Design and Performance of the OpenBSD Stateful Packet Filter (pf)

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Introduction

- part of a firewall, working on IP packet level (vs. application level proxies or ethernet level bridges)
- packet filter intercepting each IP packet that passes through the kernel (in and out on each interface), passing or blocking it
- stateless inspection based on the fields of each packet
- stateful filtering keeping track of connections, additional information makes filtering more powerful (sequence number checks) and easier (replies, random client ports)

Motivation

- OpenBSD included IPFilter in the default install
- what appeared to be a BSD license turned out to be non-free
- unlike other license problems discovered by the ongoing license audit, this case couldn't be resolved, IPFilter removed from the tree
- existing alternatives were considered (ipfw), larger code base, kernel dependencies
- rewrite offers additional options, integrates better with existing kernel features

Overview

- Introduction
- Motivation
- Filter rules, skip steps
- State table, trees, lookups, translations (NAT, redirections)
- Benchmarks
- Conclusions

Filter rules

- linear linked list, evaluated top to bottom for each packet (unlike netfilter's chains tree)
- rules contain parameters that match/mismatch a packet
- rules pass or block a packet
- last matching rule wins (except for 'quick', which aborts rule evaluation)
- rules can create state, further state matching packets are passed without rule set evaluation

Skip steps

- transparent optimization of rule set evaluation, improve performance without affecting semantics
- example: ten consecutive rules apply only to packets from source address X, packet has source address Y, first rule evaluated, next nine skipped
- skipping is done on most parameters, in pre-defined order
- parameters like direction (in, out), interface or address family (IPv4/IPv6) partition the rule set a lot, performance increase is significant
- worst case: consecutive rules have no equal parameters, every rule must be evaluated, no additional cost (linked list traversal)

State table

- TCP (sequence number checks on each packet), ICMP error messages match referred to packet (simplifies rules without breaking PMTU etc.)
- UDP, ICMP queries/replies, other protocols, pseudo-connections with timeouts
- adjustable timeouts, pseudo-connections for non-TCP protocols
- binary search tree (AVL, now Red-Black), O(log n) even in worst-case
- key is two address/port pairs

Translations (NAT, redirections)

- translating source addresses: NAT/PAT to one address using proxy ports
- translating destination: redirections (based on addresses/ports)
- mapping stored in state table
- application level proxies (ftp) in userland

State table keys

- one state entry per connection, stored in two trees
- example: 10.1.1.1:20000 -> 62.65.145.30:50001 -> 129.128.5.191:80
- outgoing packets: 10.1.1.1:20000 -> 129.128.5.191:80, replace source address/port with gateway
- incoming packets: 129.128.5.191:80 -> 62.65.145.30:50001, replace destination address/port with local host
- three address/port pairs of one connection: lan, gwy, ext
- without translation, two pairs are equal

State table keys

- two trees: tree-lan-ext (outgoing) and tree-ext-gwy (incoming), contain the same state pointers
- no addition translation map (and lookup) needed

Normalization

- IP normalization (scrubbing) to remove interpretation ambiguities, like overlapping fragments (confusing IDSs)
- reassembly (caching) of fragments before filtering, only complete packets are filtered
- sequence number modulation

Logging

- through bpf, virtual network interface pflog0
- link layer header used for pf related information (rule, action)
- binary log files, readable with tcpdump and other tools

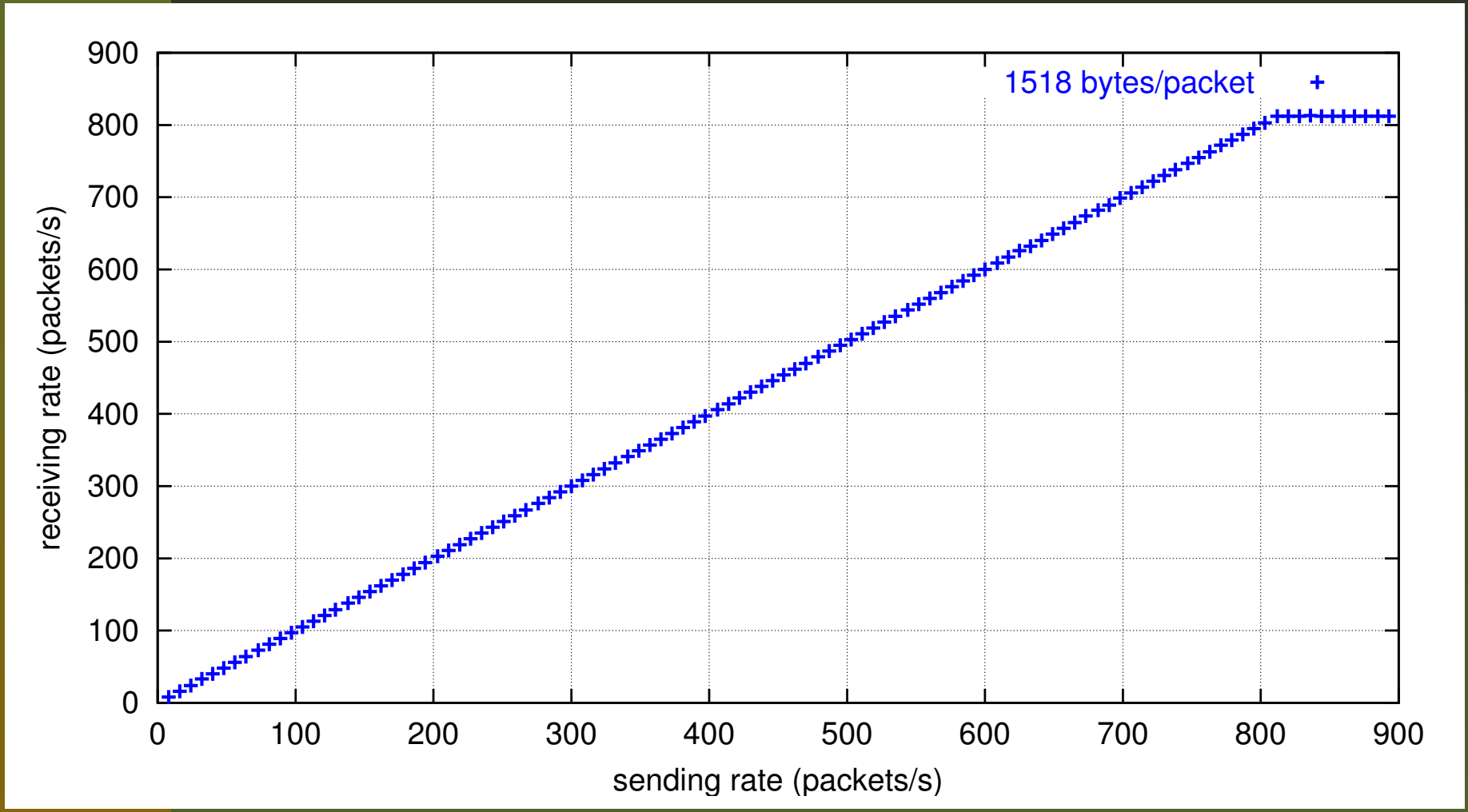
Benchmarks: Setup

- two (old) i386 machines with two network interface cards each, connected with two crosswire Cat5 cables, 10 mbit/s unidirectional
- tester: generate TCP packets on ethernet level through first NIC, capture incoming ethernet frames on second NIC
- firewall: OpenBSD and GNU/Linux (equal hardware), IP forwarding enabled, packet filter enabled, no other services, no other network traffic (static arp table)

