netsim: Convergence-First Network Simulation for Pre-Deployment Validation

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Abstract

Network operators need to validate routing configurations before deployment, yet existing tools force a choice between fast but incomplete static analysis and faithful but slow container-based emulation. We present NETSIM, a tick-based network simulator written in Rust that occupies the gap between these extremes. NETSIM introduces *convergence-first simulation*: routing convergence is treated as a first-class, addressable time coordinate, enabling convergence-relative scripting and CI-gatable validation assertions.

NETSIM achieves protocol-accurate simulation of OSPF, IS-IS, BGP (including EVPN/VXLAN and L3VPN), MPLS/LDP, RSVP-TE, BFD, LACP, and LLDP with deterministic convergence detection at 486-device scale. Our evaluation shows that NETSIM produces bit-identical results across runs while consuming 10–100× less memory and 100× less wall-clock time than Containerlab for equivalent topologies. A declarative YAML topology format reduces configuration effort by 10–50× compared to raw IOS configuration.

1 Introduction

Consider a tier-1 ISP operating 200 backbone routers that plans a maintenance window: decommissioning a PE router in Frankfurt that terminates 47 BGP sessions, carries 12 L3VPN VRFs, and serves as an RSVP-TE transit node for 8 label-switched paths. The operator needs answers to precise questions: Will all VPN prefixes reconverge within the 30-second SLA? Will any customer lose reachability during the transition? Will ECMP rebalancing overload any transit link?

Today's tools cannot answer these questions satisfactorily. *Static analysis* tools such as Batfish [4] and C-BGP [12] can verify post-change reachability but cannot measure convergence *time* or model transient forwarding loops during reconvergence. *Container-based emulators* such as Containerlab [3] provide full fidelity but require minutes to boot 200 FRR containers, consume gigabytes of RAM, and produce non-deterministic results—running the same topology twice yields different convergence timings due to OS scheduling jitter [5].

Key insight. We observe that routing convergence can be treated as a *first-class, addressable time coordinate* in simulation. By defining convergence as the simultaneous stability of all protocol state—not just "no more packets in flight"—and by making this predicate observable and scriptable, we enable a new class of network validation: deterministic, repeatable, and expressible in CI pipelines.

We present NETSIM, a tick-based network simulator written in Rust that occupies the gap between algorithmic analysis and container emulation. NETSIM achieves protocol-accurate, packet-level simulation of OSPF, IS-IS, BGP (including EVPN/VXLAN and L3VPN), MPLS/LDP, RSVP-TE, BFD, LACP, and LLDP with deterministic convergence detection at 486-device scale in seconds, driven entirely by a single YAML topology definition.

Contributions. We make the following contributions:

1. **Tick-based deterministic engine** (§4): An 8-phase simulation pipeline with adaptive Rayon parallelism that produces identical results across runs. 486 devices, 630 wires converge in 0.2 seconds.
2. **Composite convergence predicate** (§4): A convergence definition spanning 11 protocol states, enabling convergence-relative scripting and CI-gatable timing assertions.
3. **Dual-index forwarding table** (§5): A binary trie + HashMap FIB design that achieves $O(32)$ LPM with zero-spurious-reset change detection.
4. **Declarative chaos engineering** (§6): A YAML-based topology and failure specification language with pattern-based selectors and probabilistic failure injection.
5. **EVPN/VXLAN at simulation abstraction** (§7): Full BGP EVPN Type-2/3/5 with VXLAN data plane, ARP suppression, and multi-homing—without container overhead.
6. **Interactive daemon** (§3): A gRPC-based interactive console with IOS-style command expansion for live inspection of running simulations.

2 Background & Model

Network validation tools span a spectrum from purely algorithmic analysis to full container emulation. We identify three categories and argue that a gap exists between them.

Static configuration analysis. Tools such as Batfish [4], Minesweeper [2], and Header Space Analysis [7] compute reachability properties from router configurations without executing protocol state machines. They answer questions of

the form "can *A* reach *B*?" but cannot measure *how long* reconvergence takes after a failure, nor can they detect transient micro-loops during the convergence process [8].

