Synthesizing Safe and Efficient Kernel Extensions for Packet Processing

Qiongwen Xu[1], Michael D. Wong[2], Tanvi Wagle[1], Srinivas Narayana[1], Anirudh Sivaraman[3]
[1]Rutgers University [2]Princeton University [3]New York University
k2_compiler@email.rutgers.edu

ABSTRACT

Extended Berkeley Packet Filter (BPF) has emerged as a powerful method to extend packet-processing functionality in the Linux operating system. BPF allows users to write code in high-level languages (like C or Rust) and execute them at specific hooks in the kernel, such as the network device driver. To ensure safe execution of a user-developed BPF program in kernel context, Linux uses an in-kernel static checker. The checker allows a program to execute only if it can prove that the program is crash-free, always accesses memory within safe bounds, and avoids leaking kernel data.

BPF programming is not easy. One, even modest-sized BPF programs are deemed too large to analyze and rejected by the kernel checker. Two, the kernel checker may incorrectly determine that a BPF program exhibits unsafe behaviors. Three, even small performance optimizations to BPF code (*e.g.,* 5% gains) must be meticulously hand-crafted by expert developers. Traditional optimizing compilers for BPF are often inadequate since the kernel checker's safety constraints are incompatible with rule-based optimizations.

We present K2, a program-synthesis-based compiler that automatically optimizes BPF bytecode with formal correctness and safety guarantees. K2 produces code with 6–26% reduced size, 1.36%–55.03% lower average packet-processing latency, and 0–4.75% higher throughput (packets per second per core) relative to the best `clang`-compiled program, across benchmarks drawn from Cilium, Facebook, and the Linux kernel. K2 incorporates several domain-specific techniques to make synthesis practical by accelerating equivalence-checking of BPF programs by 6 orders of magnitude.

CCS CONCEPTS

• **Networks → Programmable networks**.

KEYWORDS

endpoint packet processing, BPF, synthesis, stochastic optimization

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1 INTRODUCTION

The CPU efficiency of processing packets at servers is of paramount importance, given the increasing volumes of data from large-scale applications, the stagnation of Moore's law, the monetization of CPU cores in cloud computing, and the stringent throughput and latency requirements of high-end applications. The networking community has responded with several efforts, including innovations in operating system packet-processing [53, 58, 81, 126], user-space stacks [45, 47, 64, 87, 105, 117, 123], and programmable NIC offloads [15, 22, 24, 25, 74, 76].

Recently, extended Berkeley Packet Filter (BPF) has emerged as a popular method to achieve flexible and high-speed packet processing on the Linux operating system. With roots in packet filtering in the early 90s [107], BPF has since evolved into a general-purpose in-kernel virtual machine [59, 83] with an expressive 64-bit RISC instruction set. BPF code[1] has been widely deployed in production systems—implementing load balancing [56, 131], DDoS protection [71], container policy enforcement [90], application-level proxying [21], intrusion-detection [70], and low-level system monitoring [42, 80]. Every packet sent to Facebook [131] and CloudFlare [71] is processed by BPF software.

BPF enables users to extend the functionality of the operating system without developing kernel software [79]. The user writes code in a high-level language (*e.g.,* C, Rust), and uses a standard compiler toolchain (*e.g.,* Clang-9) to produce BPF bytecode. The operating system leverages an in-kernel *static checker*, which analyzes the BPF bytecode to determine if it is safe to run in kernel context. Specifically, the checker attempts to prove that the program terminates, does not crash, does not access kernel memory beyond safe permitted bounds, and does not leak privileged kernel data. If the program is proved safe by the kernel checker, it is downloaded into kernel memory and run without any additional run-time checks. Otherwise, the program is rejected. BPF programs can be executed within several performance-critical parts of the packet-processing stack [104], like the network device driver [83], traffic control [54], congestion control [92], and socket filters [107].

BPF is unique in the combination of flexibility, safety, and performance it enables for packet processing. Unlike a kernel module that may potentially crash the kernel or corrupt kernel memory, a BPF program accepted by the kernel checker is guaranteed not to misbehave, assuming that the checker and the BPF run-time are bug-free. Unlike kernel-bypass stacks, BPF does not pin CPU cores, and retains the user-kernel privilege separation and standard management tools (*e.g.,* `tcpdump`) available on operating systems [83, 124].

Despite the promises of BPF, it is not easy to develop high-quality packet-processing code in BPF today. We outline three challenges.

[1]In this paper, we use the term BPF throughout to denote the extended version of BPF, rather than "classic" BPF used to write packet filters.

Challenge 1: Performance. Optimizing the performance of BPF code today is tantamount to optimizing assembly code. Userspace profiling tools are yet to mature [93]. Optimization support in compilers is inadequate. For the benchmarks we tested, the standard compilation toolchain (based on Clang-9) produced identical code under optimization flags `-O2` and `-O3`, missing opportunities available to optimize the `-O2` code (§8). Anecdotally, it is known that even expert developers have to put in painstaking work to improve performance of BPF code by small margins [49, 91, 122]. Yet, small improvements are worthwhile: reducing even a few clock cycles per packet is crucial to meeting the line rate at high speeds given the limited budget of CPU clock cycles available to process each packet [23, 72, 83]. Further, cutting the CPU usage of networking decreases interference to workloads co-hosted on the same machine [37, 97].

Challenge 2: Size. Running BPF programs beyond a modest size poses challenges. The kernel checker limits the complexity[2] of the programs that it deems acceptable [27, 88] to keep the time it takes to load user programs small. In practice, programs with even a few thousand instructions end up being rejected [29]. Further, hardware platforms supporting BPF offload are very sensitive to program size, given their limited amount of fast memory to hold the program [122]. Compiler support for code compaction is deficient: for most of our benchmarks, we found that `clang -Os` produces code of the same size as `clang -O2`. The only recourse for developers under size pressure is to refactor their program [3, 10, 28].

Challenge 3: Safety. It is difficult to get even small programs past the kernel checker. The checker's static analysis is incomplete and imprecise: it rejects many programs which have semantically-equivalent rewrites that can be accepted (§6). This makes it tricky to develop compilers that produce runnable BPF bytecode. The developers of Clang's BPF backend work specifically towards producing instruction sequences that the kernel checker will accept, *e.g.,* [14, 16–19]. Producing checker-acceptable code is a major challenge in designing a BPF backend to the `gcc` compiler [60, 67].

Fundamentally, generating optimized, compact, and safe BPF code is challenging due to the incompatibility between checker-enforced safety restrictions and rule-based optimizations (§2.2). We call this the *phase-ordering* problem in BPF compilation: producing safe, checker-acceptable code precludes many traditional rule-based optimizations. Conversely, applying optimizations produces code that the kernel checker rejects.

A synthesis-based compiler. We present K2, a compiler which uses *program synthesis* to automatically generate safe, compact, and performant BPF bytecode, starting from unoptimized bytecode. Program synthesis is the task of searching for a program that meets a given specification [38]. An example of a specification is that the outputs of the synthesized program must match that of a source program on all inputs. Synthesis works by searching through the space of programs, typically guided by user-provided restrictions on the structure of the synthesized program. For example, the synthesizer may search for programs that fit a user-defined grammar [132, 133], use smaller library components [82, 89], or use a low-level instruction set [41, 113, 118, 127].

While traditional compilers are designed to emit "reasonable" code within a small time budget, synthesis-based compilers can produce high-quality code by searching the space of programs more extensively over a longer time period. We believe that the longer compilation time is worthwhile for BPF programs, given their prevalence in deployed systems, their sensitivity to performance, the difficulty of achieving even small performance gains, and their portability across machines and architectures [20, 114].

K2 makes three contributions.

Contribution 1: Stochastic synthesis for BPF (§3). K2 adapts stochastic synthesis [55, 128, 130] to the domain of the BPF instruction set. At a high level, the algorithm runs a Markov chain to search for programs with smaller values of a cost function that incorporates correctness, safety, and performance. A new candidate program is synthesized probabilistically using one of several rewrite rules that modify the current state (program) of the Markov chain. The Markov chain transitions to the new state (synthesized program) with a probability proportional to the reduction in the cost relative to the current program. We show how we set up K2 to optimize programs with diverse cost functions under safety constraints. We have incorporated several domain-specific rewrites to accelerate the search. At the end of the search, K2 produces multiple optimized versions of the same input program.

Contribution 2: Techniques to equivalence-check BPF programs (§4, §5). K2 synthesizes programs that are formally shown to be equivalent to the original program. To perform equivalence-checking, we formalize the input-output behavior of BPF programs in first-order logic (§4). Our formalization includes the arithmetic and logic instructions of BPF handled by earlier treatments of BPF [77, 115, 116, 138], and goes beyond prior work by incorporating aliased memory access (using pointers) as well as BPF maps and helper functions (§2). Equivalence-checking occurs within the inner loop of synthesis, and it must be efficient for synthesis to remain practical. We present several domain-specific techniques that reduce the time required to check the input-output equivalence of two BPF programs by five orders of magnitude (§5). Consequently, K2 can optimize real-world BPF code used in production systems.

Contribution 3: Techniques to check the safety of BPF programs (§6). At each step of stochastic search, K2 evaluates the safety of the candidate program. K2 incorporates safety checks over the program's control flow and memory accesses, as well as several kernel-checker-specific constraints. To implement these checks, K2 employs static analysis and discharges first-order-logic queries written over the candidate program.

K2 resolves the phase-ordering problem of BPF compilation by considering both performance and safety of candidate programs at each step of the search. While K2's safety checks have significant overlap with those of the kernel checker, the two sets of checks are distinct, as the kernel checker is a complex body of code that is under active development [26]. It is possible, though unlikely,

[2]Older kernels (prior to v5.2) rejected programs with more than 4096 BPF bytecode instructions. On modern kernels, this limit is still applicable to non-privileged BPF program types [34] such as socket filters and container-level packet filters [35]. Since kernel v5.2, there is a limit of 1 million [13, 34] on the number of instructions examined by the checker's static analysis, which is a form of symbolic execution [57] with pruning heuristics. Unfortunately, the number of examined instructions explodes quickly with branching in the program, resulting in many programs even smaller than 4096 instructions long being rejected due to this limit [30–33, 36].

that K2 deems a program safe but the kernel checker rejects it. To guarantee that K2's outputs are acceptable to the kernel checker, K2 has a post-processing pass where it loads each of its best output programs into the kernel and weeds out any that fail the kernel checker. While the existence of this pass may appear to bring back the phase-ordering problem, it is merely a fail-safe: as of this writing, all of K2's output programs resulting from the search already pass the kernel checker.

K2 can consume BPF object files emitted by `clang` and produce an optimized, drop-in replacement. We present an evaluation of the compiler across 19 programs drawn from the Linux kernel, Cilium, and Facebook. Relative to the best `clang`-compiled variant (among `-O2`/`-O3`/`-Os`), K2 can reduce the size of BPF programs by between 6–26%, reduce average latency by 1.36%–55.03%, and improve throughput (measured in packets per second per core) by 0–4.75%. This is in comparison to a state of the art where significant effort is required from expert developers to produce 5–10% performance gains [91, 131].

K2 is an existence proof that domain-specific application of program synthesis techniques is a viable approach to automatically optimizing performance-critical packet-processing code. We call upon the community to explore such technology to alleviate the developer burden of improving performance in other contexts like user-space networking and programmable NICs. K2's source code, including all of our experimental scripts, is available at https://k2.cs.rutgers.edu/.

2 BACKGROUND AND MOTIVATION

2.1 Extended Berkeley Packet Filter (BPF)

BPF is a general-purpose in-kernel virtual machine and instruction set [59] that enables users to write operating system extensions for Linux [79]. A standard compiler (*e.g.,* Clang-9) can be used to turn C/Rust programs into BPF *bytecode*, whose format is independent of the underlying hardware architecture.

BPF programs are event-driven. BPF bytecode can be attached to specific events within the operating system, such as the arrival of a packet at the network device driver [83], packet enqueue within Linux traffic control [95], congestion control processing [92], and socket system call invocations [104].

