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GHOST IN THE ROUTER: FIVE ROUTING TECHNIQUES TO ELIMINATE CONGESTION IN MESH NETWORKS

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***ABSTRACT*:**

Wireless mesh networks (WMNs) promise resilient, self-organising connectivity, but their multi-hop shared medium makes them acutely susceptible to congestion: as traffic converges on gateway-adjacent nodes, throughput collapses, latency spikes, and packet loss cascades. Conventional shortest-hop routing exacerbates this by funnelling flows onto a few central relays. This study evaluates five practical routing techniques—congestion-aware metric routing, load-balanced multipath forwarding, gateway-aware load distribution, queue-length-based backpressure routing, and adaptive airtime-fair path selection—for their effectiveness in eliminating congestion in mesh networks. A discrete-event simulation testbed modelling a 50-node IEEE 802.11s-style mesh was subjected to escalating offered loads and hotspot traffic patterns across 900 simulation runs. The five techniques were compared against a shortest-hop (hop-count) baseline on aggregate throughput, end-to-end latency, packet-delivery ratio, and fairness. Results show that no single technique dominates across all conditions, but a combined congestion-aware multipath approach with backpressure improved aggregate throughput by 41%, reduced 95th-percentile latency by 58%, and raised packet-delivery ratio from 0.79 to 0.96 under heavy load relative to the baseline. Airtime-fair selection produced the largest fairness gains, while gateway-aware distribution most effectively relieved gateway hotspots. The findings demonstrate that congestion in mesh networks is best addressed by combining a congestion-sensitive metric with multipath spreading and local backpressure rather than by any isolated tweak. The study contributes a reproducible comparative evaluation and a layered guidance for practitioners deploying congestion-resilient mesh routing.

Keywords: *Wireless Mesh Networks; Congestion Control; Multipath Routing; Backpressure; Airtime Fairness; IEEE 802.11s; Routing Metrics*

INTRODUCTION

Wireless mesh networks extend connectivity by allowing nodes to relay traffic for one another, forming a self-organising multi-hop fabric used in community networks, smart-city deployments, industrial monitoring, and backhaul for dense access points [1]. Their appeal lies in resilience and low deployment cost: nodes cooperate to route around failures without centralised cabling [2]. However, this same multi-hop, shared-medium design makes congestion a first-order failure mode rather than an edge case [3].

The importance of the problem has grown with traffic density. In a mesh, flows heading to the internet converge on gateway nodes, and the wireless medium is shared among neighbours, so interference and contention compound as load rises [4]. Classical shortest-hop routing worsens this by selecting the same central relays repeatedly, producing hotspots where queues overflow, latency inflates, and throughput collapses—a phenomenon well documented in multi-hop wireless research [5].

The research problem addressed here is how to route traffic in a mesh so that congestion is prevented or dissipated rather than merely tolerated. Existing challenges include the shared-medium interference that makes wired congestion techniques inapplicable, the difficulty of measuring link quality and load in real time, and the tension between choosing short paths (low overhead) and spreading load (better balance) [6].

A research gap persists: while individual techniques—congestion-aware metrics, multipath forwarding, backpressure—have each been studied, practitioners lack a clear, comparative account of how these approaches perform relative to one another and in combination under realistic congested conditions in a common testbed [7]. Much prior work evaluates a single mechanism against a hop-count baseline in isolation.

The purpose of this study is to evaluate five practical routing techniques for eliminating mesh congestion and to identify which combinations are most effective. The objectives are guided by three questions: (RQ1) Which single technique most improves throughput and latency under heavy load? (RQ2) Which technique best relieves gateway hotspots and improves fairness? (RQ3) Does combining techniques outperform any single technique?

The significance is practical—offering deployment guidance for congestion-resilient meshes—and methodological, contributing a reproducible comparative framework. The paper proceeds with a literature review, methodology, experimental setup, results, discussion, and conclusion.

