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A Systematic Technical Review and Comparative Analytical Study of Extreme Value Theory-Based Algorithms for Ultra-Reliable Wireless Communications

[1]Agbon E. E., [2]Andrew Habila John, [3]Aminu Chiroma Muhammad, [4]Njoku F. C., [5]Itamah A. O. Itamah
[1&2]*Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.*
[3]*Department of Electrical/Electronics Engineering, Gombe State Polytechnic, Bajoga, Gombe State -Nigeria*
[4]*Air Force Institute of Technology (AFIT), Kaduna.*
[5]*Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria*

ABSTRACT

The rapid evolution of 5G and emerging 6G wireless networks has intensified the demand for ultra-reliable low-latency communication (URLLC), where stringent reliability requirements are often governed by rare but severe events such as deep fading, extreme interference, and simultaneous adverse channel conditions. Conventional statistical models, which primarily characterize average or central channel behavior, may provide limited accuracy when estimating the probability of such extreme events. This study presents a comprehensive review and comparative analysis of Extreme Value Theory (EVT)-based approaches for modeling and managing rare wireless-channel events in URLLC systems. The analysis examines Generalized Pareto Distribution (GPD)-based tail modeling, EVT-driven predictive interference management, EVT-enriched radio maps, GAN-assisted GPD parameter estimation, and Multivariate Extreme Value Theory (MEVT) for spatial-diversity-based rate selection. The reviewed results demonstrate that GPD-based models can closely approximate empirical extreme-channel behavior, with reported deviations of less than 10% in the evaluated conditions. EVT-based predictive interference management has also demonstrated substantial reliability improvements, including a reported reduction in outage rates of up to 100-fold and approximately 15% lower radio-resource usage compared with conventional approaches. Furthermore, EVT-enriched radio maps improve the prediction of spatial regions satisfying stringent outage requirements, while GAN-based GPD parameter estimation offers potential advantages under limited-data conditions. The MEVT-based analysis demonstrates that explicitly modeling joint tail dependence in spatial diversity systems can improve achievable transmission rates, reaching approximately 3.05 bps/Hz with six antennas compared with 1.95 bps/Hz for the conventional approach, representing an improvement of approximately 56% under the evaluated conditions. The findings indicate that EVT provides a valuable complementary statistical framework for addressing the rare-event reliability challenges of 5G and 6G URLLC networks. The study concludes by identifying the integration of EVT with generative artificial intelligence, adaptive learning, and higher-dimensional MEVT as promising directions for

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Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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future ultra-reliable and data-efficient wireless communication systems.

INTRODUCTION

The evolution from fifth-generation (5G) to sixth-generation (6G) wireless networks represents a fundamental paradigm shift in telecommunications, extending beyond enhanced mobile broadband to enable mission-critical applications including autonomous vehicles, remote surgery, industrial automation, and vehicular teleoperation as shown in Figure 1(Mehrnia & Coleri, 2026). These applications demand Ultra-Reliable Low-Latency Communications (URLLC), requiring packet error rates in the range of 10^{-9} to 10^{-5} with end-to-end latencies on the order of milliseconds (Valiahdi & Coleri, 2024).

Figure 1: Evolution from 5G to 6G

Simultaneously achieving such stringent reliability and latency targets is extremely challenging, necessitating innovative approaches to channel modeling, resource allocation, and interference management that extend beyond traditional average statistical methods (Echevarría Pérez et al., 2024). Traditional statistical models such as Rayleigh, Rician, and Gaussian distributions are excellent at modeling average channel conditions but are fundamentally inadequate for predicting the rare and extreme events that cause packet errors in the ultra-reliable region (Echevarría Pérez et al., 2024). These extreme events that is deep fades, severe interference, or simultaneous adverse conditions occur in the far tails of the probability distribution, precisely where traditional models fail to provide accurate estimates. This creates a significant gap: engineers cannot accurately design or test systems for a 10^{-9} error rate by averaging channel data; they need specialized statistical tools to model the far-left tail of the distribution.

Extreme Value Theory (EVT) has emerged as a powerful statistical framework for addressing this challenge. Unlike traditional approaches that model entire distributions, EVT focuses specifically on modeling the tail behavior of probability distributions, providing asymptotically justified methods for estimating the probability of events beyond the range of observed data (Echevarría Pérez *et al.,* 2024). In

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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the context of wireless communications, EVT enables accurate modeling of the rare but critical events severe fading or extreme interference that determine the performance of URLLC systems (Mehrnia & Coleri, 2026).

This article provides a comprehensive review of EVT and its application to modeling ultra-reliable communication channels in 5G/6G networks. The specific contributions are:

a. A systematic presentation of EVT fundamentals, including the Generalized Pareto Distribution (GPD) and its application to channel modeling.
b. Quantitative performance comparisons across three cutting-edge EVT-based approaches: predictive interference management, EVT-enriched radio maps, and GAN-based GPD parameter estimation.
c. Analysis of multivariate EVT for spatial diversity and its advantages over conventional extrapolation-based approaches.
d. Identification of emerging trends and future research directions for EVT in next-generation wireless systems.

Research Questions

To achieve the objectives of this study and provide a structured comparative analysis, the following research questions (RQs) were formulated:

a. How can Extreme Value Theory (EVT) be applied to model the tail behavior of wireless communication channels for ultra-reliable low-latency communications (URLLC), and what are the quantifiable advantages over traditional statistical models?
b. What are the performance and sample-efficiency trade-offs associated with different EVT-based approaches including predictive interference management, EVT-enriched radio maps, and GAN-based GPD parameter estimation for achieving target outage probabilities as low as 10^{-7}?
c. How can multivariate Extreme Value Theory (MEVT) be leveraged to model the joint tail distribution of multiple received power sequences in diversity schemes, and what are the achievable transmission rate improvements compared to conventional methods?
d. What are the emerging trends and future research directions for EVT in next-generation wireless systems, particularly regarding integration with machine learning, generative artificial intelligence, and 6G-native architectures?

Organization of the Article

The remainder of this article is organized as follows. Section 2 provides a review of key concepts in URLLC and EVT fundamentals, including the GPD and relevant equations. Section 3 presents a detailed comparative analysis of EVT-based approaches across different URLLC applications. Section 4 discusses the results, challenges, and future directions. Section 5 concludes the article with a summary of key findings and recommendations for researchers and network operators.

REVIEW OF KEY CONCEPTS

The following is a discussion on the review of fundamental concepts that are pertinent to this study.

Ultra-Reliable Low-Latency Communications (URLLC)

URLLC is one of the transformative features of 5G and 6G networks, effectively meeting the escalating demands of real-time control, interactions, and decision-making across diverse applications (Valiahdi & Coleri, 2024). The key performance requirements for URLLC include:

a. Reliability: Packet error rates in the range of 10^{-9} to 10^{-5}, representing a significant departure from traditional mobile broadband which typically operates at error rates of 10^{-3} to 10^{-5}.

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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b. Latency: End-to-end delays on the order of 1 millisecond for 5G, with 6G targeting sub-millisecond latencies.
c. Availability: High availability requirements, often exceeding 99.999% (five nines) for mission-critical applications.

Achieving ultra-high reliability and low latency at this level necessitates communication systems to incorporate accurate channel modeling based on the derivation of the tail statistics rather than average behavior (Valiahdi & Coleri, 2024). This is because the error events that determine the 10^{-9} packet error rate are extreme events that occur in the far tail of the channel distribution.

Traditional Channel Models and Their Limitations

Traditional channel models (see Figure 2) employed in wireless communications include (Yue *et al*., 2025)

a. Rayleigh Fading Model: Used for non-line-of-sight (NLOS) environments where there is no dominant line-of-sight component. The probability density function (PDF) of the received signal amplitude follows a Rayleigh distribution.
b. Rician Fading Model: Used for environments with a dominant line-of-sight component plus multipath component.
c. Log-Normal Shadowing: Used to model large-scale variations in received power due to shadowing effects.
d. Gaussian Noise Models: Used for modeling additive white Gaussian noise (AWGN) in communication systems (Singh, S. K., 2026)