Stateful functionality is supported using *BPF helper functions.* Helper functions are implemented as part of the kernel and can be called by the BPF program with appropriate parameters. For example, there are helper functions that provide access to persistent key-value storage known as a *map*. The map-related helper functions include lookup, update, and delete. The arguments to the map helpers include pointers to memory and file descriptors that uniquely identify the maps. The list and functionality of helpers in the kernel are steadily increasing; there are over 100 helpers in the latest kernel as of this writing [96].

The BPF instruction set follows a 64-bit RISC architecture. Each program has access to eleven 64-bit registers, a program stack of size 512 bytes (referred to by the stack pointer register `r10`), and access to the memory containing program inputs (such as packets) and some kernel data structures (*e.g.,* socket buffers). The BPF instruction set includes 32 and 64-bit arithmetic and logic operations, signed and unsigned operations, and pointer-based load and store instructions. BPF programs can be executed efficiently by leveraging just-in-time (JIT) compilation to popular architectures like `x86_64` and ARM. BPF is not intended to be a Turing-complete language; it does not support executing unbounded loops. User-provided BPF programs are run directly in kernel context. To ensure that it is safe to do so, Linux leverages an in-kernel static checker.

2.2 Phase Ordering in BPF Compilers

We illustrate why it is challenging to optimize BPF bytecode while simultaneously satisfying the safety constraints enforced by the kernel checker. These examples emerged from our experimentation with the checker in kernel v5.4. In the programs below, we use `r0 ... r9` for general-purpose BPF registers. `r10` holds the stack pointer.

Example 1. Invalid strength reduction. The sequence

```
bpf_mov rY 0        // rY = 0
bpf_stx rX rY       // *rX = rY
```

for some registers `rX` ≠ `rY` can usually be optimized to the simpler single instruction

```
bpf_st_imm rX 0    // *rX = 0
```

However, the kernel checker mandates that a pointer into the program's "context memory" [9] cannot be used to store an immediate value. If `rX` were such a pointer, the program would be rejected.

Example 2. Invalid coalescing of memory accesses. Consider the instruction sequence

```
bpf_st_imm8 rX off1 0     // *(u8*)(rX + off1) = 0
bpf_st_imm8 rX off2 0     // *(u8*)(rX + off2) = 0
```

where `rX` is a safely-accessible memory address, and `off1` and `off2` are offsets such that `off2` = `off1` + 1. Usually, two such 1-byte writes can be combined into one 2-byte write:

```
bpf_st_imm16 rX off1 0    // *(u16*)(rX + off1) = 0
```

However, the kernel checker mandates that a store into the stack must be aligned to the corresponding write size [8]. If `rX` is `r10`, the stack pointer, and `off1` is not 2-byte aligned, the checker will reject the rewritten program.

In general, applying optimizations that pass the checker's constraints requires compilers to be aware of the specific restrictions that impact each optimization. The checker has numerous restrictions [5, 6], making it tedious to consider the cross-product of optimizations and safety conditions.

2.3 K2: A Program-Synthesis-Based Compiler

We present K2, a compiler that leverages *program synthesis* to consider correctness, performance, and safety of programs together rather than piecemeal, to resolve the phase-ordering problem between efficiency and safety in BPF optimization.

Program synthesis is the combinatorial search problem of finding a program that satisfies a given specification. Appendix A overviews program synthesis approaches in the literature. Given a sequence of instructions in the BPF bytecode format, we are interested in synthesizing an alternative sequence of BPF instructions that satisfies the specification that: (i) the synthesized program is equivalent to the source program in its input-output behavior, (ii) the synthesized program is safe, and (iii) the synthesized program is more efficient

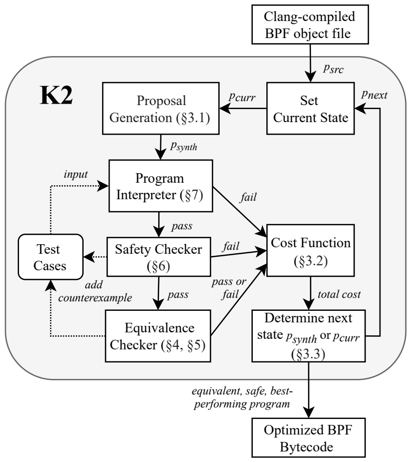

Figure 1: An overview of the K2 compiler. Solid arrows represent the flow of control. Dotted arrows represent the flow of data.

than the source program. The precise definitions of efficiency and safety will be discussed in §3 and §6.

Fig. 1 presents an overview of K2, which synthesizes programs satisfying the specification above. K2 consumes Clang-compiled BPF bytecode, and implements the *stochastic search* procedure described in §3. The search process synthesizes *proposals,* which are candidate rewrites of the bytecode. The proposal is evaluated against a suite of automatically-generated test cases to quickly prune programs which are not equivalent to the source program, or unsafe. If the proposal passes all tests, K2 uses formal equivalence-checking (§4, §5) and formal safety-checking (§6) to determine the value of a *cost function* over the proposal. The cost combines correctness, safety, and performance characteristics, and is used to guide the search process towards better programs. Formal equivalence-checking and safety-checking may generate *counterexamples, i.e.*, inputs where the proposal's output differs from that of the original bytecode, or the proposal exhibits unsafe behaviors. These tests are added to the test suite, to enable quick pruning of similar programs in the future. We describe aspects of the compiler's implementation, including the BPF program interpreter we developed in §7.

3 STOCHASTIC OPTIMIZATION OF BPF

The K2 compiler translates programs from BPF bytecode to BPF bytecode. K2 uses the stochastic optimization framework, introduced in STOKE [128], which applies a Markov Chain Monte Carlo (MCMC) sampling approach to optimize a cost function over the space of programs.

At a high level, MCMC is a method to sample states from a probability distribution over states. When we apply MCMC to program optimization, the state is a program of a fixed size. A well-known MCMC sampler, the Metropolis-Hastings (MH) algorithm [78], works as follows. From an initial state, at each step, the algorithm proposes a new state to transition to, using transition probabilities between states (§3.1). The algorithm computes a cost function over the proposal (§3.2) and determines whether to *accept* or *reject* the proposed new state (§3.3) based on the cost. If the proposal is accepted, the proposed state becomes the new state of the Markov chain. If not, the current state is the new state of the Markov chain. In the asymptotic limit, under mild conditions on the transition probabilities [78], the set of all accepted states form a representative sample of the steady-state probability distribution.

Why stochastic synthesis? Among the program synthesis approaches in the literature (Appendix A), K2 adopts stochastic search primarily because it can optimize complex cost functions, *e.g.,* the number of cache misses during program execution, with complex constraints, *i.e.*, safety. MCMC uses a standard transformation to turn very general cost functions (§3.2) into steady-state probability distributions, enabling it to perform optimization by sampling from the corresponding distribution [73, 78, 128].

3.1 Proposal Generation

The Markov chain starts by setting its initial state to p_{src}, the input program. Starting from any current state p_{curr}, we generate a candidate rewrite, *i.e.*, a proposal p_{synth}, using one of the rules below, chosen randomly with fixed probabilities $prob_{(.)}$:

(1) **Replace an instruction ($prob_{ir}$)**: at random, choose an instruction from p_{curr}, and modify both its opcode and operands. For example, change `bpf_add r1 4` to `bpf_mov r4 r2`.
(2) **Replace an operand ($prob_{or}$)**: at random, choose an instruction and replace one of its operands with another value of the same type. For example, change `bpf_add r1 4` to `bpf_add r1 10`.
(3) **Replace by NOP ($prob_{nr}$)**: at random, choose an instruction and replace it with a `nop`, effectively reducing the number of instructions in the program.
(4) **Exchange memory type 1 ($prob_{me1}$)**: at random, choose an instruction, and if it is a memory-based instruction (*i.e.,* a load or a store), sample a new width for the memory operation and a new immediate or register operand. The instruction's memory address operand (*i.e.*, address base and offset) as well as its type (load *vs.* store) are unchanged. For example, change `r1 = *(u16*)(r2 - 4)` to `r3 = *(u32*)(r2 - 4)`.
(5) **Exchange memory type 2 ($prob_{me2}$):** at random, choose an instruction, and if it is a memory-based instruction, sample a new width for the memory operation. All other instruction operands are unchanged. For example, change `r1 = *(u16*)(r2 - 4)` to `r1 = *(u32*)(r2 - 4)`.
(6) **Replace contiguous instructions ($prob_{cir}$)**: at random, choose up to k contiguous instructions (we pick $k = 2$) and replace all of them with new instructions.

These rewrite rules define the transition probabilities of the Markov chain, which we denote by $tr(p_{curr} \rightarrow p_{synth})$. We use the probabilities $prob_{(.)}$ shown in Table 8 (Appendix F.1). In our experience, any probabilities that allow the Markov chain to move "freely" through the space of programs suffice to find programs better than the input.

Non-orthogonality of rewrite rules. The rewrite rules above are not mutually exclusive in the program modifications they affect. For example, replacement by NOP (rule 3) is just a specific version of the more general instruction replacement (rule 1). Given enough time, a small set of general rules is sufficient to explore the space of programs. However, the existence of more specific rules accelerates the convergence of the Markov chain to better programs.

Domain-specificity of rewrite rules. STOKE and its variants [55, 128] proposed variants of the rewrite rules (1–3) above. Rules (4), (5), and (6) are domain-specific rules that K2 uses to accelerate the search for better BPF programs. Rules (4) and (5) help identify memory-based code optimizations (§9). Rule (6) captures one-shot replacements of multiple instructions, *e.g.,* replacing a register addition followed by a store into a single memory-add instruction. These domain-specific rules improve both the quality of the resulting programs and the time to find better programs (§8, Appendix F.1).

3.2 Cost Function

We compute a cost function over each candidate program. The cost function $f(p)$ contains three components: an error cost, a performance cost, and a safety cost.

Error cost. The error cost function $err(p)$ is 0 if and only if the program p produces the same output as the source program p_{src} on all inputs. We would like a function that provides a smooth measure of the correctness of program p with respect to the source program p_{src}, to guide the search towards "increasingly correct" programs. Similar to STOKE, we incorporate test cases as well as formal equivalence checking (§4 & §5) to compute an error cost. Using a set of tests T and executing p_{synth} on each test $t \in T$, we set

$$err(p) := c \cdot \sum_{t \in T} diff(o_{p_{synth}(t)}, o_{p_{src}(t)}) + unequal \cdot num\_tests \tag{1}$$

where:

- $o_{p_{synth}(t)}$ and $o_{p_{src}(t)}$ are the outputs of the proposal and the source program on test case t,
- $diff(x, y)$ is a measure of the distance between two values. We consider two variants: (i) $diff_{pop}(x, y) := popcount(x \oplus y)$ is the number of bits that differ between x and y, and (ii) $diff_{abs}(x, y) := abs(x - y)$, which represents the absolute value of the numerical difference between x and y. Relative to STOKE, which only considers *popcount* as the semantic distance between values, we also find that many packet-processing programs require numeric correctness (*e.g.,* counters), captured via $diff_{abs}(.)$.
- c is a normalizing constant denoting the weight of each test case. STOKE adds the full error cost for each test case, setting $c = c_{full} = 1$. We also explore a second variant, $c_{avg} = 1/|T|$, where $|T|$ is the number of test cases, to normalize the contributions of the many test cases we require to prune complex, "almost correct" BPF programs.
- *unequal* is 0 if the first-order-logic formalization of the two BPF programs (§4) finds that the programs are equivalent, else it is 1. We only run equivalence-checking if all test cases pass, since it is time-consuming. If any test case fails, we set *unequal* to 1.
- *num_tests* includes two variants: (i) the number of test cases on which p produced incorrect outputs, and (ii) the number of test cases on which p produced *correct* outputs. STOKE uses only the first variant. We consider the second variant to distinguish a program that is equivalent to the source program from one that satisfies all the test cases but is not equivalent.

Considering all variants from equation (1), there are 8 error cost functions. We run MCMC with each cost function in parallel and return the best-performing programs among all of them.

Performance cost. We use two kinds of performance costs corresponding to different scenarios, namely optimizing for program *size* and program *performance.*

The function $perf_{inst}(p_{synth})$ (instruction count) is the number of extra instructions in p_{synth} relative to p_{src}.