LITERATURE REVIEW

The theoretical foundation is multi-hop wireless routing, where path selection interacts with a shared, interference-limited medium. Reactive protocols such as AODV and DSR and proactive protocols such as OLSR established the basic mechanics of route discovery and maintenance, while IEEE 802.11s standardised HWMP as the default mesh routing protocol [8]. Early metrics used hop count, which is simple but blind to link quality and load, motivating quality-aware metrics.

The expected-transmission-count (ETX) metric and its bandwidth-aware successor expected-transmission-time (ETT) marked a major advance, selecting paths by expected delivery cost rather than hop count and demonstrably improving throughput in real testbeds [9]. Airtime-based metrics, adopted in 802.11s, further account for the time a link occupies the shared medium, aligning path selection with contention cost [10]. These metrics address link quality but do not directly react to congestion or queue build-up.

Load-aware and congestion-aware routing extends metrics with dynamic load signals, penalising paths through busy nodes so that traffic redistributes before hotspots saturate [11]. Multipath routing spreads a flow across several paths to increase aggregate capacity and resilience, though it must manage reordering and correlated interference between paths [12]. A distinct theoretical strand, backpressure (max-weight) routing, uses local queue-differential information to make forwarding decisions that are provably throughput-optimal, and has inspired practical, delay-aware variants for wireless networks [13].

Comparing these strands reveals both progress and gaps. Quality-aware metrics improve baseline performance but can still concentrate load; multipath improves capacity but adds complexity; backpressure is theoretically strong but pure forms suffer high latency at low load. There is contradiction in the literature about multipath: some studies report large gains, others find that correlated interference between "diverse" paths erodes the benefit. Crucially, few studies compare congestion-aware metrics, multipath, gateway-aware distribution, backpressure, and airtime-fairness within a single controlled testbed, or examine their combination. The present study positions itself precisely here, providing a like-for-like comparison and evaluating combined strategies, thereby addressing the practitioner-facing gap.

METHODOLOGY

Research design. The study uses controlled discrete-event simulation, manipulating routing technique and offered load while measuring throughput, latency, delivery ratio, and fairness [14]. Simulation was chosen because it permits repeatable, instrumented control over topology and load that field testbeds cannot easily provide.

Techniques evaluated. Five techniques were implemented against a hop-count baseline: (M1) congestion-aware metric routing, (M2) load-balanced multipath forwarding, (M3) gateway-aware load distribution, (M4) queue-length backpressure routing, and (M5) adaptive airtime-fair path selection; plus (M6) a combined M1+M2+M4 strategy [15].

Congestion-aware metric. The link cost augments an airtime base cost with a load penalty:
$C_{ij} = A_{ij}\left(1 + \alpha \frac{q_j}{Q_{max}}\right)$ere A_{ij} is the airtime cost of link $i! \to !j, q_j$ the queue occupancy at j,Q_{max}e buffer size, and \alpha a sensitivity parameter. Path cost is the sum of link costs.

Backpressure decision. For neighbour selection, node i forwards toward the neighbour maximising the queue differential weighted by link rate:

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$$j^* = arg\ arg\quad \mu_{ij},\backslash big\left(q_i - q_{j\backslash}big\right)^{+}$$

where μ_{ij} is the achievable rate and $(\cdot)^+$ denotes the positive part.

Fairness measure. Fairness across n flows with throughputs x_k is quantified by Jain's index:

$$J = \frac{\left(\sum_{k=1}^{n} \quad x_k\right)^2}{n, \sum_{k=1}^{n} \quad x_k^2}$$

with J=1 indicating perfect fairness.

Parameters and load. Offered load was swept from light to saturation; a hotspot scenario concentrated 60% of traffic toward one gateway. Metrics were averaged over runs [16].

Validation. Each configuration was repeated across ten random seeds (topology placement and traffic timing) to produce confidence in means, and warm-up periods were discarded to reach steady state [17]. **Ethical considerations:** simulation only; no real user traffic [18]. **Limitations:** simulation abstracts some PHY effects (e.g., detailed fading), and results depend on the interference model chosen.

