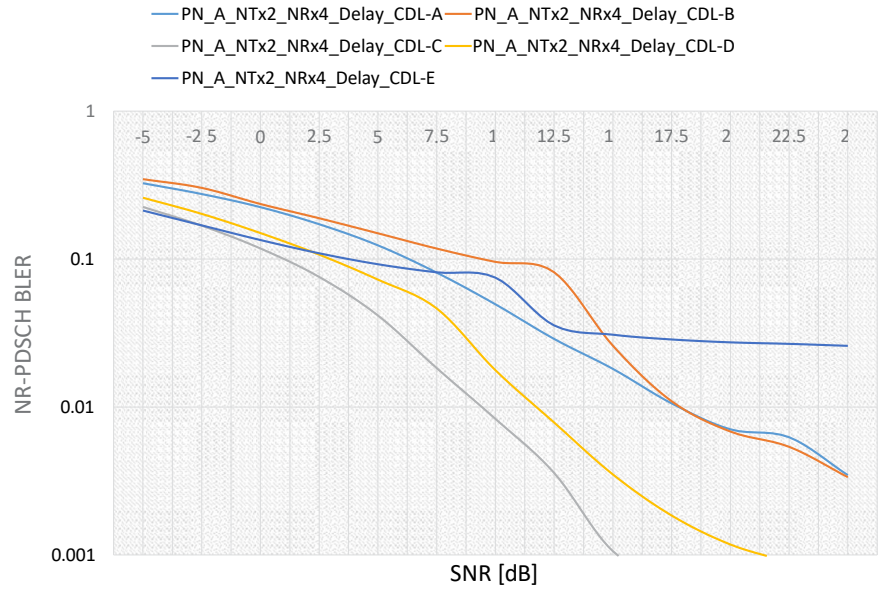


Figure 4: Impact of CDL channels on NR-PDSCH BLER performance for N_{Rx} = 4 antennas

TDL Channel Family Performance: Figures 5 and 6 present the impact of different TDL channel models on NR-PDSCH performance. TDL-D and TDL-E demonstrate superior robustness compared to TDL-A/B/C across all SNR levels in Figure 5. Indeed, TDL-D/E are designed for LOS scenarios with shorter delay spreads and more balanced power distributions among multipath components, limiting ISI. TDL-A/B/C represent cluttered/dense urban environments with higher multipath richness. Therefore, LOS-designed profiles are inherently more robust for high-SNR link-level evaluation.

Figure 6 shows that four antennas improve BLER uniformly; TDL-D and TDL-E remain superior. Similar to the 2-antenna case, the advantage of LOS profiles persists with additional receive diversity. Implication: Antenna diversity benefits are profile-dependent; gains are largest in more challenging NLOS scenarios (TDL-A/B/C).

Direct CDL vs. TDL Comparisons. Figures 7 through 11 present pairwise comparisons of matched profiles (CDL-A vs. TDL-A, CDL-B vs. TDL-B, etc.). Figure 7 shows that CDL-A demonstrates slightly lower BLER than TDL-A across the SNR range. The cluster-based model in CDL-A provides improved multipath component grouping and interference mitigation. The simpler tapped representation in TDL-A is more susceptible to time dispersion. Indeed, CDL offers marginal but consistent advantage even in NLOS scenarios. Figure 8 shows that CDL-B outperforms TDL-B with a visible performance gap at high SNR. CDL-B's spatial diversity from cluster structure provides better interference resilience. CDL is recommended for moderate NLOS conditions.

In Figure 9, CDL-C achieves 0.02% BLER at 25 dB SNR versus 0.3% for TDL-C—a clear advantage. Indeed, CDL-C's cluster representation reduces ISI impact and improves error correction leverage. TDL-C's higher delay spread causes greater interference and decoding difficulty. Therefore, for dense urban (NLOS) scenarios, CDL-C is significantly superior.

Figure 10 shows that CDL-D and TDL-D performance converges, with only marginal differences. Indeed, both models target LOS conditions with well-defined multipath structure. The clustering advantage in CDL-D is minimal in LOS propagation. Therefore, for LOS-dominant scenarios, both models are acceptable; TDL-D offers lower computational cost.