The function $perf_{lat}(p_{synth})$ is an estimate of the additional latency of executing program p_{synth} relative to p_{src}. Unfortunately, executing a candidate BPF program p_{synth} to directly measure its latency is unviable, since the kernel checker will reject most candidate programs. Instead, we profile every instruction of the BPF instruction set by executing each opcode millions of times on a lightly loaded system, and determining an average execution time $exec(i)$ for each opcode i. The performance cost function is the difference of the sum of all the opcode latencies, *i.e.,* $perf_{lat}(p_{synth}) := \sum_{i_{synth} \in p_{synth}} exec(i_{synth}) - \sum_{i_{src} \in p_{src}} exec(i_{src})$.

Safety cost. To our knowledge, K2 is the first synthesizing compiler to incorporate generic safety constraints in first-order logic into synthesis. The safety properties considered by K2 are described in §6. Our approach to dealing with unsafe programs is simple: once a program p_{synth} is deemed unsafe, we set $safe(p_{synth})$ to a large value *ERR_MAX*, leaving just a small probability for it to be accepted into the Markov chain. We set $safe(p_{synth}) = 0$ for safe programs. We do not simply reject unsafe programs because the path from the current program to a more performant and safe program in the Markov chain may pass through an unsafe program (for some intuition on why, see Fig. 4 in [128]). We leave formulating smooth cost functions to guide the search through progressively "safer" programs to future work.

The final cost function we use is $\alpha * err(p_{synth}) + \beta * perf(p_{synth}) + \gamma * safe(p_{synth})$. We run parallel Markov chains with different (α, β, γ) and return the programs with the least performance costs.

3.3 Proposal Acceptance

To determine whether a candidate proposal should be used as the next state of the Markov chain, the cost $f(p_{synth})$ is turned into the probability of p_{synth} in the steady-state distribution, as follows [78]:

$$\pi(p_{synth}) = e^{-\beta \cdot f(p_{synth})}/Z \tag{2}$$

where $Z = \sum_p e^{-\beta \cdot f(p)}$. The Metropolis-Hastings algorithm computes an *acceptance probability* for p_{synth} as follows:

$$\alpha = min\left(1, \frac{\pi(p_{synth}) \cdot tr(p_{synth} \rightarrow p_{curr})}{\pi(p_{curr}) \cdot tr(p_{curr} \rightarrow p_{synth})}\right) \tag{3}$$

With probability α, the next state of the Markov chain is set to p_{synth}, else the next state is just p_{curr}. Here, the $tr(.)$ are the transition probabilities between programs (§3.1). Intuitively, p_{synth} is always accepted if its cost is lower than that of p_{curr}. Otherwise, p_{synth} is accepted with a probability that decreases with the increase in the cost of p_{synth} relative to p_{curr}.

K2 repeats the process in §3.1, §3.2, and §3.3 from the new state of the Markov chain, looping until a timeout.

4 CHECKING THE EQUIVALENCE OF BPF PROGRAMS

K2 synthesizes output programs that are formally shown to be equivalent to the input program. To do this, we first formalize the input-output behavior of the two programs in first-order logic, using the theory of bit vectors [99]. We identify the input and output registers of the two programs based on the kernel hook they attach to [88]. Then, we dispatch the logic query below to a solver:

```
inputs to program 1 == inputs to program 2
 ∧  input-output behavior of program 1
 ∧  input-output behavior of program 2
 ⇒  outputs of program 1 != outputs of program 2
```

If the formula is satisfiable, there is a common input that causes the outputs of the two programs to differ, which is added to the test suite (§3). If the formula is unsatisfiable, the two programs are equivalent in terms of input-output behaviors.

The rest of this section describes how we obtain the input-output behavior of a single program in first-order logic. Our formalization handles arithmetic and logic instructions (§4.1), memory access instructions (§4.2), and BPF maps and other helper functions (§4.3). We have checked the soundness of our formalization using a test suite that compares the outputs produced by the logic formulas against the result of executing the instructions with given inputs.

Preliminaries. We begin by reordering the instructions in the program so that all control flow only moves forward. This is possible to do when a BPF program does not contain any loops. Then, we convert the entire program into static-single-assignment (SSA) form [39, 63]. The result after SSA conversion is a sequence of BPF bytecode instructions where (i) each assignment to a register uses a fresh label with a version number, *e.g.*, `bpf_mov r0 1; bpf_mov r0 2` is turned into `bpf_mov r0_v1 1; bpf_mov r0_v2 2`, and (ii) each statement is associated with a well-defined path condition [111]. For example, in the instruction sequence,

```
bpf_jeq r1 0 1   // if r1 != 0:
bpf_mov r2 1     //    r2 = 1
```

the second instruction is associated with the path condition `r1!=0`.

At the highest level, we construct first-order formulas corresponding to each instruction, and conjoin them, *i.e.*, through the logical conjunction operator ∧, to produce a final formula that represents the input-output relationship of the entire program. Now we discuss how K2 formalizes each kind of instruction.

4.1 Arithmetic And Logic Instructions

To model register-based arithmetic and logic instructions, we represent each version of each register using a 64-bit-wide bit vector data type. The action of each instruction is formalized by representing its impact on all the registers involved. Our formalization handles both 32-bit and 64-bit opcodes, as well as signed and unsigned interpretations of the data.

As an example, consider the 32-bit arithmetic instruction `bpf_add32 dst src` (opcode `0x04`) which has the action of taking the least significant 32 bits of the registers `dst` and `src`, adding them, and writing back a (possibly truncated) 32-bit result into `dst`, zeroing out the most significant 32 bits of the `dst` register.

Suppose we are given a single instruction `bpf_add32 dst_x src_y` (after SSA) where `x` and `y` represent the version numbers of `dst` and `src`, respectively. Suppose the result is stored in `dst_z`. This instruction results in the formula

```
(tmp == (dst_x.extract(31, 0) +
  src_y.extract(31, 0) ) )  ∧
(dst_z == concat(
  bv32(0), tmp.extract(31, 0) ) )
```

where `tmp` is a fresh variable to hold the intermediate result of the 32-bit addition of `dst_x` and `src_y`, `extract(a, b)` represents the effect of picking up bits a...b of a given bit vector, `concat(x, y)` represents the bit vector produced by concatenating the two bit vectors x and y, with x occupying the higher bits of significance in the result, and `bv32(0)` is a 32-bit bit vector representing 0.

Similarly, we have constructed semantic representations of all 64-bit and 32-bit arithmetic and logic instructions [4].

4.2 Memory Access Instructions

BPF supports memory load and store instructions of varying sizes [4] using pointers. We encode memory operations directly in the theory of bit vectors to produce an efficient encoding in a single first-order theory. We show how this encoding occurs in three steps.

Step 1: Handling loads without any stores. Suppose a BPF program contains no stores to memory, and only load instructions, *i.e.*, `bpf_ld rX rY`. To keep the descriptions simple, from here on we will use the notation `rX = *rY` to represent the instruction above.

The key challenge in encoding loads is handling *aliasing*, *i.e.*, different pointers `rY` might point to the same memory region, and hence the different `rX` must have the same value.

Suppose the i^{th} load instruction encountered in the program reads from memory address `rY_i` and loads into register `rX_i`. Then for the i^{th} load, we conjoin the formula

$$\bigwedge_{j<i} (\texttt{rY\_j == rY\_i} \Rightarrow \texttt{rX\_j == rX\_i})$$

Formulating this formula requires maintaining all the previous loads in the program that might affect a given load instruction. To achieve this, K2 maintains a *memory read table* for the program: the source and destination of each load is added to this table in the order of appearance in the post-SSA instruction sequence. K2 handles partial overlaps in loaded addresses by expanding multi-byte loads into multiple single-byte loads.

Step 2: Handling stores and loads in straight-line programs. Stores complicate the formula above due to the fact that a load of the form `rX = *rY` must capture the *latest write* to the memory pointed to by `rY`. For example, in the instruction sequence `rX_1 = *rY; *rY = 4; rX_2 = *rY`, the first and second load from `rY` may return different values to be stored in `rX_1` and `rX_2`.

Suppose the program contains no branches. Then, the latest write to a memory address can be captured by the most recent store instruction (in order of encountered SSA instructions), if any, that writes to the same address. K2 maintains a *memory write table*, which records the memory address and stored variable corresponding to each store in the program. Suppose k stores of the form `*rY_i = rX_i` (i from `1 ··· k`) have been encountered in the program before the load instruction `rX_l = *rY_l`. Then, the load is encoded by the formula

$$\bigwedge_{j:j\le k}\ \bigwedge_{i:j<i\le k} \texttt{! (rY\_i == rY\_l)} \\ \wedge \quad \texttt{rY\_j == rY\_l} \\ \Rightarrow \quad \texttt{rX\_j == rX\_l}$$

The formula $\bigwedge_{i:j<i\le k}$ `! (rY_i == rY_l)` asserts that the address loaded isn't any of the addresses from stores that are more recent than store j. Hence, if `rY_j == rY_l`, the loaded value must come from store j.

Informally, the overall formula for a load instruction takes the form: if the address was touched by a prior store, use the value from that store, otherwise use the aliasing clauses from the "loads-only" case in step (1) above.[3] Together, step (1) and step (2) complete K2's encoding of memory accesses for straight-line programs.

Step 3: Handling control flow. We construct a single formula per instruction including control flow akin to bounded model checking [46]. Our key insight to generalize the encoding from step (2) above is to additionally check whether the path condition of the load instruction is implied by the path condition of the prior store:

$$\bigwedge_{j:j\le k}\ \bigwedge_{i:j<i\le k} \texttt{! (rY\_i == rY\_l} \ \wedge\ \texttt{pc\_i} \ \Rightarrow\ \texttt{pc\_l)} \\ \wedge \quad \texttt{(rY\_j == rY\_l} \ \wedge\ \texttt{pc\_j} \ \Rightarrow\ \texttt{pc\_l)} \\ \Rightarrow \quad \texttt{rX\_j == rX\_l}$$

Note that the path conditions `pc_j` of each load or store j are already computed by K2 during the preliminary SSA pass.

4.3 BPF Maps and Helper Functions

BPF helpers (§2) provide special functionality in a program, including stateful operation. Due to space constraints, we only briefly discuss our formalization of BPF maps—the most frequently used helpers—in this subsection. A more detailed treatment of maps and other helpers is available in Appendix B.

Maps. BPF maps are similar to memory, in that they can be read and written using a key (rather than an address). However, two features make BPF maps very different from memory.

First, the inputs to lookup, update, or delete a map entry in BPF's map API are all pointers to memory holding a key or value. This results in *two levels of aliasing*: distinct pointers may point to the same location in memory (like regular pointer aliasing); additionally, distinct locations in memory may hold the same key, which must result in the same value upon a map look-up. Intuitively, we handle these two levels by keeping two pairs of tables for read and write operations. The first pair of read/write tables tracks the contents of the addresses corresponding to the key and value pointers, as in §4.2. The second pair of read/write tables tracks the updates to the value pointers corresponding to the map's actual keys.

Second, keys in a map can be deleted, unlike addresses in memory. Our encoding treats a deletion as a update of the value pointer to `0` (a null pointer) for the corresponding key, so that any subsequent lookup returns null, mimicking the BPF lookup function semantics.

Other helper functions. Each helper function considered for optimization ideally should be formalized using its specific semantics. We have added formalizations for helpers used to obtain random numbers, access the current Unix timestamp, adjust memory headroom in a packet buffer, and get the ID of the processor on which the program is running.

The list of BPF helpers currently numbers in the hundreds and is growing [62, 96]. For most helpers, it is possible to model the function application as a call to an *uninterpreted function* $f(.)$ [51]: the only governing condition on the input-output behavior of the function is that calling it with the same inputs will produce the same outputs, *i.e.*, $x == y \Rightarrow f(x) == f(y)$. (Stateful functions include the state as part of the inputs.) While such modeling is general, it limits the scope of optimization across function calls, since it is impossible to prove equivalence of code involving uninterpreted functions without requiring that the sequence of function calls and the inputs to each function call must be exactly the same in the input and the output programs.

