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Review

From Stochastic Foundations to Emerging Frontiers: A Comprehensive Survey on Packet Jitter Modeling, Measurement, and Metrics in IP Networks

Juan Eduardo Macias-Rivera, José Ricardo Gómez-Rodríguez *, Ana Gabriela Castañeda-Miranda, Remberto Sandoval-Arechiga, Víktor Ivan Rodríguez-Abdala and Salvador Ibarra-Delgado

Posgrado en Ingeniería para la Innovación Tecnológica, Unidad Académica de Ingeniería Eléctrica, Universidad Autónoma de Zacatecas, Campus UAZ Siglo XXI, Carretera Zacatecas-Guadalajara km 6, Ejido la Escondida, Zacatecas 98160, Mexico; jeduardo@uaz.edu.mx (J.E.M.-R.); agmiranda@uaz.edu.mx (A.G.C.-M.); rsandoval@uaz.edu.mx (R.S.-A.); abdala@uaz.edu.mx (V.I.R.-A.); sibarra@uaz.edu.mx (S.I.-D.)

* Correspondence: jrgrodri@uaz.edu.mx; Tel.: +52-4921760097

Abstract

Packet delay variation (jitter) affects the reliability and perceived quality of real-time IP services, but its models and metrics remain fragmented across layers and technologies. This structured survey synthesizes research published from 1990 through August 2026 in three methodological families: stochastic and analytical foundations, simulation and empirical approaches, and cross-layer application-aware methods. The evidence shows a progression from single-queue formulations to end-to-end, heavy-tailed, self-similar, and data-driven models. A reproducible illustration using 1440 RIPE Atlas measurement windows demonstrates why metric choice matters: the 99th percentile of absolute consecutive RTT differences was 8.17 ms, excess-over-minimum RTT reached 52.36 ms, and an RFC 3550-style recursive estimator peaked at only 6.14 ms. The main unresolved problems are unified modeling across heterogeneous wired–wireless paths, comparable high-resolution measurement, cross-layer QoE prediction, reproducibility, and timing-channel security. Priority directions are distribution-aware reporting, open benchmark traces, hybrid analytical–learning models, and stable closed-loop control for 5G/6G, TSN/DetNet, SDN/NFV, and edge networks.

Keywords: jitter; packet delay variation; QoS; VoIP; video streaming; network measurement; queueing models; real-time communication

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1. Introduction

Packet delay variation (PDV), commonly called jitter, is the variation in packet transit time. It is a primary performance constraint for conversational voice, interactive video, industrial control, and other delay-sensitive services because packets that arrive outside the receiver's playout or control deadline are effectively lost [1–3]. Unlike mean delay, jitter describes temporal dispersion; two paths with the same average latency can therefore produce substantially different application outcomes.

The mechanisms that generate jitter have expanded with the telecommunication infrastructure. Classical analyses focused on queue occupancy, service time, multiplexing, and multi-hop accumulation. Current paths also traverse wireless schedulers, software switches, virtualized network functions, containers, and edge platforms, where radio

retransmissions, CPU scheduling, memory contention, and control-plane updates introduce non-stationary delay components [4–7].

Operational metrics do not always expose the events that matter to applications. RFC 3550, for example, uses an exponentially smoothed estimator that is inexpensive to compute, whereas RFC 3393 defines packet-level delay variation more generally [1,8]. Newer transports such as QUIC similarly maintain smoothed round-trip and variation estimates for loss recovery, but these transport-level signals are not substitutes for application-deadline or tail-aware jitter evidence [9,10]. Windowed averages are useful for monitoring but may attenuate isolated spikes, burst clusters, and distribution tails. A structured comparison is therefore needed to distinguish what each model or metric measures, the conditions under which it is valid, and the application behavior it can predict.

This comprehensive survey examines peer-reviewed research published from 1990 to 2026. It addresses four objectives: (i) trace the evolution of jitter models from queueing foundations to empirical and cross-layer approaches; (ii) compare measurement definitions, instrumentation, and reporting practices; (iii) synthesize the effects reported for VoIP, video, and QoS mechanisms; (iv) identify gaps associated with heterogeneous, software-defined, virtualized, and emerging 5G/6G networks. Its principal contribution is an integrated view of model assumptions, measurable quantities, and application consequences, with particular attention to the limits of standard summary metrics. Figure 1 summarizes the organization and analytical scope of the survey.

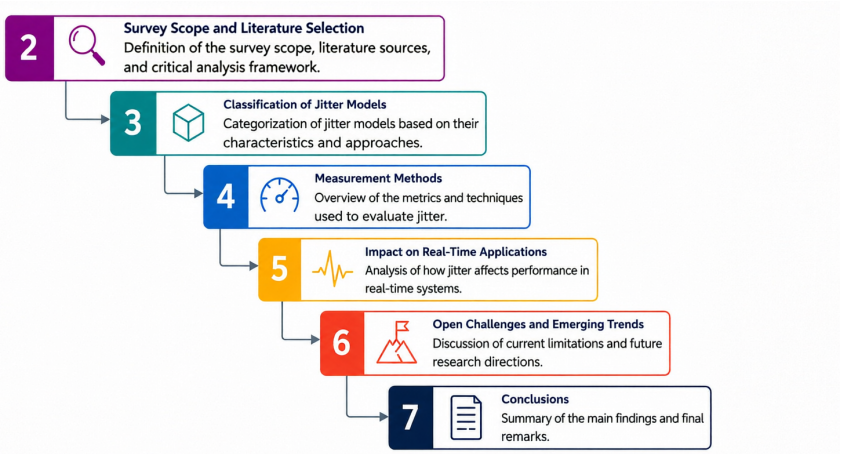


Figure 1. Scope of the review across jitter modeling, measurement, application impact, and open research problems. Source: Authors' own elaboration.

Section 2 defines the survey scope and literature selection. Section 3 synthesizes modeling approaches, Section 4 examines measurement, and Section 5 reviews application impact and mitigation. Section 6 presents open challenges and an integrated research roadmap, and Section 7 concludes the survey. Extended evidence tables and the bibliographic study inventory are provided as Supplementary Materials.

2. Survey Scope and Literature Selection

This article is a structured comprehensive survey rather than a statistical meta-analysis. Its purpose is to connect the mathematical foundations of packet delay variation with measurement practice, application effects, and emerging network architectures. The review covers literature published from January 1990 through August 2026 and uses transparent reporting and evidence-traceability practices without claiming formal PRISMA compliance.

2.1. Information Sources and Search Strategy

The literature search covered IEEE Xplore, Scopus, ScienceDirect, SpringerLink, and Google Scholar. The core query combined three concepts:

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("packet delay variation" OR "packet jitter" OR "interarrival jitter") AND
("IP network" OR VoIP OR "video streaming" OR TSN OR DetNet) AND
(model* OR measur* OR QoS OR QoE OR estimat* OR control).
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Database-specific syntax and field restrictions were adapted without changing these conceptual groups. Searches were supplemented by backward and forward citation chaining to connect foundational queueing studies with subsequent empirical, cross-layer, wireless, deterministic-networking, and data-driven research. The search/update periods and source-specific adaptations are reported in Supplementary Table S4.