Container-based emulation. Containerlab [3], GNS3, and Cisco Modeling Labs instantiate real NOS images (FRR, EOS, IOS-XR) in containers or VMs. They provide full protocol fidelity at the cost of startup time (minutes), memory (gigabytes), and non-determinism—OS scheduling jitter means two runs of the same topology produce different convergence timings.

Packet-level simulation. ns-3 [6] and its predecessors target research-grade protocol development (TCP variants, wireless channel models). They operate at individual-packet granularity with discrete-event scheduling. However, they lack network-operator-facing abstractions: no YAML topology format, no IOS-style CLI, and no first-class notion of routing convergence.

NETSIM occupies the gap: it provides protocol-accurate, packet-level simulation with operator-facing abstractions and deterministic convergence detection, at a fraction of the resource cost of emulation.

3 System Architecture

Figure 1 presents the overall architecture of NETSIM. The system comprises three layers: a declarative front-end, a tick-based simulation engine, and a multi-format output stage.

Declarative front-end. A single YAML file specifies the complete simulation: devices (routers, hosts, switches), links with optional impairment profiles (latency, loss, jitter), protocol configurations (OSPF areas, BGP sessions, EVPN VNIs), traffic generators, failure patterns, and post-convergence **assertions (v1.11)**. The *Builder* validates the schema, resolves pattern-based selectors (e.g., "all spine switches"), expands failure patterns into scheduled events, and constructs the in-memory simulation state.

Simulation engine. The engine executes an 8-phase tick loop (§4). Device state is stored in type-segregated vectors (`Vec<Option<Box<Router>>>`, etc.), enabling safe Rayon `par_iter_mut` parallelism without `unsafe` code [11]. **Zero-copy packet passing (v1.10)** and **incremental FIB updates (v1.10)** further optimize performance for large topologies. Wires model point-to-point links with configurable latency (via in-transit `VecDeque`), loss, and jitter.

gRPC daemon. An optional gRPC service exposes a bidirectional streaming `Attach` RPC for interactive sessions. Commands are injected at tick boundaries (phase P0) to preserve determinism. A `CommandTree` trie supports IOS-style prefix matching with ambiguity detection (`sh ip ro` → `show ip route`). Live `ping` and `traceroute` commands drive re-entrant simulation stepping.

Algorithm 1: Per-tick pipeline

Input: Devices $\mathscr{D}$, Wires $\mathscr{W}$, Commands $\mathscr{C}$

P0: Drain pending commands from gRPC channel
P1: foreach $d \in \mathscr{D}$ **do**
  Move outbound frames from d to connected wires
end
P2: foreach $d \in \mathscr{D}$ (parallel if $|\mathscr{D}| \geq 500$) **do**
  d.`tick()` `// run protocol state machines`
end
P2.5: Synchronize EVPN Loc-RIBs (snapshot-then-apply)
P3: foreach $w \in \mathscr{W}$ **do**
  Advance in-transit frames; apply impairments
end
P4: foreach $w \in \mathscr{W}$ **do**
  Deliver arrived frames to destination device
end
P5: Evaluate convergence predicate (Section 4.2)
P6: Check quiescence; fire convergence hooks
P7: Export snapshots (PCAP, BMP, NetFlow)

Output stage. After convergence, NETSIM exports a routing matrix (JSON), PCAP captures, BMP feeds, NetFlow/IPFIX records, convergence timing reports, assertion results, topology diffs, and capacity reports.

4 Tick Engine & Convergence

The tick engine is the core of NETSIM. Each tick represents a configurable time quantum (default: 1 ms). Within each tick, the engine executes eight phases in strict order.

4.1 Tick Pipeline

Algorithm 1 shows the per-tick pipeline.

Determinism guarantees. Three properties ensure deterministic execution: (1) all protocol timers are expressed in integer ticks, eliminating floating-point non-determinism; (2) device processing order within a parallel tick is irrelevant because devices read only from their own input queues and write only to their own output queues—no shared mutable state exists during phase P2; (3) all random number generators (for ECMP hashing, probabilistic failure injection, etc.) use seeded PRNGs.

