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ANALYSIS OF NEXT-GENERATION INTERNET TRANSPORT PROTOCOLS: QUIC, WEBTRANSPORT, HTTP/3

Introduction. *Traditional Internet transport relies on the TCP/IP stack with application-level protocols such as HTTP/1.1 and HTTP/2. This combination is reaching performance limits due to head-of-line blocking, multi-RTT handshakes, and the lack of built-in security at the transport layer. Modern latency-critical applications, including cloud gaming and AR/VR, require end-to-end latencies well below 50 ms, often below 20 ms, which the classic TCP+HTTP/1.1/2 stack struggles to provide. New transport solutions based on QUIC, combined with HTTP/3 and the WebTransport API, are designed to overcome these inefficiencies while preserving the Web programming model. Their global adoption has already grown significantly (over 40% of web traffic via QUIC/HTTP/3), which makes a systematic analysis of these protocols both timely and practically important.*

Problem statement. *Despite the rapid deployment of QUIC, HTTP/3, and WebTransport by major cloud providers and browsers, there is still a lack of consolidated analysis that connects IETF specifications, academic research, and real-world content delivery network (CDN) and 5G deployments. Practitioners often rely on scattered blog posts and partial benchmarks, which makes it difficult to understand where QUIC-based transports outperform the classic TCP+HTTP/2 stack, how different congestion control algorithms behave, and what limitations remain in latency-critical scenarios.*

Purpose *of this paper is to perform a critical analysis of next generation Internet transport based on QUIC, HTTP/3, and WebTransport, focusing on their architectural evolution, congestion control algorithms, deployment models, and security properties. To achieve this aim, the paper traces the evolution from SPDY and HTTP/2 to HTTP/3 over QUIC, compares congestion control schemes (CUBIC, BBRv2, and HyStart++ variants), reviews deployment optimizations (XDP and eBPF offload, 5G L4S), and identifies open issues such as multicast support, satellite links, and observability.*

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Methods. *We survey IETF RFCs (for example RFC9000, RFC9114, and the QUICv2 draft) and recent research and industry reports. Performance is inferred from published benchmarks and experimental studies. The work has a survey and analytical character; original in house experiments are limited to indicative tests that complement these benchmarks. We also include anecdotal insights from our CDN and research experience ("under the hood" observations) to illustrate real world behavior.*

Results. *QUIC's streamlined handshake (1-RTT, optional 0-RTT) and encrypted headers significantly reduce latency. Adoption is confirmed by major tech firms (Meta: ~75% traffic on QUIC/HTTP3). QUIC's congestion controls show trade-offs: CUBIC is well-tested but can overshoot, whereas BBRv2 offers robust throughput in shallow buffers, with HyStart++ alleviating startup losses. WebTransport extends HTTP/3 with multiplexed streams and unreliable datagrams, now supported in browsers (e.g. Firefox 114). Offload strategies (XDP/eBPF) and libraries like Cloudflare's quiche improve edge performance.*

Conclusions. *(1) QUIC/HTTP3 effectively address TCP/UDP bottlenecks, e.g. eliminating TCP's head-of-line blocking. (2) Security enhancements (TLS1.3, header protection) mean almost entire packet payloads are encrypted. (3) Emerging CC algorithms like BBRv2 and hybrid slow-starts improve fairness and reduce loss. (4) WebTransport enables new web architectures (streaming, gaming) by combining QUIC with WebCodecs. (5) Practical deployment benefits from kernel-bypass (XDP) and QUIC libraries (quiche, lsquic). (6) Open issues include multicast-capable QUIC (e.g. MCQUIC), satellite scheduling, and richer logging (qlog) for observability. Future work may explore PERC-over-QUIC (forward-error correction), pluggable CC frameworks, and QUICv2-based enhancements.*

Keywords: *QUIC, HTTP/3, WebTransport, UDP, congestion control, low-latency networking, TLS, header protection; QUICv2 draft.*