Figure 10 shows that TDL-E significantly outperforms CDL-E at high SNR levels; CDL-E shows BLER saturation beyond 20 dB SNR. CDL-E exhibits high spatial correlation among cluster components, reducing effective diversity. TDL-E's simpler, less-correlated tap structure maintains frequency selectivity and progressive gains with SNR. Therefore, CDL-E should be avoided in high-mobility scenarios; TDL-E is preferred despite its simplicity.

5.2. Summary of Key Findings

Table 4 provides a compact summary of BLER per-formance at two SNR thresholds across representative profiles.

Key Observations:

1. **NLOS Scenarios (CDL-A/B/C vs. TDL-A/B/C):** CDL models consistently achieve 2–15Œ lower BLER at high SNR, with the largest advantage in CDL-C/TDL-C (0.02% vs. 0.3% at 25 dB).
2. **LOS Scenarios (CDL-D/E vs. TDL-D/E):** CDL-D and TDL-D converge; TDL-E outperforms CDL-E due to reduced spatial correlation. This highlights that cluster-based modeling does not always provide an advantage in low-dispersion environments.
3. **Antenna Diversity:** Increasing NRx from 2 to 4 reduces BLER by 30–50% on average, with greatest gains in high-dispersion NLOS profiles.
4. **Practical Implications:** For urban NLOS deployments (CDL-C preferred), use CDL. For rural/LOS deployments (CDL-D/E scenarios), TDL-D offers sufficient accuracy with reduced computational burden.

5.3. Limitations of this Work

Despite the relevance of the results obtained, the current study presents certain limitations:

- **Single-frame Evaluation:** The simulation runs a single 5G-NR frame (10 ms) per SNR point. Multi-frame simulations would improve statistical robustness, but are computationally intensive.
- **Static Propagation:** The channel models are evaluated in a static context. Dynamic mobility (time-varying channel realizations) was not fully considered, limiting applicability to vehicular or high-speed scenarios.
- **Common Phase Error Only:** The study primarily addresses CPE compensation; Noisy Phase Error (NPE) estimation was not fully evaluated. NPE handling requires more sophisticated techniques beyond PT-RS.

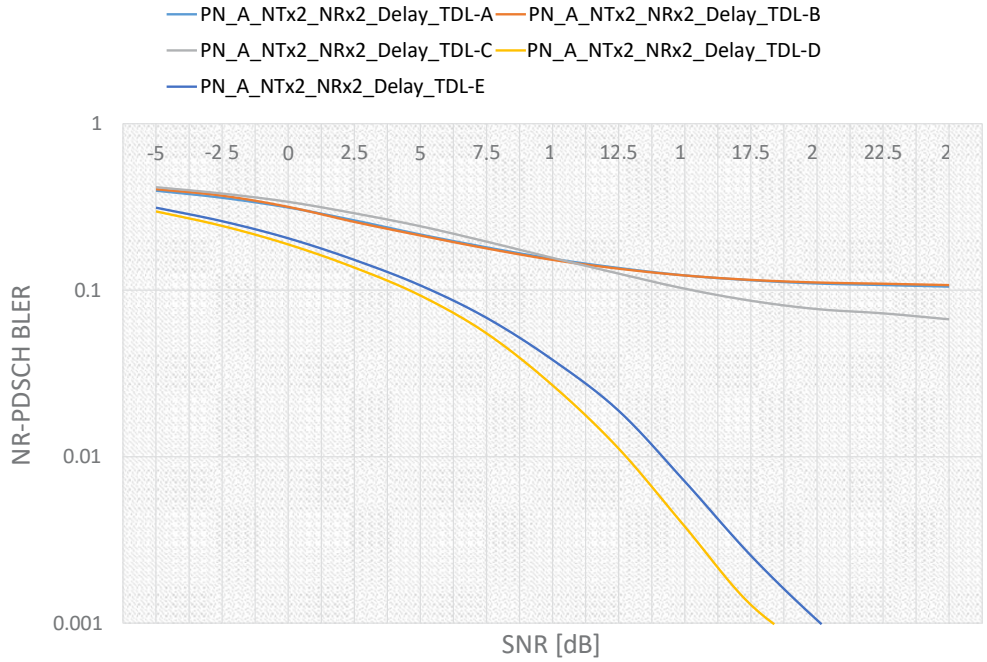


Figure 5: Impact of TDL channels (TDL-A through TDL-E) on NR-PDSCH BLER performance for N_{Rx} = 2 antennas