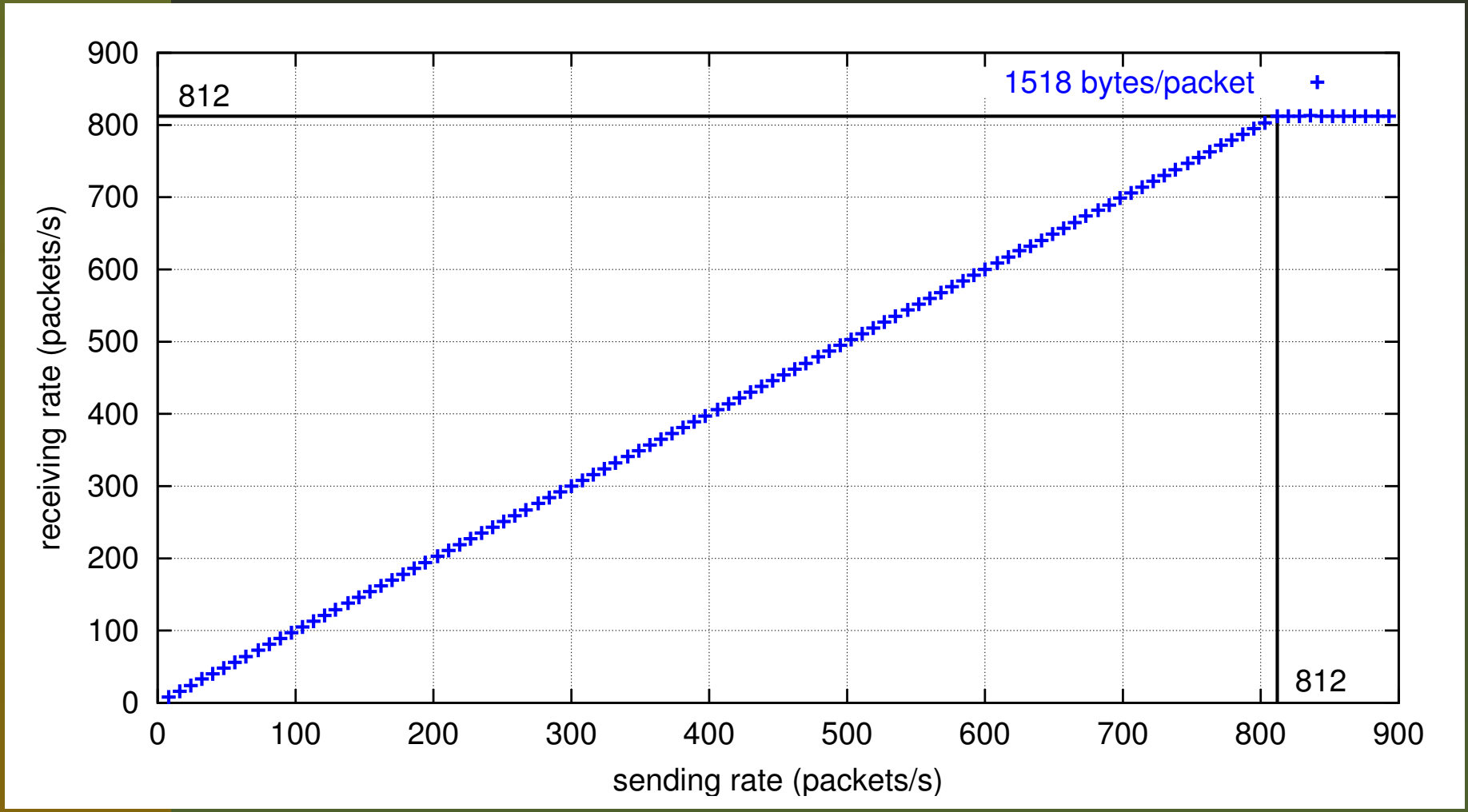
Benchmarks: Packet generation

- TCP packets of variable size, random source/destination addresses and ports
- embedded timestamp to calculate latency, incremental serial number to detect packet loss
- send packets of specified size at specified rate for several seconds, print throughput, latency and loss
- verify that setup can handle maximum link rate correctly