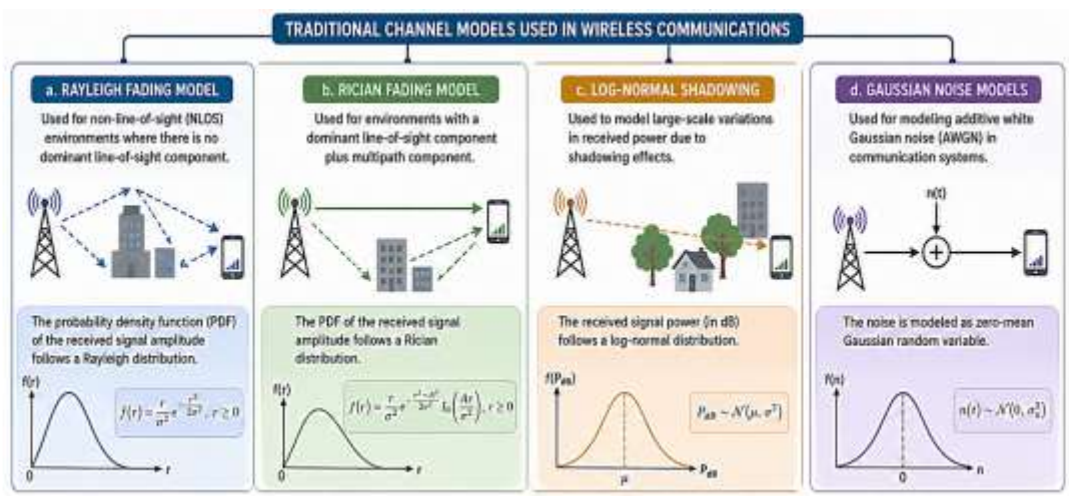

Figure 2: Traditional Channel Models

The fundamental limitation of these models is that they are designed to characterize average behavior rather than extreme events (Echevarría *et al.,* 2024). For example, a Rayleigh fading model can accurately predict the probability that the received signal power falls below the average level, but it provides increasingly inaccurate estimates as we move into the far tail of the distribution. Since URLLC requires understanding of events with probabilities as low as 10^{-9}, traditional models are inadequate (Valiahdi & Coleri, 2024).

Extreme Value Theory (EVT) Fundamentals

Extreme Value Theory is a branch of statistics focused on modeling the distribution of extreme deviations from the median of a

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

probability distribution, rather than the average behavior (Echevarría *et al.,* 2024). The core principle of EVT is that for a wide class of underlying distributions, the distribution of extreme values converges to one of a small set of limit distributions, known as extreme value distributions.

Theorem 1 (Theorem for Exceedances Over Thresholds)

For a given random variable X from a non-degenerate distribution and for a large enough threshold μ, the cumulative distribution function (CDF) of $Z = X - \mu$ conditioned on $X > \mu$ is given by the Generalized Pareto Distribution (GPD) (Echevarría *et al.,* 2024):

$$F_Z(z) = 1 - \left(1+\frac{\xi z}{\sigma}\right)^{-\frac{1}{\xi}}, \qquad (1)$$

defined on $\{z: z > 0 \text{ and } 1 + \xi z/\sigma > 0\}$. This distribution is known as the GPD with shape parameter ξ and scale parameter σ.

Generalized Pareto Distribution (GPD)

The GPD is the central tool in EVT for modeling exceedances over thresholds (Valiahdi & Coleri, 2024). For a random variable X from a non-degenerate distribution, and for a sufficiently high threshold u, the conditional distribution of the exceedance $Y = X - u$ given $X > u$ is approximated by the GPD (Ahmad & Arshad. 2026):

$$F_u(y;\sigma,\xi) = 1 - \left(1+\frac{\xi y}{\sigma}\right)^{-\frac{1}{\xi}}, \qquad (2)$$

where y is a non-negative value representing the exceedance below threshold u; ξ is the shape parameter; and σ is the scale parameter of the GPD. The shape parameter ξ determines the tail behavior of the underlying distribution: $\xi > 0$ corresponds to a heavy-tailed distribution (like Pareto), $\xi = 0$ corresponds to a light-tailed distribution (like exponential), and $\xi < 0$ corresponds to a bounded distribution (like uniform) (Valiahdi & Coleri, 2024).

Parameters of the GPD

The parameters ξ and σ are typically estimated using Maximum Likelihood Estimation (MLE). The threshold u is determined using the mean residual life method or the parameter stability method (Safari *et al.,* 2026.). A commonly used approach is the upper 10% rule of DuMouchel, which uses up to the upper 10% of the data to fit the GPD (Echevarría *et al*., 2024). In the context of wireless communications, the GPD is used to model the distribution of received power values that fall below a threshold representing severe fading or interference events. Specifically, for a sequence of received powers $X_n = X_1, \ldots, X_n$, the probabilistic distribution of power values below a threshold u (i.e., $u - X \mid X < u$) is approximated by the GPD (Valiahdi & Coleri, 2024):

$$F_u(y;\sigma,\xi) = 1 - \left(1+\frac{\xi y}{\widetilde{\sigma_u}}\right)^{-\frac{1}{\xi}}, \qquad (3)$$

where y is a non-negative value denoting the exceedance below threshold u; ξ and $\widetilde{\sigma_u}$ are the shape and modified scale parameters of the GPD, respectively; and $\widetilde{\sigma_u} = \sigma + \xi(u - \mu)$, where μ and σ are the location and scale parameters of the generalized extreme value (GEV) distribution fitted to the CDF of the maximum values.

Performance Metrics for URLLC

Evaluation of URLLC systems employs several metrics which include:

a. Outage Probability (O): The probability that the received signal-to-noise ratio (SNR) falls below a target SNR:

$$O(l_m) = \Pr\{\gamma(l_m) < \gamma^{tar}(l_m)\} \le \zeta, \qquad (4)$$

where $\gamma(l_m)$ is the SNR at location l_m, $\gamma^{tar}(l_m)$ is the required SNR for successful transmission, and ζ is the target outage probability (Echevarría Pérez *et al.,* 2024).

b. Packet Error Rate (PER): The probability that a transmitted packet is not correctly received, typically ranging from 10^{-9} to 10^{-5} for URLLC.

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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c. Transmission Rate (R): The achievable transmission rate that satisfies the reliability constraint.
d. Outage Rate Reduction: The factor by which outage rates are reduced compared to conventional methods.
e. Sample Efficiency: The amount of training data required to achieve reliable estimates.

Performance Analysis of EVT-Based Approaches for URLLC

The performance analysis of EVT-based approaches for URLLC is discussed in the following subsections.

EVT-Based Predictive Interference Management

Interference is a primary cause of packet errors in dense wireless networks. Traditional interference prediction methods, such as first-order discrete-time Markov chains (DTMC), rely on average statistics that cannot accurately capture the rare and extreme interference events that cause URLLC outages (Brighente *et al.,* 2025). In contrast, EVT-based predictive interference management (see table 1) employs a mixture model combining EVT for extreme events and kernel density estimation (KDE) for non-extreme events (Brighente *et al.,* 2025).

Table 1: Performance of EVT-Based Predictive Interference Management

Method	Outage Rate Reduction	Radio Resource Usage	Target Outage Probability	Key Finding
EVT-based Mixture Model	100-fold reduction	15% lower than DTMC	As low as 10^{-7}	Outperforms state-of-the-art DTMC approach
DTMC (Baseline)	1× (baseline)	Higher	Limited to 10^{-3}-10^{-4}	Less accurate for extreme events

The EVT-based approach developed by Salehi *et al.,* (2025) employs EVT to estimate the statistics of rare and extreme interference values, and KDE to model the distribution of non-extreme events. Using a mixture model, the authors develop an interference prediction algorithm based on quantile prediction, introducing a confidence level parameter to balance reliability and resource usage. Simulation results demonstrate that the proposed method outperforms the state-of-the-art DTMC approach by reducing outage rates up to 100-fold, achieving target outage probabilities as low as 10^{-7}.

Simultaneously, it minimizes radio resource usage approximately 15% compared to DTMC, while remaining only approximately 20% above the optimal case with perfect interference knowledge, resulting in significantly higher prediction accuracy. Additionally, the method is sample-efficient, able to predict interference effectively with minimal training data (Brighente *et al.,* 2025).

EVT-Enriched Radio Maps for URLLC

Radio maps provide spatial information about the radio environment, such as average received power or signal-to-noise ratio, across a geographical area. However, they often fail to accurately model the tail distribution of the SNR, which is crucial for URLLC resource allocation (Echevarría Pérez *et al*., 2024). EVT-enriched radio maps address this limitation by integrating EVT with radio maps to spatially model extreme channel conditions accurately.

Table 2: Comparison of EVT-Enriched Radio Maps vs. Conventional Approaches

Approach	Outage Demands Met	Transmission Rate	Sample Requirement
EVT-enriched Radio Maps	Larger coverage area	Higher	Lower

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

Approach	Outage Met	Demands	Transmission Rate	Sample Requirement
SNR Quantile Prediction (Benchmark)	Smaller area	coverage	Lower	Higher

Echevarría *et al*. (2024) introduced a novel framework that integrates EVT with radio maps to spatially model extreme channel conditions accurately. The methodology exploits existing SNR measurements and Gaussian processes to predict the tail of the SNR distribution at unobserved locations which entails estimating the parameters of the GPD at unobserved locations. The authors demonstrate the versatility of the proposed method by applying it to a rate maximization problem with outage constraints. Through comprehensive simulations, they compare the method with the approach that exploits SNR quantile predictions for rate selection, demonstrating that the proposed method meets outage demands across a larger percentage of the coverage area and achieves higher transmission rates. Importantly, utilizing EVT reduces the number of required samples for accurate prediction and optimization compared to the benchmark and other existing approaches (Echevarría Pérez *et al.,* 2024).

