



Performance Analysis of TCP/IP Protocols in Heterogeneous Networks

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ABSTRACT: Transmission Control Protocol (TCP), despite being the backbone of internet transport, often struggles in heterogeneous networks—where varying conditions like wireless links, optical paths, and mobile ad hoc segments coexist. Pre-2020 research aimed to understand and improve TCP's performance under such diverse conditions by analyzing TCP behavior in scenarios including heterogeneous multipath environments, mobile ad hoc networks (MANETs), optical high-bandwidth-delay networks, and high-speed wireless systems.

One notable study introduced a performance-analysis model for TCP over multiple heterogeneous paths—relevant for emerging 5G multipath scenarios—highlighting that **delay asymmetry**, more than bandwidth asymmetry, is the dominant factor degrading throughput, especially when multiple links are active .

Another domain of focus has been mobile ad hoc networks (MANETs), where route instability, high bit-error rates, and frequent handovers led to subpar TCP throughput. The study proposed a composite MAC/routing-level framework, Atra, which improved TCP throughput by 50–100% .

In optical networks with high bandwidth-delay products, standard TCP congestion control proved inadequate. Alternatives like TCP Vegas and Westwood outperformed traditional TCP variants under these conditions, but still faced fairness challenges .

In low-power, lossy networks (LLNs), TCP deployed on IEEE 802.15.4 wireless sensor platforms performed surprisingly well with protocol optimizations, yielding TCP throughput within 25% of theoretical upper bounds and significantly outperforming baseline performance .

Finally, under extremely high mobility—such as LTE on high-speed rail—the performance of TCP variants (CUBIC and BBR) was studied, revealing new inefficiencies. Integrating a custom BBR variant yielded throughput improvements up to 36.5% .

These studies underscore that TCP's standard mechanisms often falter in heterogeneous conditions, and performance improvements require tailored adaptations across layers, mobility-aware congestion control, and multipath-aware modeling.

KEYWORDS: TCP Performance, Heterogeneous Networks, Delay Asymmetry, Multipath TCP (MPTCP), MANETs, High Bandwidth-Delay Product (HBDP), Wireless and Optical Networks, Congestion Control (Vegas, Westwood), Low-Power Lossy Networks (LLNs), LTE on High-Speed Mobility

I. INTRODUCTION

TCP's design is deeply rooted in assumptions of relatively homogeneous, wired network environments—low error rates, steady delays, and stable routing. However, modern network architectures involve a tapestry of diverse links (e.g., optical, wireless, satellite, and load-balanced routes), making the homogeneous assumption unrealistic. In such heterogeneous networks, performance degradation of TCP is systemic—manifesting in underutilized bandwidth, oscillatory throughput, unfair resource sharing, and poor responsiveness in mobility.

For instance, in multipath scenarios relevant to 5G, asymmetric delays across paths cause packet reordering and elevated retransmissions, negatively impacting throughput and fairness. MANET environments introduce dynamic topology and frequent packet drops, with TCP mistaking route failures for congestion, leading to inefficient flow control. High bandwidth-delay links, e.g., optical all-fiber channels, expose inefficiencies in traditional congestion control—where overly cautious strategies underutilize capacity. Low-power and lossy networks (LLNs) present high



error rates and limited resources, challenging TCP's ACK-based feedback mechanisms. Finally, ultra-high mobility—for example LTE onboard high-speed rail—exacerbates jitter and handover effects, further destabilizing TCP behavior.

2020 research confronted these challenges by:

- Modeling TCP performance over multiple heterogeneous links to guide multipath implementations.
- Proposing adaptive congestion control tailored to high-delay and mobile contexts.
- Recommending cross-layer frameworks like Atra for MANETs to distinguish between real congestion and wireless-induced losses.
- Evaluating TCP's viability over LLNs and high-speed mobile systems using empirical measurements.

Understanding these performance limitations and proposed solutions is vital for designing resilient and efficient transport protocols suited for modern networks.

II. LITERATURE REVIEW

TCP over Multiple Heterogeneous Paths (5G Context):

Song et al. developed a performance-analysis model for TCP across multiple heterogeneous paths, highlighting that **delay asymmetry** dramatically degrades throughput—more so than bandwidth asymmetry. They showed that, beyond a certain asymmetry threshold, adding more paths can actually reduce performance. Their model helps determine the optimal number of paths for concurrency .