Introduction

Traditional TCP/UDP transport is straining under modern demands. TCP's sequential delivery causes head of line blocking (HOL), while its 3 way handshake incurs 1–2 round trip times (RTTs) of delay before any data flows. Even UDP, though simple, lacks congestion control and encryption by default, forcing applications to reimplement these features. Modern services — e.g. cloud gaming, AR/VR — target latencies below ~20 ms for responsiveness, far tighter than typical Web workloads. For instance, cloud gaming research suggests keeping frame-to-frame latency under 50 ms; WebRTC-style real-time comms similarly aim for sub-100 ms. Under these constraints, the latency of TCP's handshake or retransmission dramatically degrades UX.

Meanwhile, industry trends confirm rapid uptake of new protocols. By early 2025, ~40% of global web traffic used HTTP/3 (on QUIC), and over 75% of a major CDN's traffic was reported via QUIC/HTTP3. Chrome's QUIC usage hovered ~40% mid-2023. In our own 2024 CDN tests, enabling HTTP/3 reduced typical handshake delay by about one RTT, noticeably cutting page load times on high-latency links. This progress likens QUIC to an "express lane" in the network stack: it combines TLS encryption and transport in one, removing traditional slow steps.

What changed under the hood? QUIC (RFC9000, May 2021) was designed to fix TCP/TLS inefficiencies. It moved handshakes into user space and encrypts nearly all packet headers, thwarting passive profiling. HTTP/3 (RFC9114, June 2021) rides on QUIC, bringing HTTP semantics

(stream multiplexing, header compression) over this new transport. This paper critically examines these protocols and related APIs, highlighting their design trade-offs, deployment challenges, and open research questions.

Problem Statement

Despite the rapid deployment of QUIC, HTTP/3, and WebTransport by major cloud providers and browsers, there is still a lack of consolidated analysis that connects IETF specifications, academic research, and real world CDN and 5G deployments. Practitioners often rely on scattered blog posts and partial benchmarks, which makes it difficult to understand where transports based on QUIC and HTTP/3 outperform the classic TCP plus HTTP/1.1 and HTTP/2 stack, how different congestion control algorithms behave, and what limitations remain in latency sensitive scenarios.

Protocol Stack Evolution

The journey to HTTP/3 began years ago. Google's SPDY (2009) introduced multiplexed streams and header compression atop TCP as a testbed. Its lessons became part of HTTP/2 (2015), but still on TCP. Meanwhile Google experimented with a UDP-based transport ("gQUIC") to avoid TCP's ossification. The IETF standardized a clean-slate QUIC (with many gQUIC ideas) in RFC 9000 (May 2021). By combining transport and security layers (embedding TLS 1.3), QUIC enables *0-RTT* handshakes for repeat connections. Shortly after, HTTP/3 (RFC 9114) defined HTTP semantics on QUIC, leveraging its stream multiplexing and flow control. Notably, many HTTP/2 features (like HPACK header compression state) are modified or subsumed: e.g. QPACK replaces HPACK to avoid head-of-line blocking across streams. In summary, HTTP/3 is essentially "HTTP/2.5 on QUIC", and was formalized once QUIC proved stable.

Over these transitions, the industry saw growing QUIC adoption: Cloudflare's blog notes HTTP/3 on ~31% of global sites by 2025, and heavy hitters like Meta push most traffic over QUIC. In our experience, moving to QUIC/HTTP3 in the CDN smoothly replaced TCP/HTTP2 stacks without client-side upgrades (browsers just speak QUIC by default). The standardization of HTTP/3 (mid-2021) was a key milestone.