5 FAST EQUIVALENCE CHECKING

The formulas generated in §4.1–§4.3 are in principle sufficient to verify the equivalence of all BPF programs we have tested. However, the corresponding verification task is too slow (§8). Equivalence-checking time grows quickly with the number of branches, the number of memory accesses, and the number of distinct maps looked up in the BPF programs. Equivalence checking is in the inner loop of synthesis (Fig. 1): large verification times render synthesis impractical.

We have developed several optimizations that accelerate equivalence-checking times by 6 orders of magnitude on average over the programs we tested. This section summarizes the key ideas; more details are available in Appendix C. Several optimizations leverage lightweight static analysis that is only feasible due to the restrictions in the BPF instruction set.

The time to solve a logic formula is often reduced significantly by assigning specific values to, *i.e.*, *concretizing,* formula terms whose value is otherwise unconstrained, *i.e.*, symbolic [46, 50, 57, 98, 120]. Our first three optimizations are of this kind.

I. Memory type concretization. All pointers to memory in BPF programs have well-defined provenance, *i.e.*, it is possible to develop a static analysis to soundly and completely track the *type* of memory (stack, packet, *etc.*) that each pointer references. This allows K2 to maintain separate read and write tables (§4.2) for each memory type. Consequently, the size of aliasing-related formulas reduces from $O((\sum_t N_t)^2)$ to $O(\sum_t N_t^2)$, where N_t refers to the number of accesses to memory of a specific type t.

II. Map type concretization. Similar to memory-type concretization, a simple static analysis can soundly and completely determine the map that is used for a specific lookup or update instruction. This has the effect of breaking map accesses across several maps in the two-level map tables (§4.3) into separate map-specific two-level tables.

III. Memory offset concretization. Many packet-processing programs perform reads and writes into memory at offsets that can be determined at compile time, for example, specific packet header fields. We developed a "best-effort" static analysis to soundly determine if a pointer holds a reference to a compile-time-known

[3] It is possible for a load to occur without a prior store *e.g.,* when an instruction reads from input packet memory.

offset into a memory region. If such a constant offset is determined, a formula like `rY_i == rY_l` (appearing in §4.2) can be simplified to `constant == rY_l`, or even `constant1 == constant2`. The latter doesn't even require a solver to be evaluated, and can result in several cascading clause simplifications. In the limit, if all offsets can be concretely determined, this optimization has the effect of modeling the entire memory as if it is a set of named registers. If we cannot statically determine concrete offsets, we fall back to the symbolic formulas described in §4.2.

IV. Modular verification. K2 scales to large programs by synthesizing and verifying instruction sequences of smaller length within localized "windows" in the program, and then combining the results across the windows. Hence, K2 pares down the verification task to correspond to the size of the window rather than that of the full program. Effectively, this would turn K2 into a peephole optimizer [108]. However, traditional peephole optimizers necessitate that the rewrites must apply in *any* program context, rejecting many strong optimizations that could work conditionally within a specific part of the program (*e.g.,* `r1 *= r3` may be changed into `r1 <<= 2` if the value of `r3` is known to be 2). To discover strong optimizations but keep equivalence-checking fast, we develop window-based formulas that use stronger preconditions and weaker postconditions than peephole optimizers. K2 leverages variable *liveness* (as in prior work [40]) as well as *concrete values* of the live variables, both of which are inferred through static analysis:

```
variables live into window 1
== variables live into window 2
 ∧  inferred concrete valuations of variables
 ∧  input-output behavior of window 1
 ∧  input-output behavior of window 2
 ⇒  variables live out of window 1
    != variables live out of window 2
```

V. Caching. We cache the outcomes of equivalence-checking a candidate program to quickly determine if a structurally-similar program was checked earlier. This has the effect of reducing the number of times we call the solver. We canonicalize the program by removing dead code before checking the cache.

6 SAFETY OF BPF PROGRAMS

K2 ensures that the programs returned by the compiler are *safe*, which requires proving specific control-flow and memory-access safety properties about the output programs, described below.

K2's safety checks are implemented using static analysis and first-order logic queries over the candidate programs generated at each step of the stochastic search (§3). By considering safety with optimization at each step, K2 resolves the phase-ordering problem (§2.2) that hampers traditional optimizing compilers for BPF.

K2's safety checks are distinct from those of the kernel checker, though there is a significant overlap between them. We developed safety-checking directly within K2, eschewing the alternative approach of invoking the kernel checker on a candidate program at each step of search, for two reasons. First, in addition to reporting that a program is unsafe, K2's safety queries also return a *safety counterexample*, *i.e.,* an input that causes the program to exhibit unsafe behaviors. The counterexample can be added to the test suite (Fig. 1) to prune unsafe programs by executing them in the interpreter, rather than using an expensive kernel checker (system) call. This has the overall effect of speeding up the search loop. Second, the kernel checker is a complex piece of software that is evolving constantly. We believe that, over the long term, a logic-based declarative encoding of the safety intent will make it easier to understand and maintain the compiler's safety constraints.

K2 guarantees that the output programs returned to the user will pass the kernel checker. K2 achieves this using a post-processing pass: outputs from K2's search loop which fail the kernel checker are removed before presenting them to the user. As of this writing, all the outputs from K2's search already pass the kernel checker without being filtered by this post-processing.

Now we discuss K2-enforced safety properties in detail.

Control flow safety. The structure of BPF jump instructions [4] allows the set of possible jump targets in the program to be determined at compile time. Hence, K2 constructs the complete control flow graph over basic blocks at compile time [39]. Programs synthesized by K2 satisfy the following safety properties:

(1) There are no unreachable basic blocks.
(2) The program is loop-free (*i.e.,* no "back-edges" in the control flow), and hence, terminates. K2 ensures this during proposal generation (§3.1) by only producing jump offsets taking control flow "forward" in a topologically-sorted list of basic blocks.
(3) The program has no out-of-bounds jumps. K2 ensures this by only synthesizing jump targets that are within the program's valid set of instructions.

The rest of the safety checks below are implemented using first-order logic queries. Logic queries provide safety counterexamples, which also allow K2 to prune an unsafe program using the interpreter rather than an expensive solver query down the road. To our knowledge, K2 is the first to leverage counterexamples for both correctness and safety during synthesis.

Memory accesses within bounds. K2 ensures that programs it synthesizes only access operating system memory within the bounds they are allowed to. The access bounds for each type of memory are known ahead of time. For example, the size of the program stack is fixed to 512 bytes [88]; packet inputs are provided with metadata on the start and end addresses; and BPF map values have a pre-defined fixed size based on the known attributes of the map.

K2 leverages a sound and complete static analysis to determine the type of memory that a load or store instruction uses. Then, K2 formulates a first-order query to determine if there are any program inputs that cause the access to violate the known safe bounds of that memory. K2 considers both the offset and the size of the access, and models the types of pointers returned from BPF kernel helper functions very precisely. For example, the instruction sequence corresponding to `r0 = bpf_map_lookup(...); r1 = *r0;` will produce a safety counterexample for the case when the lookup returns a NULL pointer. However, `r0 = bpf_map_lookup(...); if (r0 != 0) { r1 = *r0; }` is considered safe, since the path condition ensures a valid value for `r0`.

Memory-specific safety considerations. The BPF kernel checker explicitly requires that a stack memory address cannot be read by a BPF program before that address is written to [88]. The same rule applies to registers which are not program inputs. This restriction is distinct from placing safe bounds on an address that is read, since an address that is considered unsafe to read at one moment, *i.e.*, before a write, is considered safe to read after the write. K2 leverages the memory write table (§4.2) to formulate a first-order query that checks for semantically-safe loads from the stack under all program inputs. Further, the stack pointer register `r10` is read-only; K2's proposal generation avoids sampling `r10` as an instruction operand whenever that operand might be modified by the instruction (§3.1).

Access alignment. The kernel checker enforces that memory loads and stores of a certain size happening to specific memory types (*e.g.,* the stack) must happen to addresses aligned to that size. That is, an address a with an N-byte load or store must be such that $a \ (mod\ N) == 0$. For example, the two instructions `bpf_stxw` and `bpf_stxdw` will require two different alignments, up to 32 bits and up to 64 bits, respectively.

Somewhat surprisingly, all of the safety properties above can be decided with sound and complete procedures due to the simplicity of the BPF instruction set.

Modeling checker-specific constraints. We encode several other specific properties enforced by the kernel checker. These checks can distinguish semantically-equivalent code sequences that meet with different verdicts (accept versus reject) in the Linux checker. We added these checks "on-demand", as we encountered programs from K2 that failed to load. A selection of kernel-checker-specific safety properties we encoded include:

(1) Certain classes of instructions, such as ALU32, NEG64, OR64, *etc.* are disallowed on pointer memory;
(2) storing an immediate value into a pointer of a specific type (PTR_TO_CTX [6]) is disallowed;
(3) Registers `r1 ··· r5` are clobbered and unreadable after a helper function call [88];
(4) aliasing pointers with offsets relative to the base address of a (permitted) memory region is considered unsafe.

Our encoding of kernel checker safety properties is incomplete; we believe it will be necessary to keep adding to these checks over time as the kernel checker evolves. A distinct advantage of a synthesis-based compiler is that such checks can be encoded once and considered across *all possible* optimizations, rather than encoded piecemeal for each optimization as in a rule-based compiler.

7 IMPLEMENTATION

We summarize some key points about the implementation of K2 here. More details are available in Appendix D.

K2 is implemented in 24500 lines of C++ code and C code, including proposal generation, program interpretation, first-order logic formalization, optimizations to equivalence-checking, and safety considerations. K2 consumes BPF bytecode compiled by `clang` and produces an optimized, drop-in replacement. The interpreter and the verification-condition-generator of K2 can work with multiple BPF hooks [104], fixing the inputs and outputs appropriately for testing and equivalence-checking. K2 uses `Z3` [65] as its internal logic solver for discharging equivalence-checking and safety queries.

K2 includes a high-performance BPF interpreter that runs BPF bytecode using an optimized jumptable implementation similar to

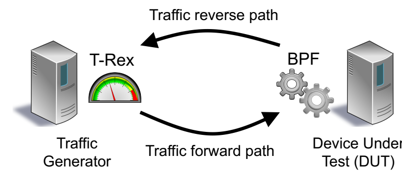

Figure 2: Evaluation setup to measure the throughput and latency benefits of K2 (§8).

the kernel's internal BPF interpreter [2]. We encoded a declarative specification of the semantics of most arithmetic and logic instructions in BPF using C preprocessor directives. This enabled us to auto-generate code for both K2's interpreter and verification formula generator from the same specification of the BPF instruction set, akin to solver-aided languages [115, 137].

8 EVALUATION

In this section, we answer the following questions:
(1) How compact are K2-synthesized programs?
(2) How beneficial is K2 to packet latency and throughput?
(3) Does K2 produce safe, kernel-checker-acceptable programs?
(4) How useful are the optimizations to equivalence checking (§5)?
(5) How effective are K2's search parameters to find good programs?
(6) How beneficial are K2's domain-specific rules (§3.1)?

For questions (1) and (2), we compare K2-synthesized results with the best program produced by `clang` (across `-O1/O2/O3/Os.`).

First, we describe how K2 is set up to compare against `clang-9`.[4] We choose the desired performance goal, which is either to reduce the instruction count or program latency. For the performance goal, we use a profile of instruction execution latencies obtained on a machine with the x86 architecture. Then, we set off multiple runs of K2 in parallel, starting from the output of `clang -O2`, and run them until a timeout. Each run uses a different parameter setting for its Markov chain (§3.2). In particular, we explore the 16 parameter settings described in Appendix F.1. Among these parallel runs, we choose the top-k best-performing programs which are safe and equivalent to the source program across all the Markov chains. We set $k = 1$ for the instruction count performance goal and $k = 5$ for the latency goal. Since the latency-based cost function used inside K2 is just an estimate of performance (§3.2), we *measure* the average throughput/latency performance of the top-k programs and return the best program.

We obtain our benchmark programs from diverse sources, including the Linux kernel's BPF samples, recent academic literature [52], and programs used in production from Cilium and Facebook. We have considered 19 BPF programs in all, which attach to the network device driver (XDP), transport-level sockets, and system calls.