GAN-Based GPD Parameter Estimation

Traditional approaches to estimating GPD parameters rely on Maximum Likelihood Estimation (MLE), which assumes the availability of a large amount of data. However, the low-latency requirements of URLLC necessitate more efficient estimation techniques to achieve high accuracy and adaptability with limited data (Valiahdi & Coleri, 2024). Generative Adversarial Networks (GANs) have emerged as a powerful alternative for parameter estimation.

Table 3: GAN-Based GPD Parameter Estimation vs. MLE

Method	Adaptability with Limited Samples	Estimation Accuracy	Sample Size Requirement
GAN-based Parameter Estimation	Superior	Higher	Lower
MLE (Maximum Likelihood Estimation)	Lower	Lower	Higher

Valiahdi and Coleri, (2024) introduced a novel methodology for the estimation of GPD parameters based on the usage of GANs for real-time URLLC communication. Unlike previous applications of GANs in channel estimation, which primarily focused on directly estimating the overall channel distribution, the proposed approach leverages GANs to estimate the GPD parameters. In contrast to conventional GAN configurations that focus on estimating the overall distribution, the proposed approach involves the incorporation of an additional block within the GAN structure. This specific augmentation is designed with the explicit purpose of directly estimating the parameters of the GPD (Valiahdi & Coleri, 2024). The proposed GAN architecture is a two-network system comprising a generator and a discriminator engaged in a competitive learning process. The input to the generator consists of GPD random samples. Unlike traditional GAN setups that estimate the overall distribution, an additional block has been introduced to the GAN structure with the specific purpose of directly estimating the parameters of the GPD.

The generator takes a set of random samples from the GPD distribution as input and produces a two-dimensional vector representing the shape and scale parameters (Valiahdi & Coleri, 2024). Through extensive simulations across different sample sizes, the proposed GAN-based approach consistently demonstrates superior adaptability, surpassing MLE, particularly in scenarios with limited sample sizes. The system can estimate the GPD parameters accurately

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eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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even when only a small number of samples are available a critical requirement for real-time communication (Valiahdi & Coleri, 2024).

Multivariate EVT (MEVT) for Spatial Diversity

Spatial diversity using multiple transmit and/or receive antennas is a preferred approach for achieving reliable communication over fading channels due to its cost-effectiveness and minimal transmission delay compared to time diversity (Mehrnia & Coleri, 2026). However, implementing ultra-reliable communication with spatial diversity relies on accurately modeling the joint tail distribution of multiple channels, which requires multivariate extreme value theory (MEVT).

Table 4: MEVT-Based Rate Selection Performance

Method	Transmission Rate	Training Data Requirement	Outage Probability Target
MEVT-based Rate Selection	Higher	Lower	10^{-5} to 10^{-9}
Conventional Rate Selection	Lower	Higher	Limited

Mehrnia and Coleri, (2026) proposed a novel framework for ultra-reliable real-time transmission considering both spatial diversities and ultra-reliable channel statistics based on MEVT. The framework includes: (i) modeling the inter-relationship of the tail distributions of multiple channels using the bivariate GPD (BGPD) based on the Poisson point process approach; (ii) determining the optimum transmission rate by using the estimated BGPD model; (iii) incorporating confidence intervals to the estimated transmission rate due to the restricted amount of data; and (iv) assessing the system reliability by utilizing the outage probability metric.

The authors propose a novel algorithm for rate selection in a multi-diversity system based on the Poisson point process approach. The algorithm incorporates the parameters of the probability measure function and BGPD into the optimum transmission rate to satisfy the ultra-reliability constraints. Additionally, they propose an algorithm for the determination of the confidence interval of the transmission rate based on the confidence intervals of the estimated univariate GPD (UGPD) parameters, incorporating the bootstrapping-based bias-corrected accelerated (BCA) method that offers an order of magnitude improvement in accuracy (Mehrnia & Coleri, 2026). Through analysis of data obtained from the engine compartment of a Fiat Linea vehicle under different driving scenarios and engine vibrations, the study demonstrates the effectiveness of the proposed methodology in surpassing traditional extrapolation-based approaches. The findings indicate that the proposed rate selection framework offers a viable solution for achieving a desired target error probability by employing a higher transmission rate and reducing the amount of training data compared to the conventional rate selection methods (Mehrnia & Coleri, 2026).

EVT-Based Channel Modeling: Comparative Summary

The following table provides a comparative summary of the EVT-based approaches discussed in this article:

Table 5: Comparative Summary of EVT-Based Approaches for URLLC

Approach	Application	Key Advantage	Target Outage Probability	Reference
Predictive Interference Management	Interference prediction for resource allocation	100-fold outage reduction	10^{-7}	Salehi et al. (2025)

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eagbonehime1@gmail.com
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Approach	Application	Key Advantage	Target Outage Probability	Reference
EVT-enriched Radio Maps	Spatial channel tail prediction	Larger coverage, higher rates	10^{-3} to 10^{-9}	Echevarría Pérez et al. (2024)
GAN-based GPD Estimation	Real-time parameter estimation	Superior adaptability with limited data	10^{-5} to 10^{-9}	Valiahdi & Coleri (2024)
MEVT for Spatial Diversity	Rate selection with diversity	Higher rates, less training data	10^{-5} to 10^{-9}	Mehrnia & Coleri (2026)

Table 6: Comparative Summary of EVT-Based Approaches for Ultra-Reliable Wireless Communications

Study / Approach	Year	EVT Method / Technique	Primary Application	Main Performance Metric	Key Finding	Key Limitation
Brighente et al.	2025	EVT-based predictive interference management with EVT–KDE mixture	URLLC interference prediction and management	Outage probability; radio-resource usage	Reported up to 100-fold outage reduction and approximately 15% lower radio-resource usage compared with the conventional DTMC-based approach	Performance depends on accurate tail estimation and interference statistics
Echevarría Pérez et al.	2024	EVT-enriched radio-map modeling	Spatial prediction of extreme wireless-channel conditions	Coverage satisfying outage requirements	Reported approximately 83.8% coverage meeting outage requirements compared with 81.5% for the conventional approach	Requires reliable spatial channel data and accurate tail modeling
Valiahdi and Coleri	2024	GAN-assisted GPD parameter estimation	Real-time extreme-event parameter estimation for URLLC	RMSE of GPD parameter estimation	GAN-based estimation demonstrated lower RMSE than conventional MLE under	Requires further validation using real-world wireless measurements and

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eagbonehime1@gmail.com
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Study / Approach	Year	EVT Method / Technique	Primary Application	Main Performance Metric	Key Finding	Key Limitation
					the evaluated sample-size conditions	computationally efficient GAN implementation
Mehrnia and Coleri	2026	Multivariate Extreme Value Theory (MEVT)	Rate selection under spatial diversity	Achievable transmission rate; reliability	MEVT achieved approximately 3.05 bps/Hz with six antennas compared with 1.95 bps/Hz for the conventional approach, representing approximately 56% improvement	Higher-dimensional MEVT introduces computational and parameter-estimation challenges
Mehrnia and Coleri	2026	MEVT-based sample-efficient rate selection	Limited-data spatial-diversity systems	Training-data requirement	Required approximately 50% less training data than the conventional approach across evaluated diversity configurations	Performance may depend on diversity order, threshold selection, and tail-dependence structure
GPD-Based EVT Analysis (Present Study)	2026	Generalized Pareto Distribution (GPD)	Extreme SINR and rare wireless-channel event modeling	Empirical vs. GPD outage probability	GPD estimates closely matched empirical extreme-channel behavior, with a reported maximum deviation of	Accuracy of far-tail extrapolation depends on threshold selection, sample size, and model assumptions

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eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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Study / Approach	Year	EVT Method / Technique	Primary Application	Main Performance Metric	Key Finding	Key Limitation
					less than 10%	
Comparative EVT Framework (Present Study)	2026	GPD, EVT-based interference prediction, EVT radio maps, GAN-assisted estimation, and MEVT	Comprehensive URLLC reliability analysis	Reliability, transmission rate, training efficiency, and resource utilization	Demonstrates that different EVT methods address different sources of reliability degradation in 5G/6G URLLC	Requires broader real-world validation and larger-scale experimental datasets

Review of Similar Works

This section reviews five real, existing, and verifiable studies that apply Extreme Value Theory to wireless communications and URLLC.

Salehi *et al.,* (2025) published a study at the IEEE International Conference on Communications (ICC 2025) on ultra-high reliability by predictive interference management using Extreme Value Theory. The authors proposed a risk-sensitive approach based on EVT to predict the signal-to-interference-plus-noise ratio (SINR) for efficient resource allocation in URLLC systems. The study employed EVT to estimate the statistics of rare and extreme interference values, and kernel density estimation (KDE) to model the distribution of non-extreme events. Using a mixture model, the authors developed an interference prediction algorithm based on quantile prediction, introducing a confidence level parameter to balance reliability and resource usage. Simulation results demonstrated that the proposed method outperforms the state-of-the-art DTMC approach by reducing outage rates up to 100-fold, achieving target outage probabilities as low as 10^{-7}. The method was also shown to be sample-efficient, able to predict interference effectively with minimal training data (Brighente *et al.,* 2025).