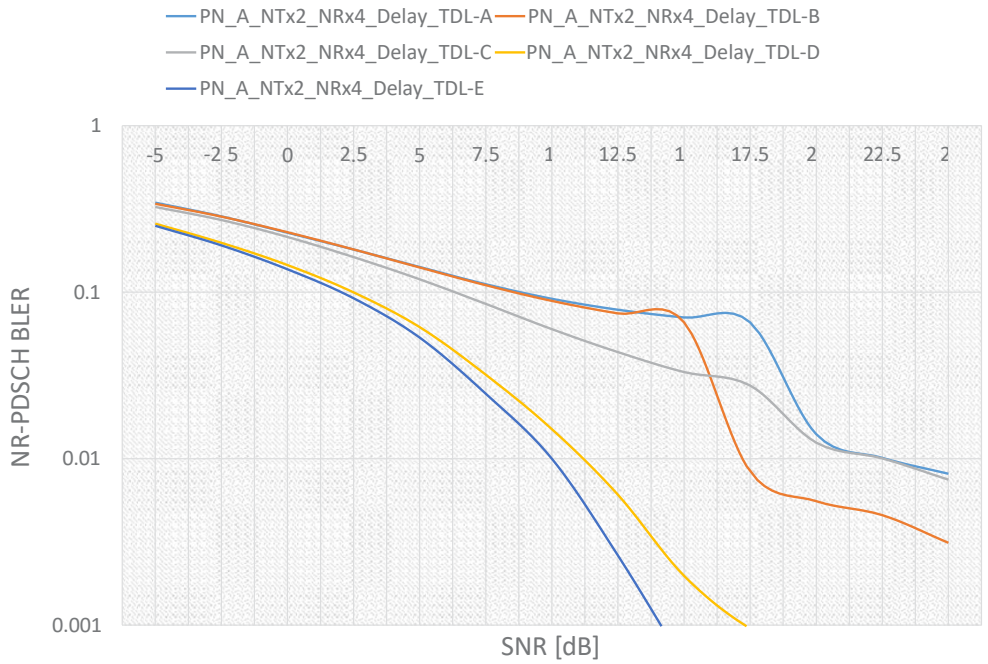


Figure 6: Impact of TDL channels on NR-PDSCH BLER performance for N_{Rx} = 4 antennas