2.2. Eligibility and Study Selection

Peer-reviewed journal articles and conference papers were eligible when packet jitter, packet delay variation (PDV), IP packet delay variation (IPDV), or an equivalent packet-timing-dispersion quantity was an explicit modeling, measurement, experimental, performance, or control variable. Eligible contributions addressed at least one of the following: analytical or stochastic modeling; simulation, emulation, or empirical characterization; measurement and metrology; application-level effects on delay-sensitive services; or mitigation and architectural control.

Records were excluded when they addressed only mean latency, throughput, or packet loss without explicit delay variation analysis; used jitter solely for physical-layer phase, frequency, or clock phenomena unrelated to packet timing; or provided insufficient technical evidence for classification. IETF RFCs and ITU-T Recommendations were retained separately when they supplied normative definitions, measurement procedures, or performance objectives. They support interpretation but are not counted as peer-reviewed studies.

Selection proceeded through deduplication, title-and-abstract relevance assessment, and full-text eligibility assessment. Studies found through citation chaining were subjected to the same criteria. A study-level inventory in the Supplementary Materials records the final classification and distinguishes peer-reviewed publications, normative standards, and supporting documents. This distinction prevents the number of research studies from being conflated with the length of the reference list.

The original search was developed iteratively and the platform-level result counts at each historical update were not archived. We therefore do not reconstruct a retrospective PRISMA flow diagram or claim formal PRISMA compliance, because doing so would require unverifiable screening counts. Instead, this survey reports the sources, conceptual query, eligibility rules, update period, evidence fields, final corpus composition, and complete supporting inventory.

2.3. Evidence Extraction and Taxonomic Rationale

For each retained study, the review recorded year, network context, application domain, modeling family, traffic assumptions, jitter definition, observation point, measurement or evaluation method, synchronization requirements, reported performance evidence, and principal limitation. Direct numerical aggregation was not attempted because the studies differ substantially in topology, load, packet size, timestamping, measurement duration, metric definition, and application context.

The three principal modeling families are based on the dominant methodological role of each contribution: *stochastic and analytical foundations* represent jitter through mathematically tractable mechanisms; *simulation and empirical approaches* characterize observable behavior through controlled or operational evidence; and *cross-layer and application-aware*

methods jointly represent jitter with scheduling, buffering, codec, radio, platform, or control state. Application domain and network technology remain secondary classification dimensions within these families. This structure preserves the historical and methodological progression while allowing the same study to be located by technology, application, observation point, and metric in the extended evidence matrix.

The survey is guided by four questions:

1. How have packet jitter models evolved from single-node queueing abstractions to end-to-end and data-driven formulations?
2. Which measurement definitions and instruments are used, and which packet-timing properties does each report?
3. How does jitter interact with buffering, codecs, scheduling, and traffic management in real-time services?
4. Which modeling, measurement, control, reproducibility, and security problems remain open in heterogeneous, SDN/NFV, TSN/DetNet, and 5G/6G environments?

3. Taxonomy and Analysis of Jitter Models

The reviewed evidence shows three successive, overlapping modeling traditions: analytical queueing models, simulation and measurement-driven models, and cross-layer estimators. The progression is not a simple replacement. Closed-form models remain useful for bounds and design insight, while empirical and adaptive methods address traffic and platform behavior that violates stationary assumptions.

3.1. Stochastic and Analytical Foundations

3.1.1. Single-Node Queueing Models

Early work represented jitter as the difference between successive packet delays produced by a queue. M/M/1 and related Markovian models provided tractable relations among arrival rate, service rate, utilization, and waiting-time variation [11,12]. Their value lies in interpretable sensitivity analysis and closed-form bounds. Their main limitation is the assumption of independent arrivals and simple service distributions, which is often violated by multiplexed, variable-rate, and bursty traffic.

Generalized queues, priority scheduling, and fluid approximations relaxed some assumptions. These models explain why jitter rises rapidly near saturation and why service differentiation can protect delay-sensitive flows, but accuracy depends on traffic characterization and scheduler knowledge. They are best treated as design abstractions rather than universal predictors.

3.1.2. Multi-Node and End-to-End Models

End-to-end jitter is not generally the sum of independent per-hop variances. Correlated cross-traffic, route asymmetry, and scheduling interactions can amplify or partially cancel variation. Network-calculus and stochastic-bound approaches estimate worst-case or probabilistic envelopes, while decomposition methods attribute variation to individual nodes [13,14]. These methods support admission control and provisioning, although conservative assumptions can overstate required resources.

3.1.3. Advanced Stochastic Models

Markov-modulated Poisson processes, self-similar traffic models, multifractal descriptions, and heavy-tailed distributions were introduced to represent burst persistence and extreme delay events [4,15]. Their empirical fit is typically better than Gaussian or Poisson baselines under aggregation and congestion. The trade-off is increased parameter estimation, reduced portability between scenarios, and limited closed-form tractability.

The evidence therefore favors selecting a distribution after testing stationarity, dependence, and tail behavior rather than assuming a universal family.

3.2. Simulation and Empirical Models

3.2.1. Simulation-Based Studies

Discrete-event simulators have been used to compare queue disciplines, traffic engineering, wireless access, and codec configurations under controlled load. Simulation enables repeatable counterfactual experiments, but reported jitter depends strongly on traffic generators, warm-up periods, topology, timestamp resolution, and the selected estimator. Reproducibility requires explicit reporting of these elements and validation against measured traces.

3.2.2. Emulation and Perceptual QoE Frameworks

Emulation inserts controlled delay variation into real protocol stacks and applications. It provides a useful bridge between mathematical models and operational deployments, particularly for playout buffers and codec studies. QoE frameworks then map network impairment to MOS, stalls, or deadline misses. Recent WebRTC and 5G-and-beyond multimedia studies reinforce that the mapping is non-linear because concealment, buffering, transport behavior, and adaptation change the effect of the same network trace [2,16–18].

3.2.3. Empirical Measurements

Measurement studies consistently report non-stationarity across time, path, load, and access technology. High-percentile and distributional analyses reveal events that are not visible in averages. However, comparisons remain difficult because studies use different packet sizes, sampling windows, clock synchronization, directions, and definitions of jitter. Public traces and shared reporting profiles are still uncommon.

3.3. Cross-Layer and Adaptive Models

3.3.1. Application-Aware Performance Mapping

Application-aware models combine network measurements with codec, buffer, and decoder state. They predict service outcomes more directly than network-only metrics and support adaptive playout or rate control. Their limitations are application specificity, feature drift, and the need for synchronized cross-layer telemetry.

3.3.2. Wireless Scheduling and Heterogeneous System Integration

Wireless models incorporate channel variation, retransmissions, scheduling intervals, handover, and multi-connectivity. In heterogeneous paths, these components interact with wired queues and virtualized functions, producing regime changes that a single stationary model cannot represent [6,19–21]. Recent work on converged 5G–TSN systems further shows that stochastic radio delay changes the parameters required by deterministic Ethernet scheduling [22–25]. Related programmable-network studies use traffic prediction and reinforcement learning to adapt routing and allocation with delay, jitter, loss, and throughput as joint objectives [26–29]. These approaches can reduce jitter under evaluated conditions, but their generalization, telemetry cost, and control-loop stability remain open concerns. Hybrid models that combine interpretable constraints with adaptive estimation are therefore more promising than a single stationary end-to-end distribution.