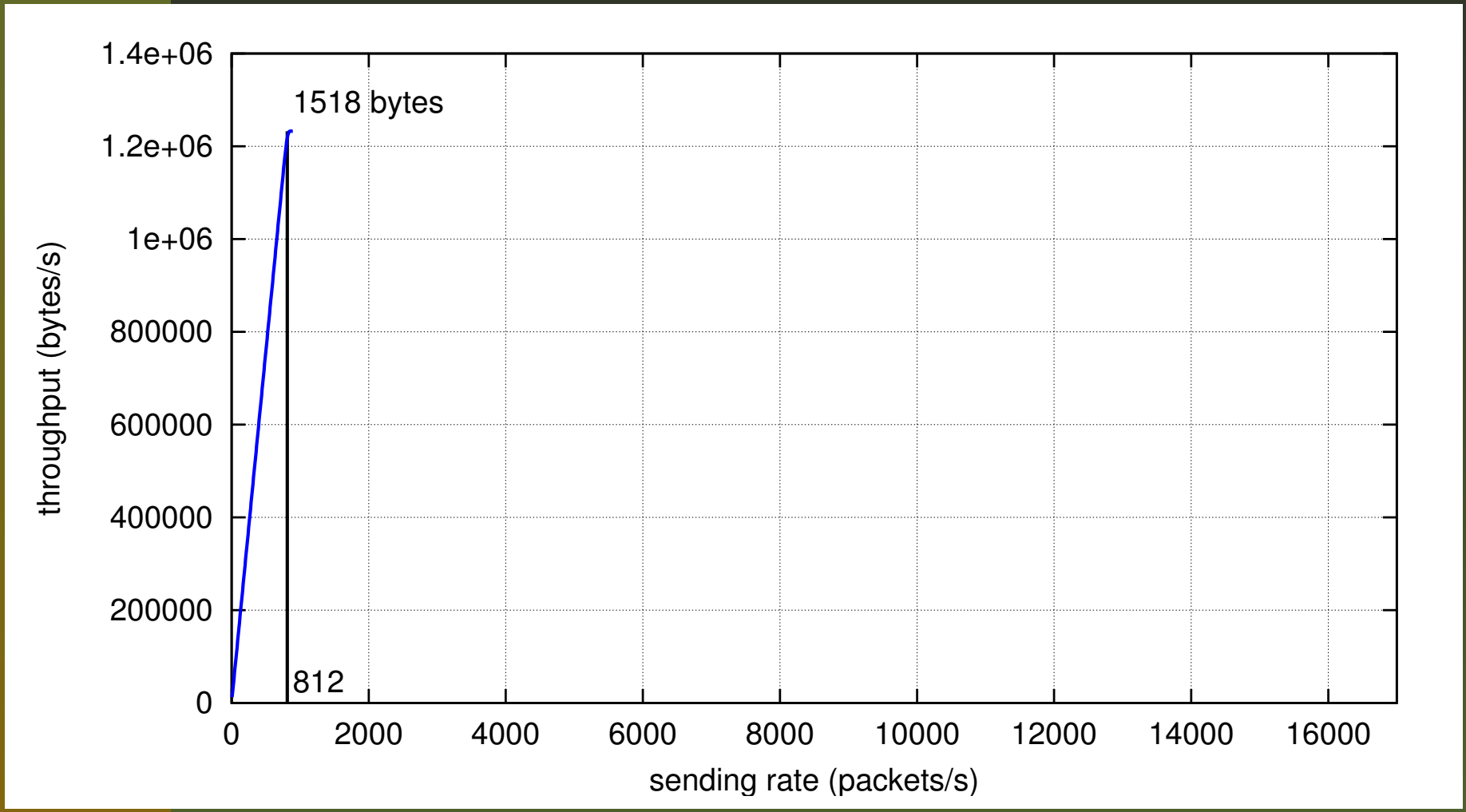
Local, reaching link limit



Local, reaching link limit



Local, varying packet sizes



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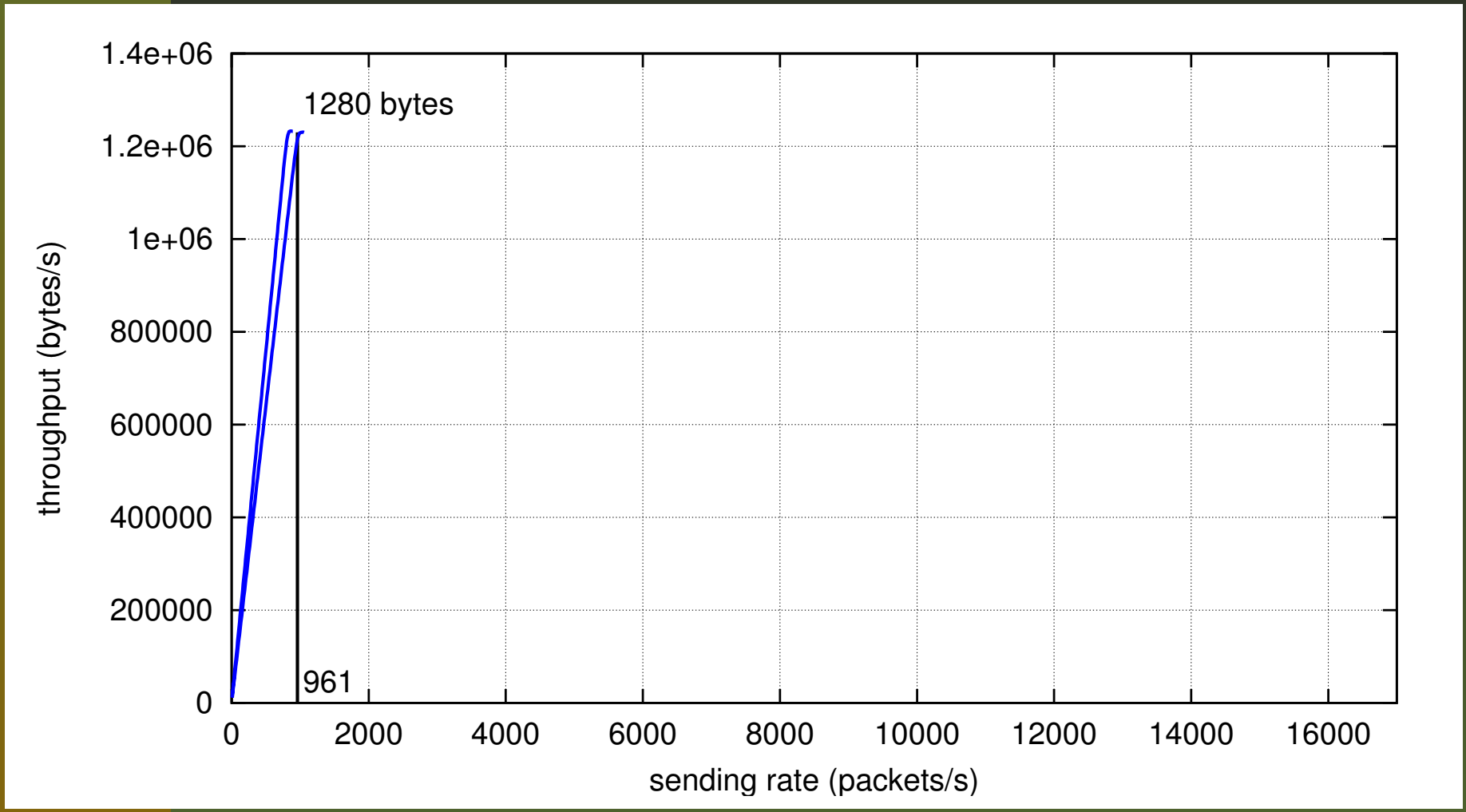
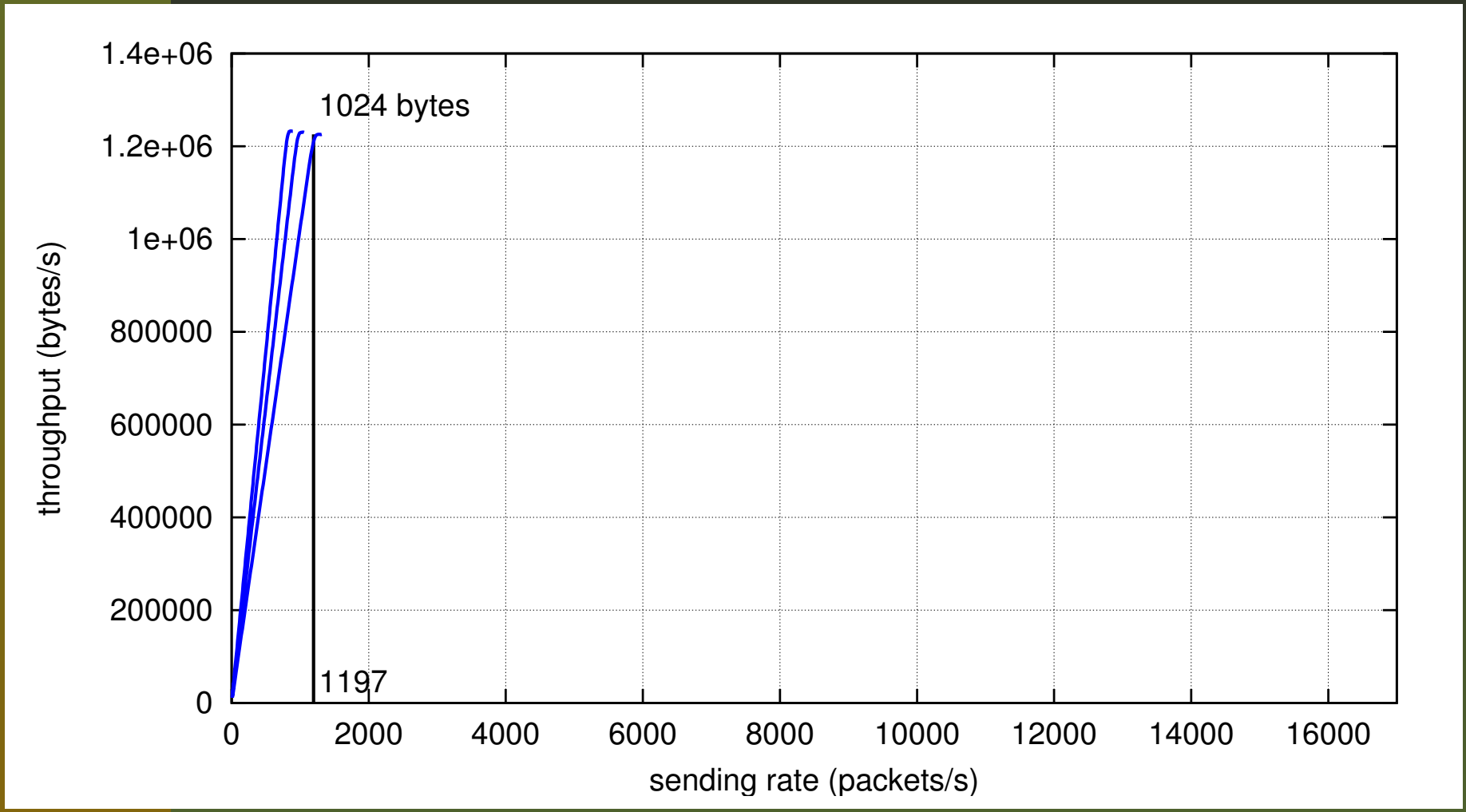