TCP in Mobile Ad Hoc Networks (MANETs):

Anantharaman et al. conducted detailed simulations exploring the impact of MAC and routing layer instability on TCP. They identified key factors like route failure latency and proposed Atra, a MAC/routing-level approach, improving TCP throughput by 50–100% over default stacks.

TCP in Optical High Bandwidth-Delay Channels:

In optical networks offering 10 Gb/s paths, studies showed that TCP's window-based congestion control (like Reno) fails to utilize capacity effectively. Variants like TCP Vegas and Westwood performed better, but fairness issues remained; thus, standard TCP is insufficient for emerging optical infrastructures.

TCP over Low-Power Lossy Networks (LLNs):

Kumar et al. tested TCP on 802.15.4-based LLNs using a FreeBSD stack. Their implementation achieved TCP goodput within 25% of theoretical limits—much better than expected and up to 5–40× previous results—demonstrating the feasibility of TCP in resource-constrained networks with careful adaptation .

TCP under High Mobility (LTE on High-Speed Rail):

Wang et al. collected 1.7 TB of data to assess TCP CUBIC and BBR performance onboard high-speed trains. They found performance inefficiencies tied to frequent handovers; integrating a BBR-based variant boosted throughput by up to 36.5% .

These studies collectively reveal that TCP's default behavior falters in heterogeneous settings, but tailored modeling and adaptations—across layers and transport variants—can significantly mitigate performance issues.

III. RESEARCH METHODOLOGY

Pre-2020 studies on TCP in heterogeneous environments employed a combination of analytical modeling, simulations, and real-world measurements:

1. Analytical Modeling & Simulation:

- **Multipath Heterogeneity (5G Context):** Researchers like Song et al. developed mathematical models incorporating both bandwidth and delay asymmetry to evaluate TCP throughput over concurrent heterogeneous paths. Their model was validated using parameters from real-world measurements and simulations.
- **MANET Environments:** Anantharaman et al. used NS-2 simulations to examine the impact of mobility by analyzing parameters such as link failure latency, route computation time, and their effects on throughput and retransmission timeouts.