3.3.3. Taxonomic Synthesis and Architectural Trade-Offs

Analytical models offer interpretability and low computational cost; simulation offers experimental control; empirical models provide deployment fidelity; and cross-layer meth-

ods improve application relevance. No family dominates across all criteria. Model selection should follow the engineering question: bounding, diagnosis, prediction, or control.

3.4. Summary and Comparative Insights

The historical trend is toward models that preserve analytical structure while learning time-varying parameters from telemetry. The strongest future candidates are thus hybrid rather than purely closed-form or purely data-driven. Table 1 summarizes the comparative strengths and limitations of the five modeling families.

Table 1. Concise synthesis of packet jitter modeling families. Extended study-level Tables S1 and S2 are provided in the Supplementary Materials.

Family	Representative Basis	Primary Strength	Main Limitation
Queueing and analytical	M/M/1, generalized queues, network calculus	Interpretable mechanisms and bounds	Simplified arrival and service assumptions
Advanced stochastic	MMPP, self-similar, multifractal, heavy-tailed models	Captures dependence and tail behavior	Parameter sensitivity and reduced tractability
Simulation and emulation	Discrete-event networks and controlled impairment	Repeatable comparison of mechanisms	Scenario and configuration dependence
Empirical and data-driven	Trace fitting, regression, machine learning	High fidelity within observed regimes	Dataset shift and limited explainability
Cross-layer and adaptive	Network, buffer, codec, radio, and platform state	Direct application relevance and control support	Telemetry cost and application specificity

4. Measurement Methods

Packet delay variation studies differ in delay reference, packet selection, observation point, timestamping, synchronization, and aggregation. These differences can prevent direct comparison even when studies use the same generic term jitter. Recent TSN, 5G, and transport studies further show that end-system generation, scheduled transmission, edge placement, and transport estimation expose different timing regimes [10,30,31].

4.1. Normative Framework and Common Definitions

Standardized packet-timing metrics use different references and should not be treated as interchangeable. Let $t_i^{(s)}$ and $t_i^{(r)}$ denote the transmission and reception timestamps of packet i, respectively, and let its one-way delay be

$$d_i = t_i^{(r)} - t_i^{(s)}. \tag{1}$$

RFC 3393 defines IP packet delay variation (IPDV) for a selected packet pair (i, j) as [1]

$$\mathrm{IPDV}(i, j) = d_j - d_i. \tag{2}$$

For consecutive packets, this becomes $\mathrm{IPDV}_i = d_i - d_{i-1}$. IPDV is signed; its value and interpretation depend on the packet-selection function and packet ordering.

RFC 5481 distinguishes this pairwise difference from packet delay variation (PDV), which expresses delay relative to a common reference such as the minimum delay observed over measurement set $\mathcal{I}$ [32]:

$$d_{\min} = \min_{k \in \mathcal{I}} d_k, \qquad \mathrm{PDV}_i = d_i - d_{\min}. \tag{3}$$

PDV is non-negative and preserves the shape of the one-way delay distribution after translation. It is therefore suitable for distributional and tail-oriented analysis, subject to the measurement interval and sample selection.

RFC 3550 adopts a packet-spacing perspective for RTP monitoring [8]. If S_i is the RTP timestamp and R_i the reception time in the same units, the spacing difference for consecutively received packets is

$$D(i-1,i) = (R_i - R_{i-1}) - (S_i - S_{i-1}), \tag{4}$$

and the interarrival jitter estimator is updated as

$$J_i = J_{i-1} + \frac{|D(i-1,i)| - J_{i-1}}{16}. \tag{5}$$

This is an exponentially smoothed runtime estimator of absolute packet-spacing variation, not a realization of either IPDV or PDV.

ITU-T Y.1540 defines IP packet-transfer performance parameters, and Y.1541 specifies corresponding network-performance objectives and QoS classes [33,34]. At the terminal and application levels, G.1020 relates packet-network impairments to de-jitter buffer delay and late-packet discards, while G.114 provides guidance for conversational transmission delay [35,36]. RFC 8655 places bounded latency and low packet delay variation within a deterministic-networking architecture, but does not replace the metric definitions above [37].

Table 2 formalizes the distinct references and interpretations used by the principal standardized metrics.

Table 2. Formal distinction among standardized packet delay variation metrics.

Reference	Metric	Delay Reference	Principal Interpretation
RFC 3393	IPDV	Selected packet pair	Signed difference between two one-way delays; sensitive to packet selection and ordering.
RFC 5481	PDV	Common reference, typically minimum observed delay	Non-negative distribution of excess one-way delay relative to the reference.
RFC 3550	RTP interarrival jitter	Sender–receiver packet-spacing difference	Exponentially smoothed estimator for continuous RTP/RTCP monitoring.

4.2. Taxonomy of Measurement Methods

The structural taxonomy presented in Figure 2 provides a systematic organization of these measurement methods into six primary analytical categories. This organization demonstrates that network jitter evaluation scales from raw physical-layer or link-layer interval timing captures up to abstract cross-layer perceptual mappings, depending entirely on whether the tracking objective targets localized router performance calibration or end-to-end user satisfaction.

Figure 2 organizes the measurement space by temporal observable and reference. The comparison below separates metric definition from acquisition mechanism and application-level interpretation.

No single accuracy value can be compared across all approaches because several rows define different quantities rather than competing estimators of the same ground truth. The extended study-level matrix therefore records the numerical outcome reported by each publication and uses “NR” when accuracy, runtime, sample size, or complexity was not provided. This avoids converting missing evidence into an inferred performance ranking.

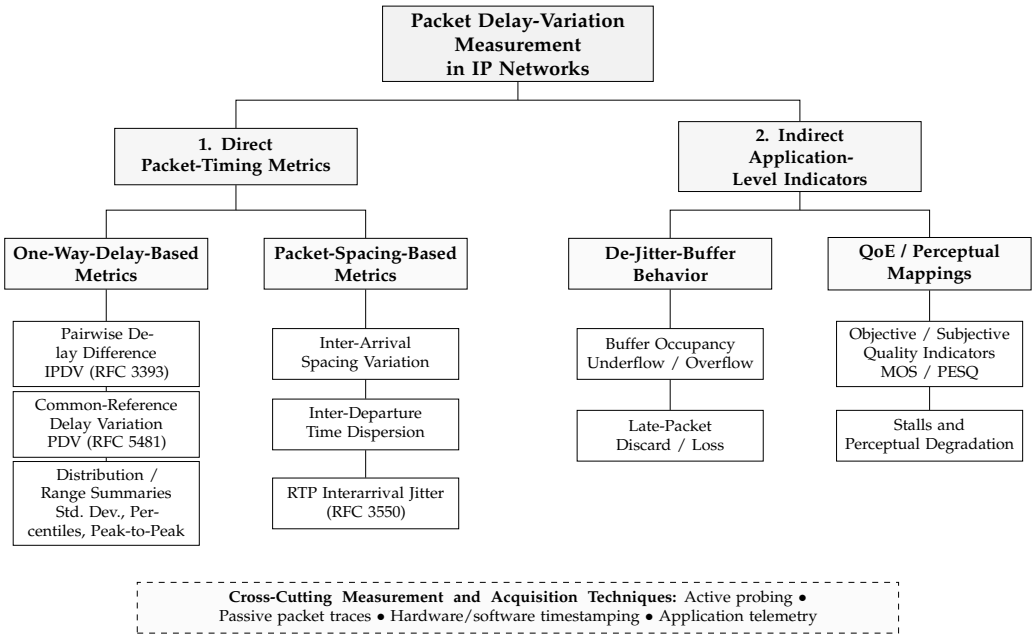


Figure 2. Hierarchical taxonomy of packet delay variation measurement approaches in IP networks, organized according to the primary temporal observable and measurement reference. Source: Authors' own elaboration.