Quic Congestion Control Algorithms

QUIC's design separates congestion control from the TCP kernel stack, allowing pluggable congestion control algorithms in user space. Early QUIC implementations (for example Google's quic-go and Cloudflare's quiche) defaulted to the CUBIC algorithm (RFC 8312) for TCP friendliness. CUBIC, the default in Linux, steadily increases its congestion window in a cubic fashion, but can overshoot on very large bandwidth delay links. Google's BBR (Bottleneck Bandwidth and round trip time) is an al-

ternative congestion control algorithm that targets the measured bottleneck rate and minimal round trip time, resetting its pacing periodically. BBR excels under small buffers or lossy links, often maintaining high throughput with low queuing. Its downside has historically been unfairness: early versions of BBR could grab more than their fair share against coexisting flows. Version BBRv2, which has recently been integrated into Linux TCP stacks and QUIC drafts, explicitly addresses fairness and buffer issues. For example, LiteSpeed's published tests note that BBR offers minimal latency and high throughput but performs poorly with shallow buffers and can claim most of the bandwidth over older algorithms; BBRv2 is designed to mitigate these issues.

Slow-start refinement is another active area. QUIC's default also included NewReno or CUBIC slow start, but experiments found NewReno's aggressive doubling often triggered unnecessary loss in high-speed networks. Cloudflare's quiche (via NGINX) recently added HyStart++: a hybrid slow-start that observes RTT delay increases to exit slow-start early. In tests, HyStart++ dramatically reduces startup loss compared to classic slow-start. For instance, an internal comparison showed CUBIC+HyStart++ and BBRv2 both improved p99 latency stability under 1% loss, whereas Reno had many timeouts. Anecdotally, during early QUIC rollouts we *saw* HyStart++ cutting packet loss by over 50% at the start of bursty flows, smoothing performance. Overall, the consensus is that QUIC's flexible CC framework is a "winning hand": newer algorithms (BBRv2, Copa, Sprout) can be tried without OS patches, and the option to hook custom CC is exploited by all major QUIC stacks.

Fairness issues: CUBIC generally shares well with TCP, but in practice we've seen (consistent with [14]) that mixed flows (BBR with CUBIC) can lead to BBR hogging. QUIC's flow fairness can be tuned by choosing CC. Our CDN tests showed mixed patterns: under bufferbloat conditions, BBRv2 flows recovered bandwidth that CUBIC flows starved on. The key takeaway: QUIC enables experimenting with CC without kernel changes, so it's outpacing TCP's decade-old battle.

WebTransport and Datagram Apis

While HTTP/3 established a new transport, WebTransport builds on it to offer developers a richer web API. Conceptually, WebTransport is "WebSockets on HTTP/3" — a bidirectional, stream- and datagram-oriented API over QUIC. Unlike WebSockets (TCP-based), WebTransport runs over HTTP/3, gaining all QUIC benefits: multiple bidirectional streams, independent flow control per stream, and optional unreliable datagrams for low-latency data. This out-of-order delivery path (via unsequenced datagrams) is reminiscent of WebRTC's SCTP data channels, but with simpler semantics and no need for ICE/STUN (since it's pure server-client). Security-wise, WebTransport is as strong as HTTP/3 – TLS provides confidentiality and integrity end-to-end.

In practice, WebTransport is still emerging. Browser support rolled out in late 2023: for example, Firefox 114 (June 2023) shipped WebTransport API (with multi-stream and unidirectional support). By Chrome 125 (early 2024), DevTools could display WebTransport connections, indicating it was enabled. (WebTransport still may require enabling via flags in some builds.) We have experimented with a WebTransport proof-of-concept for live gaming: using WebTransport's datagram mode combined with the WebCodecs API for frame delivery. These early trials show dramatically smoother frame delivery under packet loss, since we can send keyframes reliably over streams and diff frames as datagrams. The upcoming W3C "Media over QUIC (MoQ)" working group is formalizing such use cases.

Crucially, WebTransport's architecture avoids TCP-like head-of-line issues on the browser side. MDN notes it "provides a modern update to WebSockets" by allowing multiple streams and even unreliable, out-of-order data. In real-world terms, this means one WebTransport connection can carry a video stream, audio stream, and game-state datagrams in parallel. During a recent origin-trial, we saw a 30% reduction in video latency when switching a live streaming app to WebTransport vs WebSocket, thanks to QUIC's packetization and datagram delivery. Such results hint at WebTransport's potential to revolutionize interactive web apps.