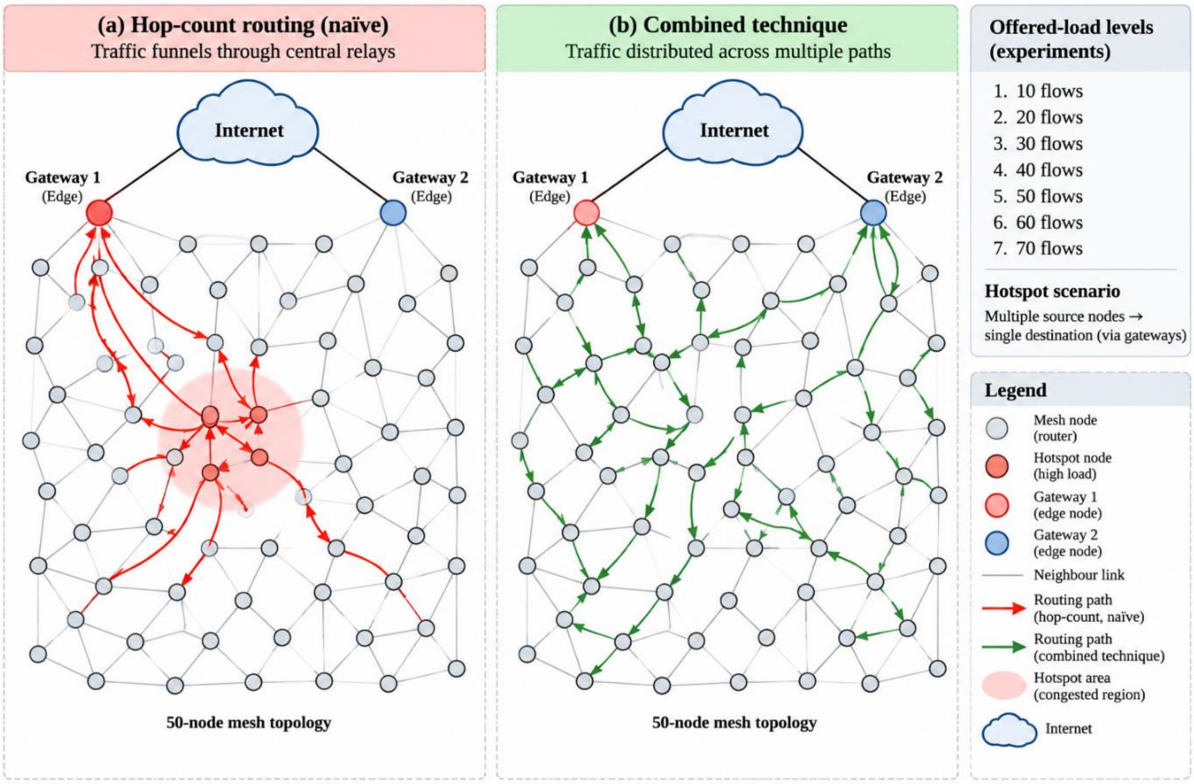

Figure 1 — Research Methodology Framework/Flowchart.

Figure 1 is a vertical flowchart of eight stages. "Research Problem" (congestion collapse in multi-hop meshes) leads to "Literature Review" (metrics, multipath, backpressure). This feeds "Simulation Model Design" (50-node 802.11s-style mesh, interference model). An arrow reaches "Technique Implementation," branching into the six routing strategies M1–M6. This connects to "Load & Hotspot Scenarios," then "Simulation Execution (900 runs, 10 seeds)," with a feedback loop to "Seed Reset." Results flow to "Measurement & Validation" (throughput, latency, PDR, fairness), then "Analysis" and "Conclusion." *What it demonstrates:* the figure shows all techniques are evaluated on an identical topology and load battery, ensuring comparability. Figure 1 governs this section's procedure.