Table 3 compares the operational requirements, computational characteristics, and limitations of these approaches.

Table 3. Technical comparison of principal packet delay variation measurement approaches. Complexity refers to processing n observations and excludes packet capture. NR denotes not reported by the cited studies.

Approach	Timing and Data Requirements	Processing Cost	Reported Performance Evidence	Principal Limitation
RFC 3393 IPDV	One-way delays for selected packet pairs; synchronized or otherwise calibrated clocks	$O(n)$ time; $O(1)$ streaming memory	Timestamp uncertainty and packet-selection sensitivity are evaluated in metrology studies [38–40]	Signed pair differences do not by themselves describe the full delay distribution or buffer outcome.
RFC 5481 PDV	One-way delay sample and a common reference; normally minimum observed delay	$O(n)$ time; $O(n)$ storage for exact empirical distribution	Supports percentiles and distributional summaries relevant to service objectives [32–34]	Results depend on interval duration, sample selection, loss handling, and reference stability.
RFC 3550 RTP jitter	RTP timestamps and receiver arrival times in consistent units; wall-clock synchronization is not required	$O(1)$ per packet	Lightweight continuous reporting through RTCP [8,41,42]	Exponential smoothing attenuates isolated excursions and does not report tail probabilities.
Percentile and peak-to-peak summaries	Delay or PDV observations; consistent sampling and loss policy	$O(n \log n)$ for exact sorting; $O(n)$ with selection or streaming sketches	p95/p99 and extrema expose high-delay events when studies report sufficient sample size [43,44]	Cross-study comparison is invalid without sample size, interval, quantile method, and confidence reporting.
Active probing	Controlled OWAMP, TWAMP, or ICMP probes; one-way methods require clock synchronization	$O(n)$ plus injected traffic	Enables repeatable path measurements and calibrated timestamp studies [45–47]	Probe traffic, spacing, direction, and observation point may differ from application traffic.
Hardware timestamping	NIC, FPGA, or test equipment with calibrated clocks	$O(n)$ processing; equipment-dependent capture cost	Sub-microsecond timestamp resolution is reported in controlled Ethernet environments [40,44]	High resolution does not guarantee end-to-end representativeness; calibration and deployment cost remain.
QoE or buffer-based inference	Network timing plus codec, playout buffer, or application state	Model-dependent; NR consistently	Studies report MOS, late loss, stalls, or buffer events rather than estimator error [2,16,18,48]	Application-specific mappings do not constitute a universal network-layer jitter definition.
Data-driven prediction/control	Telemetry features, training data, topology or control state	Training and inference cost varies; NR consistently	Recent studies report scenario-specific reductions in delay/jitter or routing reward [26–29]	Dataset shift, reproducibility, explainability, and control-loop stability limit generalization.

4.3. Reproducible Trace Illustration

To make the practical distinction among the metrics concrete, we analyzed a public RIPE Atlas built-in IPv4 ping trace [49] (measurement 1001, K-root target 193.0.14.129) from probe 6398 in Mexico. The fixed interval was 240 s; the selected interval, 28–31 August 2026 UTC, contains 1440 measurement windows and three ICMP replies per complete window. The raw JSON response, derived CSV series, and analysis script are included with the reproducibility files.

RIPE Atlas reports round-trip time (RTT), not synchronized one-way delay. We therefore compute RTT-derived analogs solely to illustrate metric behavior: the signed consecutive difference $d_i - d_{i-1}$, excess RTT above the sample minimum $d_i - d_{\min}$, and the RFC 3550 recursive smoother applied to the absolute consecutive difference. These quantities are not presented as standards-conformant one-way IPDV/PDV or as RTP measurements.

Across the valid windows, mean RTT was 67.47 ms and the minimum was 47.47 ms. The 95th, 99th, and 99.9th percentiles of absolute consecutive differences were 2.12, 8.17, and 34.94 ms, respectively. Excess-over-minimum RTT reached 41.57 ms at the 99th percentile, 45.86 ms at the 99.9th percentile, and 52.36 ms at its maximum; the RTT peak-to-peak range was therefore 52.36 ms. Relative to the global minimum reference, 89.79%, 89.79%, and 4.65% of windows exceeded 10, 20, and 30 ms, respectively. These are threshold-exceedance rates, not a measured RTP de-jitter buffer loss rate, because the trace contains RTT probes rather than media-packet playout timestamps. The recursive estimate reached only 6.14 ms at its maximum. Figure 3 therefore demonstrates the interpretive distinction: a signed pairwise metric detects direction and abrupt change, a common-reference metric preserves the distribution of excess delay, and an RFC 3550-style recursion supplies a stable online indicator at the cost of attenuating isolated spikes. The numerical values are trace-specific and are not offered as universal performance thresholds.

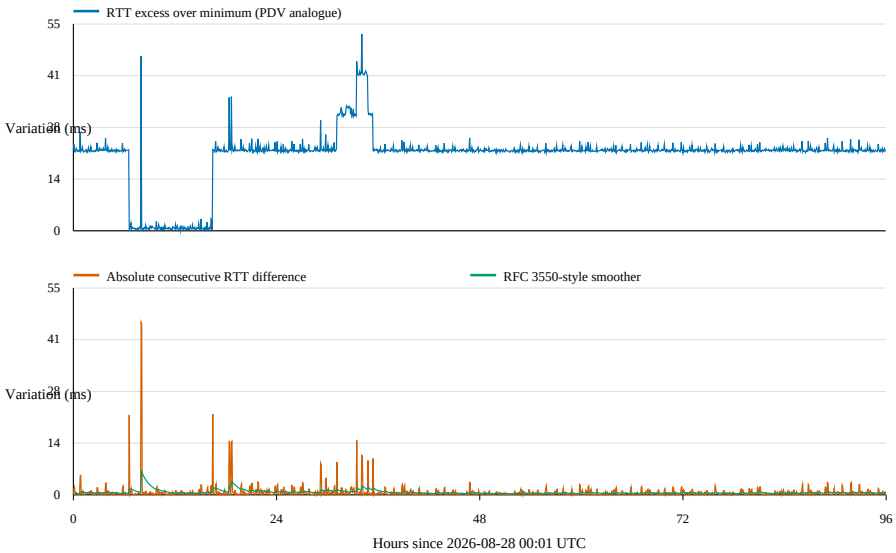


Figure 3. Metric behavior on the public RIPE Atlas trace. The common-reference series retains sustained excess delay, while the recursive estimator smooths individual excursions. Source: Authors' calculation from RIPE Atlas measurement 1001.