0-RTT and Handshake Optimization

Reducing connection setup latency is central to QUIC's appeal. With TLS 1.3, QUIC can often send data in the first packet of a resumed handshake (0-RTT). However, 0-RTT comes with replay risk: as RFC9001 warns, "0-RTT data can be replayed by an attacker, so it is not suitable for data that might cause unwanted effects if replayed". In practice, many servers allow only idempotent or read-only requests in 0-RTT (like GET for caching). QUIC adds mitigations: clients must prove address ownership to the server to trigger 0-RTT. In particular, servers issue *address-validation tokens*(NEW_TOKEN frames) during a handshake; the client includes that token in future inital packets to validate its IP. This, plus rate-limiting, thwarts amplification attacks.

Anti-amplification is a key constraint. RFC9000 dictates that a server MUST limit the data sent to an unverified client address to 3× the data it has received. In practice, QUIC servers will hold back sending large flows (or retried packets) until a client proves reachability. For example, if a malicious UDP spoofing can reach a server, this limit means the server cannot flood the victim with more than three times what it received. In our tests, this often meant a tiny (1–2 packet) delay before large server data started flowing on a fresh connection – a worthwhile tradeoff for security. In summary, QUIC's handshake optimizes latency (often 1-RTT vs TCP+TLS's 2-RTT) while carefully employing tokens and limits to avoid replay/amplification abuse.

Token binding: We note that QUIC's use of session tickets (PSK) and NEW_TOKEN effectively "binds" resumption or address validation to the connection. Importantly, RFC9001 cautions that reuse of these tokens "requires stronger protections against replay". Cloudflare's deployment of QUIC-SSL integration ensures that every session ticket is single-use to sidestep reuse vulnerabilities. Our CDN logging shows token misuse was negligible once strict replay counters were enforced. In short, TLS1.3's replay risk is managed via server-side checks and QUIC's design (address validation, anti-amplification) such that fast handshake is safe enough for practical use.

Edge-Native Deployment

QUIC's user-space nature means it can (and should) leverage new OS and hardware features. One hot area is kernel-bypass/XDP: by using eBPF's eXpress Data Path, a QUIC stack can process packets before the full kernel networking stack, reducing syscall overhead. Recent research shows QUIC implementations (e.g. MsQuic, s2n-quic) getting 30–50% faster packet processing via XDP/Af_XDP. For example, an academic prototype used XDP to bypass UDP parsing and directly extract QUIC payloads, cutting latency. In our lab, we integrated QUIC-Go with AF_XDP on Linux; even without tuning, it halved CPU usage on bursty UDP workloads. The [47] study confirms: since QUIC avoids IP fragmentation and heavy stack processing, XDP's simplicity "shows great promise for reducing kernel overhead in QUIC implementations".

In production, edge servers also exploit multi-core: Cloudflare's udp grm demonstrates routing QUIC flows across CPUs using SO_REUSEPORT+eBPF. Open-source libraries matter: Cloudflare's quiche (Rust) and LiteSpeed's LSQUIC offer high-performance QUIC stacks. Notably, LiteSpeed's web servers (OpenLiteSpeed) had advanced HTTP/3 support in 2019, and claim up to twice throughput over nginx/quiche. We regularly use quiche via NGINX-QUIC; it supports all the same CC (CUBIC, BBRv2) plus HyStart++. Our team's edge deployment uses quiche and BBRv2, which gave us an 8% higher goodput vs CUBIC under 0.5% loss on a 5 G core network (consistent with reports).

Finally, cellular cores are evolving. 5G release 18 introduced L4S (Low Latency, Low Loss, Scalable throughput) marking based on explicit congestion notification (ECN) with dual priority codepoints to minimize queuing. Telecom demonstrations (for example Elisa and Nokia in February 2024) show L4S cutting latency for extended reality (XR) use cases. Although L4S is transport agnostic, QUIC congestion control can explicitly react to ECT(1) marks that encode L4S signals. Some operators are already testing QUIC plus L4S in standalone 5G cores to realize below 10 ms round trip times under load. This edge integration, combining QUIC kernel bypass stacks with advanced 5G quality of service (QoS) features, is cutting edge practice that we and others are actively exploring.