Local, varying packet sizes



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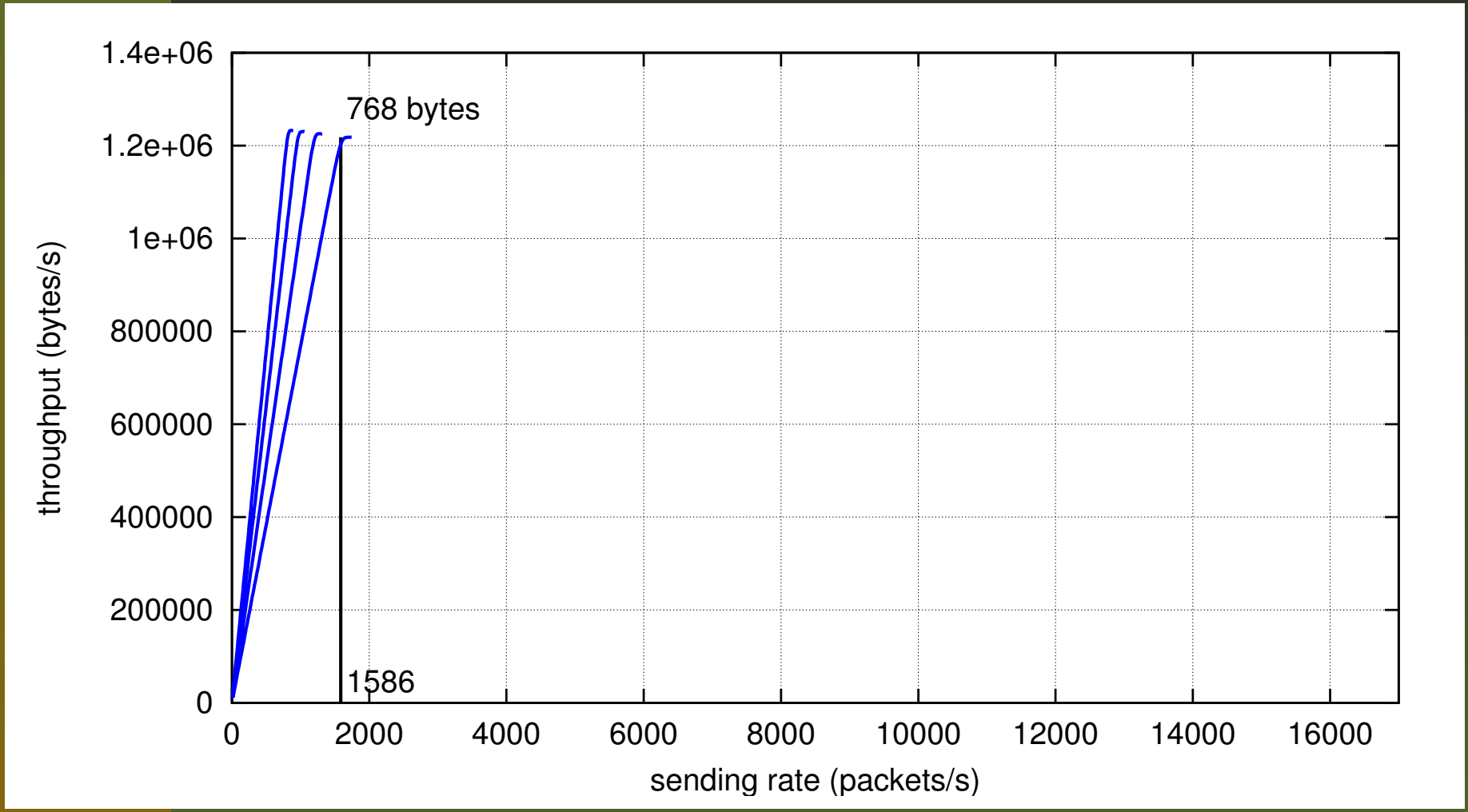

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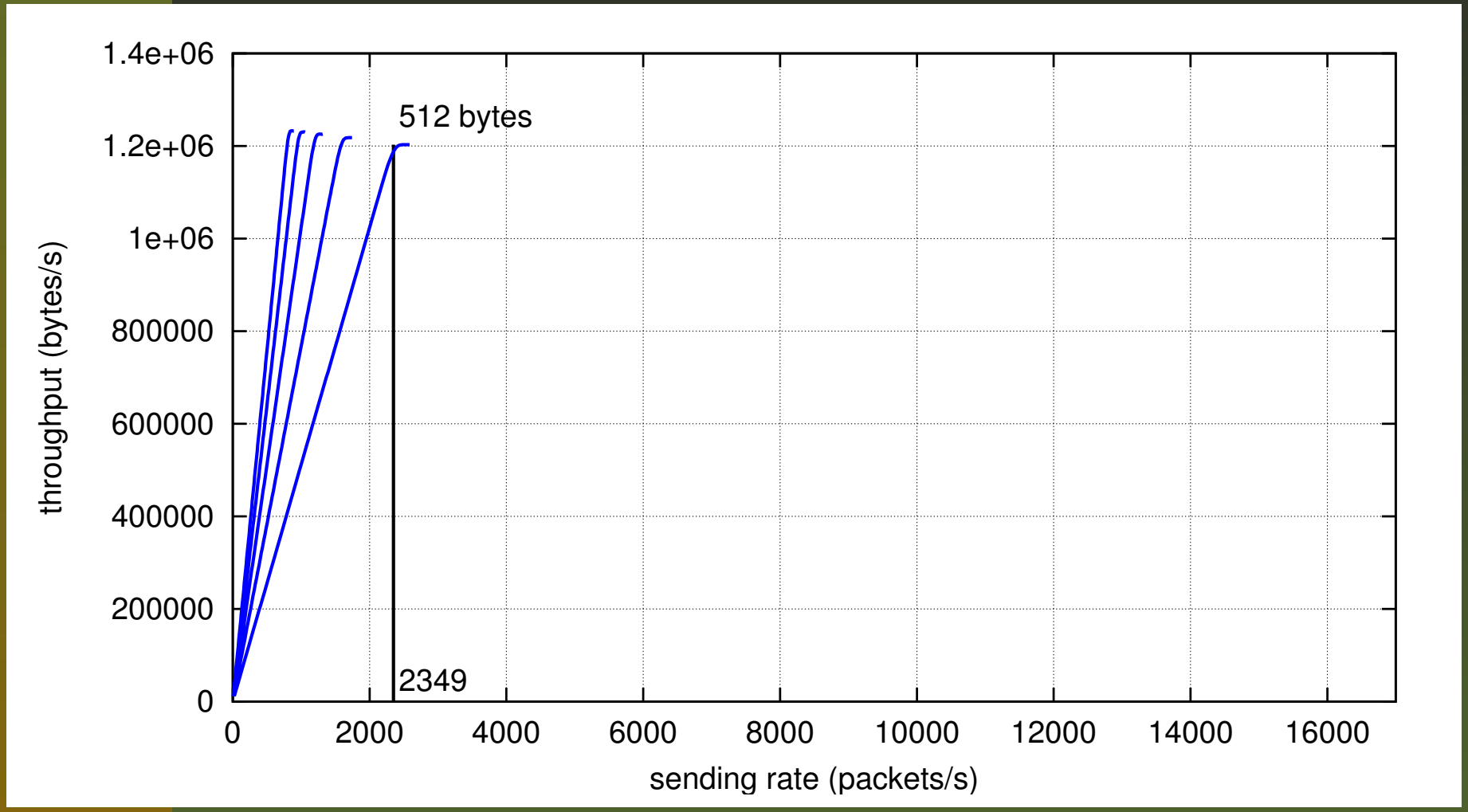

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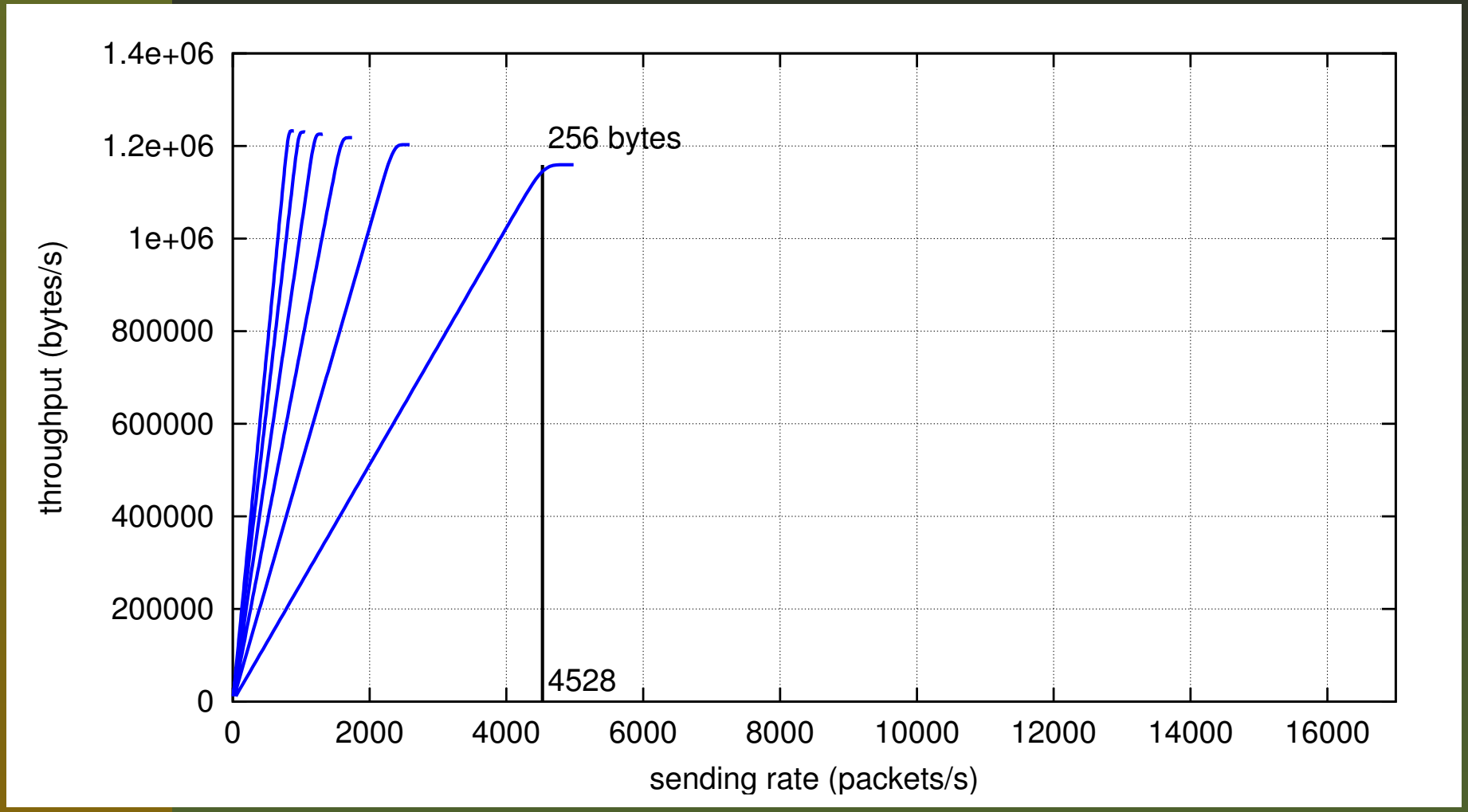