5. Impact of Jitter on Real-Time Applications

Packet delay variation serves as a critical determinant of user-perceived quality in real-time application domains, where the temporal consistency of packet delivery dictates system stability as much as raw throughput or baseline loss rates. In unmanaged, best-effort IP networks, stochastic packet serialization and transient queueing anomalies modify the

inter-packet gap, introducing timing distortions that disrupt streaming applications. This section explores the structural and perceptual impact of jitter across two major domains: Voice over IP (VoIP) and video streaming, concluding with a comprehensive evaluation of Quality of Service (QoS) and traffic management orchestration frameworks.

5.1. Voice over IP (VoIP)

Deploying conversational Voice over IP (VoIP) platforms over legacy IP architectures introduces substantial technical challenges. Speech codecs commonly packetize audio at intervals on the order of 10–20 ms, while ITU-T G.114 treats approximately 150 ms as guidance for the complete one-way mouth-to-ear delay path rather than for the de-jitter buffer alone [35,36]. Packet delay variation consumes part of that end-to-end budget: arrivals that miss the finite playout window are discarded or concealed by the receiver, and increasing buffer depth reduces late loss at the cost of conversational delay.

To map how the networking literature addresses these temporal challenges, Table 4 categorizes prominent VoIP-focused jitter research based on its core methodological and architectural contributions.

Table 4. Taxonomic classification of reviewed studies on jitter mechanics in VoIP services.

Analytical Category	Sources	Primary Operational Observation
Stochastic & Queueing Modeling	[15,50–55]	Demonstrates that voice jitter is driven by core multi-hop queueing dynamics and background traffic bursts. Evaluates how playback buffers smooth timing variations at the expense of adding conversational latency.
Empirical Loss & Multifractal Analysis	[4,41,56]	Models packet arrival dispersion profiles using empirical captures, showing that unmanaged voice flows exhibit complex self-similarity and long-range dependence.
Adaptive Estimation & Spike Detection	[42]	Formulates link-adaptive estimation matrices equipped with sudden delay-spike detection to reduce deadline-driven packet losses at the receiver.
Playout Adaptation & Buffer Management	[16,57–59]	Validates that dynamic playout buffer sizing is mandatory to mitigate late-packet drops while balancing conversational interactivity.
Perceptual Quality Calibration (MOS/E-model)	[60–64]	Enhances the ITU-T E-model framework by explicitly integrating buffer-induced loss profiles, yielding precise Mean Opinion Score (MOS) forecasts.
Cross-Layer Telemetry Mapping	[65,66]	Establishes tight mathematical correlations between transport-layer IPDV metrics and application-layer MOS-LQO values to enable passive monitoring.
Metrological Sampling & Frameworks	[1,38,67]	Confirms that the calculated voice jitter profile depends heavily on observation window choices, sampling frequencies, and processing filters.
Passive ISP Monitoring	[68–70]	Utilizes operational network probes to confirm that concurrent jitter, loss, and latency act as joint indicators of perceptual voice degradation.
Topological QoS Simulations	[71–77]	Leverages OPNET/OMNeT++ models to show that link scheduling and traffic prioritization mitigate jitter, though voice remains sensitive to core congestion.
Call Admission Control (CAC)	[78]	Develops a proactive call admission scheme that evaluates real-time delay variation statistics from active network probes to block over-provisioning.

The systematic mapping in Table 4 highlights that voice-layer quality degradation cannot be isolated to a single network variable. Instead, packet delay variation acts as a primary catalyst that forces client-side de-jitter buffer overflows or starvation events. When packets arrive past their designated playout deadline, the application layer is forced to discard them, converting transport-layer timing dispersion directly into effective packet loss. This conversion causes audible clipping and synthesis artifacts, showing that voice stability requires a strict balance between network prioritization and dynamic playout adaptation.

5.2. Video Streaming

Measuring internet protocol packet delay variation (IPDV) is equally critical in high-bandwidth, real-time video streaming infrastructures [79]. For digital video payloads, packet delay variation manifests through structural distortions that cause frame freezing, macroblocking, and visible decoding artifacts. Because video payloads are highly bursty and grouped into large multi-packet frames (such as I-frames), timing dispersion within a single spatial cluster can stall the entire decoding pipeline. This latency triggers buffer underflows even under low baseline packet loss rates [2,3,17,18].

Table 5 organizes prominent research contributions analyzing the specific effects of packet delay variation on digital video streaming architectures.

Table 5. Taxonomic classification of reported jitter research contributions in video streaming services.

Analytical Category	Sources	Primary Operational Observation
Cross-Layer Video Quality Mapping	[79–81]	Maps transport-layer IPDV parameters directly to video degradation benchmarks, proving that active telemetry captures perceptual impairment.
Subjective QoE Assessment	[3,48,82,83]	Proves that severe timing dispersion triggers visible decoding stalls and frame drops, reducing user retention metrics and overall satisfaction.
Objective Metric Benchmarking	[2,64,84]	Evaluates video payloads using objective VQM, SSIM, and PSNR frameworks, showing that joint loss and jitter cause non-linear drop-offs in quality.
Playout Adaptation Mechanisms	[85–88]	Employs selective packet discarding and continuous-rate playout strategies to reduce frame stalls and prevent receiver-side buffer overflows.
Adaptive Streaming Control (ABR)	[89,90]	Connects dynamic bandwidth estimates with jitter bounds, showing that adaptive rate controllers are required to prevent playback underflows.
Statistical Curve-Fitting Models	[53,91–93]	Applies heavy-tailed probability distribution modeling to characterize IPTV and low-rate video traffic across asymmetric access networks.
Architectural Resource Provisioning	[73,94,95]	Demonstrates that traffic-shaping via DiffServ-MPLS and dynamic DBA algorithms in EPON architectures suppresses multi-hop video delay variation.
Multi-Connectivity Frameworks	[19,20]	Utilizes simultaneous cellular links and link-layer HARQ tuning to optimize the operational delay-jitter trade-off for high-definition streaming.

The structural insights categorized in Table 5 confirm that the perceptual impact of jitter varies significantly between interactive voice and video streaming because their playout architectures and latency budgets differ. In conversational VoIP, additional de-jitter buffering consumes part of the complete one-way mouth-to-ear delay budget and can therefore impair bidirectional interaction even when it reduces late-packet loss [35,36].

Conversely, non-interactive video streaming can absorb short-term timing variation through deeper receiver buffers and adaptive bit rate mechanisms. Voice remains especially sensitive to abrupt consecutive-packet changes because its interactivity budget limits buffering, whereas video analysis often benefits from common-reference PDV distributions, high percentiles, exceedance duration, and buffer-event measurements. RFC 3393 IPDV remains a selected-pair delay difference; it is not a discrete-window statistic.

5.3. Role of QoS and Traffic Management

Suppressing packet delay variation within congested transport segments requires active Quality of Service (QoS) orchestration and traffic-shaping frameworks. Bounding jitter cannot be achieved through passive edge monitoring alone; instead, it demands coordinated resource allocation policies across both access loops and backbone routing cores.

Table 6 maps the core research vectors where advanced QoS architectures, traffic-shaping policies, and queue management algorithms have been deployed to control timing dispersion.

Table 6. Classification of reviewed QoS and traffic management approaches for systemic jitter control.