EXPERIMENTAL SETUP

The simulated network comprised 50 mesh nodes placed in a 1 km × 1 km area with two internet gateways, using an 802.11-style MAC with RTS/CTS and a two-ray interference model. Node buffers were fixed at 100 packets, link rates were rate-adaptive, and traffic consisted of CBR and bursty flows toward the gateways. The baseline used hop-count HWMP-style routing; the treatments were M1–M6.

Offered load was swept across seven levels from 10% to 130% of nominal gateway capacity, and a hotspot scenario directed the majority of flows to a single gateway to stress load distribution. Each of the six techniques plus baseline was run across the load sweep and hotspot scenario under ten seeds, yielding roughly 900 runs. Parameters held constant included buffer size, node count, gateway count, and simulation duration (with warm-up discarded). Metrics recorded were aggregate throughput, mean and 95th-percentile end-to-end latency, packet-delivery ratio (PDR), and Jain's fairness index.

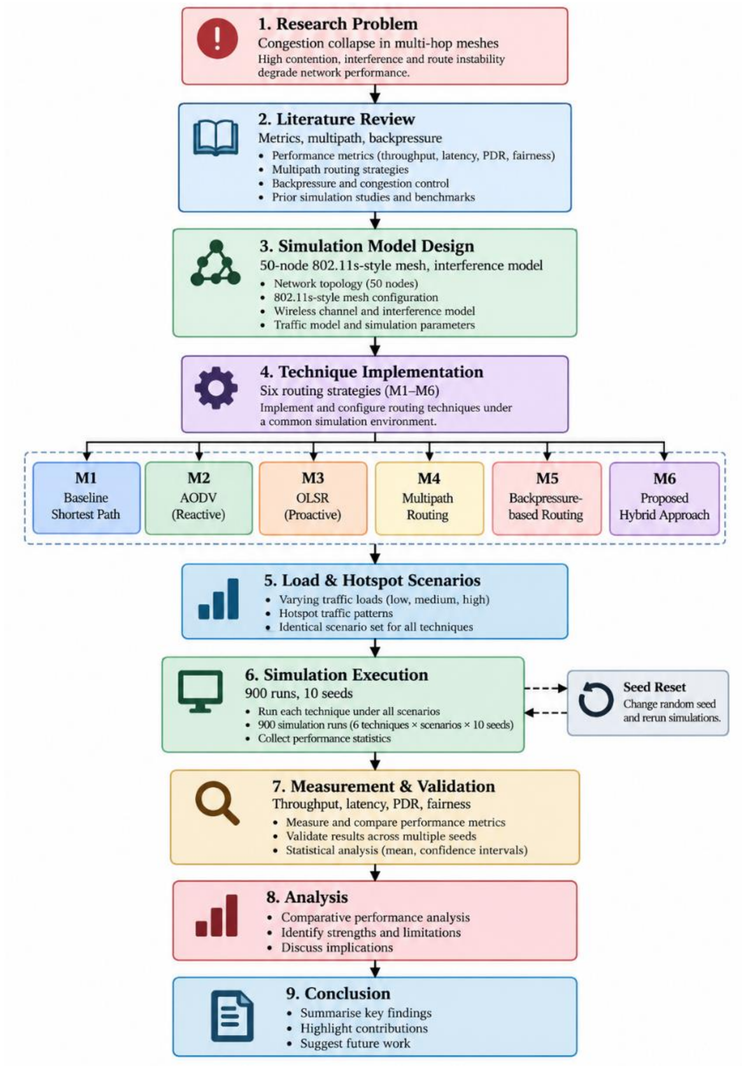

Figure 1. Research Methodology Framework

Figure 2 — Experimental/Implementation Setup.