Program Compactness. Table 1 reports the number of instructions in K2-optimized programs relative to those of `clang -O1/-O2/-O3/-Os` (`-O2` and `-O3` are always identical). We show the compression achieved, the overall compile time, the time to uncover the smallest program for each benchmark, as well as some metrics on the complexity of

[4]We were able to compile all our benchmarks successfully with `clang-9` except `xdp-balancer` [11], for which we used `clang-8`.

Benchmark	Number of basic blocks		Number of instructions					When smallest prog. is found	
	All	Longest path	-O1	-O2/-O3	-Os	K2	Compression	Time (sec)	Iterations
(1) xdp_exception	5	5	18	18	18	16	11.11%	79	372,399
(2) xdp_redirect_err	5	5	19	18	18	16	11.11%	10	889
(3) xdp_devmap_xmit	6	6	36	36	36	29	19.44%	1,201	659,903
(4) xdp_cpumap_kthread	5	5	24	24	24	18	25.00%	1,170	628,354
(5) xdp_cpumap_enqueue	4	3	26	26	26	21	19.23%	1,848	300,438
(6) sys_enter_open	13	6	24	24	24	20	16.67%	519	834,179
(7) socket/0	13	6	32	29	29	27	6.90%	6	914
(8) socket/1	20	17	35	32	32	30	6.25%	9	3,455
(9) xdp_router_ipv4	5	5	139	111	111	99	10.81%	898	354,154
(10) xdp_redirect	18	16	45	43	43	35	18.60%	523	228,101
(11) xdp1_kern/xdp1	5	4	72	61	61	56	8.20%	472	739,416
(12) xdp2_kern/xdp1	15	11	93	78	78	71	8.97%	157	100,811
(13) xdp_fwd	19	14	170	155	155	128	17.42%	6,137	2,851,203
(14) xdp_pktcntr	4	3	22	22	22	19	13.64%	288	614,569
(15) xdp_fw	24	22	85	72	72	65	9.72%	826	342,009
(16) xdp_map_access	6	6	30	30	30	26	13.33%	27	69,628
(17) from-network	21	18	43	39	39	29	25.64%	6,871	4,312,839
(18) recvmsg4	4	4	98	94	94	81	13.83%	3,350	904,934
(19) xdp-balancer	247	96	DNL	1,811	1,771	1,607	9.26%	167,428	10,251,406
Avg. of all benchmarks							13.95%	10,096	1,240,505

Table 1: K2's improvements in program compactness across benchmarks from the Linux kernel (1–13), Facebook (14, 19), hXDP [52] (15, 16), and Cilium (17, 18). "DNL" means that the program variant did not load as it was rejected by the kernel checker.

the program being optimized, such as the number of total basic blocks and the length of the longest code path (measured in basic blocks). In all cases, K2 manages to compress the program beyond the best known `clang` variant, by a fraction that ranges from 6–26%, with a mean improvement of 13.95%. The average time to find the best program[5] is about 22 minutes; often, the best program can be found much sooner.

Notably, K2 can handle programs with more than 100 instructions, something that even state-of-the-art synthesizing compilers find challenging [118]. The time to reach the best program displays significant variability. Programs with more instructions take longer to compress by the same relative amount. However, we do not find any significant relationship between optimization time and the number of basic blocks. Some examples of optimizations are in §9.

Latency and throughput improvements. We measure the improvements in packet-processing throughput and latency obtained by optimizing programs with K2. (Improvements in the compiler's *estimated* performance are presented in Appendix E.)

We use two server-class machines on CloudLab [66] to set up a high-speed traffic generator (T-Rex [7]) and a device-under-test (DUT). Our setup is visualized in Fig. 2. The DUT runs a subset of our benchmark BPF programs that attach to the network device driver using the XDP hook [83]. The servers house 10-core Intel Broadwell (E5-2640v4) 2.4 GHz processors with a PCIe 3.0 bus and 64 GB of memory. The servers are equipped with Mellanox ConnectX-4 25G adapters. Test traffic moves from the traffic generator to the DUT and back to the traffic generator to form a loop, in the spirit of the benchmarking methodology outlined in RFC 2544 [1], allowing us to measure both the packet-processing throughput and the round-trip latency to forward via the DUT. Within the CloudLab network, the two machines connect over a Mellanox switch.

We tuned the DUT following instructions from the XDP benchmarking configurations described in [83]. Specifically, we set up Linux Receive-Side Scaling (RSS) [53], IRQ affinities for NIC receive queues [86], PCIe descriptor compression, the maximum MTU for the Mellanox driver to support BPF, and the RX descriptor ring size for the NIC. Our configurations and benchmarking scripts are publicly available from the project web page [121].

We report program throughput as the *maximum loss-free forwarding rate* (MLFFR [1]) of a single core. This is measured by increasing the offered load from the traffic generator slowly and recording the load beyond which the packet loss rate rises sharply. We measure throughput in millions of packets per second (Mpps) at 64-byte packet size. We use the minimum packet size since network-related CPU usage is proportional to packets per second rather than bytes per second, and XDP programs can easily saturate 100 Gbit/s on a single core with larger packet sizes [83]. Since latency varies with the load offered by the traffic generator, we report the latencies of the program variants at four separate offered loads: (i) low (load smaller than the throughput of the slowest variant), (ii) medium (load equal to the throughput of the slowest variant), (iii) high (load equal to the throughput of the fastest variant), and (iv) saturating (load higher than the throughput of all known variants). We average the results of 3 trials, with each result obtained after waiting 60 seconds or until the numbers stabilize.

K2's measured improvements in throughput and latency over the best `clang`-compiled variant of the same program are summarized in

[5]This average excludes the largest benchmark `xdp-balancer`, which is an outlier.

Table 2 and Table 3. K2 provides small improvements in throughput ranging from 0–4.75%, while K2's latency benefits range from 1.36%–55.03%. These benefits arise from target-specific optimizations with the latency cost function. (Appendix H shows detailed pictures of packet latency at varying loads.) More work remains before fully attaining the potential benefits of synthesis (§11).

Benchmark	-O1	-O2/-O3	K2	Gain
xdp2	8.855	9.547	9.748	2.11%
xdp_router_ipv4	1.496	1.496	1.496	0.00%
xdp_fwd	4.886	4.984	5.072	1.77%
xdp1	16.837	16.85	17.65	4.75%
xdp_map_access	14.679	14.678	15.074	2.70%
xdp-balancer	DNL	3.292	3.389	2.94%

Table 2: Throughput reported as the maximum loss-free forwarding rate (MLFFR) in millions of packets per second per core (§8).

Safety of synthesized programs. We loaded the XDP program outputs produced by K2 into the kernel. All 38 out of the 38 programs found by K2's search were successfully accepted by the kernel checker, even without K2's safety post-processing (§6). Table 5 in Appendix F lists the programs we loaded into the kernel.

Benefits of equivalence-checking optimizations. We show the benefits of the optimizations (in §5) to reducing equivalence-checking time and also the number of calls to the solver. Table 4 shows the benefits of optimizations I–IV (memory type, map type, and memory offset concretization, and modular verification) by starting with all optimizations turned on (I, II, III, IV) as the baseline. We progressively turn off each optimization, and show absolute verification times and slowdown relative to the baseline. We find that, across benchmarks, the collective benefits of the optimizations range between 2–7 orders of magnitude, with a mean improvement of 6 orders of magnitude across programs. The larger the program, the more pronounced the impact of the optimizations. Among all the optimizations we apply, modular verification produces the most consistent and significant gains across programs.

Table 6 in Appendix F shows the impact of reductions in the number of queries to the logic solver by caching canonical versions of programs (optimization V, §5). We find caching to be very effective: 93% or more queries otherwise discharged to the solver can be eliminated by caching the equivalence-checking outcomes of syntactically-similar programs checked earlier.

Impact of parameter choices on stochastic search. K2's stochastic search proceeds in parallel with 16 different sets of parameters. These parameters correspond to variants of the cost functions, with different coefficients used to combine error and performance, as well as different program rewrite rules (§3.2). The full set of values parameterizing each set is described in Appendix F.1. Across 13 programs, we show the efficacy of each set of parameters in optimizing instruction size. Despite K2's current use of 16 parameter sets, some of those sets are much more likely to produce optimal results than others. Hence, it is possible to obtain K2's gains with much less parallelism. More generally, exploring the identification of hyperparameters that provide the best results given a limited compute budget is an interesting problem deserving further exploration [101].

Impact of domain-specific rewrite rules. We evaluate the benefits imparted by K2's domain-specific program rewrite rules (§3.1) to the quality of generated programs. Table 10 in §8 shows the results from optimizing the instruction count of programs with different settings where we selectively turn the domain-specific rules on or off. Each domain-specific rule is necessary to find the best program for each benchmark. Disabling any one of the rules entirely results in the quality of the output programs dropping by as much as 12% relative to the best outcome.

9 OPTIMIZATIONS DISCOVERED BY K2

We present two classes of optimizations that K2 discovered while reducing the number of instructions in the program. Several more examples from these classes and others are in Appendix G.

Example 1. Coalescing multiple memory operations. In the program `xdp_pktcntr` [12] developed by Facebook, K2 transformed

```
bpf_mov r1 0          // r1 = 0
bpf_stx_32 r10 -4 r1  // *(u32*)(r10-4) = r1
bpf_stx_32 r10 -8 r1  // *(u32*)(r10-8) = r1
```

into the single instruction

```
bpf_st_imm64 r10 -8 0 // *(u64*)(r10-8) = 0
```

by coalescing a register assignment and two 32-bit register stores into a single 64-bit store that writes an immediate value. The original instruction sequence comes from two assignments in the C code: `u32 ctl_flag_pos = 0; u32 cntr_pos = 0`. This example is one of the simplest of this class of optimizations that K2 found. In a couple of cases, K2 shrunk sequences of 12 instructions containing complex swaps of memory contents into 4–8 instructions.

Example 2. Context-dependent optimizations. K2 discovered rewrites that depend on the specific context (*e.g.,* current register values) of instructions within a program. For example, in the `balancer_kern` program [11] developed by Facebook, K2 transformed the sequence

```
bpf_mov64 r0 r2     // r0 = r2
bpf_and64 r0 r3     // r0 = r0 & r3
bpf_rsh64 r0 21     // r0 = r0 >> 21
```

into the sequence

```
bpf_mov32 r0 r2     // r0 = lower32(r2)
bpf_arsh64 r0 21    // r0 = r0 >> 21
```

This transformation does not generally hold under all values of `r3`. K2 used the precondition that the value of `r3` prior to this sequence was `0x00000000ffe00000`. More generally, we found optimizations where K2 leveraged *both* preconditions and postconditions on the values and liveness of registers and memory addresses.

We believe that the specificity of the optimizations described above (and in Appendix G) may well be challenging to match with a rule-based optimizing compiler. Beyond the categories described above, K2 derived optimizations using complex opcodes (*e.g.,* `bpf_xadd64 rX off rY` ⇔ `*(u64*)(rX + off) += rY`) and non-trivial dead code elimination that leverages the liveness of memory addresses. More examples are available in Appendix G.

Benchmark	Low	clang	K2	Reduction	Medium	clang	K2	Reduction	High	clang	K2	Reduction	Saturating	clang	K2	Reduction
xdp2	9	29.148	25.676	11.91%	9.5	51.157	30.237	40.89%	9.7	89.523	40.259	55.03%	10.3	103.872	97.754	5.89%
xdp_router_ipv4	1	63.323	59.834	5.51%	1.5	84.450	76.929	8.91%	1.5	84.450	76.929	8.91%	1.8	619.291	610.119	1.48%
xdp_fwd	4.4	32.272	30.358	5.93%	5	87.291	71.645	17.92%	5	87.291	71.645	17.92%	5.2	192.936	188.199	2.46%
xdp-balancer	3	38.650	37.152	3.88%	3.3	73.319	55.741	23.97%	3.4	237.701	119.497	49.73%	3.7	296.405	292.376	1.36%

Table 3: Average latencies (in microseconds) of the best `clang` and K2 variants at different offered loads (in millions of packets per second). We consider 4 offered loads: low (smaller than the slowest throughput of `clang` or K2), medium (the slowest throughput among `clang` and K2), high (the highest throughput among `clang` and K2), and saturating (higher than the fastest throughput of `clang` or K2).