Analytical Category	Sources	Primary Operational Observation
Heterogeneous Fabric Coordination	[19,77,91,93–97]	Confirms that mitigating jitter demands coordinated scheduling across core, wireless, and optical network boundaries to protect multimedia streams.
Predictive Boundary Modeling	[98,99]	Develops analytical bounds and predictive traffic-shaping frameworks to prevent quality violations prior to queue saturation.
Deterministic Networks (TSN)	[30,100–104]	Shows that deterministic scheduling and regulation can provide bounded timing behavior in industrial networks; some approaches achieve zero-jitter delivery without requiring time synchronization, so deterministic MAC scheduling is not asserted as the only mechanism.
Shaping vs. Latency Trade-offs	[11,12,51,53,59,86–88,105–108]	Identifies a fundamental engineering trade-off where in-network traffic smoothing suppresses arrival dispersion but increases absolute latency.
Traffic Engineering (TE) & Routing	[78,89,109–112]	Demonstrates that embedding strict jitter constraints modifies traditional shortest-path routing, capacity planning, and flow allocation decisions.
Qualitative Framework Taxonomy	[113–115]	Establishes the standard terminology for multi-service networks, detailing the structural properties of IntServ, DiffServ, and SLA policies.
Joint QoS/QoE Infrastructure Monitoring	[2,3,47,48,56,60,64,66,68,70,75, 81,84,116]	Demonstrates that network delay variation must be evaluated alongside packet loss, throughput, and subjective MOS data to maintain visibility.
Active Queueing Scheduling	[50,52,55,71–74,76,92,117,118]	Validates that implementing priority mechanisms (e.g., PQ, WFQ, CBWFQ, and WRED) isolates real-time packets from background traffic bursts.
Software-Defined Traffic Orchestration	[5,20,90,119]	Leverages dynamic SDN flow reconfiguration to bypass congested routers and adaptively route traffic under volatile network loads.

The technical findings compiled across these management frameworks reveal that jitter mitigation is governed by systemic engineering trade-offs. Priority scheduling architectures (such as Class-Based Weighted Fair Queueing and Strict Priority Queueing) isolate voice and video streams from lower-priority cross-traffic bursts. However, this optimization can increase packet delay variation for elastic data flows, compromise link equity, and demand significant processing overhead at intermediate routers.

Furthermore, using in-network traffic shapers and leaky-bucket regulators to smooth out bursty packet flows introduces an unavoidable delay penalty, as packets are intentionally delayed to restore original timing profiles. Consequently, modern network orchestrators cannot treat jitter control as an isolated mathematical objective; instead, it must be solved as a multi-variable optimization problem that balances timing consistency, absolute delay bounds, packet drop rates, and architectural fairness.

5.4. Summary of Key Findings

The extensive review of application behaviors and active mitigation frameworks yields several key findings:

- **Direct Perceptual Degradation:** Packet delay variation acts as a primary driver for voice and video quality degradation, directly reducing MOS values by turning timing instability into deadline-driven packet loss at the application layer.
- **Asymmetric Sensitivity Boundaries:** Interactive voice infrastructures remain highly vulnerable to short-term micro-jitter due to low latency requirements. Conversely, video streaming services can tolerate higher traffic dispersion by leveraging large playout buffers and dynamic ABR mechanisms.
- **Operational Mitigation Trade-offs:** While active scheduling policies (such as DiffServ, MPLS-TE, and SDN routing) suppress network-layer jitter, they introduce systemic trade-offs that increase baseline latency, affect link equity, and add processing overhead.
- **Telemetry Metrics Mismatch:** Standardized transport-layer jitter parameters often mask the extreme, tail-end delay variation events that trigger client-side buffer starvation. This mismatch underscores the need to develop and deploy context-aware, cross-layer telemetry metrics.

These architectural insights highlight that modern network design cannot rely on best-effort models. Instead, engineers must combine jitter-aware routing fabrics with adaptive application layers to maintain quality of experience over congested infrastructures.

6. Open Challenges and Future Research Directions

Despite decades of progressive optimization in modeling, measuring, and mitigating packet delay variation, establishing universal determinism across modern communication infrastructures remains an unresolved engineering frontier. As networks migrate toward highly virtualized, software-defined, and multi-access topologies, the physical and stochastic properties of traffic dispersion shift dynamically. This section exposes the core structural research gaps within the current state of the art and delineates strategic research trajectories for the telecommunications community.

6.1. Lack of Unified Jitter Models for Heterogeneous Fabrics

A primary limitation of the contemporary jitter theory is its situational fragmentation. Specialized formulations achieve high precision in isolated domains—including LTE uplinks [19], multi-connectivity wireless flows [20], xDSL access segments [93], deterministic Time-Sensitive Networks (TSNs) [102,103], and 5G/MEC field deployments [31]—but do not generalize reliably to heterogeneous end-to-end paths.

The structural fragmentation caused by the absence of a unified mathematical abstraction is synthesized in Figure 4. Deterministic TSN domains exhibit tightly bounded profiles, whereas wireless and virtualized segments introduce non-stationary impairments, creating analytical silos that single-distribution models fail to bridge. The resulting research problem is to develop tractable hybrid transfer functions that capture non-linear jitter accumulation across optical, terrestrial, non-terrestrial, edge, and radio segments without reducing each path to a localized empirical approximation.

6.2. Inadequacy of Traditional Jitter Metrics

Standardized metrics—such as RFC 3550 RTP jitter, RFC 3393 IPDV, QUIC RTT variation, and rolling packet arrival variance [1,9,43]—serve as vital operational tools for baseline network monitoring. However, these metrics are fundamentally limited by their reliance on successive packet-difference formulations or low-pass smoothing windows.

As Figure 5 illustrates, their smoothing behavior can conceal the short, high-amplitude events that trigger de-jitter buffer starvation, frame drops, and control-loop instability. This blind spot becomes critical for long-range-dependent, multi-scale, and heavy-tailed traffic [4]. Standardization should therefore extend beyond mean dispersion to distribution-aware measures of tails, burst duration, temporal dependence, and application-relevant threshold exceedance.