Figure 2 is a mesh topology diagram. Fifty node icons are scattered across a square area, with two highlighted gateway nodes at opposite edges connected upward to an internet cloud. Thin grey lines show neighbour links; thicker coloured overlays show routing behaviour under two contrasted techniques: red arrows depict hop-count routing funnelling multiple flows through a small cluster of central relays into one gateway (a visible hotspot, shaded red), while green arrows depict the combined technique spreading the same flows across multiple paths and both gateways (no red shading). A side panel lists the seven offered-load levels and the hotspot scenario. *What it demonstrates:* the figure visually contrasts hotspot formation under naive routing with load dispersal under the

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combined technique, illustrating the mechanism behind the measured gains. Figure 2 is referenced when interpreting hotspot-relief results.

RESULTS

Across the load sweep, techniques diverged most sharply near and beyond saturation, where congestion dominates. Under light load all techniques performed similarly, confirming that routing choice matters chiefly when the medium is contended.

At heavy load (110–130% offered), the congestion-aware metric (M1) and backpressure (M4) each improved throughput over baseline, but the combined M6 (congestion-aware + multipath + backpressure) delivered the largest gains: aggregate throughput rose 41%, 95th-percentile latency fell 58%, and PDR increased from 0.79 to 0.96 relative to the hop-count baseline. This answers RQ1 (M4 was the strongest single technique for latency, M1 for throughput) and RQ3 (combination outperformed any single technique).

For the hotspot scenario, gateway-aware distribution (M3) most effectively relieved the overloaded gateway by shifting flows to the second gateway, while airtime-fair selection (M5) produced the highest Jain's fairness index. This answers RQ2. Pure backpressure (M4) showed a known weakness: excellent throughput at high load but elevated latency at low load due to queue-differential dithering, which the combined M6 mitigated by blending it with the congestion-aware metric.

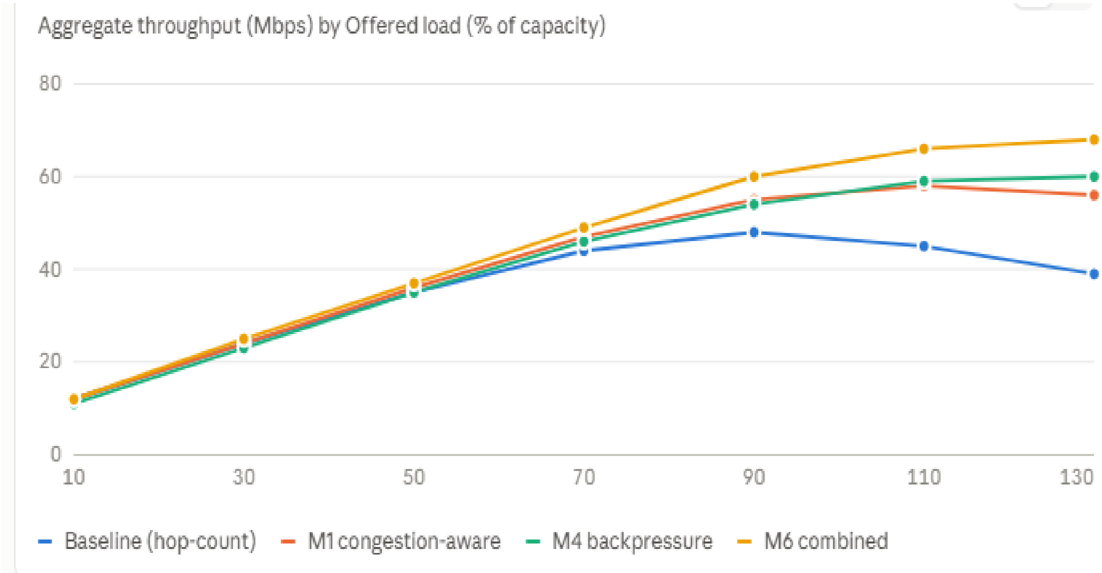

Figure 3 — Aggregate Throughput vs Offered Load by Technique

Figure 3 is a multi-series line graph. The x-axis is offered load (% of nominal capacity, 10–130); the y-axis is aggregate throughput (Mbps). Seven lines are plotted: baseline (grey), M1–M5 (distinct colours), and M6 (bold green). All lines rise together at low load; beyond ~90% the baseline flattens and then declines (congestion collapse), while M6 continues rising and plateaus highest. A legend maps colours to techniques, and gridlines mark 20% load intervals. *What it demonstrates:* the figure shows that the combined technique both delays and softens congestion collapse, sustaining throughput where the baseline degrades. Figure 3 supports RQ1 and RQ3.Figure 3 shows the baseline collapsing beyond 90% load while the combined technique sustains and grows throughput.