Benchmark		I, II, III, IV	I, II, III		I, II		I		None	
name	#inst	time (μs)	time (μs)	slowdown	time (μs)	slowdown	time (μs)	slowdown	time (μs)	slowdown
(1) xdp_exception	18	25,969	465,113	18×	5,111,940	197×	2,160,340	83×	21,119,700	813×
(2) xdp_redirect_err	18	30,591	855,942	28×	3,795,580	124×	1,574,910	51×	11,105,500	363×
(3) xdp_devmap_xmit	36	48,129	42,887,200	891×	49,529,900	1,029×	45,789,000	951×	303,043,000	6,296×
(4) xdp_cpumap_kthread	24	7,414	23,387,700	3,155×	24,583,300	3,316×	26,223,200	3,537×	165,283,000	22,294 ×
(5) xdp_cpumap_enqueue	26	73,769	30,974,000	420×	36,360,800	493×	26,968,500	366×	123,350,000	1,672×
(14) xdp_pktcntr	22	9,181	1,030,280	112×	43,656,800	4,755×	80,963,000	8,819×	23,390,200	2,548×
(17) from-network	39	9,804	4,791,680	489×	33,758,000	3,443×	93,730,700	9,560×	7,836,910,000	799,343×
(18) recvmsg4	94	6,719	58,299,300	8,676×	1,533,220,000	228,181×	10,701,400,000	1,592,631×	> 86,400,000,000	> 12,858,444 ×
Avg. of all benchmarks	31	26,447	20,336,402	1,724×	216,252,040	30,192×	1,372,351,206	202,000×	> 11,860,525,175	> 1,711,472×

Table 4: Reductions in equivalence-checking time (§5, §8). We study the following optimizations: (I) memory type, (II) map type, and (III) memory offset concretizations, and (IV) modular verification. All optimizations are turned on (I, II, III, IV) as the baseline. Slowdowns relative to this baseline are reported as optimizations are turned off progressively.

10 RELATED WORK

Data plane code optimization has been a topic of recent interest [72, 75, 110]. Chipmunk [75] generates code for high-speed switches, where programs must fit within the available hardware resources or they won't run at all. In contrast, K2 starts with a program that can run; the goal is to improve its performance safely. In concurrent work, Morpheus [110] explores dynamic recompilation of data plane code based on workload characteristics, reminiscent of conditionally-correct optimization [130]. K2's approach is orthogonal: it is purely compile-time and the optimizations are valid across all run-time configurations. Farshin's thesis [72] suggests, but stops short of applying stochastic search to NFVs, due to performance variability. hXDP [52] executes BPF code on FPGAs; K2's goal is to optimize BPF over ISA-based processors.

There is a rich literature on synthesizing data plane rules and control plane policies for high-speed routers [43, 44, 68, 69, 125, 134, 135]. K2 must synthesize BPF instructions, which are more expressive than router data plane rules and control policies.

K2 builds significantly on the literature on program synthesis [38, 40, 55, 82, 85, 89, 94, 106, 113, 118, 127, 128, 136, 140] and accelerating formal verification [46, 48, 50, 57, 98, 120]. Below, we summarize three key technical differences from this literature.

First, K2 makes several domain-specific contributions in formalizing BPF programs relative to prior work. Sound BPF JITs [115, 116, 138, 139] assert the equivalence between BPF bytecode instructions and lower-level machine instructions on a per-instruction basis. K2 solves a fundamentally different problem: synthesizing new BPF bytecode and checking the equivalence of synthesized and source BPF bytecode. Unlike sound JIT compilers, K2 requires modeling control flow and pointer aliasing which are not concerns for per-instruction verification tasks. Prevail [77] implements a fast abstract interpretation of BPF programs to prove in-bound memory access safety and control flow safety. In contrast to Prevail, K2 performs synthesis, and considers several additional kernel-checker-specific safety properties to generate kernel-executable BPF bytecode. To our knowledge, none of the prior works formalize BPF maps and helpers in sufficient detail to support equivalence-checking, which requires modeling two levels of aliasing (§4.3). Further, K2 contributes several domain-specific techniques to accelerate equivalence-checking by 6 orders of magnitude.

Second, most prior x86 code synthesizers do not handle program safety considerations [40, 113, 118, 127–130]. To our knowledge, the only prior approach to synthesize safe code is the NaCl loop superoptimizer [55], which considers only access alignment (§6).

Finally, K2 includes several domain-specific program rewrites (§3) that accelerate convergence to better programs.

11 CONCLUSION

We presented K2, a compiler for BPF based on program synthesis technology. K2 can produce safe and optimized drop-in replacements for existing BPF bytecode.

K2 naturally leads to several avenues for follow-up research. (1) *Scaling to larger programs:* Currently, K2 cannot optimize large programs (200+ instructions) within a short time (*e.g.,* a minute). Developing techniques to optimize large programs quickly is a direction ripe for further research. (2) *Designing better cost functions:* K2's latency cost function is a weak predictor of actual latency. The design of high-fidelity cost functions to statically estimate program performance metrics such as tail latency and maximum per-core throughput will help boost the throughput and latency gains available from synthesis. (3) *Addressing engineering challenges:* The active evolution of the BPF ecosystem [26] makes it challenging to keep K2's safety checks in sync with that of the kernel checker and to develop support for emerging BPF hooks and helper functions.

We hope that the community will build on our compiler and the techniques in this paper. K2's source code, including all of our experimental scripts, is available at https://k2.cs.rutgers.edu/.

This work does not raise any ethical issues.

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Appendices are supporting material that has not been peer-reviewed.

A APPROACHES TO PROGRAM SYNTHESIS

In this paper, we are given a sequence of instructions in a fixed instruction set, *i.e.*, a BPF bytecode source program. We are interested in generating an alternative sequence of instructions, *i.e.*, a synthesized program, that satisfies the specification that (i) the synthesized program is equivalent to the source program in its input-output behaviors, (ii) the synthesized program is safe, and (iii) the synthesized program is more efficient than the source program. The precise meanings of efficiency and safety in the BPF context are described in §2.3 and §6.

To simplify the following discussion, suppose the program specification is simply (i) above, *i.e.*, $spec := p_{synth}(x) == p_{src}(x)$ for source program p_{src} and synthesized program p_{synth} for all program inputs x. At a high level, the program synthesis problem we are interested in can be formulated as the logical query

$$\exists p.\forall x.p(x) \ == \ p_{src}(x) \tag{4}$$

where p is any program composed of instructions from the BPF instruction set. As written down, this problem is a quantified boolean formula (QBF) with alternating quantifiers, which does not permit efficient decision procedures for problems that arise in synthesis [132]. Hence, program synthesizers take the approach of *counterexample guided inductive synthesis* (CEGIS) [132, 133]. First, a candidate program p_{cand} is determined through a search procedure. Then, the synthesizer checks whether the candidate satisfies the specification, by asking

$$\exists x.p_{cand}(x) \ != \ p_{src}(x) \tag{5}$$

for the *fixed* program p_{cand}.

Typically, synthesis algorithms use test cases to quickly prune candidates that do not satisfy the specification. If test cases do not eliminate p_{cand} as a candidate satisfying the specification, the query above can usually be formulated in a first-order logic theory [51] which permits efficient decision procedures. The query above is an example of *equivalence-checking*, which determines whether two programs produce the same output on all inputs. If the query (5) is satisfiable, we get a *counterexample*, which can be added to the set of test cases to prune the same or similar programs in the future without discharging computationally-expensive logic queries. If (5) is unsatisfiable, we have found a program p_{cand} that produces the same output as p_{src} on all inputs, and hence meets the specification.

The synthesis approaches in the literature differ mainly in the search procedures they use to propose candidate programs p. There are broadly four search approaches. Enumerative search (*e.g.,* [40, 106, 118]) searches the space in order from smallest to largest programs, terminating the search with the smallest program that satisfies the specification. Rule-based search [94, 136, 140] uses targeted rewrite rules to transform the source program into another program that satisfies the specification yet is more optimal. Deductive search [38, 82, 85, 89, 113, 127] encodes the search into a deductive query discharged to a solver whose solution implies a program within a specified grammar. Stochastic search [55, 128] searches the space guided by cost functions that enable sampling new random programs. Further, there are search algorithms that combine the best of multiple approaches [84, 118].

Among the synthesis approaches above, in our view, stochastic synthesis is the easiest to generalize to new and diverse contexts, due to its ability to support very expressive cost functions and constraints. We adopt and adapt stochastic synthesis in this paper.

B VERIFICATION CONDITIONS FOR BPF MAPS AND HELPER FUNCTIONS

BPF maps are a special kind of memory. Like memory, a BPF program could read a map with a specific key (*look-up*) and write a value corresponding to an existing key (*update*). However, three aspects make BPF maps very different from memory from the formalization perspective. First, the BPF map API [96] requires input keys in the form of *pointers* to memory, and further, returns values that are themselves pointers to memory. Second, keys can be *deleted* in a BPF map, unlike addresses in memory. Third, the keys and values in BPF maps are *persistent* structures that exist before and after program execution. Together, these aspects of BPF maps prevent us from directly applying the same formalization methods as memory access (§4.2) or other existing axiomatizations (*e.g.,* partial maps [119]) to model BPF maps in first-order logic. None of the prior works on formalizing BPF [77, 115, 116, 138] handle any aspect of BPF maps.

In the rest of this subsection, we show how our compiler handles pointer inputs/outputs as well as deletions. We show how we address the last aspect (map persistence) while performing program equivalence checking (§4).

B.1 Handling pointer access to map memory

Supplying an input key to a map operation (*e.g.,* look-up) as a pointer creates *two* levels of aliasing behaviors: First, two distinct registers may point to the same memory address (same as regular pointer aliasing). Second, a map needs to return the same value given the same (value of) key, *even if the keys are supplied from distinct memory addresses.*

We formalize map access in bit vector theory by decomposing the two levels of aliasing as follows. First, we create a new symbolic variable for each key supplied to the map API and each pointer value it returns. We call these variables the *valuations* of the (input) key pointer and the (output) value pointer. We apply the formulas in §4.2 to the key pointer, where the data that is read is the key's valuation.

To handle aliasing among the valuations of the keys themselves, we write down formulas analogous to memory aliasing (§4.2) over the valuations of the key and the value. This entails maintaining *map write and read tables* analogous to memory read and write tables.

Addressing aliasing among key valuations has the added benefit of encoding the partial map axioms [119], *e.g.,* a look-up of a key following an update of that same key returns the value from that update. No guarantees are made over the returned value *pointer* itself (this is a reference to the kernel's memory) except that it is non-zero.

Handling map manipulations through memory-access instructions. BPF map values can be manipulated directly through memory-access instructions, *e.g.,* to increment a counter stored as a map value using a `bpf_xadd` instruction, which has the impact of performing `*ptr = *ptr + reg`. K2 uses the static analysis described in §5 to determine the memory region corresponding to the pointer being loaded or stored. The memory read and write tables (§4.2) ensure that K2 puts down the right formulas for subsequent operations over these map value memory regions.

B.2 Handling map deletions

Keys in a BPF map can be deleted, unlike memory locations. If a deleted key is subsequently looked up, the result is a null pointer. We model this by the simple trick of setting the value address corresponding to the valuation of a deleted key to `0` in the map write table. When another key with the same valuation is looked up, the returned value address is `0`, indicating to the program that the key does not exist in the map. Luckily, this return value coincides with BPF's semantics for the return value of map lookup, which is `0` whenever the key does not exist in the map. We also handle setting the right return value for the BPF map delete API call, which provides distinct return values depending on whether the key currently exists in the map.

B.3 Handling multiple maps

The discussion so far assumes the existence of a single map with all operations over this map. BPF programs may look-up several maps in one program by loading map descriptors. However, the set of all possible maps accessed by the program is known at compile time. Hence, we can handle the general case by prefixing the precondition `map_id == K` as the head of an implication, with the body of the implication being the formula generated using the methods described above.