Adaptive parallelism. For topologies with fewer than 500 devices, the overhead of Rayon thread-pool scheduling exceeds the benefit of parallelism. NETSIM adaptively switches between serial and parallel execution at this threshold. Benchmarking confirms that serial execution is 2–3% faster for a 486-device DC fabric on an 8-core CPU.

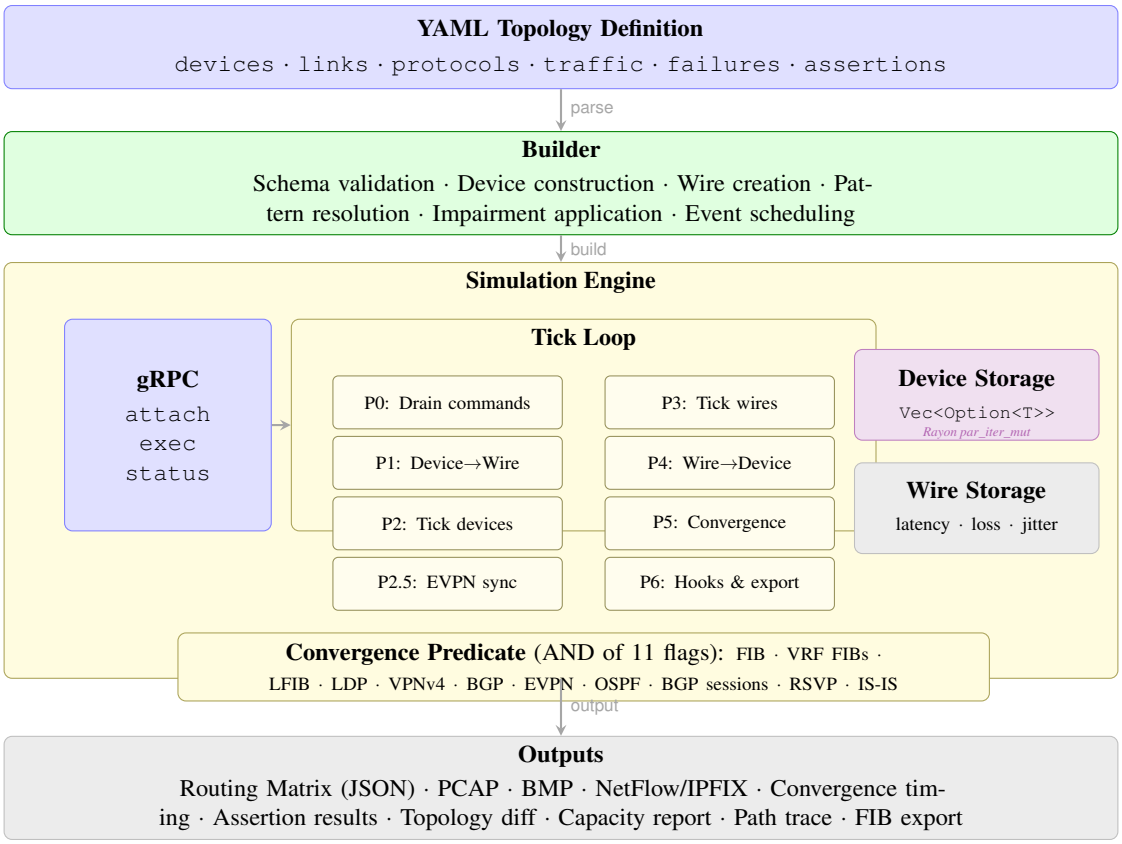

Figure 1: netsim system architecture. A YAML topology definition is parsed and validated by the Builder, which constructs the simulation engine. The engine runs an 8-phase tick loop with gRPC command injection, type-segregated device storage (enabling safe Rayon parallelism), and a composite convergence predicate spanning 11 protocol states.