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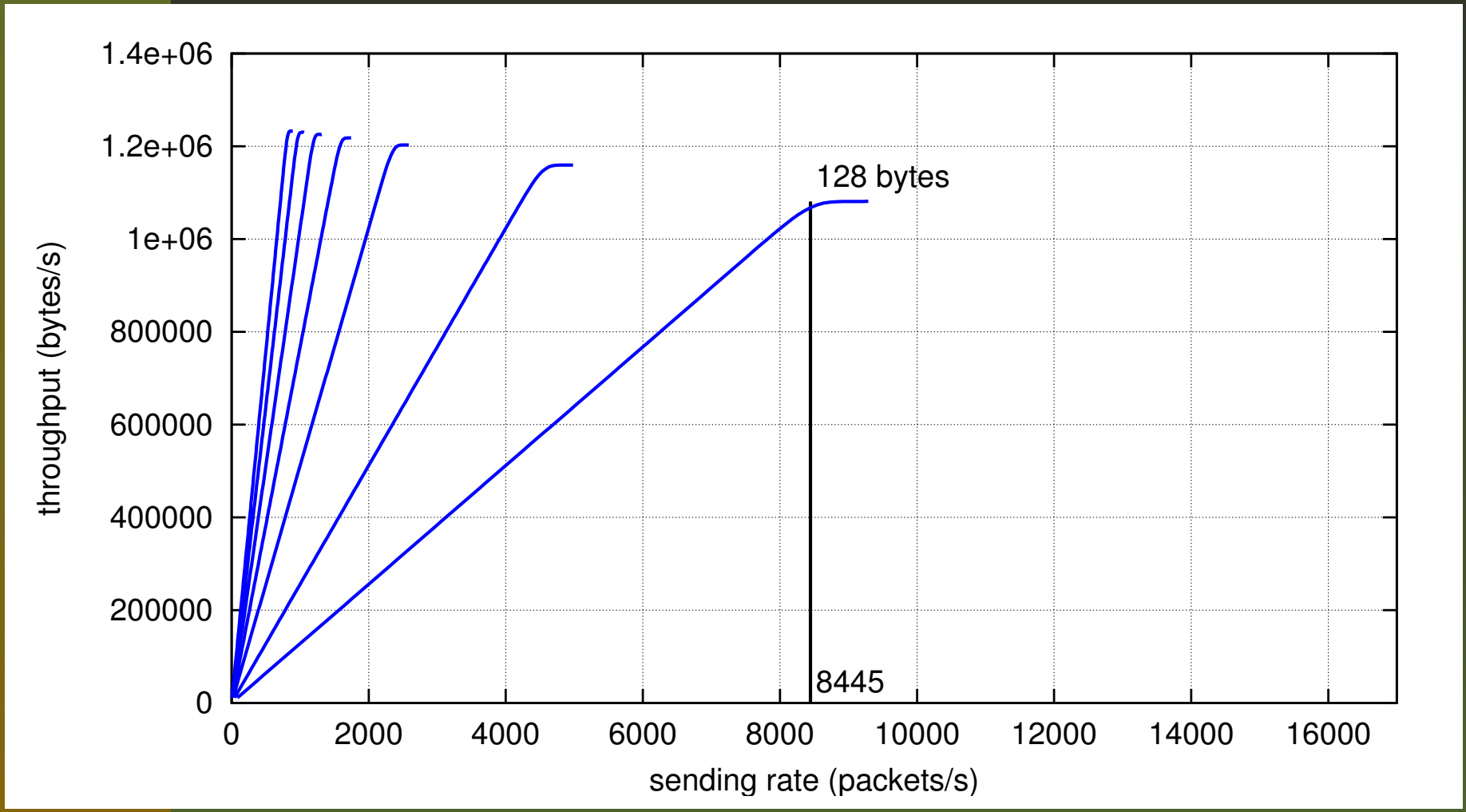

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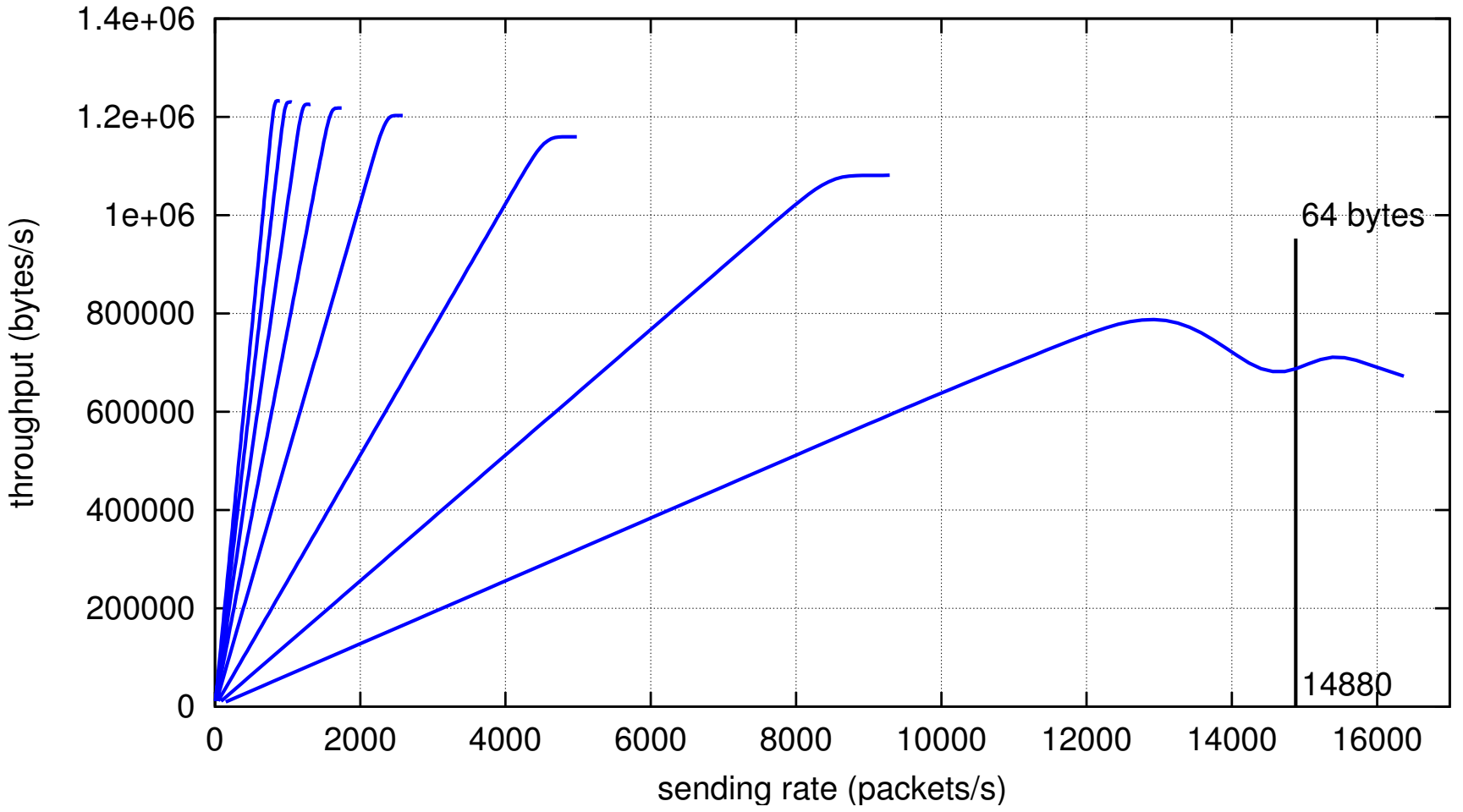