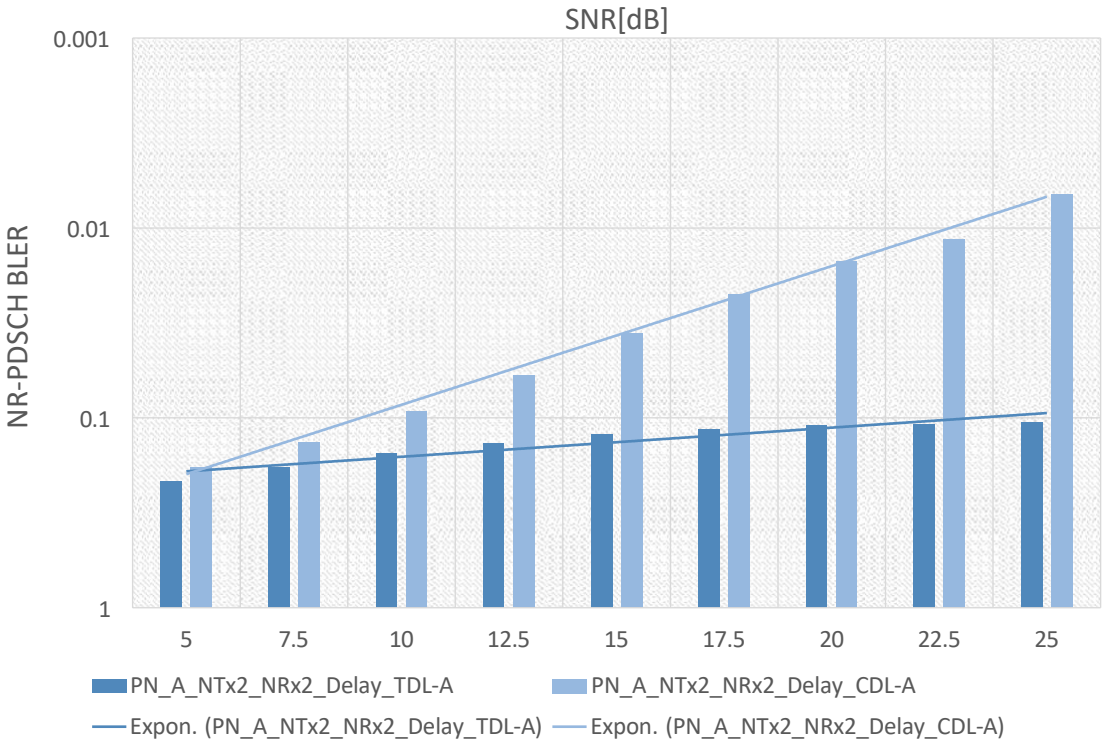


Figure 7: CDL-A vs. TDL-A channels for N_{Rx} = 2 antennas.