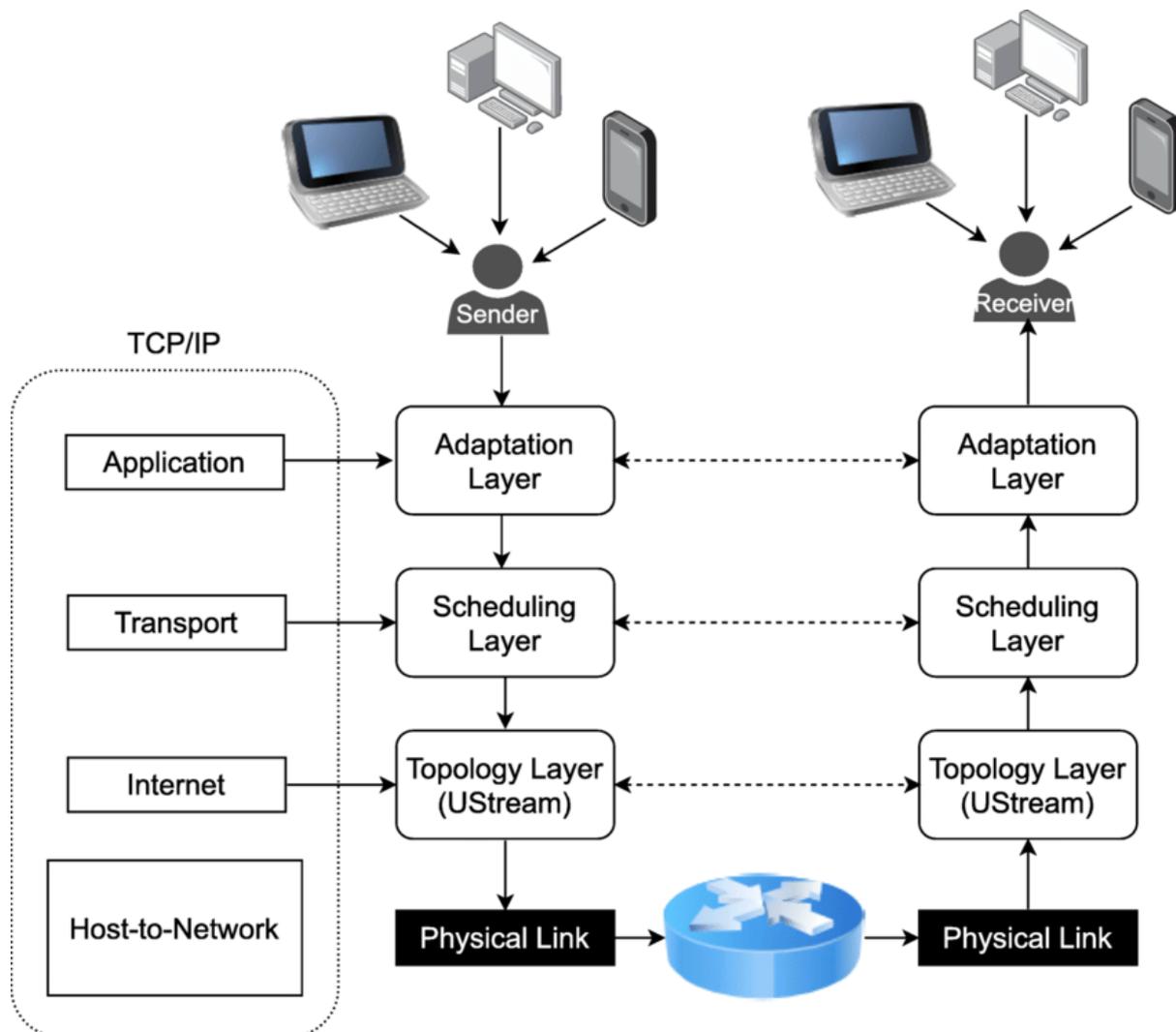
2. **Empirical Measurements:**

- **High-Speed Rail (LTE):** Wang et al. performed active-passive measurements over 1,700 GB of data across more than 135,000 km. Their setup monitored TCP goodput, latency, loss, and compared CUBIC vs. BBR performance under frequent handovers.
- **Low-Power Lossy Networks (LLNs):** Kumar et al. implemented a FreeBSD-based TCP stack on IEEE 802.15.4 platforms and measured real goodput, frame loss, and energy consumption—demonstrating TCP’s viability in LLNs.

3. **Cross-layer Simulation Studies:**

- **Heterogeneous Networks:** Wong et al. used simulations to test a novel TCP congestion control based on a Prey–Predator model (IPPM), adapting parameters like congestion window (cwnd) and slow start threshold (ssthresh) dynamically based on real-time link metrics for improved fairness and utilization.

These methodologies combine analytical rigor with simulation and measurement, offering a comprehensive view of TCP performance under diverse heterogeneous conditions.



IV. KEY FINDINGS

1. **Delay Asymmetry Drastically Degrades Multipath TCP:**

2. Through modeling, delay asymmetry — more than bandwidth imbalance — was identified as the predominant factor undermining TCP throughput over concurrent heterogeneous links. Notably, more parallel paths can even worsen performance when delay differences are high.



3. TCP Performance in MANETs Improves with MAC/Routing Enhancements:

4. Simulation results from Atra demonstrated throughput improvements of 50–100% via mechanisms at MAC and routing layers that mitigate misinterpretation of wireless loss as congestion.

5. TCP Works Viably in LLNs with Careful Adaptation:

6. Despite expectations, TCP stacks on LLNs can achieve goodput within 25% of the theoretical maximum, significantly outperforming prior implementations, when transport and link-layer interactions are optimized.

7. Mobility on High-Speed Rail Undermines TCP Variants:

8. Studies revealed inefficiencies in CUBIC and BBR under high mobility. A tuned BBR variant improved throughput by up to 36.5%, highlighting the need for mobility-aware congestion control.