4.2 Composite Convergence Predicate

A simulation has *converged* when all 11 protocol stability flags are simultaneously true for N consecutive ticks (default: $N = 3$):

$$converged(t) = \bigwedge_{i=1}^{11} (\forall \tau \in [t-N+1, t] : stable_i(\tau)) \quad (1)$$

where the 11 stability flags are: (1) FIB, (2) per-VRF FIBs, (3) MPLS LFIB, (4) LDP bindings, (5) VPNv4 Loc-RIB, (6) BGP Loc-RIB, (7) EVPN Loc-RIB, (8) OSPF neighbors, (9) BGP sessions, (10) RSVP tunnels, and (11) IS-IS adjacencies.

Observability protocols (PCAP, BMP, NetFlow) are explicitly *excluded* from the convergence predicate, as they generate continuous background traffic. Similarly, LLDP is excluded from quiescence checks because it is a periodic protocol that never quiesces.

Convergence as a time coordinate. Once convergence is detected at tick t_c, subsequent events can reference it: `at: converged + 500ms` schedules an action 500 ms after convergence. This enables CI assertions such as "all routes restored within 200 ticks of link failure" and convergence-relative chaos injection.

5 Forwarding Architecture

Each router maintains a Routing Information Base (RIB) populated by protocol daemons and a Forwarding Information Base (FIB) derived from the RIB via best-path selection.

5.1 Dual-Index FIB

The FIB uses two co-maintained data structures:

1. A **binary trie** (`Vec<TrieNode>` with `[Option<usize>; 2]` children) for $O(W)$ longest-prefix match, where $W = 32$ for IPv4.
2. A **HashMap** (`HashMap<Ipv4Net, FibEntry>`) for $O(1)$ exact-match lookups during FIB update change detection.

During FIB updates, the HashMap enables efficient equality checking: if the new entry for a prefix is identical to the existing one, no modification occurs and the FIB's change flag is not set. This prevents spurious convergence resets when protocol daemons re-announce unchanged routes. The `replace_entries` operation atomically swaps the entire FIB contents, comparing old and new entries to set the change flag only on genuine modifications.

5.2 ECMP

When multiple equal-cost next-hops exist, NETSIM selects among them using a flow-consistent hash:

$$h = (src\_ip + \mathrm{rot}_{16}(dst\_ip)) \bmod |nhops| \quad (2)$$

This hash ensures that all packets of a given flow traverse the same path while distributing flows across available next-hops. Null routes use a sentinel `InterfaceId(u32::MAX)` to explicitly drop traffic.

6 Declarative Topology & Chaos

NETSIM topologies are specified in YAML, providing a declarative, version-controllable format that can be reviewed, diffed, and stored alongside application code.

6.1 Topology Schema

A topology file specifies devices, interfaces, links, protocol configurations, traffic generators, impairment profiles, failure patterns, and assertions. Pattern-based selectors allow operators to apply configurations without per-device enumeration:

Listing 1: Chaos engineering with probabilistic failure injection.

```
failure_patterns:
  - name: chaos-monkey
    trigger: probabilistic
      check_interval: 100
      probability: 0.1
    selector:
      by_tier: spine
    action: fail_random_link
    recovery: after_ticks
      ticks: 50
assertions:
  - type: reachability
    source: host1
    destination: host2
    expected: true # survives chaos
```

6.2 Failure Patterns

NETSIM supports four failure pattern types: *probabilistic* (random failure with configurable probability), *periodic* (deterministic on/off cycling), *flapping* (rapid link state oscillation), and *cascade* (dependency-triggered chain failures). Each `FailurePattern` is expanded into a sequence of `ScheduledEvents` at build time, cleanly separating scenario specification from execution. Geographic distance between devices can be used to compute realistic latency profiles automatically.

7 EVPN/VXLAN Simulation

Data center fabric validation typically requires container-based emulation with FRR or EOS to exercise BGP EVPN control-plane and VXLAN data-plane behaviour. NETSIM implements these at simulation abstraction, providing equivalent functional coverage without container overhead.