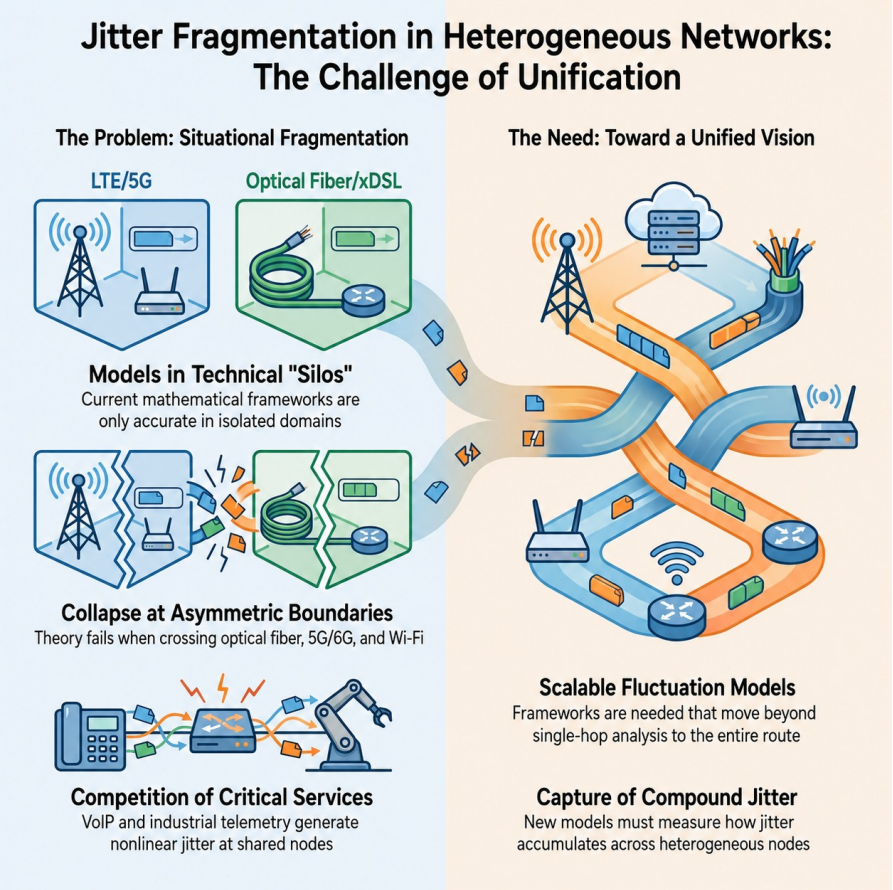


Figure 4. Fragmentation of jitter models across heterogeneous network fabrics and the requirements for a unified cross-domain abstraction. Source: Authors' own elaboration.

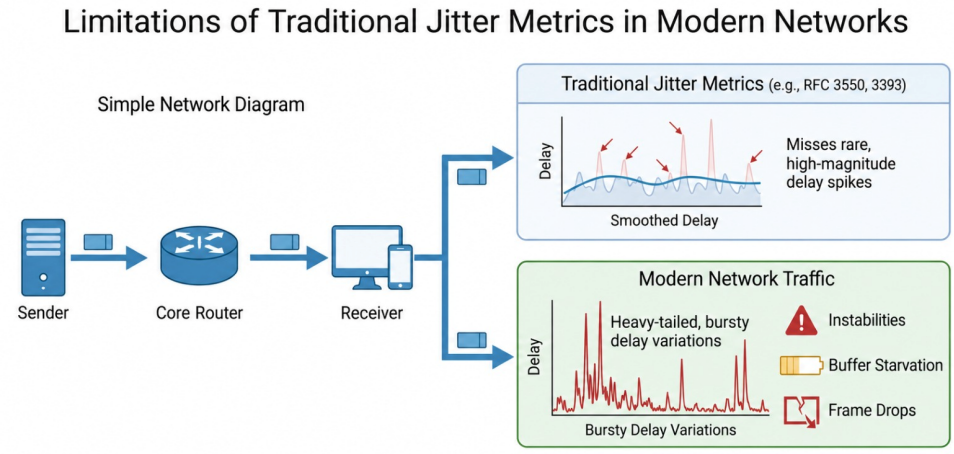


Figure 5. Operational blind spot of traditional jitter metrics: smoothing can suppress transient peaks that dominate application-level failures. The blue line represents the smoothed metric, the red line represents bursty delay variation, and the red arrows identify high-amplitude spikes attenuated by smoothing. Source: Authors' own elaboration.

6.3. Integration of Jitter in Quality of Experience (QoE) Engines

While jitter is classified as a low-level network-layer Quality of Service (QoS) parameter, its final impact on user satisfaction is highly non-linear and mediated by a complex ecosystem of application-layer variables. Although advanced ITU-T E-model extensions attempt to mathematically couple jitter distributions with packet-loss profiles [61,62], these frameworks remain static and retrospective. Figure 6 outlines a next-generation benchmarking and prediction pipeline in which synchronized high-resolution telemetry is transformed into distributional features and then mapped to application outcomes. Such engines must combine jitter with loss, codec state, buffer occupancy, and playout stalls in real time, while retaining interpretable links between network events and subjective quality estimates.

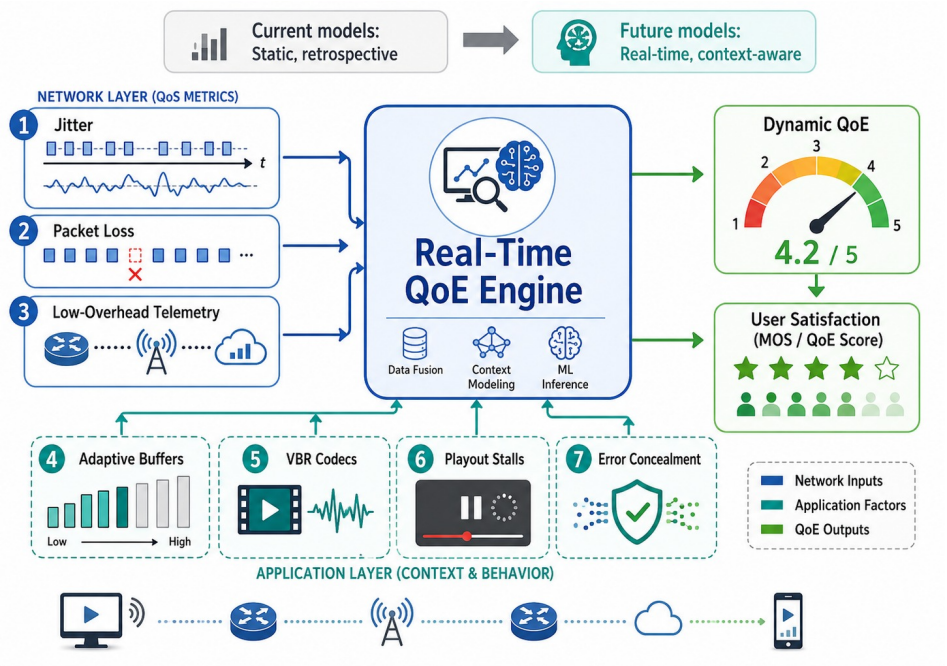


Figure 6. High-precision benchmarking pipeline for context-aware jitter analysis and cross-layer QoE prediction. Source: Authors' own elaboration.

6.4. Jitter Dynamics in Emerging Architectural Paradigms

Next-generation networking architectures decouple software from underlying hardware, but this abstraction introduces novel, unpredictable vectors of timing dispersion:

- **Software-Defined Networking (SDN):** Centralized controller orchestrators allow for global, jitter-aware path routing. However, the control-to-data plane interface introduces severe transient timing spikes during dynamic flow-table reconfigurations, signaling bursts, and variable controller processing cycles.
- **Network Function Virtualization (NFV):** Moving from dedicated hardware appliances to Virtualized Network Functions (VNFs) exposes traffic to hypervisor scheduling latency, CPU core contention, and shared memory bus saturation. These factors inject highly unstable stochastic micro-jitter directly into packet processing pipelines.
- **Edge, Fog, and Multi-Access Edge Computing (MEC):** Migrating computational tasks closer to the user reduces absolute round-trip latency. However, it introduces complex jitter profiles driven by runtime container migrations, horizontal load balancing, and variable multi-path backhaul topologies; recent 5G automotive trials show that MEC placement can materially reduce latency variability compared with cloud paths [31].

6.5. Security Implications of Jitter: Covert Channels and Exfiltration

Beyond its conventional role as a performance degradation vector, packet delay variation represents a critical, high-risk security vulnerability. Advanced state-of-the-art security studies demonstrate that inter-packet arrival gaps can be intentionally manipulated to establish highly resilient Covert Timing Channels (CTCs) across interactive or background traffic streams [43].