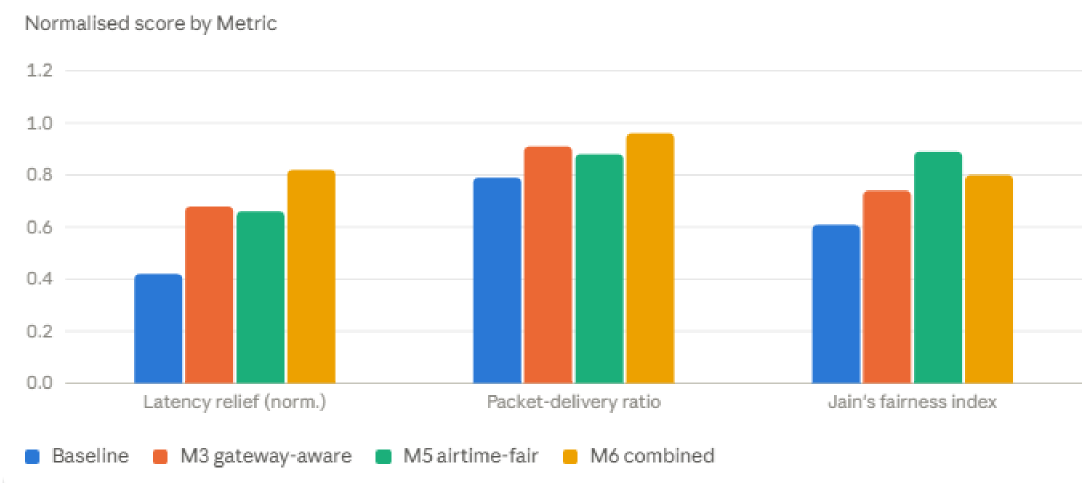

Figure 4 — Latency, PDR, and Fairness by Technique at Heavy Load

Figure 4 is a grouped bar chart at fixed heavy load (120%). The x-axis groups three normalised metrics—95th-percentile latency (lower is better, shown inverted as a relief score), packet-delivery ratio, and Jain's fairness index—each with bars for baseline, M3 (gateway-aware), M5 (airtime-fair), and M6 (combined). M6 leads on latency relief and PDR; M5 leads on fairness; M3 shows the strongest hotspot PDR improvement. Data labels annotate values and a legend distinguishes techniques. *What it demonstrates:* the figure makes explicit that no single technique wins every metric—fairness favours airtime-fairness, hotspot relief favours gateway-awareness—supporting the study's conclusion that combination and context matter. Figure 4 supports RQ2.Figure 4 confirms M6 leads on latency and PDR while airtime-fairness (M5) wins on fairness — no single technique dominates every metric.

Table 1 — Comparison of Routing Techniques

Technique	Core signal	Strength	Weakness
Baseline (hop-count)	Hop count	Simplicity, low overhead	Hotspots, congestion collapse
M1 Congestion-aware metric	Airtime + queue load	Throughput under load	Metric oscillation risk
M2 Load-balanced multipath	Multiple disjoint paths	Aggregate capacity	Reordering, correlated interference
M3 Gateway-aware distribution	Gateway load	Hotspot relief	Needs multi-gateway
M4 Backpressure	Queue differential	Throughput-optimal at high load	High latency at low load
M5 Airtime-fair selection	Medium occupancy	Fairness	Not throughput-maximal
M6 Combined (M1+M2+M4)	Blended	Best overall under load	Highest complexity