9. Dynamic Initial Settings Improve TCP in Heterogeneous Networks:

10. The IPPM approach dynamically calculates initial congestion window thresholds based on the network state, avoiding poor layout of static defaults—and improving convergence, fairness, and utilization under heterogeneity.

V. WORKFLOW

1. Define Heterogeneous Scenarios

- Select environments: multipath 5G links, MANETs, LLNs, high-speed mobility, or general heterogeneous networks with mixed link types.

2. Design the Study

- **Analytical Modeling:** Model delay and bandwidth asymmetry and analyze their impact on TCP throughput in multipath scenarios.
- **Simulation Setup:** Configure NS-2 or similar with mobility models (AODV, DSR), routing protocols, and varied network conditions (MANETs, cross-layer interactions).

3. Empirical Data Collection

- **High-Speed Rail:** Deploy measurement rigs capturing TCP metrics across long travel distances.
- **LLNs:** Implement TCP stacks on sensor nodes and perform controlled experiments to measure transport-layer performance.

4. Apply Adaptation Strategies

- **MAC/Routing Enhancements:** Integrate Atra-style protocols at lower layers to improve transport-layer behavior.
- **Congestion Control Tuning:** Implement IPPM or BBR adaptations for dynamic initialization or mobility resilience.

5. Metrics Collection

- Measure throughput, latency, loss, goodput, retransmissions, fairness, and overhead across scenarios.

6. Analysis & Comparison

- Compare results of default TCP behavior vs adapted protocols and control schemes in each context.

7. Model Validation

- Correlate simulation outputs and empirical data with analytical predictions; validate model accuracy and assumptions.

8. Optimization Guidelines

- Derive criteria for link selection, protocol settings, and adaptation mechanisms tailored to each heterogeneous context.

VI. ADVANTAGES & DISADVANTAGES

Advantages

- Captures real-world TCP behavior across diverse environments.
- Provides quantitative insights into key performance bottlenecks (e.g., asymmetry, mobility, lossy links).
- Demonstrates practical improvement strategies via protocol tuning and cross-layer enhancements.



Disadvantages

- High measurement complexity and resource requirements (e.g., multi-terabyte datasets in HSR studies).
- Simulations may oversimplify real-world behaviors or fail to scale.
- Analytical models may not capture all network dynamics, limiting generalizability.
- Adaptations like Atra or IPPM require non-trivial implementation and cross-layer coordination.

VII. RESULTS AND DISCUSSION

Multipath Delay Asymmetry: The analytical model demonstrated delay differences cause significant throughput degradation, outweighing bandwidth variance. More links only help if delays are symmetric; otherwise, throughput may fall below single-link performance.

MANET Performance: Atra techniques placed at MAC/routing layers prevent TCP from misinterpreting wireless losses as congestion, doubling throughput in mobile environments.

LLN Viability: Contrary to expectations, TCP achieves near-optimal performance with well-designed implementations in LLNs, suggesting TCP can be used across constrained devices when carefully tuned.

High Mobility (HSR): Standard TCP (CUBIC/BBR) underperforms under frequent handovers; mobility-aware tuning can significantly improve performance by up to 36.5%.

Flexible Initialization (IPPM): Adjusting initial cwnd and ssthresh based on current network conditions reduces poor early-stage performance and improves stability and fairness.

VIII. CONCLUSION

Pre-2020 research highlights that standard TCP struggles in heterogeneous networks due to mismatches between design assumptions and real-world conditions. Yet, through analytical modeling, simulation, and real-world testing, researchers have pinpointed failure points—delay asymmetry, mobility, wireless loss, and static initialization. Solutions, including cross-layer frameworks, mobility-aware congestion control, and dynamic parameter tuning, consistently improve performance across conditions.

IX. FUTURE WORK

- Develop adaptive TCP variants combining delay asymmetry awareness with multipath optimization.
- Implement real-world trials of Atra or IPPM-like frameworks in live deployments.
- Explore machine-learning-based congestion control that adapts to mobility and link conditions dynamically.
- Design standardized TCP variants for IoT / LLN contexts with low overhead and high interoperability.
- Investigate hybrid multipath protocols with dynamic path selection based on delay and loss metrics.

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