Performance Benchmarks

Quantitative performance of QUIC stacks varies with workload and loss. In synthetic tests, QUIC's p99 RTT (overall request latency) scales reasonably well even with random loss: modern CC (e.g. BBRv2) often limit latency inflation to double of loss-free RTT at 1% loss, whereas TCP floods can explode. Goodput (throughput of data transfer) under loss also remains high: for example, LiteSpeed's HTTP/3 maintained ≈95% of line-rate at 0.5% loss, whereas a naive TCP loopback fell to ~70%. Published benchmarks back these observations: Dmitri Tikhonov (LiteSpeed) found OpenLiteSpeed's HTTP/3 achieved "twice or more" throughput than nginx/quiche in identical tests. He reported that at 20 ms RTT, OpenLiteSpeed hit ~6400 req/sec vs nginx's ~4100 (≈1.6×), and that at high load, nginx was CPU-saturated while LiteSpeed had headroom.

Our own experiments echo this: we ran h2load fetching 100 MB files at 0.5% random loss. NGINX-quic (quiche) saw ~30% more retransmissions than LSQUIC (LiteSpeed's QUIC) with CUBIC, reducing its goodput accordingly. We also tested Envoy's new QUIC integration (Envoy-QUIC using MsQuic). Envoy's performance was between NGINX and LiteSpeed; in medium RTT (~50 ms) it delivered about 10–15% lower throughput than OpenLiteSpeed on identical hardware, due mostly to queue length and pacing differences. (Envoy-QUIC currently uses Google's quic-go/Bbr by default.)

These comparisons are summarized in Table 1, where shows example HTTP/3 throughput (requests/sec) and p99 RTT under varying loss and RTT, for different servers (OpenLiteSpeed vs NGINX/quiche vs Envoy-QUIC). Data from public reports and our tests; LiteSpeed often leads due to optimized I/O and CPU use (n/s = not shown).

Overall, the available benchmarks and our limited experiments suggest that QUIC tends to perform better than TCP in lossy or long fat (high delay) networks, because its fast retransmission behavior and streamlined congestion control work well in these conditions. The bottleneck still tends to be the implementation's efficiency and the chosen congestion control algorithm. In particular, we observed that latency critical

Table 1. **Example HTTP/3 throughput and p99 RTT**

Server / Stack	Congestion Control	Requests / sec @ RTT 10 ms	Requests / sec @ RTT 20 ms	Requests / sec @ RTT 100 ms	p99 RTT, 1 % loss (ms)
OpenLiteSpeed 1.6.4 (LSQUIC)	CUBIC	6 420	3 915	935	14 *
NGINX 1.26 + quiche	CUBIC	4 100	2 910	890	22 *
Envoy 1.29 + MsQuic	BBRv2	5 600 *	3 300 *	980 *	18 *

** Benchmarked in-house with **h2load** (12 May 2025), 100 Mbps link, 100 concurrent connections, 10k GETs, tc netem 1 % random loss.*
Non-starred values reproduced from LiteSpeed Tech public tests (Nov 2019).

scenarios (for example 10 ms RTT streams) can cause CUBIC based stacks to increase CPU usage (as seen in [51]), whereas BBRv2 kept latency low at the expense of using more available bandwidth. A key figure is the median versus 99th percentile delay: QUIC and HTTP/3 p99 usually doubles the p50 at 0.5 percent loss, whereas TCP with 1 RTT TLS handshakes can explode under the same conditions. In practice, this means QUIC maintains reasonable tail latency and throughput for most flows; the noticeable penalties occur only with extremely short bursts of errors.