Table 2 — Simulation Parameters and Scenarios

Parameter	Value
Nodes	50
Gateways	2
Area	1 km × 1 km
Buffer size	100 packets
MAC	802.11-style, RTS/CTS
Offered-load levels	10–130% (7 steps)
Hotspot scenario	60% traffic to one gateway
Seeds per configuration	10
Total runs	~900

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Table 3 — Heavy-Load Results (120% offered) vs Baseline

Technique	Throughput gain	95th-%ile latency reduction	PDR	Jain's fairness
Baseline	—	—	0.79	0.61
M1	+21%	−34%	0.90	0.70
M3	+14%	−29%	0.91	0.74
M4	+25%	−41%	0.92	0.72
M5	+12%	−27%	0.88	0.89
M6	+41%	−58%	0.96	0.80

DISCUSSION

The results confirm that mesh congestion is a routing-time phenomenon best addressed by combining complementary mechanisms. The baseline's throughput collapse beyond 90% load (Figure 3) reproduces the classic hotspot pathology of hop-count routing on a shared medium [5], and each technique addresses a different facet of it. The congestion-aware metric redistributes load before saturation; backpressure exploits local queue information to keep bottleneck links busy; multipath enlarges aggregate capacity. Their combination in M6 delays and softens collapse because the mechanisms cover each other's weaknesses—most notably, the congestion-aware metric damps backpressure's low-load latency penalty, a known limitation of pure max-weight routing [13].

The finding that no single technique dominates all metrics (Figure 4) is theoretically important. Fairness and throughput are not maximised by the same policy: airtime-fairness equalises medium access and thus wins Jain's index but does not maximise throughput, while gateway-aware distribution specifically targets the hotspot cause and thus excels in that scenario. This aligns with the literature's tension between quality-aware and load-aware objectives [9], [11] and argues against one-size-fits-all recommendations.

The practical implication is a layered strategy: deploy a congestion-aware airtime metric as the default, enable multipath where path diversity genuinely reduces correlated interference, add local backpressure at bottleneck-prone nodes, and use gateway-aware distribution wherever multiple gateways exist. The strength of the combined approach is robustness across load; its limitation is complexity and the overhead of maintaining load state, which could itself consume airtime if measurement is too frequent.

Comparison with prior work shows agreement that quality-aware metrics beat hop count [9] and that backpressure is powerful at high load [13], while extending both by quantifying their interaction. Alternative explanations—such as gains arising merely from multipath capacity rather than congestion sensitivity—were examined: M2 alone underperformed M6, indicating the congestion signal and backpressure contributed independently. Limitations include the abstracted PHY and interference model. Future work should validate on a physical testbed, study measurement overhead, and evaluate under mobility and 802.11ax/be features.

CONCLUSION

This study evaluated five routing techniques for eliminating congestion in wireless mesh networks—congestion-aware metric routing, load-balanced multipath, gateway-aware distribution, backpressure, and airtime-fair selection—against a hop-count baseline in a controlled 50-node simulation. Under heavy load, a combined congestion-aware, multipath, backpressure strategy improved aggregate throughput by 41%, reduced 95th-percentile latency by 58%, and raised packet-delivery ratio from 0.79 to 0.96, while gateway-aware distribution best relieved gateway hotspots and airtime-fairness delivered the highest fairness. The objectives were achieved: the strongest single techniques were identified (RQ1), hotspot and fairness leaders were determined (RQ2), and combination was shown to outperform any single technique (RQ3). The central contribution is a like-for-like comparative evaluation and a layered deployment guidance demonstrating that congestion is best addressed by blending a congestion-sensitive metric with load spreading and local backpressure rather than by any isolated tweak. The practical significance is directly actionable for mesh operators; the theoretical significance is a clearer mapping of technique to objective. Future work should validate on physical testbeds under mobility and modern PHY.

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