B.4 Limitation of map model

The current modeling of maps ignores concurrency among threads (kernel or user) accessing the same map. K2 does not make formal guarantees about the equivalence of its output programs to input programs when running in multi-threaded contexts where data races are permissible. However, BPF provides mutual exclusion for map contents through BPF spinlocks [61], and for code that enforces mutual exclusion to map access, the semantics of K2's output programs are indeed equivalent to those of the input program under concurrent access.

B.5 Other kernel helper functions

In addition to map helper functions, we also modeled a number of other BPF kernel helper functions, including functions to get random numbers, obtain a Unix timestamp, adjust the headroom in a memory buffer containing a packet, get the processor ID on which the program is executing, among others. The list of all BPF helper functions numbers over a hundred (and growing [96]). Out of engineering expediency, we only formalized the actions of helper calls as we needed them, rather than support all of them.

C DETAILS ON OPTIMIZATIONS TO EQUIVALENCE-CHECKING

The techniques described in §4 are sufficient to produce a working version of a BPF bytecode compiler. However, we found that the time to compile a single program of even modest size (~100 BPF instructions) is intractably large. The underlying reason is the significant time required to perform equivalence checking, which runs to several hours on even just a single pair of BPF programs on a modern server (§8).

This section presents domain-specific optimizations that bring down this verification time by several orders of magnitude to a few milliseconds. We show the impact of each optimization in §8. Several features of the BPF instruction set and packet-processing programs contribute to increased equivalence checking time: aliasing in memory and map access, multiple types of memories (stack, packet, metadata, and so on), usage of multiple maps, encoding the semantics of helper functions, and the existence of control flow within programs. K2 incorporates two broad approaches to reduce verification time: *concretization* of symbolic terms in the formula (§C.1) and *modular verification* of smaller parts of the program (§C.2) to verify the larger formula from §4.

C.1 Concretizations of Symbolic Terms

It is well known that an explosion in the size and solving difficulty of a formula under symbolic evaluation can be mitigated by assigning specific values to, *i.e.*, *concretizing,* terms in the formula [46, 50, 57, 98, 120].

We leverage the unique characteristics and simplicity of packet-processing BPF programs, as well as the feasibility of constructing simple static analyses (*e.g.,* sound inference of types) within the K2 compiler, to infer concrete values of several terms within the equivalence-checking formulas dispatched to the solver. These concretizations are "best effort" in the sense that we do not need the analysis within K2 to be complete: we apply the simplifications where possible, falling back to the general versions in §4 where they are not applicable. We eschewed complicated alias relationship mining techniques [55, 102] in favor of simpler domain-specific ones.

To simplify the discussion, we describe our techniques for straight-line programs (no branches) first, and then show how they generalize to loop-free programs with control flow.

I. Memory type concretization. BPF programs use multiple memory regions: the stack, packet, maps, and various kernel data structures like sockets. The handling of pointer-based aliasing of memory access discussed in §4.2 uses a single write table and read table for all of memory.

Instead, K2 leverages multiple read/write tables, one corresponding to each distinct memory region. This is feasible to do since any reference to a specific memory originates from pre-defined inputs to the BPF program [88], such as the `R10` register (stack), an input register like R1 (packet or packet metadata), or return values from specific helper calls (map memory, kernel socket structure, *etc.*). The type of each pointer in a program can then be easily inferred through a simple information-flow static analysis. For example, given a code sequence `bpf_mov r1 r10; bpf_mov r2 r1`, it is straightforward to infer that `r2` is pointing into the stack memory. K2 tracks types for all registers across each instruction in this manner.

The benefit of maintaining separate tables for separate memories is that the size of aliasing formulas in a memory read reduces from

$O(N^2_{all\ mem\ types})$ to $\sum_{t \in mem\ types} O(N_t^2)$, where $N_{(.)}$ refers to the number of accesses to memory of a specific type (or all types).

II. Memory offset concretization. The exact memory address contained in a register during a BPF program's execution is in general hard to determine at compile time, since the program stack or the packet contents may be located anywhere within the kernel's memory. However, in many packet-processing programs, the *offsets* relative to the base address of the memory region, *e.g.,* such as the offset (from the beginning of the packet) of a header field, are known at program compile time. Further, BPF stack locations can only be read after they are written, and it is feasible to track which concrete offsets are being written to in the first place. K2 attempts to maintain a concrete offset into the memory region for each register known to be a pointer. Each subsequent operation on the register is associated with the corresponding operation on the concrete offset. For example, the instruction `bpf_mov r1 r10; bpf_sub r1 2 /* r1 := r10 - 2 */` associates the offset `-2` with the register `r1`. A subsequent operation `bpf_mov r2 r1; bpf_sub r2 4` would also update the corresponding offset of `r2` to `-6`. (Both registers have a STACK memory type.)

Offset concretization has the effect of turning a clause like `addr_i == addr_j` (§4.2) into a clause like `offset_i == offset_j`, where `offset_i` and `offset_j` are concrete values, *e.g.,* -2 == -6. When a load instruction results in comparing a register offset to other offsets stored in the write table, any comparison of a concrete pair of offsets can be evaluated at compile time without even a solver call. If all pairs of offsets compared are concrete, this can simplify an entire memory read into a single clause of the form `value_i == value_j`. Even if only one of the offsets being compared is known concretely, it simplifies the clause overall.

In the limit, this optimization has the effect of turning the entire memory into nameable locations akin to registers. Similar ideas have been applied in prior efforts to scale verification time [40, 128]. K2 applies this idea in a best-effort manner, falling back to general aliasing when concrete offsets cannot be soundly inferred.

III. Map concretization. BPF programs access several maps and frequently perform operations such as lookups, which are among the most expensive BPF operations in terms of verification. Map lookups generate large verification conditions because of two levels of aliasing (§4.3). Accessing multiple maps in a single BPF program further explodes the formula sizes, since one set of clauses is generated for each possible map the program may have accessed. Similar to the idea of concretizing memory types for each access, K2 statically determines the map to which a given lookup or update occurs. This is feasible due to a property of BPF's map-related instructions: there is a unique opcode `LD_MAP_ID` which loads a unique and concrete `map_id` (obtained from a file descriptor), which is then supplied as a parameter to each BPF map call.

We did not generalize our approach to concretize the keys that are looked up or values that are presented to the map update function call. The BPF map API (§2) mandates map function parameters and return values to be *pointers* to keys and values, rather than registers containing the keys and values themselves. Map keys are pointers to the stack, and the keys on the stack are often from input memory regions, such as packet fields. As noted above (cf. memory offset concretization), we concretize memory addresses that are accessed, but not the bits stored at concrete addresses in memory. If the keys are symbolic, then the values are symbolic, too. We leave leveraging opportunities to concretize map keys and values to future work.

Incorporating control flow into optimizations. So far, the discussion of the static analysis in K2 to determine concrete terms has focused on straight-line code. In the presence of branches, this analysis is generalized as follows. First, statically known information (*e.g.,* pointer type, offset) is annotated with the basic block and path condition under which it is determined. Next, for a subsequent read, to determine the concrete information (*e.g.,* offset) to apply, we use the following procedure iteratively for each prior write to the pointer, starting from the latest to the earliest in order of program execution:

- If the last write is from a basic block that *dominates* [63] the basic block of the reading instruction, we use the corresponding entry's concrete information and stop. SSA dominance analysis is performed just once per program.
- If the last write is from a basic block from which control never *reaches* the basic block of the reading instruction, we skip the corresponding entry's concrete information and move to the next entry. Reachability analysis is performed just once per program.
- If neither of the above is true, there is a path through the basic block of the write to the current instruction, but there are also other paths. K2 conjoins the clause `path condition of the entry ⇒ read offset == entry offset`. The process continues to the next entry.

For example, after processing the instruction sequence

```
jneq r5 r6 1 /* if r5 == r6 */
b1: bpf_mov r1 r10 -2 /* r1 = r10 - 2 */
b2: bpf_mov r1 r10 -4 /* else r1 = r10 - 4 */
b3: bpf_load_32 r3 r1 /* r3 = (uint32) *r1 */
```

the compiler stores the following information:

```
(block b1, cond r5 == r6, r1 STACK, offset -2)
(block b2, cond !(r5 == r6), r1 STACK, offset -4)
```

To determine the offset read by block b3 (`r3 = *r1`), the compiler determines that neither b1 nor b2 dominates b3, but they can both reach b3, hence producing the verification conditions

```
(r5 == r6) ⇒ read_offset == -2 ∧
 ! (r5 == r6) ⇒ read_offset == -4
```

It is not always possible to make the `read_offset` concrete, as seen in this example.

IV. Caching We also cache the verification outcomes of *canonicalized* versions of a given program to quickly determine if a structurally similar program was equivalence-checked earlier. We canonicalize the program by removing dead code. Then, the canonicalized program is hashed into a key that is used to look-up a program cache of verification outcomes. Equivalence-checking is only performed when there is a cache miss; the outcome of the equivalence checking is inserted into the cache along with the program that was checked.

C.2 Modular Verification

Synthesis and optimization typically scale to large programs by operating over a sequence of smaller *windows*, where a window is a contiguous sequence of instructions as they appear in the text of the program [103, 109, 118, 130]. Small windows (rather than the full programs) lead to smaller verification conditions, which are much faster to solve.

Verifying the correctness of synthesized windows be thought of in one of two ways. A peephole optimizer [40, 108] would only produce instruction sequences that exhibit equivalent behavior under *any* values that the window consumes (precondition) and ensure *any* values it produces are equal to that produced by the original program (postcondition). This is similar to the verification conditions from §4, written just for a window in the program.

An alternative possibility is to consider stronger preconditions and weaker postconditions to verify the window [118, 130]. This enables stronger optimizations: for example, the instruction `bpf_mul r2 r1` can be optimized into `bpf_lshift r2 2` *provided* a compiler can infer that `r1 == 4` during the multiplication, but not in general. Similarly, other optimizations become possible with weaker postconditions.

We call the part of the program before the window the *prefix* and the part after the window the *postfix*. Automatically inferring strong preconditions (that hold after the prefix) and weak postconditions (that must hold before the postfix) is a challenging problem [103, 109, 130]. Recent work [118] takes the approach of using the strongest possible precondition and weakest possible postcondition, by constructing the entire first-order logical representation of the prefix and postfix programs. This approach, while enabling strong optimizations, reduces to using the verification conditions for the full program.

Instead, we build on an earlier approach [40] that uses the *live variables* [111] to generate stronger preconditions and weaker postconditions than peephole optimizers. Additionally, K2 also infers sets of concrete values for variables, if they exist, and pose those as preconditions for the optimization. K2 chooses windows among basic blocks of a certain maximum instruction count and uses the following window-based verification condition:

```
variables live into window 1
== variables live into window 2
 ∧  inferred concrete valuations of variables
 ∧  input-output behavior of window 1
 ∧  input-output behavior of window 2
 ⇒  variables live out of window 1
    != variables live out of window 2
```

Here, variable set "live into" the window contains all variables written in the prefix that are readable in the window, and the set "live out of" the window contains all variables that are written inside the window *and* read by the postfix. The concrete valuations of variables are inferred through static analysis that determines the set of concrete values that a register might take on, along with the corresponding path conditions. For example, in the code sequence

```
if r0 > 4:
  r1 = 6
else if r2 < 6:
  r1 = 10
else:
  r1 = 8
---- window begins ----
/* use r1 somewhere here */
---- window  ends  ----
```

the clause of the precondition with inferred values is

```
p1  ⇒  r1 == 6
 ∧  p2  ⇒  r1 == 10
 ∧  p3  ⇒  r1 == 8
 ∧  exactly one of p1, p2, p3 is true
```

where `p1, p2,` and `p3` are fresh boolean variables corresponding to the path conditions where `r1` takes on distinct concrete values.

If the formula is satisfiable, the solver produces an input state at the beginning of the window that results in the two windows producing different output states at the end of the two window executions. If not, the two windows are conditionally-equivalent under the specific precondition and postcondition above.