Security and Privacy

QUIC was designed with encryption from the start. Unlike TCP+TLS where only payload is encrypted, QUIC encrypts most of its headers. RFC9001 §5.4 specifies *Header Protection*: e.g. the Packet Number field is hidden under a second AEAD key. This makes passive analysis very difficult: an observer cannot tell packet numbers or congestion control signals. In effect, virtually the entire QUIC packet (except fixed-format flags) is protected. This is a big privacy win and also thwarts simple on-path fingerprinting attacks.

However, encrypting the header also means middleboxes can't extract flow identifiers. To address compatibility, QUICv1 kept Version Negotiation and Retry packets unencrypted (so routers could still route unknown QUIC flows). This led to a subtle attack: the "version-negotiation oracle," where an on-path probe can trigger a server's Version Negotiation response (revealing what versions it supports), or spoof a NewConnection ID. To combat this, the QUIC community has drafted Version 2 of the protocol. QUICv2's only changes are in how the client initial keys are derived (a new salt) and in RFC844-Draft style version negotiation enforcement. In short, all initial handshake keys are separated per-version, preventing passive demux of packets. Draft-ietf-quic-v2 notes that endpoints supporting multiple versions *must* implement version negotiation and recommends not accepting downgrade attempts. This closes the "oracle" loophole by tightly binding the cryptographic identity to the version.

Other threats: QUIC's linkage to TLS 1.3 means it inherits TLS 1.3's strong security (certificate authentication, forward secrecy). The main added risk was amplification, which we discussed (mitigated by 3× limits). Note also that QUIC's Retry packets use a cryptographic integrity tag (short header) to prevent forging. Our reading of recent security reviews confirms QUIC has no new major bugs beyond traditional network attacks: it eliminates some (no SYN floods) but introduces new ones (complex handshake logic). Overall, the interplay of TLS key scheduling and QUIC frames appears sound. In our deployments, we trust QUIC's confidentiality (it uses AEAD ciphers) and rely on IETF updates (e.g. QUICv2 draft) for any subtle fixes.

Open Issues & Research Gaps

Despite these advances, open challenges remain. Multicast: QUIC today is strictly unicast (one server-to-one-client). Large-scale streaming (e.g. live events, OS updates) could benefit from one-to-many multicast. Recently, researchers have proposed "MCQUIC," an extension where QUIC streams are replicated via IP multicast addresses. MCQUIC inserts minimal new frames to join multicast groups and verify clients. Preliminary results show it can seamlessly switch to unicast if multicast fails. However, this is still experimental (implemented in quiche) and not standardized. More work is needed to handle group re-keying and congestion control across mixed unicast/multicast paths.

Satellite and wireless: GEO/LEO satellite links have huge RTT (e.g. 600 ms GEO round-trip). QUIC's handshake and stream deadlines may not mesh well without adaptation. Some suggestions include longer timers and enhanced pacing (borrowing from TCP SATCOM research). Additionally, scheduling multiple QUIC flows over asymmetric or multi-link conditions (like hybrid satellite + 5G) is unexplored. One could borrow ideas from Multipath QUIC (still experimental) or adapt scheduling algorithms. We lack extensive testbeds for this; our anecdotal tests over a simulated satellite link showed stalling of short video streams unless we raised the initial congestion window. Future research should address QUIC tuning for >100 ms-delay networks.

Observability (qlog/QPACK): Modern network operators demand traceability. The IETF's QLOG draft (July 2025) defines a JSON schema for logging QUIC events. This covers connection state, frame types, and some transport metrics. Integrations (h3log) are emerging. However, logging HTTP/3 header blocks (QPACK) efficiently is tricky: capturing the dynamic Huffman-coded instructions and table updates remains complex. There's an ongoing QUIC Working Group issue on enriching qlog with QPACK events. In practice, we see that without adequate qlog/QPACK logging, diagnosing header-compression stalls or flow issues is hard. As one example, our CDN had a bug where recycled QPACK entries caused mis-decoding; only detailed qlog output let us catch it. Advancing open-source debugging (like h3i, Wireshark QPACK plugins) is part of the path forward.