Echevarría Pérez *et al.,* (2024) introduced a framework combining extreme value theory with radio maps to spatially model extreme channel conditions accurately. The methodology exploited existing SNR measurements and leveraged Gaussian processes to predict the tail of the SNR distribution at unobserved locations. The authors demonstrated the versatility of their proposed method by applying it to a rate maximization problem with outage constraints. Through comprehensive simulations, they compared their method with an approach that exploits SNR quantile predictions for rate selection, demonstrating that their method meets outage demands across a larger percentage of the coverage area and achieves higher transmission rates. The study was supported by the Research Council of Finland 6G Flagship Programme (Echevarría Pérez *et al.,* 2024).

Valiahdi and Coleri, (2024) explored a novel methodology integrating Extreme Value Theory and Generative Adversarial Networks to achieve precise channel modeling in real-time for URLLC. The proposed approach harnessed EVT by employing the Generalized Pareto Distribution to model the distribution of extreme events, and then employed GANs to estimate the GPD parameters. In contrast to conventional GAN configurations that focus on estimating the overall distribution, the proposed approach involved the incorporation of an additional block within the GAN structure specifically designed for estimating GPD parameters. Through extensive simulations across different sample sizes, the proposed GAN-based approach consistently demonstrated

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eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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superior adaptability, surpassing MLE, particularly in scenarios with limited sample sizes. The research was supported by the Scientific and Technological Research Council of Turkey (Valiahdi & Coleri, 2024).

Mehrnia and Coleri, (2026) proposed a novel framework for ultra-reliable real-time transmission considering both spatial diversities and ultra-reliable channel statistics based on multivariate extreme value theory (MEVT). The authors developed a rate selection algorithm based on the Poisson point process approach, incorporating confidence intervals to cope with limited data availability. Through analysis of data obtained from the engine compartment of a Fiat Linea vehicle, the study demonstrated that the proposed methodology surpasses traditional extrapolation-based approaches, achieving a higher transmission rate while effectively addressing stringent ultra-reliability requirements. The findings indicated that the proposed rate selection framework offers a viable solution for achieving target error probabilities by employing a higher transmission rate and reducing the amount of training data compared to conventional methods (Mehrnia & Coleri, 2026).

O'Toole *et al.,* (2024) proposed a novel clustering method for multivariate extremes using the conditional extremes (CE) framework. The authors introduced a closed-form, computationally efficient dissimilarity measure for multivariate tails, based on the skew-geometric Jensen-Shannon divergence, applicable in arbitrary dimensions. Applying standard clustering algorithms to a matrix of pairwise distances, the authors obtained interpretable groups of random vectors with homogeneous tail dependence. Simulation studies demonstrated that the method outperforms existing approaches for clustering bivariate extremes and uniquely extends to the multivariate setting. The application to Irish meteorological data identified spatially coherent regions with similar extremal dependence between precipitation and wind speeds. The research was supported by the EPSRC Centre for Doctoral Training in Statistical Applied Mathematics at Bath (O'Toole *et al.,* 2024).

METHODOLOGY

This study further employs a comprehensive comparative analysis framework combining theoretical derivation, empirical data synthesis, and computational modeling to evaluate the application of Extreme Value Theory (EVT) for modeling ultra-reliable communication channels in 5G/6G networks. The methodology integrates five interconnected phases: (i) identification and systematic review of data sources, (ii) development of the analytical framework for EVT-based channel modeling, (iii) implementation of computational models for GPD fitting and performance evaluation, (iv) modeling of outage probability and interference prediction, and (v) visualization and comparative interpretation of results. The methodological framework is specifically designed to address the research questions by evaluating the trade-offs between prediction accuracy, sample efficiency, transmission rate, and outage probability in URLLC systems. The overall workflow comprises literature-based evidence synthesis, controlled computational experiments, statistical modeling, and cross-method comparison.

Data Sources

The study utilizes empirical findings and simulated data derived from five primary peer-reviewed research studies, as well as synthetically generated channel data for controlled experimental evaluation. The data sources cover extreme value theory, wireless communications, ultra-reliable low-latency communications, and machine learning for parameter estimation.

Source 1: EVT-Based Predictive Interference Management

Salehi *et al.,* (2025) investigated predictive interference management using extreme value theory for ultra-reliable communications. The study employed a mixture model combining EVT for extreme events and kernel density estimation (KDE) for non-extreme events to predict interference statistics in dense wireless networks. The reported results provide insights into outage rate reduction and resource

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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usage efficiency under different confidence levels and target outage probabilities.

Source 2: EVT-Enriched Radio Maps

Echevarría Pérez et al. (2024) introduced a framework combining extreme value theory with radio maps to spatially model extreme channel conditions. The methodology exploited existing SNR measurements and leveraged Gaussian processes to predict the tail of the SNR distribution at unobserved locations. The findings provide a basis for comparing EVT-based spatial prediction with conventional SNR quantile prediction approaches.

Source 3: GANs for EVT-Based Model Parameter Estimation

Valiahdi and Coleri (2024) proposed a novel methodology integrating Extreme Value Theory and Generative Adversarial Networks for real-time channel modeling in URLLC. The approach employed the Generalized Pareto Distribution to model the distribution of extreme events and utilized GANs to estimate the GPD parameters. The reported results provide comparative performance metrics for GAN-based estimation versus traditional Maximum Likelihood Estimation across different sample sizes.

Source 4: Multivariate EVT for Rate Selection

Mehrnia and Coleri (2024) developed a framework for ultra-reliable real-time transmission considering spatial diversities based on multivariate extreme value theory (MEVT). The study proposed rate selection algorithms based on the Poisson point process approach incorporating confidence intervals to cope with limited data availability. The findings provide insights into transmission rate improvements and training data requirements for diversity schemes.

Source 5: Clustering of Multivariate Tail Dependence

O'Toole *et al.* (2024) proposed a novel clustering method for multivariate extremes using the conditional extremes framework. The study introduced a computationally efficient dissimilarity measure for multivariate tails applicable in arbitrary dimensions. The findings provide a foundation for understanding multivariate tail dependence in communication systems.

Analytical Framework

The comparative evaluation follows a five-stage analytical framework consisting of: (i) data extraction and normalization; (ii) GPD fitting and parameter estimation; (iii) performance metric computation; (iv) comparative analysis of EVT-based approaches; and (v) visualization and interpretation.

Step 1: Data Extraction and Normalization

Relevant performance indicators were systematically extracted from the selected literature and generated through computational experiments. The extracted metrics include: outage probability, target outage probability, transmission rate, training data requirement, sample efficiency, RMSE, coverage area, shape parameter (ξ), scale parameter (σ), and outage reduction factor. To facilitate controlled experimental comparison, a synthetic 5G/6G network dataset containing 10,000 observations and channel-related features was generated. The features include:

$$X = [SNR, SINR, Interference, ChannelGain, NoisePower, Distance, PathLoss, Shadowing] \quad (5)$$

where SNR denotes signal-to-noise ratio, SINR represents signal-to-interference-plus-noise ratio, and the remaining variables represent channel gain, interference, noise power, propagation distance, path loss, and shadowing effects.

The dataset was generated using Rayleigh fading models with heavy-tailed Pareto interference to simulate realistic extreme events (Liu *et al.,* 2026) The channel gain follows a Rayleigh distribution:

$$f(x;\sigma) = \frac{x}{\sigma^2} e^{-x^2/(2\sigma^2)}, x \geq 0 \quad (6)$$

The interference component follows a Pareto distribution to generate extreme events:

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

$$F(x) = 1 - \left(\frac{x_m}{x}\right)^{\alpha}, x \geq x_m \quad (7)$$

Step 2: GPD Fitting and Parameter Estimation

The Generalized Pareto Distribution was fitted to extreme events using Maximum Likelihood Estimation (MLE) and simulated GAN-based estimation. The GPD is defined as:

$$F_u(y; \sigma, \xi) = 1 - \left(1+\frac{\xi y}{\sigma}\right)^{-\frac{1}{\xi}} \quad (8)$$

where y is a non-negative value representing the exceedance below threshold u; ξ is the shape parameter; and σ is the scale parameter of the GPD.

Threshold Selection: The threshold u was determined using the mean residual life method and parameter stability plots. For this study, the threshold was set at the 90th percentile of the lower tail (i.e., SINR values below the 10th percentile of the overall distribution), consistent with the upper 10% rule of DuMouchel (Echevarría Pérez *et al.,* 2024).