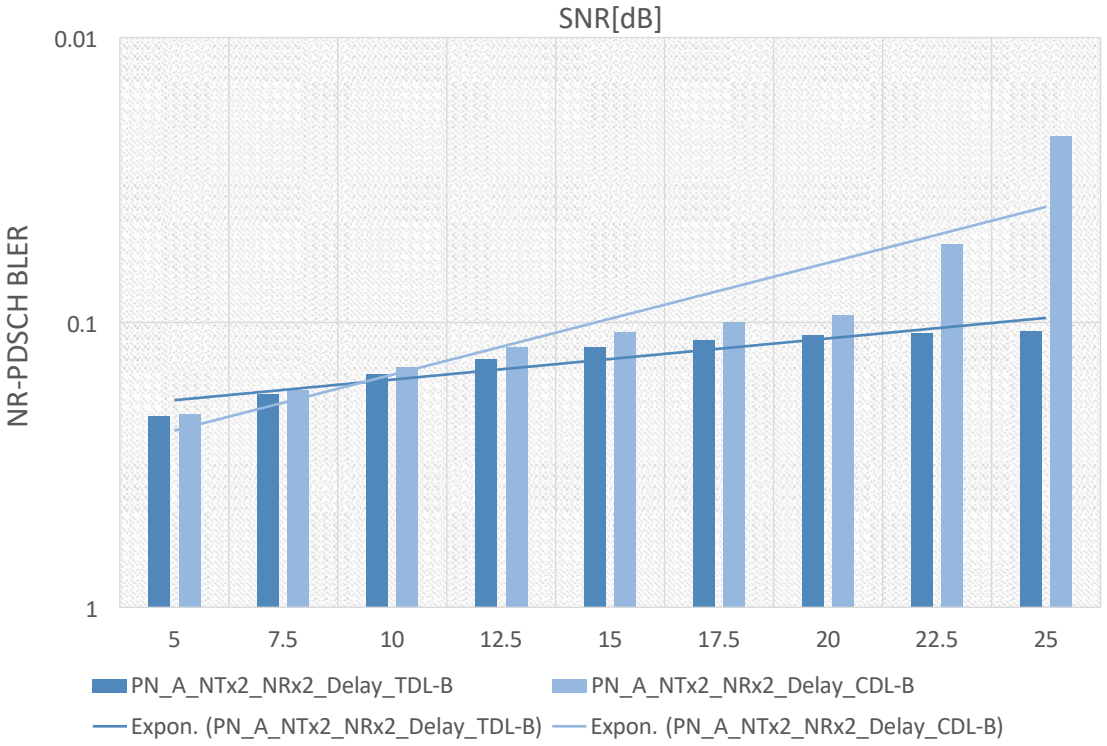


Figure 8: CDL-B vs. TDL-B channels for N_{Rx} = 2 antennas

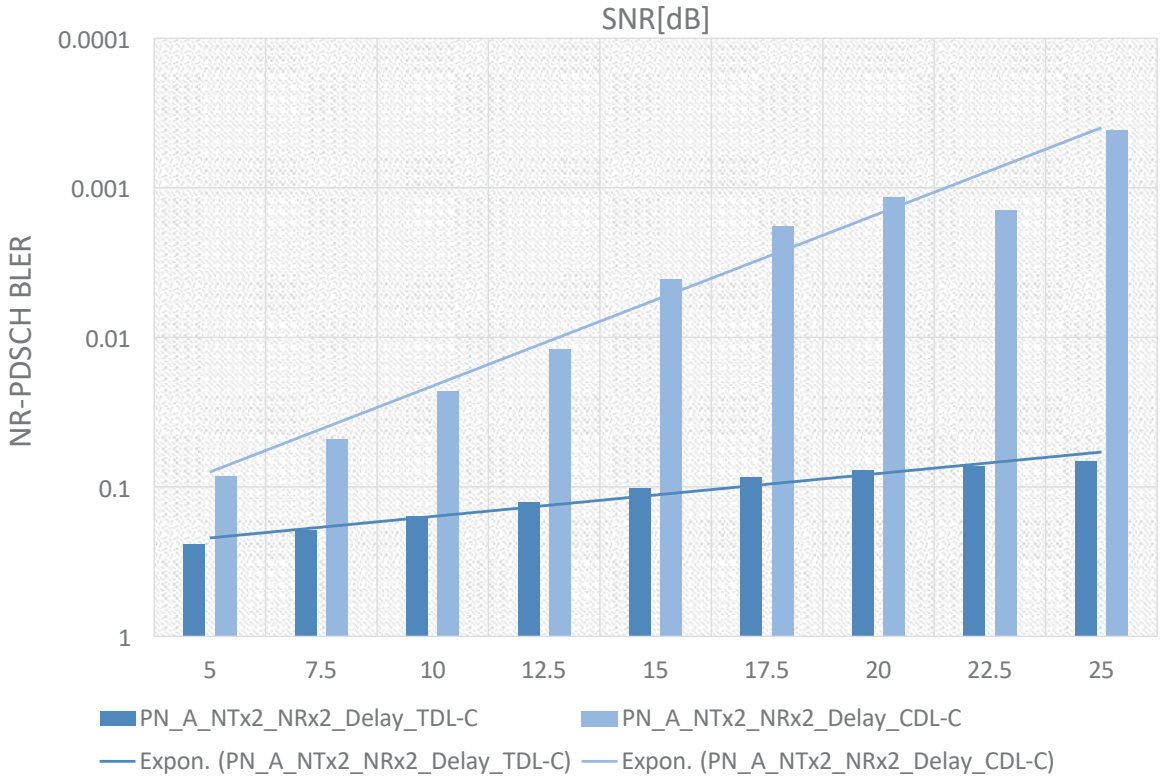


Figure 9: CDL-C vs. TDL-C channels for N_{Rx} = 2 antennas

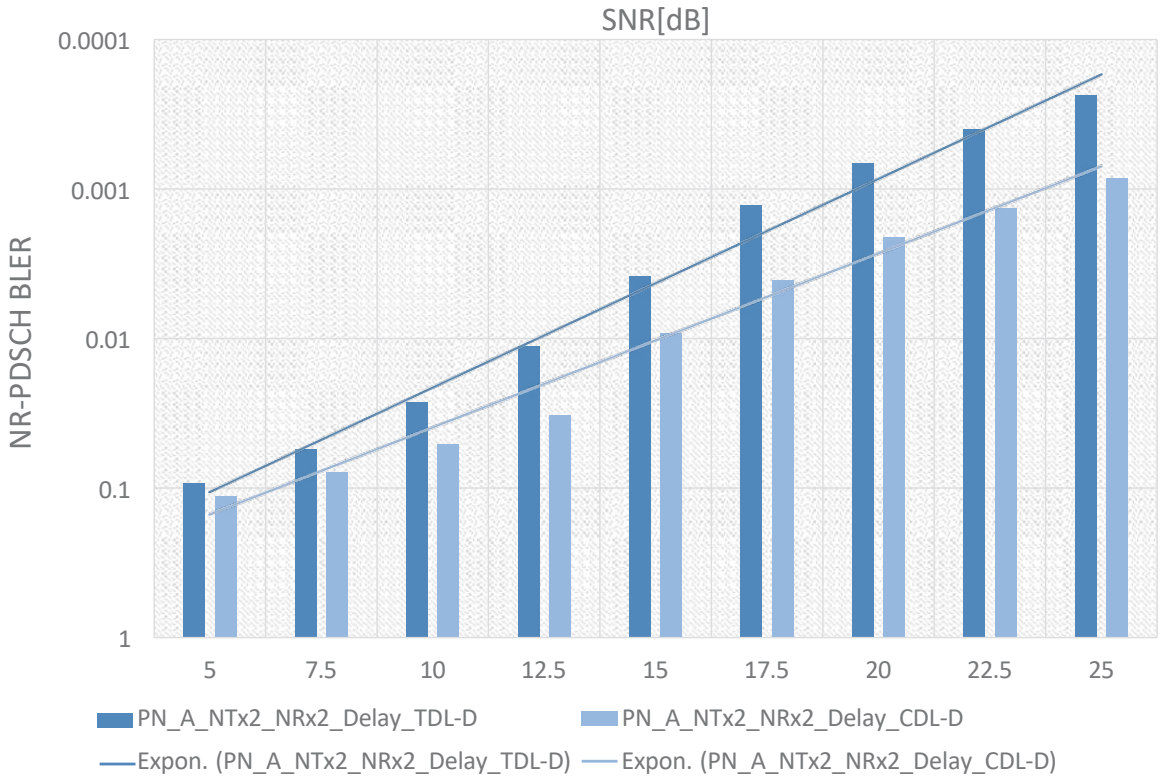


Figure 10: CDL-D vs. TDL-D channels for N_{Rx} = 2 antennas

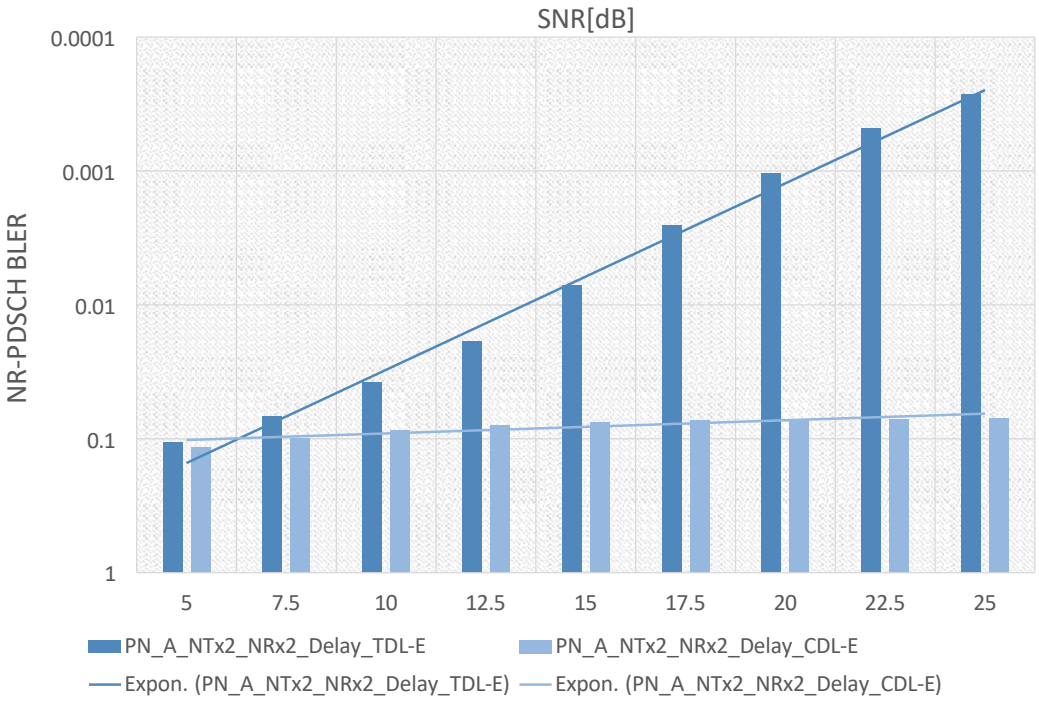


Figure 11: CDL-E vs. TDL-E channels for N_{Rx} = 2 antennas

Channel Profile	BLER @ 10 dB SNR	BLER @ 20 dB SNR	BLER @ 25 dB SNR	Profile Type
CDL-A TDL-A	$\approx 8 \times 10^{-2}$ $\approx 10 \times 10^{-2}$	$\approx 5 \times 10^{-3}$ $\approx 8 \times 10^{-3}$	$\approx 1 \times 10^{-3}$ $\approx 2 \times 10^{-3}$	NLOS/Dense Urban NLOS/Dense Urban
CDL-C TDL-C	$\approx 4 \times 10^{-2}$ $\approx 6 \times 10^{-2}$	$\approx 2 \times 10^{-3}$ $\approx 5 \times 10^{-3}$	$\approx 0.02\%$ (0.0002) $\approx 0.3\%$ (0.003)	NLOS/Urban NLOS/Urban
CDL-D TDL-D	$\approx 1 \times 10^{-2}$ $\approx 1.5 \times 10^{-2}$	$\approx 5 \times 10^{-4}$ $\approx 7 \times 10^{-4}$	$\approx 0.06\%$ (0.0006) $\approx 0.1\%$ (0.001)	LOS/Urban LOS/Urban
CDL-E TDL-E	$\approx 3 \times 10^{-3}$ $\approx 2 \times 10^{-3}$	$\approx 5 \times 10^{-5}$ $\approx 1 \times 10^{-5}$	$\approx 5 \times 10^{-4}$ (saturation) 6.495×10^{-5}	High Mobility High Mobility

Table 4: BLER Performance Summary at Key SNR Points (Single Frame, N_{Rx} = 2)