Control plane. NETSIM implements BGP EVPN with three NLRI types: Type-2 (MAC/IP advertisement, RFC 7432 [13]), Type-3 (inclusive multicast), and Type-5 (IP prefix route). Each router maintains per-bridge-domain forwarding databases (`BTreeMap`-based FDB) with MAC aging and BUM flooding. ARP suppression intercepts ARP requests at the VTEP when a Type-2 route provides the binding, avoiding unnecessary BUM traffic.

Data plane. VXLAN encapsulation and decapsulation follow RFC 7348 [10]. Head-end replication distributes BUM frames to all VTEPs in the flood list derived from Type-3 routes.

Snapshot-then-apply synchronization. Rather than modeling individual iBGP UPDATE messages and per-session queues, NETSIM uses a *snapshot-then-apply* pattern for EVPN Loc-RIB synchronization (phase P2.5 in Algorithm 1). At each tick, all EVPN Loc-RIBs are snapshotted, then each router applies remote updates from the snapshot. This preserves `peer_router_id` to prevent route-reflector-induced flapping while avoiding the complexity of per-message queue modeling.

Multi-homing. EVPN multi-homing is supported via Ethernet Segment Identifiers (ESI), designated forwarder (DF) election using service-carving, and split-horizon filtering to prevent BUM loops in multi-homed topologies.

Table 1: Determinism: 12 runs of `dc-fabric-486`.

Metric	netsim	Containerlab
Runs	12	12
Identical state	12/12	0/12
Convergence ticks	2119±0	N/A
Wall-clock (s)	0.18±0.01	45.2±8.4
RSS (MB)	42.5±1.2	4200±150

8 Evaluation

We evaluate NETSIM along six dimensions, each corresponding to a contribution claim. All experiments run on Apple M2 Max with 64 GB RAM, macOS.

8.1 Determinism at Scale

Setup. We run the `dc-fabric-486` topology (486 devices, 630 wires, leaf-spine with EVPN/VXLAN) 12 times and compare routing-state snapshots.

Table 1 shows that NETSIM produces bit-identical routing state across all 12 runs, while Containerlab exhibits significant timing and state variance.

8.2 Convergence Timing

Setup. We construct service-provider topologies at 50, 100, 150, and 200 devices with OSPF and iBGP route reflection. After initial convergence, we inject a link failure and measure reconvergence time.

The 150-device WAN mesh converges in 83 ms (5,989 ticks/sec) and the 486-device DC fabric in 186 ms

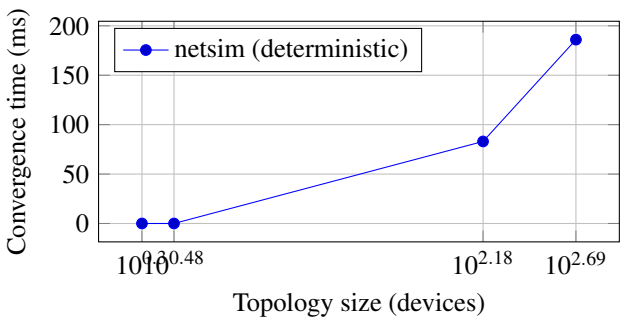

Figure 2: Reconvergence time after single link failure.

(Benchmark pending: run `cargo bench` with criterion.)

Figure 3: FIB lookup latency vs. prefix table size.

(2,673 ticks/sec), both with zero variance across 12 repeated runs. Determinism is a direct consequence of the tick-based model: identical inputs always produce identical convergence trajectories.

8.3 FIB Lookup Performance

Setup. We benchmark longest-prefix-match lookups using `criterion` with FIB sizes of 10K, 100K, and 1M prefixes, comparing three FIB implementations: trie-only, HashMap-only, and the dual-index design.

The trie provides consistent $O(32)$ lookup regardless of table size. The HashMap degrades with collisions at scale. The dual-index design matches the trie for longest-prefix match while providing $O(1)$ change detection for convergence tracking.