By encoding encrypted, exfiltrated data within the microscopic variations in packet arrival timing, malicious actors can bypass stateful firewalls, deep-packet inspection engines, and traditional intrusion detection systems (IDS). This dual nature of jitter—acting simultaneously as an operational QoS impairment and a sophisticated exfiltration vector—demands the development of high-resolution metrology frameworks capable of distinguishing between natural, network-induced queueing jitter and intentional, artificially injected security anomalies.

6.6. Strategic Roadmaps for Future Research Directions

The agenda in Figure 7 organizes the identified gaps into phased priorities. Near-term work should establish open, high-resolution measurement fabrics and distribution-aware metrics. Medium-term research should integrate interpretable machine learning with queueing models and close the loop between application telemetry, scheduling, and routing. Longer-term efforts should pursue interoperable cross-domain models and deterministic SDN control with enforceable jitter bounds. Together, these priorities connect reproducible evidence, predictive modeling, and deployable network control.

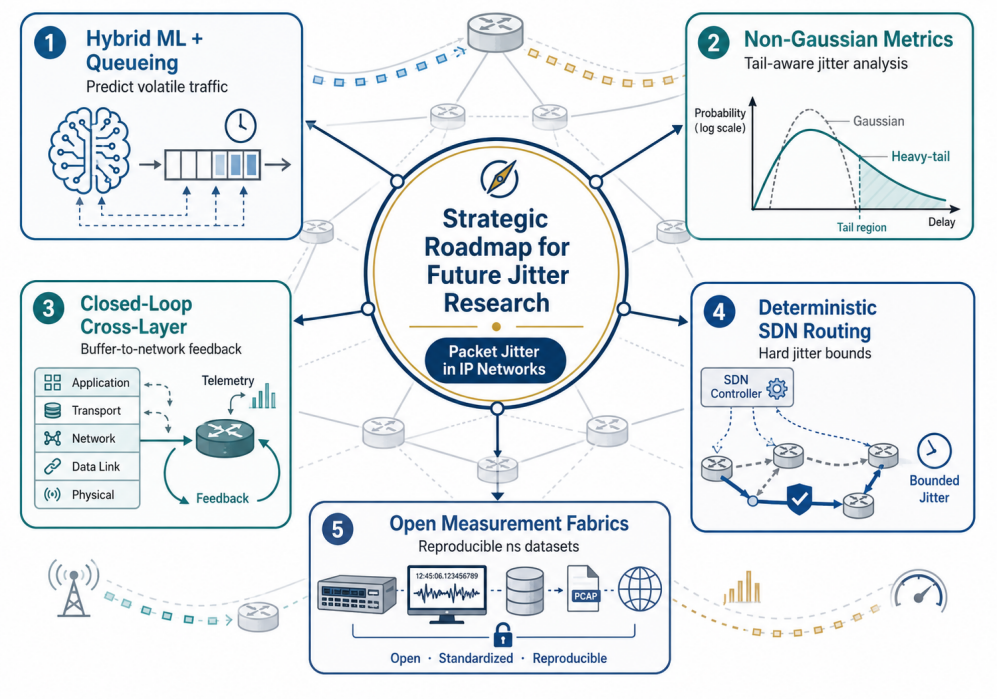


Figure 7. Strategic research roadmap for packet jitter measurement, modeling, standardization, and closed-loop control. Source: Authors' own elaboration.

7. Conclusions

This survey shows that packet jitter cannot be represented by a single interchangeable model or metric. The three modeling families capture distinct methodological roles: analytical models explain mechanisms and bounds; simulation and empirical studies test behavior under specified workloads; and cross-layer methods connect timing variation with scheduling, buffering, radio, codec, and control state. Application domain and net-

work technology remain necessary secondary dimensions rather than substitutes for this methodological classification.

The measurement synthesis distinguishes signed IPDV, common-reference PDV, and RTP interarrival jitter, and shows that their numerical outputs answer different questions. In the public-trace illustration, the 99th percentile of absolute consecutive RTT differences was 8.17 ms, excess-over-minimum RTT reached 52.36 ms, and the recursive estimator peaked at 6.14 ms. These trace-specific results demonstrate why an online smoother cannot by itself characterize tail exposure or buffer risk.

For VoIP, video streaming, and emerging deterministic services, mitigation remains a multi-objective problem. Scheduling, shaping, traffic engineering, and adaptive playout can reduce timing dispersion, but may increase baseline delay, processing cost, or unfairness. Results are therefore not transferable unless the metric definition, observation point, workload, sampling interval, loss treatment, and application state are reported.

The most consequential gaps are cross-domain modeling for heterogeneous wired–wireless paths, reproducible high-resolution benchmarks, interpretable cross-layer QoE prediction, stable closed-loop control, and detection of malicious timing manipulation. The roadmap in Section 6 accordingly prioritizes distribution-aware metrics and open traces in the near term, hybrid analytical–learning models and cross-layer control in the medium term, and interoperable bounded-jitter abstractions for 5G/6G, TSN/DetNet, SDN/NFV, and edge networks in the longer term.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/telecom7050124/s1. Table S1: Taxonomic synthesis of models proposed to characterize and predict jitter in real-time IP networks—Part 1: Analytical models; Table S2: Taxonomic synthesis of models proposed to characterize and predict jitter in real-time IP networks—Part 2: Simulation, empirical, and cross-layer models; Table S3: Classification of jitter evaluation methodologies in architectural studies omitting explicit mathematical formulas; Table S4: Information sources and search-strategy adaptations; Table S5: Composition of the final bibliographic corpus. The Supplementary Materials also contain the complete bibliographic inventory supporting the survey. The additional inventory entries document analytical, stochastic, and empirical jitter models [120–128]; measurement uncertainty, teleoperation timing, and network-jitter modeling [129–133]; service quality and video perception [134–136]; measurement methods, IP jitter metrics, and correlated-traffic models [137–140]; and recent TSN–6G scheduling, network-slicing data, virtualized-network resource management, and 5G–TSN integration [141–144].

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Abbreviations

The following abbreviations are used in this manuscript:

AF	Assured Forwarding
CBR	Constant Bit Rate
DiffServ	Differentiated Services
DoS	Denial of Service
EF	Expedited Forwarding
FEC	Forwarding Equivalence Class
IPDV	IP Packet Delay Variation
IPP	Interrupted Poisson Process
ITU-T	International Telecommunication Union–Telecommunication Standardization Sector
LER	Label Edge Router
LSP	Label Switched Path
LTE	Long-Term Evolution
MMPP	Markov-Modulated Poisson Process
MOS	Mean Opinion Score
MPLS	Multiprotocol Label Switching
NFV	Network Function Virtualization
OWAMP	One-Way Active Measurement Protocol
PDV	Packet Delay Variation
QoE	Quality of Experience
QoS	Quality of Service
RFC	Request for Comments
RTCP	RTP Control Protocol
RTP	Real-time Transport Protocol
RTT	Round-Trip Time
SDN	Software-Defined Networking
TSN	Time-Sensitive Networking
TWAMP	Two-Way Active Measurement Protocol
URLLC	Ultra-Reliable Low-Latency Communication
VNF	Virtualized Network Function
VoIP	Voice over IP

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