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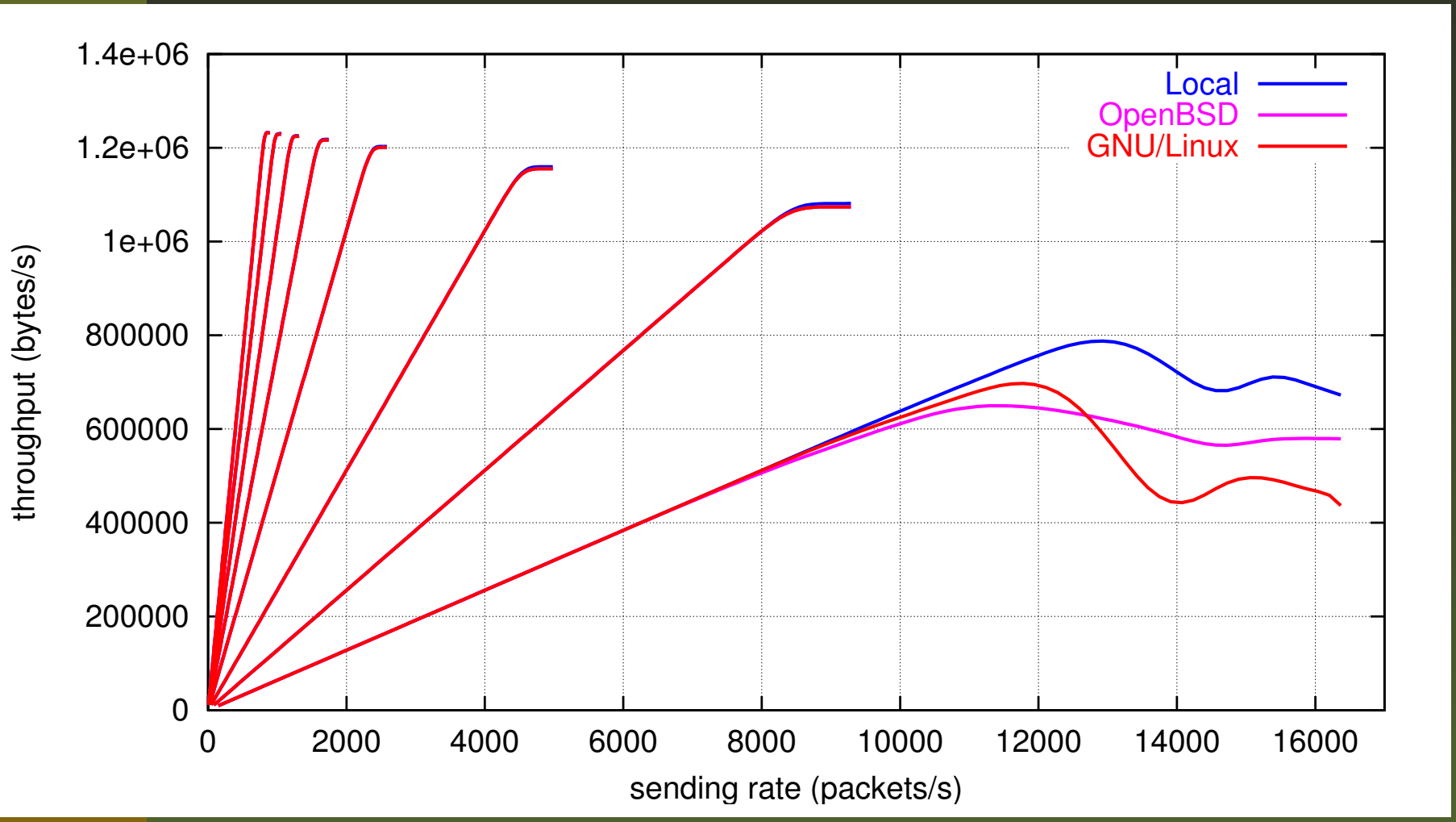
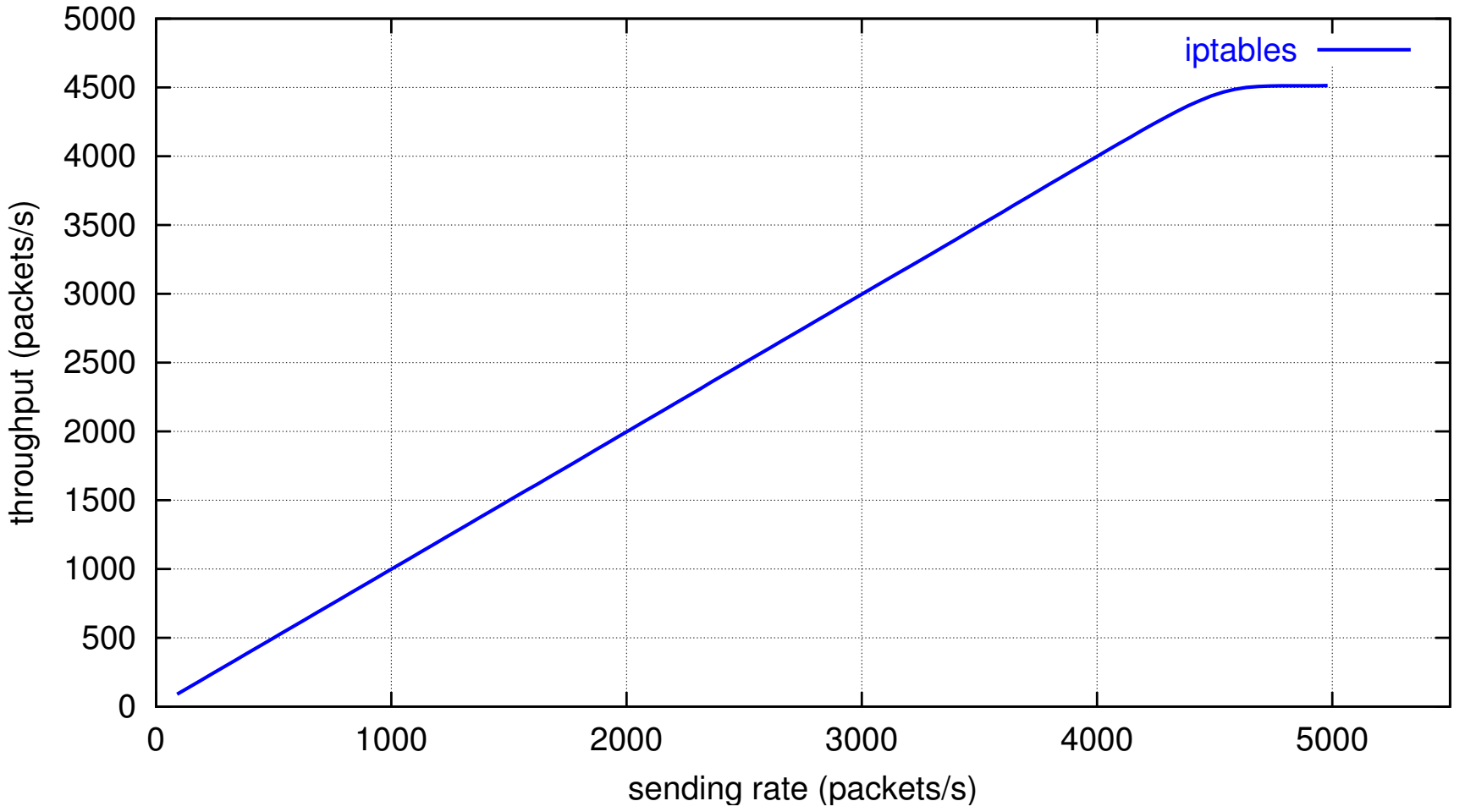