- No Inter-Cell Interference: Simulations were conducted in an isolated cell framework without evaluating interference from neighboring cells—a significant factor in dense 5G deployments.
- 3GPP Model Assumptions: The CDL and TDL models, while standardized, do not fully capture all real-world phenomena (diffraction, dynamic shadowing, blockage microstructure).

6. Conclusion and Future Work

This study has presented a comprehensive performance comparison of standardized CDL and TDL channel models within the context of 5G-NR mmWave systems. By leveraging a 3GPP-compliant simulation framework, we evaluated key metrics such as BLER and SNR under varying LOS and NLOS propagation conditions. The results revealed that CDL models consistently outperform TDL counterparts, particularly under challenging NLOS scenarios. For instance, CDL-C achieved a BLER of 0.02% compared to 0.3% for TDL-C at 25 dB SNR, while CDL-D delivered superior performance in LOS conditions with 0.06% BLER. Furthermore, increasing antenna diversity (e.g., N_{Rx} = 4) led to notable improvements in network reliability, reinforcing the importance of spatial processing in high-frequency 5G systems.

Our findings emphasize the crucial role of accurate channel modeling in optimizing next-generation wireless networks. In particular, CDL models pro-vide enhanced spatial resolution and Doppler support which are essential for advanced applications such as real-time beamforming, intelligent network slicing, and ultra-dense urban deployments. These results are directly applicable to urban planning for 5G small cells, mobility-aware infrastructure design, and scenario-specific performance tuning. From a signal processing standpoint, the integration of MMSE-based equalization and PT-RS-based CPE compensation proved effective in mitigating both multipath fading and phase noise distortions. This reinforces the viability of combining accurate channel modeling with robust error correction mechanisms.

Future Research Directions:

- Extend simulations to multiple frames and vary noise realizations for enhanced statistical confidence.
- Incorporate dynamic mobility models (e.g., 3GPP mobility scenarios) to evaluate Doppler effects and handover performance.
- Develop hybrid CDL–TDL models that balance computational efficiency with spatial fidelity for edge and core network deployments.
- Evaluate integration of machine learning techniques to dynamically select and adapt CDL/TDL parameters based on real-time channel telemetry.
- Conduct field trials to validate simulation predictions under practical deployment constraints and outdoor measurement campaigns.

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