Personal note: During a 2024 rollout of HTTP/3 at our CDN, we literally saw a stream's recoverability improve – a page that stalled under TCP now loaded fully in a single QUIC connection. QUIC felt like adding a turbo mode to the network.

Conclusion

Thus, the following conclusions can be done:

• **QUIC/HTTP3 dramatically reduce latency bottlenecks.** By combining TLS and transport, QUIC replaces TCP's multi-RTT handshake with

0–1 RTT, and by encrypting headers it avoids TCP head-of-line blocking. This means web pages often start rendering one RTT sooner.

• **Adoption is already high.** Cloud and browser vendors have deployed QUIC: e.g. Meta (>75% traffic on HTTP/3) and ~40% of Chrome load is QUIC. Protocol maturity (RFC9000/9114) and proven gains have accelerated uptake.

• **New congestion controls and hybrid slow-start are effective.** Modern CCs like BBRv2 deliver high throughput even in lossy, high-bandwidth paths (unlike TCP Reno), and HyStart++ curbs startup overshoots. Still, choice of CC matters: there is no one-size-fits-all, but QUIC's pluggable design makes it easy to deploy the best CC for each network.

• **WebTransport opens webRTC-like scenarios.** By layering on HTTP/3, WebTransport lets web apps use QUIC streams and UDP-like datagrams securely from JavaScript. This paves the way for features like live gaming and AR streaming in browsers, reducing reliance on native plugins.

• **Edge and kernel optimizations pay off.** Offloading QUIC packet I/O to XDP/eBPF or specialized NICs greatly boosts packet processing (research shows 2–3× gains). Libraries like Cloudflare's quiche and LiteSpeed's stack, running in userspace, allow rapid iteration. In field deployments (e.g. CDNs, 5G cores), combining QUIC with network customizations (L4S marking, CPU pinning) is yielding real performance.

• **Security features are robust, but vigilance needed.** QUIC encrypts most of its control plane (header protection), closing many old TCP-era security gaps. Known issues like version negotiation have mitigation in flight via QUICv2. Implementers must continue auditing new exten*sion points (e.g. multipath, 0-RTT) and keep libraries updated.*

Future research areas include developing **PERC-over-QUIC** schemes (Proactive FEC) to recover from losses without re-transmits, further lowering tail latency. Explore an **extensible CC framework** (akin to Linux's qdisc) for QUIC libraries so new algorithms can plug-and-play. Advance **multipath QUIC** and scheduling algorithms to leverage 5G/6G network diversity. Finally, enhance **observability** by completing qlog/QPACK logging standards and integrating tracing (e.g. with OpenTelemetry) to make QUIC flows as debuggable as HTTP/2 was.

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АНАЛІЗ ПРОТОКОЛІВ ІНТЕРНЕТ-ТРАНСПОРТУ НОВОГО ПОКОЛІННЯ: *QUIC, WEBTRANSPORT, HTTP*/3

Вступ. Традиційний інтернет-транспорт базується на стеку *TCP/IP* з прикладними протоколами *HTTP*/1.1 та *HTTP*/2. Така комбінація досягає меж продуктивності через блокування на початку черги, багатоетапні рукостискання та відсутність вбудованих механізмів безпеки на транспортному рівні. Сучасні затримкочутливі застосунки, зокрема хмарні ігри та *AR/VR*, вимагають наскрізної затримки значно меншої за 50 мс (часто близько 20 мс), що є проблемним для класичного стеку *TCP+HTTP*/1.1/2. Нові транспортні рішення на базі *QUIC* у поєднанні з *HTTP*/3 та *API WebTransport* покликані подолати ці обмеження, зберігаючи веб-парадигму розробки. Їх глобальне впровадження вже суттєво зросло (понад 40 % веб-трафіку через *QUIC/HTTP*/3), що робить систематичний аналіз цих протоколів своєчасним і практично значущим.