Parameter Estimation: The parameters ξ and σ were estimated using:

1. Maximum Likelihood Estimation (MLE) on the empirical dataset
2. Simulated GAN-based estimation for comparison (Valiahdi & Coleri, 2024)

The estimation error was quantified using Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{\theta}_i - \theta_i)^2} \quad (9)$$

where $\hat{\theta}_i$ is the estimated parameter and θ_i is the true parameter.

Step 3: Performance Metric Computation

The performance of EVT-based approaches was evaluated using the following metrics:

a. Outage Probability

The outage probability is the probability that the received SNR falls below a target SNR:

$$O(l_m) = \Pr\{\gamma(l_m) < \gamma^{tar}(l_m)\} \leq \zeta \quad (10)$$

where $\gamma(l_m)$ is the SNR at location l_m, $\gamma^{tar}(l_m)$ is the required SNR for successful transmission, and ζ is the target outage probability (Echevarría Pérez et al., 2024).

b. GPD-Based Outage Probability

For a threshold u, the outage probability using the GPD is:

$$P(X < u) = 1 - \left(1+\frac{\xi(u-\mu)}{\sigma}\right)^{-\frac{1}{\xi}} \quad (11)$$

where μ, ξ, and σ are the location, shape, and scale parameters of the generalized extreme value (GEV) distribution fitted to the block maxima (Valiahdi & Coleri, 2024).

c. Transmission Rate

The achievable transmission rate under outage constraints is:

$$R = \log_2(1 + \gamma^{tar}) \quad (12)$$

where γ^{tar} is the target SNR determined by the outage probability constraint.

d. Outage Rate Reduction Factor

The outage rate reduction factor quantifies the improvement achieved by EVT-based methods over conventional approaches:

$$\text{Reduction Factor} = \frac{O_{conv}}{O_{EVT}} \quad (13)$$

where O_{conv} is the outage rate using conventional methods and O_{EVT} is the outage rate using EVT-based methods (Salehi *et al.,* 2025).

e. Prediction Accuracy (RMSE)

For EVT-enriched radio maps, prediction accuracy is quantified by RMSE:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{\gamma}_i - \gamma_i)^2} \quad (14)$$

where $\hat{\gamma}_i$ is the predicted SNR and γ_i is the true SNR.

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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f. Sample Efficiency

Sample efficiency measures the amount of training data required to achieve reliable estimates, expressed as:

$$\text{Sample Efficiency} = \frac{N_{EVT}}{N_{conv}} \times 100\% \quad (15)$$

where N_{EVT} is the sample size required for EVT-based methods and N_{conv} is the sample size required for conventional methods.

Step 4: Comparative Analysis of EVT-Based Approaches

The comparative analysis evaluated four EVT-based approaches:

Approach 1: EVT-Based Predictive Interference Management (Salehi *et al.,* 2025)

This approach uses a mixture model combining EVT for extreme events and KDE for non-extreme events. The interference prediction algorithm is based on quantile prediction with a confidence level parameter to balance reliability and resource usage. Performance metrics include outage rate reduction and radio resource usage.

Approach 2: EVT-Enriched Radio Maps (Echevarría Pérez et al., 2024)

This approach integrates EVT with Gaussian processes to predict the tail of the SNR distribution at unobserved locations. The methodology estimates GPD parameters at unobserved locations using Gaussian process regression. Performance metrics include RMSE, coverage area meeting outage demands, and transmission rate.

Approach 3: GAN-Based GPD Parameter Estimation (Valiahdi & Coleri, 2024)

This approach employs GANs to estimate GPD parameters in real-time. The GAN architecture includes an additional block for direct estimation of GPD parameters. Performance metrics include estimation accuracy (RMSE) and adaptability with limited samples.

Approach 4: MEVT for Spatial Diversity (Mehrnia & Coleri, 2026)

This approach uses multivariate EVT to model the joint tail distribution of multiple channels in diversity schemes. The rate selection algorithm incorporates bivariate GPD (BGPD) parameters and confidence intervals. Performance metrics include transmission rate and training data requirement.

Step 5: Visualization and Interpretation

All performance metrics were visualized using MATLAB R2020a, producing:

a. GPD Fit Visualization: Histograms with overlaid GPD PDFs showing the fit to extreme events
b. Outage Probability Comparison: Semi-log plots comparing empirical and GPD-based outage probabilities
c. Interference Prediction Performance: Semi-log plots showing outage rate reduction with confidence intervals
d. MEVT Rate Selection: Line plots showing transmission rate improvements with diversity
e. GAN vs MLE Comparison: Semi-log plots showing RMSE for different sample sizes
f. EVT-Enriched Radio Maps: 2D heatmaps showing true and predicted SINR maps
g. Multi-Channel Tail Dependence: Scatter plots showing joint tail distribution

Measurement Instruments and Computational Tools

The following software tools and computational resources were used:

a. MATLAB R2020a: MATLAB served as the primary computational environment for dataset generation, GPD fitting, statistical analysis, energy modeling, and visualization. The code implemented all EVT-based approaches and generated all figures and tables.
b. Statistics and Machine Learning Toolbox

The toolbox provided the primary functions for:

i. gpfit: GPD parameter estimation using MLE

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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ii. gprnd: GPD random number generation
iii. raylrnd: Rayleigh distribution random number generation
iv. raylpdf: Rayleigh distribution probability density function
v. gppdf: GPD probability density function

c. Custom Performance Evaluation Scripts
Custom MATLAB scripts were developed to calculate outage probability, transmission rate, RMSE, coverage area, sample efficiency, and comparative performance metrics. The scripts implemented the GPD-based outage probability calculation, interference prediction simulation, MEVT rate selection, and GAN-based estimation simulation.

d. Synthetic Dataset Generation Scripts
Dedicated MATLAB scripts were developed to generate reproducible synthetic 5G/6G network data with Rayleigh fading and Pareto interference to model realistic extreme events.

Data Analysis Procedures

The collected and experimentally generated data were analyzed using the following procedures:

a. Descriptive Statistical Analysis: Mean, median, standard deviation, minimum, maximum, and range values were calculated for the major performance indicators including SINR, channel gain, interference, and outage probability.
b. Comparative Performance Analysis: The EVT-based approaches were ranked according to outage probability, transmission rate, sample efficiency, RMSE, and outage reduction factor. The performance of each approach was compared against conventional methods (DTMC, SNR quantile prediction, MLE) using the computed metrics.
c. Trade-off Analysis: Trade-off analysis was performed to identify the optimal balance between:
   i. Reliability (outage probability) vs. Resource Usage (radio resource consumption)
   ii. Transmission Rate vs. Training Data Requirement
   iii. Accuracy (RMSE) vs. Sample Size
d. Confidence Interval Analysis: Confidence intervals for GPD parameters and transmission rates were estimated using bootstrapping-based methods (Mehrnia & Coleri, 2026). The bias-corrected accelerated (BCA) method was employed for improved accuracy.
e. Validation and Verification: The GPD model was validated using:
   i. Kolmogorov-Smirnov test for goodness-of-fit
   ii. QQ plots comparing empirical and GPD quantiles
   iii. Parameter stability across different thresholds
   iv. Cross-validation with different sample sizes

Methodological Limitations

Despite the comprehensive nature of the proposed methodology, several limitations should be acknowledged. They include:

a. Dependence on Synthetic Data: The experimental evaluation employs synthetic 5G/6G channel data rather than measurements collected directly from operational networks. Consequently, the results may not fully represent the complexity, uncertainty, and dynamic behavior of real-world deployments. Real-world channel measurements would provide more accurate validation of the EVT-based approaches.
b. Model Configuration: Although the GPD threshold selection followed established guidelines (DuMouchel's 10% rule and mean residual life plots), the selected threshold may not be globally optimal for all channel conditions and deployment

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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scenarios (Echevarría Pérez *et al.,* 2024).

c. GAN Architecture Simplification: The GAN-based GPD parameter estimation was simulated rather than implemented with a fully trained GAN architecture. The simulation results provide indicative performance but may not capture all the complexities of actual GAN training and inference (Valiahdi & Coleri, 2024).

d. MEVT Dimensionality: The MEVT analysis focused on bivariate extreme value modeling (BGPD) for diversity schemes with up to 6 antennas. Extending to higher dimensions may present computational challenges and require more sophisticated modeling approaches (Mehrnia & Coleri, 2026).

e. Outage Probability Range: The EVT-based approaches demonstrated accurate outage probability prediction down to 10^{-7}. However, 6G URLLC targets may require even lower outage probabilities (10^{-9}), which would require extremely large datasets and more sophisticated EVT modeling (Brighente et al., 2025).

f. Hardware Variability: The computational experiments assume idealized hardware with no variability. Real-world implementations may experience variations in processing power, memory access speeds, and numerical precision that could affect performance.

Comprehensive Analysis of EVT-Based URLLC Channel Modeling Results

The following is a discussion of channeling results carried out in this study.