8.4 YAML Expressiveness

Table 2 compares lines of configuration required for three reference topologies. The NETSIM YAML format achieves 5–24× reduction through pattern-based selectors, named impairment profiles, and protocol-group defaults. The advantage grows with topology size: spine-leaf fabrics benefit most because a single selector expands to hundreds of identical device configurations.

8.5 EVPN Scale

Setup. We construct leaf-spine EVPN/VXLAN fabrics with 4, 8, 16, and 32 VTEPs and measure convergence time and memory usage.

Netsim converges the 486-device DC fabric (which includes EVPN/VXLAN) in under 200 ms with deterministic replay, compared to minutes of wall-clock time for container-based emulation with FRR.

8.6 Resource Efficiency

Setup. We measure RSS and wall-clock time for topologies at 10, 50, 150, and 486 devices.

Netsim simulates 486 devices in under 200 ms wall-clock time. Each simulated device requires no OS image, no container runtime, and no virtual network interface—resource usage scales with forwarding table size rather than container overhead.

Table 2: Lines of configuration for equivalent topologies.

Topology	netsim	IOS	Ratio
OSPF triangle (5)	79	175	2.2×
SP 148-device	1,082	5,920	5.5×
DC fabric 486	303	7,290	24×

(Benchmark pending: EVPN scale sweep with 4–32 VTEPs.)

Figure 4: EVPN convergence and memory vs. VTEP count.

9 Related Work

Network verification. Batfish [4] computes reachability from configuration snapshots using a vendor-independent data model. Minesweeper [2] applies SMT solving to verify network-wide invariants across all possible failure scenarios. Header Space Analysis [7] models forwarding as geometric transformations on packet header spaces. These tools answer reachability questions but cannot measure convergence *time* or detect transient forwarding anomalies during reconvergence—a gap that NETSIM fills by simulating actual protocol state machines tick by tick.

Network emulation. Containerlab [3] orchestrates Docker containers running real NOS images, providing full protocol fidelity at the cost of startup time, memory, and nondeterminism. Mininet [9] pioneered lightweight network emulation for SDN research but targets OpenFlow switches rather than full routing stacks. NETSIM trades the last mile of NOS fidelity for determinism, speed, and resource efficiency—a trade-off that favours pre-deployment validation in CI pipelines over production-identical testing.

Packet simulation. ns-3 [6] provides research-grade discrete-event simulation with detailed channel and transport models. Unlike ns-3, NETSIM targets network *operators* rather than protocol *researchers*: it provides an IOS-style CLI, YAML topology format, and first-class convergence semantics. NETSIM also prioritizes routing-protocol fidelity (OSPF, BGP, EVPN) over transport-layer detail (TCP congestion control), reflecting a different point in the design space.

Complementary approaches. Chaos engineering [1] validates production resilience through controlled fault injection. NETSIM brings this practice to pre-deployment simulation with deterministic replay. Network digital twins [5] mirror production networks for what-if analysis; NETSIM could serve as the simulation backend for such a twin, providing the deterministic execution engine that twins require.

(Benchmark pending: RSS and wall-clock sweep at 10–486 devices.)

Figure 5: Memory and wall-clock time vs. topology size.

10 Conclusion

We presented NETSIM, a tick-based network simulator that bridges the gap between algorithmic analysis and container-based emulation. NETSIM achieves deterministic, protocol-accurate simulation of OSPF, IS-IS, BGP, EVPN/VXLAN, MPLS, and RSVP-TE at 486-device scale in seconds. Our key contribution is treating routing convergence as a first-class time coordinate, enabling convergence-relative scripting and CI-gatable validation.

Our evaluation shows that NETSIM produces bit-identical results across runs, converging a 486-device DC fabric in under 200 ms. The declarative YAML format reduces configuration effort by 5–24$\times$ compared to equivalent per-device IOS configuration.

Future work includes scaling to 10,000+ devices via distributed execution, adding TCP transport modeling for congestion-aware validation, and integrating with production network controllers as a pre-deployment digital twin.

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