Stateless, 100 rules, throughput



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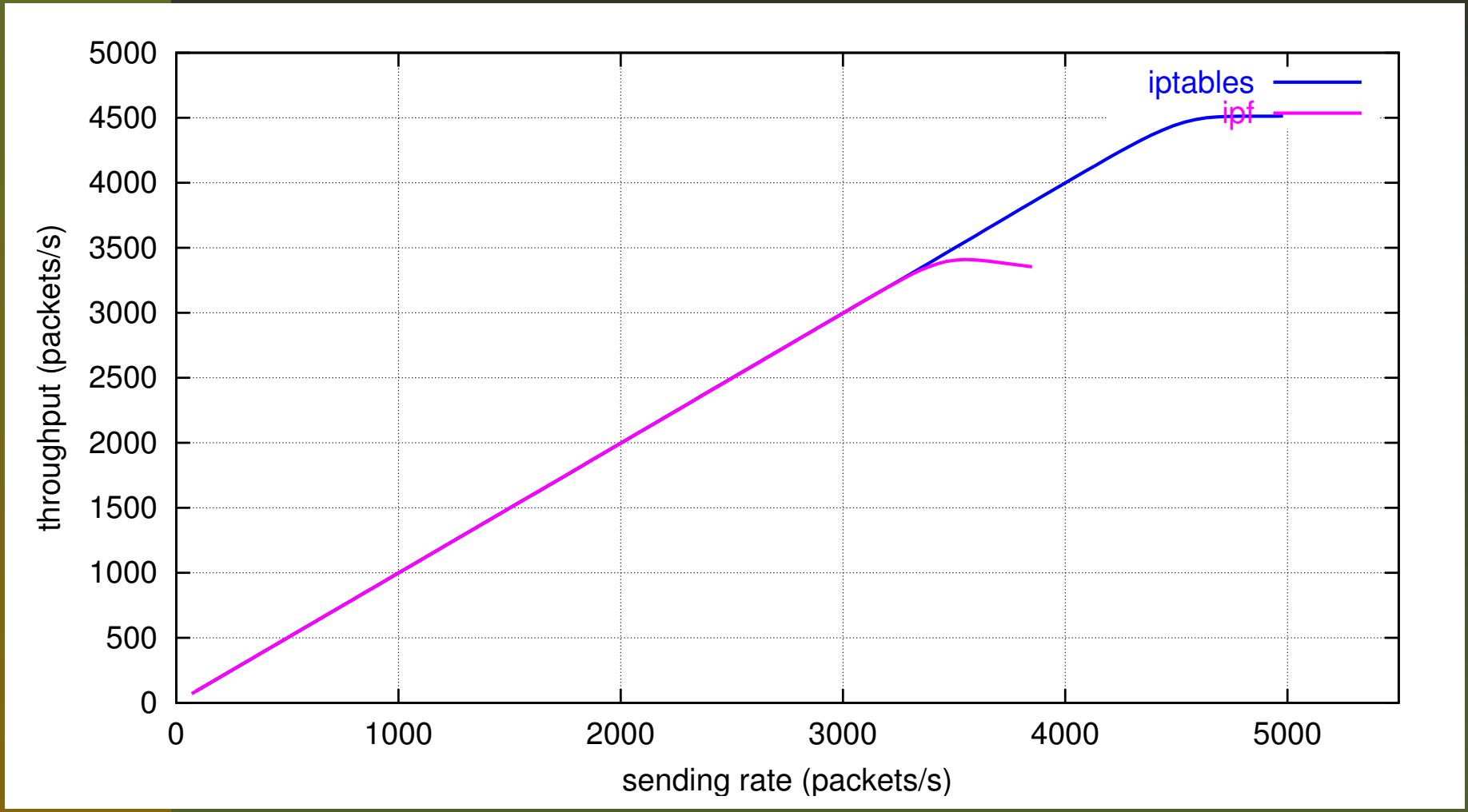