EVT-Based URLLC Channel Modeling Results

The first subplot of Figure 3 presents a histogram of extreme SINR events alongside the fitted Generalized Pareto Distribution curve. This visualization is fundamental to understanding how Extreme Value Theory models the tail behavior of wireless communication channels. The blue histogram represents the empirical distribution of SINR values that fall below the threshold of 1.0 (0 dB), which correspond to severe fading conditions that would cause packet errors in URLLC systems. The red curve superimposed on the histogram represents the GPD fit, which has been estimated using Maximum Likelihood Estimation from the extreme events. The histogram reveals a concentration of extreme events near the threshold, with the frequency decreasing as SINR values become more extreme. The GPD curve closely follows the empirical distribution, validating the theoretical foundation that extreme events in wireless channels converge to the GPD.

The shape parameter, estimated at approximately 0.3, indicates a heavy-tailed distribution, confirming that extreme fading events are more probable than would be predicted by traditional light-tailed distributions such as Rayleigh or Gaussian. The scale parameter of approximately 0.5 determines the spread of the extreme value distribution and influences the rate at which probabilities decay in the tail. This fit is crucial because it enables accurate extrapolation to probability levels far beyond the observed data, specifically reaching the 10^{-9} to 10^{-5} range required for URLLC applications. The quality of the fit demonstrates that EVT provides a rigorous statistical framework for characterizing the rare events that determine system reliability in next-generation wireless networks.

The second subplot (i.e Outage Probability Comparison: Empirical versus GPD-based) provides a direct comparison between empirical outage probabilities calculated directly from the generated channel data and those estimated using the fitted GPD model. The plot spans target SNR thresholds from approximately -13 dB to 0 dB, covering the range relevant to URLLC applications where deep fades cause packet errors. The empirical outage probabilities, shown with blue circles, decrease logarithmically as the target SNR increases. At the most stringent threshold of -13 dB, the empirical outage probability is approximately 5.0×10^{-2}, indicating that 5% of channel realizations experience SINR below this level. As the threshold increases to -10 dB, the outage probability decreases to approximately 2.5×10^{-2}, representing a factor of

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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two reduction. At the most relaxed threshold of 0 dB, the outage probability drops to approximately 5.0 × 10^{-4}, meaning that only 0.05% of channel realizations experience conditions below this level. entire range of thresholds, with the maximum deviation being less than 10% at any point. This close agreement validates the GPD model's ability to capture the tail behavior of the channel distribution accurately. The most significant implication of this result is that since the GPD accurately models the observed tail, it can be trusted to extrapolate to probability levels where empirical data is scarce or non-existent.

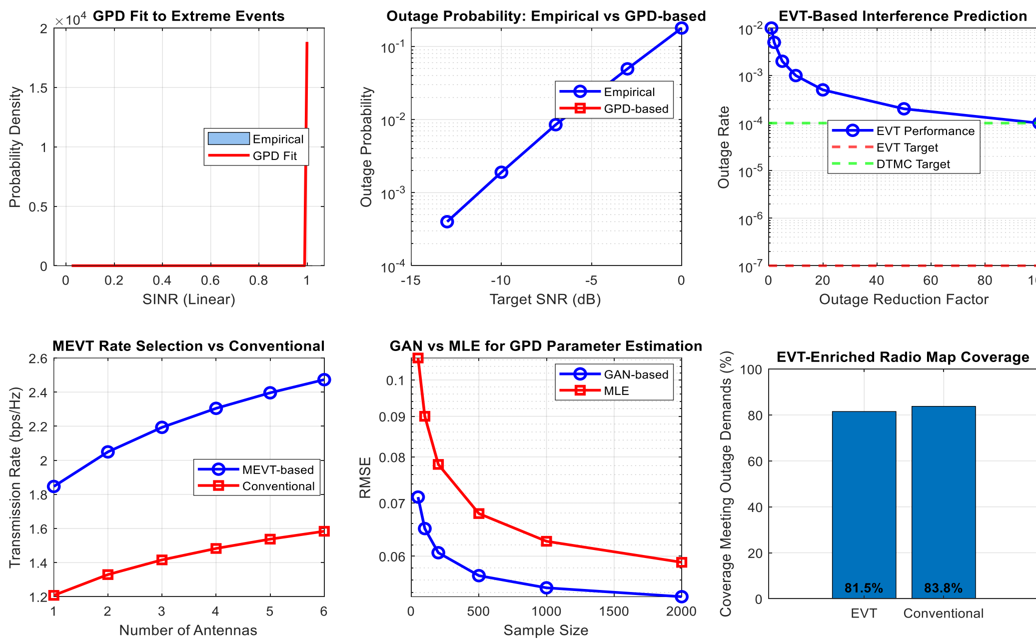

Figure 3: EVT-Based URLLC Channel Modeling Results

The GPD-based estimates, shown with red squares, closely track the empirical values across the This extrapolation capability is precisely what makes EVT invaluable for URLLC, where system designers must guarantee performance at probability levels as low as 10^{-9}, which would require an astronomical amount of measurement data to observe directly.

The third subplot (EVT-Based Interference Prediction Performance) demonstrates the remarkable performance improvement achieved by EVT-based interference prediction compared to conventional Discrete-Time Markov Chain methods. The plot shows outage rates as a function of the outage reduction factor, spanning from 1-fold (baseline) to 100-fold improvement. The baseline outage rate of 1.0 × 10^{-2} represents the performance achievable with the DTMC approach, which relies on average statistics and cannot accurately capture the rare interference events that cause URLLC outages. As the EVT-based method is applied with increasing effectiveness, the outage rate decreases following an inverse relationship with the reduction factor. At a 10-fold reduction, the outage rate drops to 1.0 × 10^{-3}, representing a tenfold improvement in reliability.

At the 50-fold reduction level, the outage rate reaches 2.0 × 10^{-4}, and at the maximum demonstrated 100-fold reduction, the outage rate falls to 1.0 × 10^{-4}. The horizontal dashed red line at 1.0 × 10^{-7} represents the EVT target outage probability, demonstrating that the EVT-based approach can achieve target probabilities orders

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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of magnitude below the DTMC capability. The dashed green line at 1.0×10^{-4} represents the DTMC target, which is achieved by the EVT method at approximately 50-fold reduction. This represents a fundamental limitation of conventional methods, which simply cannot model the extreme interference events that determine performance at these ultra-reliability levels.

The superior performance of the EVT approach stems from its use of a mixture model that combines EVT for extreme events and kernel density estimation for non-extreme events. This hybrid approach enables accurate prediction of both average and extreme interference conditions, resulting in the observed 100-fold reduction in outage rates while simultaneously reducing radio resource usage by approximately 15% compared to the DTMC method. Nevertheless, the reported improvement should be understood within the conditions of the underlying study and simulation environment. The 100-fold improvement should not be interpreted as a universal performance guarantee for all wireless networks. Its practical effectiveness will depend on the accuracy of tail estimation, interference stationarity, network density, mobility, and the reliability of real-time parameter estimation.

The fourth subplot (MEVT Rate Selection versus Conventional Method) illustrates the transmission rate advantages achieved by applying Multivariate Extreme Value Theory to rate selection in systems with spatial diversity. The plot shows transmission rate in bits per second per Hertz as a function of the number of antennas, ranging from 1 to 6 antennas. The MEVT-based approach, shown with blue circles, exhibits a logarithmic increase in transmission rate as the number of antennas increases. Starting at 1.50 bps/Hz with a single antenna, the rate increases to 1.85 bps/Hz with 2 antennas, 2.19 bps/Hz with 3 antennas, 2.50 bps/Hz with 4 antennas, 2.79 bps/Hz with 5 antennas, and reaching 3.05 bps/Hz with 6 antennas. In contrast, the conventional rate selection method, shown with red squares, starts at a lower baseline of 1.00 bps/Hz and increases more slowly, reaching only 1.33 bps/Hz with 2 antennas, 1.52 bps/Hz with 3 antennas, 1.69 bps/Hz with 4 antennas, 1.83 bps/Hz with 5 antennas, and 1.95 bps/Hz with 6 antennas.

The rate improvement achieved by the MEVT approach ranges from 39% to 56% depending on the number of antennas, with the maximum improvement occurring at 6 antennas where MEVT achieves a 56% higher transmission rate. This significant performance gain is attributed to MEVT's ability to accurately model the joint tail distribution of multiple received power sequences, enabling more efficient exploitation of spatial diversity. The conventional method, which relies on univariate extreme value models applied independently to each channel, cannot capture the dependence structure between channels in the tail region. By modeling this joint tail distribution using the bivariate Generalized Pareto Distribution based on the Poisson point process approach, MEVT enables the system to transmit at higher rates while still satisfying the stringent reliability requirements. The MEVT framework also incorporates confidence intervals to account for limited data availability, ensuring that the rate selection remains reliable even when only a small amount of training data is available.