Постановка проблеми. Попри швидке впровадження *QUIC, HTTP*/3 та *WebTransport* основними хмарними провайдерами та браузерами, досі бракує цілісного аналізу, який би поєднував специфікації *IETF*, академічні дослідження та практику розгортання в мережах доставки контенту (*CDN*) і ядрах 5*G*. Практики змушені спиратися на розрізнені дописи в блогах і часткові бенчмарки, що ускладнює розуміння, у яких сценаріях транспорти на базі *QUIC* перевершують класичний стек *TCP+HTTP*/2, як поводяться різні алгоритми контролю перевантаження та які обмеження залишаються в затримкочутливих сервісах.

Мета. Метою статті є критичний аналіз інтернет транспорту нового покоління на базі *QUIC, HTTP*/3 та *WebTransport* з акцентом на еволюції архітектури, алгоритмах контролю перевантаження, моделях розгортання та властивостях

безпеки. Для досягнення цієї мети простежується перехід від *SPDY* та *HTTP*/2 до *HTTP*/3 поверх *QUIC*, порівнюються схеми контролю перевантаження (*CUBIC, BBRv*2 та варіанти *HyStart*++), узагальнюються підходи до оптимізації розгортання (розвантаження *XDP/eBPF,* 5*G L*4*S*) та окреслюються відкриті питання, зокрема підтримка багатоадресної розсилки, супутникові канали та спостережуваність.

Методи. Ми аналізуємо документи *RFC IETF* (зокрема *RFC*9000, *RFC*9114 та чернетку *QUICv*2) і сучасні наукові публікації та галузеві звіти. Продуктивність узагальнюється на основі опублікованих бенчмарків та експериментальних досліджень. Робота має оглядовий та аналітичний характер; власні експерименти обмежуються індикативними тестами, що доповнюють наявні бенчмарки. Додатково ми залучаємо окремі висновки з нашого досвіду роботи з *CDN* та досліджень (спостереження «під капотом») для ілюстрації поведінки в реальних умовах.

Результати. Оптимізоване рукостискання *QUIC* (1-*RTT*, необов'язково 0-*RTT*) та зашифровані заголовки значно зменшують затримку. Впровадження підтверджено великими технологічними компаніями (Мета: ~75 % трафіку на *QUIC/HTTP*3). Контроль перевантаження *QUIC* демонструє компроміси: *CUBIC* добре протестований, але може перевищувати норму, тоді як *BBRv*2 пропонує надійну пропускну здатність у неглибоких буферах, а *HyStart*++ зменшує втрати при запуску. *WebTransport* розширює *HTTP*/3 за допомогою мультиплексованих потоків та ненадійних дейтаграм, що тепер підтримується в браузерах (наприклад, *Firefox* 114). Стратегії розвантаження (*XDP/eBPF*) та бібліотеки, такі як *quiche* від *Cloudflare*, покращують продуктивність периферійних мереж.

Висновки. (1) *QUIC/HTTP*3 ефективно вирішує вузькі місця *TCP/UDP*, наприклад, усуваючи блокування *TCP* «заголовок рядка». (2) Покращення безпеки (*TLS*1.3, захист заголовків) означають, що майже всі корисні навантаження пакетів шифруються. (3) Новітні алгоритми СС, такі як *BBRv*2 та гібридні повільні запуски, покращують чесність та зменшують втрати. (4) *WebTransport* дозволяє створювати нові веб-архітектури (потокове передавання, ігри), поєднуючи *QUIC* з *WebCodecs*. (5) Практичні переваги розгортання від бібліотек обходу ядра (*XDP*) та *QUIC* (*quiche, lsquic*). (6) Відкриті питання включають *QUIC* з підтримкою багатоадресної розсилки (наприклад, *MCQUIC*), планування супутників та багатше ведення журналу (*qlog*) для спостереження. У майбутньому може бути досліджено *PERC-over-QUIC* (виправлення помилок уперед), підключаються фреймворки СС та покращення на основі *QUICv*2.

Ключові слова: *QUIC, HTTP/3, WebTransport, UDP, контроль перевантаження, мережа з низькою затримкою, TLS, захист заголовків, чернетка QUICv*2.