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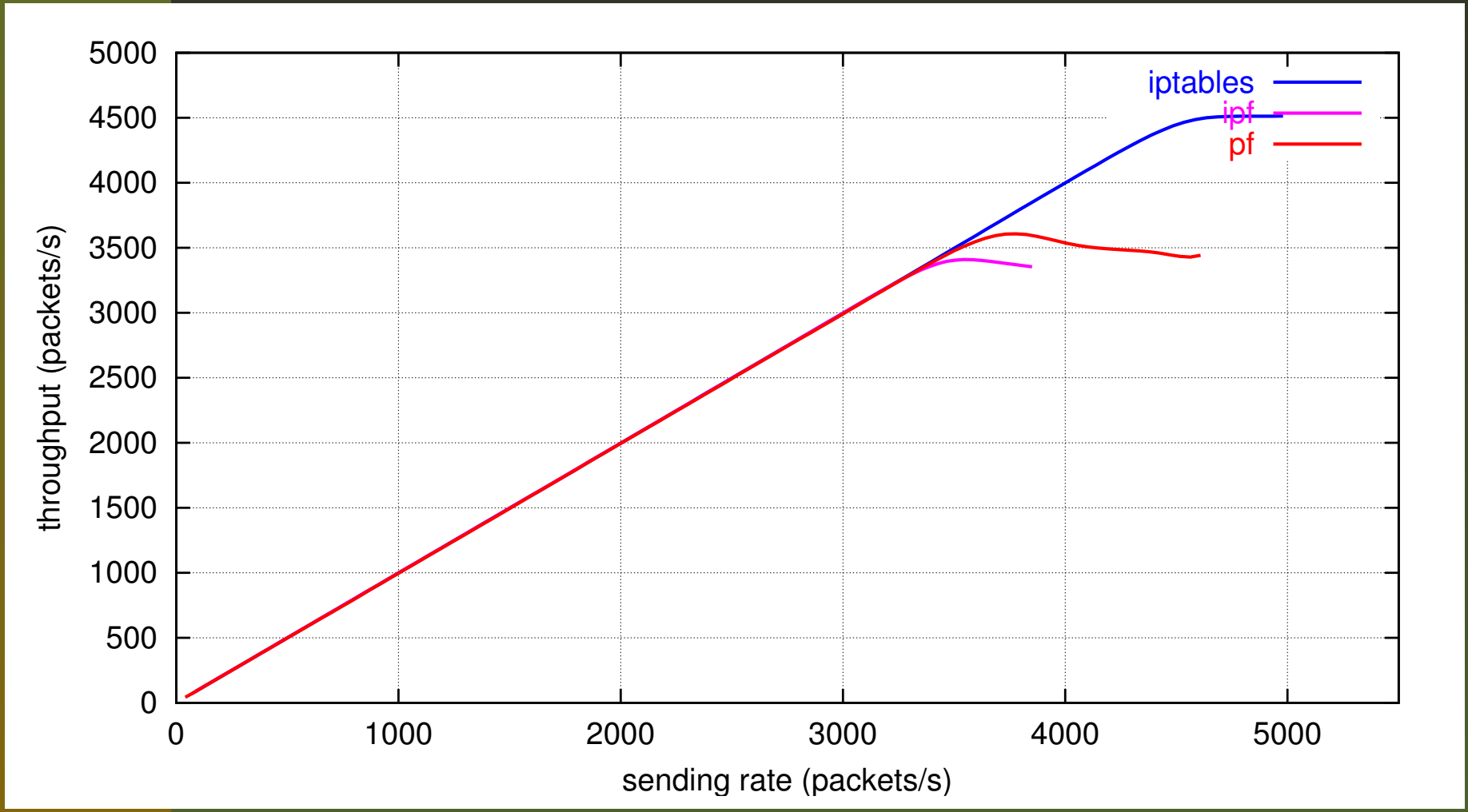
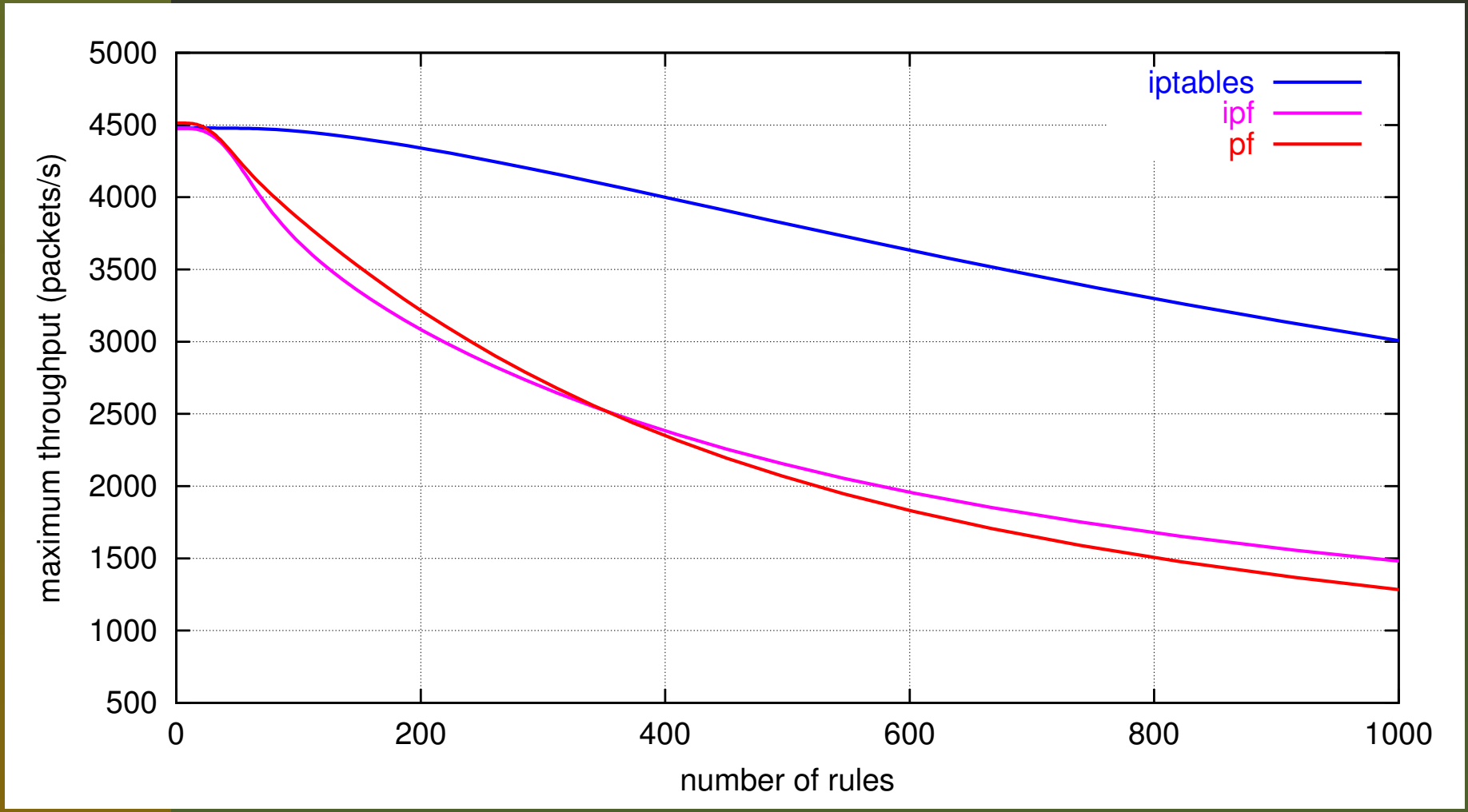
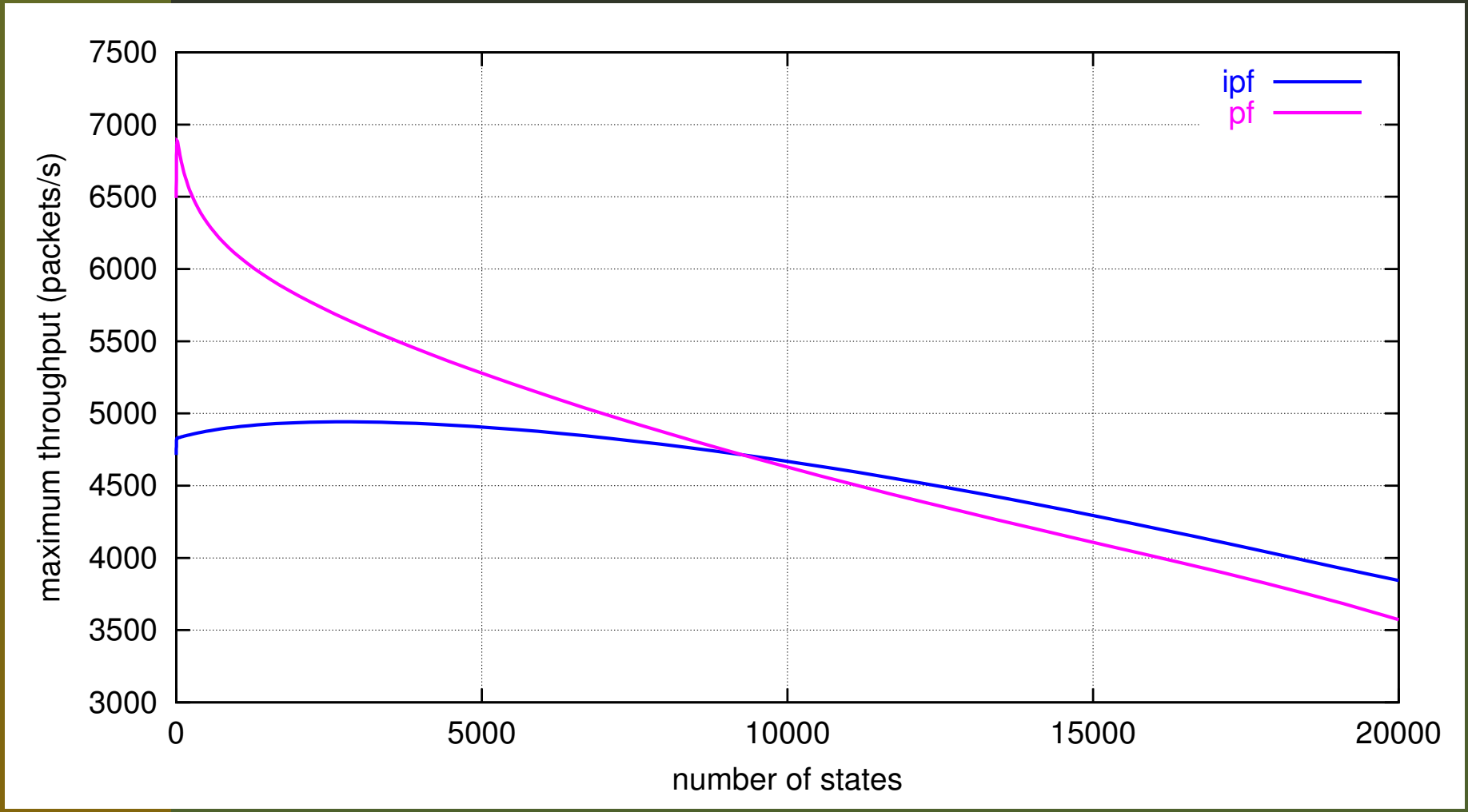


Maximum throughput vs. rules



Maximum throughput vs. states



Conclusions

- rule set evaluation is expensive. State lookups are cheap
- filtering statefully not only improves filter decision quality, it actually increases performance
- memory cost: 64000 states with 64MB RAM (without tuning), increasing linearly
- binary search tree for states scales with O(log n)

Production results

- Duron 700MHz, 128MB RAM, 3x DEC 21143 NICs
- 25000-40000 concurrent states
- average of 5000 packets/s
- fully stateful filtering (no stateless passing)
- CPU load doesn't exceed 10 percent
- (same box and filter policy with IPFilter was 90 percent load average)

Questions?

- The OpenBSD Project: http://www.openbsd.org/
- Paper and slides: http://www.benzedrine.cx/pf.html
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