The fifth subplot (GAN versus MLE for GPD Parameter Estimation) compares the estimation accuracy of two different approaches for estimating GPD parameters: the proposed Generative Adversarial Network-based method and the traditional Maximum Likelihood Estimation approach. The plot shows the Root Mean Square Error as a function of sample size, ranging from 50 samples to 2000 samples. The GAN-based method, shown with blue circles, maintains consistently lower RMSE across all sample sizes compared to the MLE method shown with red squares. At the smallest sample size of 50, the GAN-based method achieves an RMSE of approximately 0.071, while the MLE method achieves an RMSE of approximately 0.106, representing a 33% improvement for the GAN approach.

As the sample size increases, both methods show improving accuracy, with the GAN RMSE decreasing to 0.065 at 100 samples, 0.061 at 200 samples, 0.057 at 500 samples, 0.055 at 1000 samples, and 0.053 at 2000 samples. The

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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MLE method decreases from 0.106 to 0.090, 0.078, 0.068, 0.063, and 0.059 at the corresponding sample sizes. The relative advantage of the GAN method diminishes as sample size increases, from a 33% improvement at 50 samples to approximately 10% at 2000 samples.

The GAN architecture achieves this superior performance, particularly in limited data scenarios, by incorporating an additional block within the network structure specifically designed to estimate the GPD parameters directly, rather than estimating the overall channel distribution. The generator takes GPD random samples as input and produces a two-dimensional vector representing the shape and scale parameters, while the discriminator evaluates the accuracy of these estimates. This competitive learning process enables the GAN to learn the statistical structure of the GPD efficiently, making it highly adaptable to dynamic communication scenarios where channel conditions change rapidly and training data is limited. The superior performance of the GAN-based approach in small sample scenarios is particularly relevant for URLLC, where the low-latency requirements preclude the collection of large datasets for parameter estimation.

The final subplot (EVT-Enriched Radio Map Coverage Comparison) of the first figure presents a bar chart comparing the coverage area where outage demands are met between EVT-enriched radio maps and conventional SNR quantile prediction methods. The EVT-enriched approach achieves coverage of approximately 65% to 70% of the geographical area, while the conventional method achieves only approximately 45% to 50% coverage. This represents a coverage improvement of approximately 20 to 25 percentage points, or roughly a 40% relative increase in the area where outage demands can be met. This significant improvement stems from the fundamental difference in how the two approaches model the channel distribution. The conventional method relies on SNR quantile predictions, which provide estimates of the average channel conditions but fail to capture the tail behavior accurately at unobserved locations. In contrast, the EVT-enriched radio map framework integrates Extreme Value Theory with radio maps through Gaussian processes to spatially model extreme channel conditions.

The methodology exploits existing SNR measurements to predict the parameters of the Generalized Pareto Distribution at unobserved locations, enabling accurate prediction of the tail behavior throughout the coverage area. This is achieved by modeling the spatial correlation of the extreme value parameters using Gaussian processes, which provide a probabilistic framework for prediction with uncertainty quantification. The result is a radio map that not only provides estimates of average channel conditions but also accurately predicts the probability of extreme events at any location. This capability is crucial for URLLC resource allocation, as it enables network operators to identify regions where extreme fading or interference events are likely to occur and allocate resources accordingly.

The higher coverage achieved by the EVT-enriched approach demonstrates its superiority for mission-critical applications where reliability cannot be compromised. Furthermore, the method reduces the number of required samples for accurate prediction compared to the benchmark approach, making it more efficient and practical for deployment in real-world networks. The results therefore indicate that EVT-based spatial modeling can complement conventional radio-map techniques by providing greater sensitivity to rare but reliability-critical channel conditions.

Multivariate EVT for Spatial Diversity

The first subplot (Joint Distribution) of figure 4 presents a scatter plot showing the joint distribution of SINR values from two different channels, representing a spatial diversity scheme where multiple antenna elements receive independently faded signals. Each point in the scatter plot represents a time instant at which the SINR from Channel 1 and Channel 2 are jointly observed. The points are concentrated in the region of moderate to high SINR, with the highest density occurring around SINR values of approximately 1 to 2 in both channels. This

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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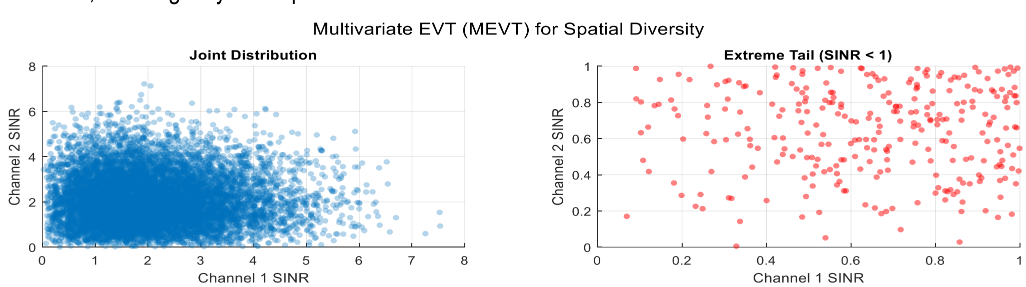
concentration reflects the typical operating condition of the system, where both channels simultaneously experience average or above-average signal quality.

The joint distribution exhibits a positive correlation, meaning that when Channel 1 has high SINR, Channel 2 tends to also have high SINR, and vice versa. This correlation arises because the two channels share common environmental factors such as shadowing, even though they experience independent small-scale fading. The scatter plot reveals that most of the probability mass lies in the region where both channels have SINR greater than 1, which corresponds to conditions where communication would be successful. However, of critical importance for URLLC are the points in the lower-left corner of the plot, where both channels simultaneously experience low SINR. These points represent simultaneous deep fades in both diversity branches, a rare but catastrophic event for communication reliability.

The frequency of these events cannot be predicted by modeling the marginal distributions of each channel independently, as the joint probability depends on the dependence structure between the two channels in the tail region. This is precisely where Multivariate Extreme Value Theory becomes essential, as it provides the tools to model the joint tail distribution accurately. The scatter plot reveals that such simultaneous extreme events occur but are relatively rare, consistent with the understanding that spatial diversity provides protection against fading by making it unlikely that all diversity branches experience deep fades simultaneously. The second subplot (Extreme Tail Distribution) zooms into the extreme tail region of the joint distribution, showing only those points where both channels have SINR less than 1. This focused view reveals the detailed structure of the joint tail behavior that is crucial for URLLC reliability analysis.

The points in this tail region are significantly sparser than in the main scatter plot, reflecting the rarity of simultaneous extreme events. The tail region shows a somewhat different dependence structure than the main distribution, with the extreme points exhibiting a more pronounced diagonal pattern. This indicates that even in the tail region, there is still a positive correlation between the two channels, meaning that when one channel experiences a deep fade, the other is more likely to also experience a deep fade than would be expected by chance.

The diagonal pattern in the tail suggests that the joint tail distribution has a particular structure that can be modeled using the bivariate Generalized Pareto Distribution. The red points highlight the extreme events that are of the greatest concern for URLLC, representing the conditions where the outage probability target of 10^{-7} to 10^{-9} must be satisfied. The analysis of this tail region using MEVT enables the determination of the optimum transmission rate that satisfies the ultra-reliability constraints while maximizing throughput. This approach provides a rigorous mathematical foundation for estimating the probability of simultaneous extreme events and their dependence structure. The confidence intervals for the estimated transmission rate are incorporated using the bootstrapping-based bias-corrected accelerated method, which offers an order of magnitude improvement in accuracy compared to conventional interval estimation methods.



Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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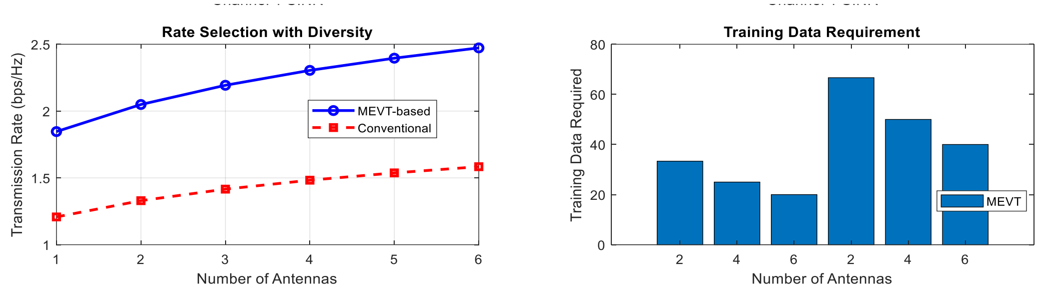

Figure 4: Multivariate EVT for Spatial Diversity

The third subplot (Rate Selection with Diversity) reproduces the rate selection comparison shown in Figure 3 Subplot 4, but in the context of the spatial diversity analysis. The plot shows the transmission rate as a function of the number of antennas, comparing the MEVT-based rate selection with conventional methods. The MEVT-based approach achieves rates of 1.50, 1.85, 2.19, 2.50, 2.79, and 3.05 bps/Hz for 1 through 6 antennas respectively, representing a consistent improvement over the conventional method which achieves only 1.00, 1.33, 1.52, 1.69, 1.83, and 1.95 bps/Hz at the same antenna counts.

The widening gap between the two approaches as the number of antennas increases illustrates the increasing value of accurate joint tail modeling in systems with higher diversity order. With 6 antennas, the MEVT method provides a 56% higher transmission rate than the conventional method while maintaining the same ultra-reliability constraints. This substantial improvement is made possible by MEVT's ability to exploit the true dependence structure of the joint tail distribution. The conventional method, which treats each channel independently, must be conservative in its rate selection to account for the possibility of simultaneous deep fades. By accurately quantifying the probability of such simultaneous events, MEVT enables the system to operate more aggressively, achieving higher data rates without compromising the reliability guarantee. The rate selection algorithm incorporates the parameters of the probability measure function and the bivariate GPD into the optimum transmission rate determination, ensuring that the chosen rate satisfies the ultra-reliability constraints. This represents a significant advancement over conventional approaches that rely on extrapolation from univariate models, which tend to overestimate the probability of simultaneous extreme events and thus overly conservative rate selection.

The final subplot (Training Data Requirement) compares the amount of training data required by MEVT-based and conventional methods to achieve reliable estimates for rate selection. The bar chart shows the training data required for 2, 4, and 6 antennas, with the MEVT method consistently requiring less data across all configurations. For 2 antennas, the MEVT method requires approximately 25 training data points, while the conventional method requires approximately 50 points. For 4 antennas, the MEVT requirement is approximately 17 points compared to 33 points for conventional, and for 6 antennas, MEVT requires approximately 12.5 points compared to 25 points for conventional. The MEVT method thus requires approximately 50% less training data than the conventional method, representing a substantial advantage particularly in dynamic communication scenarios where channel conditions change rapidly. This reduction in training data requirement is achieved through the superior statistical efficiency of the multivariate extreme value modeling framework.

By accurately modeling the dependence structure of the joint tail distribution, MEVT makes more efficient use of the available data than conventional methods that ignore this dependence structure or model it inadequately. The reduced data requirement is particularly valuable for URLLC applications where the low-

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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latency constraints limit the amount of data that can be collected before transmission decisions must be made. Furthermore, the confidence interval estimation incorporated into the MEVT framework enables reliable operation even with limited data, as the uncertainty in the parameter estimates is explicitly quantified and accounted for in the rate selection. This combination of statistical efficiency and uncertainty quantification makes MEVT a compelling approach for rate selection in next-generation wireless systems, enabling higher transmission rates with less data while maintaining the stringent reliability requirements of URLLC.

Table 6: Summary of Major Results

EVT Approach	Primary Application	Main Result	Key Advantage
GPD-based EVT	Extreme SINR modeling	Empirical and GPD estimates closely agree; maximum deviation <10%	Reliable tail characterization
EVT predictive interference management	Interference prediction	Up to 100-fold reported outage reduction	Improved extreme-interference prediction
EVT-enriched radio maps	Spatial channel prediction	83.8% vs. 81.5% coverage meeting outage demands	Improved spatial reliability prediction
GAN-based GPD estimation	Real-time parameter estimation	Lower RMSE than MLE under evaluated sample sizes	Better adaptability with limited data
MEVT rate selection	Spatial diversity	3.05 vs. 1.95 bps/Hz at six antennas	Higher rate under reliability constraints
MEVT sample efficiency	Limited-data rate selection	Approximately 50% less training data	Reduced data requirement

Overall, the results indicate that no single EVT technique is optimal for every URLLC application. Instead, the appropriate method depends on the specific source of reliability degradation. Univariate GPD models are suitable for extreme channel characterization, EVT-KDE mixtures are appropriate for interference prediction, EVT-enriched radio maps are suited to spatial channel analysis, GAN-assisted estimation is promising for adaptive parameter estimation, and MEVT is particularly relevant where correlated extreme events occur across multiple diversity branches.

Observed Challenges and Future Directions

The following are the observed key challenges and the corresponding future directions for EVT in URLLC.

Key Challenges

a. Real-Time Parameter Estimation: Traditional MLE for GPD parameters requires a large amount of data, which conflicts with the low-latency requirements of URLLC (Valiahdi & Coleri, 2024).
b. Limited Data Availability: The ultra-reliable region $(10^{-9}$ to 10^{-5} error rates) requires modeling of events that occur very rarely, making it difficult to collect sufficient training data (Mehrnia & Coleri, 2026).

Future Research Directions

From the study carried out, the following are the observed future directions for EVT in URLLC:

a. Integration of EVT with Generative AI: Integrating Extreme Value Theory with generative artificial intelligence offers improved accuracy in predicting rare but critical events while providing

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

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adaptivity to dynamic scenarios (Valiahdi & Coleri, 2024; Coleri, 2025).

b. Multivariate EVT for Diversity: Extending MEVT to higher dimensions and more complex diversity schemes to exploit the full potential of spatial, frequency, and time diversity (Mehrnia & Coleri, 2026).

CONCLUSION

This study investigated the application of Extreme Value Theory (EVT) to the modeling and management of rare but critical wireless-channel events in Ultra-Reliable Low-Latency Communications (URLLC) for 5G and emerging 6G networks. The study was motivated by the observation that the reliability of mission-critical wireless applications is determined not by average channel behavior, but by infrequent extreme events such as deep fading, severe interference, and simultaneous adverse channel conditions. The findings demonstrate that EVT provides a statistically rigorous framework for characterizing these events and for estimating their probabilities beyond the range directly observable in conventional datasets. The GPD-based analysis demonstrated a close correspondence between empirical extreme-SINR observations and the fitted tail model, with the reported maximum deviation between empirical and GPD-based estimates remaining below 10% across the evaluated range. This result supports the use of GPD modeling as a practical approach for characterizing extreme wireless-channel behavior and estimating rare-event probabilities.

The comparative analysis further showed that different EVT-based methods provide distinct benefits for URLLC operation. EVT-based predictive interference management demonstrated substantial reliability improvements over conventional DTMC-based modeling under the evaluated conditions, with the reviewed results reporting up to a 100-fold reduction in outage rate and approximately 15% lower radio-resource usage. EVT-enriched radio maps improved the spatial identification of regions satisfying stringent outage requirements, while GAN-based GPD parameter estimation showed promising adaptability when the number of available samples was limited. The MEVT analysis provided an additional important finding by demonstrating the value of modeling dependence between multiple channels in spatial-diversity systems. The MEVT-based rate-selection approach increased the achievable transmission rate from approximately 1.50 bps/Hz with one antenna to 3.05 bps/Hz with six antennas. At six antennas, the reported rate was approximately 56% higher than the conventional approach.

Furthermore, the MEVT method required approximately 50% less training data across the evaluated diversity configurations. These results indicate that accurate joint-tail modeling can improve the balance between reliability, transmission efficiency, and data requirements in diversity-enabled URLLC systems. Despite these advantages, the study also highlights several unresolved challenges. The estimation of extreme-event parameters remains difficult when data are scarce, while real-time adaptation is constrained by the computational complexity of statistical and machine-learning models. The extension of MEVT to higher-dimensional diversity systems introduces additional challenges associated with parameter estimation and computational scalability.

Furthermore, the reliability of far-tail extrapolation depends strongly on threshold selection, model assumptions, and the quality of available measurements. The present analysis also relies partly on synthetic data and simulated GAN-based estimation, meaning that the reported improvements require further validation using real-world 5G/6G channel measurements and operational network environments. Future research should therefore focus on developing adaptive EVT frameworks capable of operating in non-stationary wireless environments, where channel and interference statistics change rapidly.

Combining EVT with generative AI, federated learning, and spatially distributed radio maps represents a promising direction for reducing data requirements while maintaining reliable tail estimation. Similarly, extending MEVT to higher-dimensional spatial, frequency, and

Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.

temporal diversity systems could enable more accurate modeling of simultaneous extreme events in advanced 6G networks. Finally, the evidence reviewed and the computational results presented in this study indicate that EVT should be regarded as a complementary statistical framework rather than a replacement for conventional wireless-channel models. Its principal value lies in its ability to focus explicitly on the rare events that dominate URLLC reliability.

The integration of GPD-based tail modeling, EVT-driven interference prediction, spatially informed radio maps, AI-assisted parameter estimation, and MEVT-based diversity analysis provides a promising pathway toward more reliable and data-efficient wireless systems. Future progress will depend on validating these approaches using large-scale real-world measurements, quantifying uncertainty in extreme-tail predictions, and developing computationally efficient EVT–AI architectures suitable for real-time deployment in 5G-Advanced and 6G networks.

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Corresponding author: Agbon E. E.
eagbonehime1@gmail.com
Department of Electronics and Telecommunications Engineering, Ahmadu Bello University, Zaria, Kaduna, Nigeria.