We specialize the liveness analysis to the BPF context by handling BPF registers as well as BPF memory (stack, packet, map values). We build on optimizations (I–III) in §C.1 and track liveness information along with concrete types and offsets. In particular, with map values, we treat each map value as a distinct type of memory, with its own concretizations of each access within the window, since we do not have concrete offsets into the kernel's (value) memory.

Window-based verification condition generation and equivalence checking are particularly useful in the BPF context for many reasons. First, it becomes unnecessary to track aliasing for map access, since each window typically just contains one live map value pointer, and we only care about aliasing within the value memory itself. In fact, we don't even use any information about the key in the verification condition. Second, it becomes possible to handle several new helpers in a much more expedient way with window verification, since we can optimize "around" the function by simply tracking the inputs and outputs of the helper, rather than "across" the function, which requires capturing its input-output semantics. Third, window verification allows us to guide the stochastic search better for programs that output a small number of output bits—programs known to be hard to optimize with typical error functions [128]. This is because K2's window postcondition ensures that the window obtains other intermediate values in the program correctly, rather than (just) the output.

The fundamental disadvantage of window-based verification relative to full-program verification is its inability to discover some strong optimizations that would be found with equivalence-checking full programs [118]. Unlike window-based equivalence checking, full program checking can detect aliasing conditions over the entire program, optimize across helper functions (with full semantics), and can optimize instructions under the strongest possible preconditions and weakest possible postconditions.

D MORE DETAILS ON THE IMPLEMENTATION OF K2

Please see §7 for an overview of K2's implementation.

K2 uses the same internal BPF instruction structure as the kernel, so that K2 can consume BPF instructions directly from the binary

Benchmark	# Variants produced	# accepted by kernel checker	Cause(s) of checker failure
xdp1	5	5	-
xdp2	5	5	-
xdp_redirect	5	5	-
xdp_map_access	5	5	-
xdp_router_ipv4	5	5	-
xdp_pktcntr	3	3	-
xdp_fwd	5	5	-
xdp_fw	5	5	-

Table 5: We loaded 38 K2-optimized program variants (known to be equivalent to the corresponding source programs) into the kernel. All programs were successfully accepted by the kernel checker.

Benchmark	# progs. hit cache	total # calls to the cache	Hit rate	# iters.
(1)	13,479	14,470	93%	1,000,000
(2)	32,706	35,072	93%	1,500,000
(3)	30,557	31,833	96%	4,000,000
(4)	68,828	72,220	95%	4,000,000
(14)	15,827	16,552	96%	2,000,000
(17)	134,505	140,686	96%	5,000,000
(18)	100,641	109,046	92%	5,000,000

Table 6: The benefit of caching (§5) in reducing the number of solver calls. The benchmark numbers correspond to those in Table 1.

ELF format of the instructions (*i.e.*, the `.o` files) without explicitly decoding from and encoding into another format. Binary encode/decode is known to be a significant source of compiler bugs [112].

The compiler consumes inputs from pre-compiled BPF bytecode object files as well as instruction sequences encoded through the kernel `bpf_insn` data structure. The extraction of the inputs from ELF binaries uses `libbpf`, the kernel's standard library to work with BPF bytecode. A tricky aspect of BPF bytecode is that the text section of the ELF file is not directly executable. The text section must be processed using *relocations* [100] during the loading process [114] to ensure that run-time references to map file descriptors and other symbols are updated before execution (the text section is independent of these run-time parameters). K2 consumes instructions from relocated ELF.

The output of the compiler can take on two forms: a sequence of binary instructions, which is useful to test simple programs quickly, or a patched ELF object file that contains the sections of the original ELF input with the optimized instruction sequence patched in lieu of the original instructions in the text section. K2 uses `pyelftools` to perform the patching.

K2 uses relocation metadata, specifically the set of instructions that are touched by the `libbpf` loader, to ensure that the linkages between the text section and the remaining ELF sections are unmodified. Hence, outputs from K2 can serve as drop-in replacements to existing BPF object files.

K2 includes a high-performance BPF interpreter that runs BPF bytecode instructions using an optimized jumptable implementation akin to the kernel's internal BPF interpreter [2]. Using C preprocessor directives, we share code for most instructions between the interpreter and the equivalence checker. Before adopting this design, we found that the mismatch between the behaviors of the interpreter and the semantics of the first-order logic formulation of the same program was a significant and vexing source of bugs. We found that using a shared semantic description of each instruction that is common to the interpreter and the first-order logic verification condition generator was helpful in ensuring that the input-output behaviors of the interpreter and the program's formalization were compatible.

We construct first-order logic representations using `Z3` [65] and also use it as our solver. To reduce the impact of large memory-bound queries on the overall compile time, we use two separate Z3 solver processes, with the query discharged to the solvers using a serialized `smtlib2` format. We pick the solver that returns a response first and respawn server processes after a fixed number of discharged queries.

K2's interpreter and the equivalence-checking query formulation can distinguish different BPF program types and fix the inputs and outputs appropriately.

E ESTIMATED PERFORMANCE FROM K2

In this section, we show the performance estimated by K2 with the latency goal. We perform latency and throughput measurements of the top-k programs from these experiments in §8.

F ADDITIONAL EVALUATION RESULTS

F.1 Parameters of stochastic search

Table 8 shows the best-performing parameter settings of K2. Table 9 shows K2's instruction count reductions from those parameter settings. Table 10 shows the benefits of K2's domain-specific rules in stochastic synthesis.

F.2 Efficacy of safety checks

The results of loading the outputs of K2 using the kernel checker are shown in Table 5.

F.3 Caching efficacy

The efficacy of caching in reducing the number of solver queries to perform equivalence checking is illustrated in Table 6.

F.4 Benefits of domain-specific rewrite rules

In Table 10, we show the benefits of including domain-specific program rewrite rules (§3.1) while generating proposals within the stochastic optimization loop.

G MORE OPTIMIZATIONS DISCOVERED BY K2

Table 11 lists several optimization case studies across benchmarks from the Linux kernel, hXDP, and Cilium.

Benchmark	Program Runtime (sec)				When lowest perf cost prog. is found	
	-O1	-O2/-O3	K2	Gain	Time (sec)	Iterations
(9) xdp_router_ipv4	57.45	50.34	47.21	6.22%	1,455	450,502
(10) xdp_redirect	17.15	16.08	14.52	9.70%	472	203,332
(11) xdp1_kern/xdp1	31.33	25.57	24.55	3.99%	155	240,116
(12) xdp2_kern/xdp1	34.79	30.88	28.86	6.54%	145	107,089
(13) xdp_fwd	57.02	51.56	43.73	15.19%	4,316	2,850,176
(14) xdp_pktcntr	12.32	12.32	11.85	3.81%	48	201,057
(15) xdp_fw	65.02	46.61	45.01	3.43%	858	345,320
(16) xdp_map_access	27.96	27.96	27.28	2.43%	20	50,814
(17) from-network	32.27	30.96	29.17	5.78%	713	401,730
(18) recvmsg4	68.12	68.12	63.83	6.30%	3,444	907,834
(19) xdp-balancer	DNL	760.12	724.73	4.66%	170,154	7,502,210
Avg. of all benchmarks				6.19%	16,525	1,205,471

Table 7: Improvements in *estimated* performance of programs according to K2.

Setting ID	1	2	3	4	5
Compute error cost	ABS	POP	POP	ABS	ABS
Avg. total error cost by # test cases or not	No	No	No	No	Yes
Weight of error cost (α)	0.5	0.5	0.5	0.5	0.5
Weight of performance cost (β)	5	5	5	5	1.5
Probability of instruction replacement ($prob_{ir}$)	0.2	0.17	0.2	0.17	0.17
Probability of operand replacement ($prob_{or}$)	0.4	0.33	0.4	0.33	0.33
Probability of replacement by NOP ($prob_{nr}$)	0.15	0.15	0.15	0.15	0.15
Probability of memory exchange type 1 ($prob_{me1}$)	0.2	0.17	0.2	0	0
Probability of memory exchange type 2 ($prob_{me2}$)	0	0	0	0.17	0.17
Probability of replacement of contiguous instructions ($prob_{cir}$)	0.05	0.18	0.05	0.18	0.18

Table 8: Details of K2's five best-performing parameter settings (§3). ABS corresponds to the absolute error cost function, while POP corresponds to population count of the bitwise difference.

Benchmark	Parameter setting ID					# instructions of the smallest prog.	% of paras get the smallest prog.	Time to find the smallest prog. (sec)
	1	2	3	4	5			
(1) xdp_exception	16	18	16	16	16	16	80%	323
(2) xdp_redirect_err	16	16	16	16	16	16	100%	10
(3) xdp_devmap_xmit	30	29	30	32	30	29	20%	1,213
(4) xdp_cpumap_kthread	19	18	19	22	18	18	40%	1,170
(5) xdp_cpumap_enqueue	22	21	22	26	22	21	20%	1,848
(6) sys_enter_open	21	21	21	20	21	20	20%	519
(7) socket/0	27	27	27	27	27	27	100%	6
(8) socket/1	30	30	30	30	30	30	100%	9
(9) xdp_router_ipv4	101	99	99	100	100	99	40%	898
(10) xdp_redirect	35	35	35	35	37	35	80%	523
(11) xdp1_kern/xdp1	56	56	56	57	58	56	60%	598
(12) xdp2_kern/xdp1	71	72	71	71	72	71	60%	159
(13) xdp_fwd	128	130	130	133	134	128	20%	6,137
(14) xdp_pktcntr	19	19	19	20	19	19	80%	288
(15) xdp_fw	65	65	65	68	69	65	60%	826
(16) xdp_map_access	26	26	26	27	26	26	80%	32
(17) from-network	30	30	30	31	29	29	20%	6,871
(18) recvmsg4	81	81	81	83	84	81	60%	3,350
(19) xdp-balancer	1,624	1,607	1,627	1,679	1,684	1,607	20%	167,428

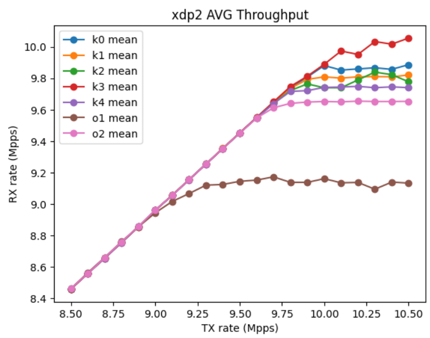
Table 9: Performance of K2 under different parameter settings.

Benchmark	MEM_1 & $CONT$		MEM_2 & $CONT$		MEM_1 only		MEM_2 only		$CONT$ only		None	
	# instr.	time (sec)	# instr.	time (sec)	# instr.	time (sec)	# instr.	time (sec)	# instr.	time (sec)	# instr.	time (sec)
(1) xdp_exception	16*	8	16*	315	16*	90	16*	91	16*	183	16*	93
(2) xdp_redirect_err	16*	10	16*	40	16*	29	16*	160	16*	416	16*	84
(3) xdp_devmap_xmit	29*	1,201	30	497	30	914	30	2,988	30	791	30	3,454
(4) xdp_cpumap_kthread	18*	1,848	18*	3,998	19	344	21	535	19	1,364	19	2,933
(5) xdp_cpumap_enqueue	21*	214	21*	2,647	22	52	22	360	22	1,108	22	373
(6) sys_enter_open	21	6	20*	519	21	55	21	214	21	364	21	31
(7) socket/0	27*	9	27*	19	27*	10	27*	72	27*	5	27*	10
(8) socket/1	30*	598	30*	10	30*	60	30*	154	30*	5	30*	56
(9) xdp_router_ipv4	99*	482	99*	2,704	99*	1,073	99*	992	105	4,949	106	299
(10) xdp_redirect	35*	826	35*	2,681	35*	724	35*	764	39	507	39	1,441
(11) xdp1_kern/xdp1	56*	269	56*	472	57	41	57	286	57	62	57	42
(12) xdp2_kern/xdp1	71*	3,350	71*	334	71*	328	71*	185	75	6	75	5
(13) xdp_fwd	128*	4,944	130	3,036	128*	2,847	130	4,686	144	4,003	145	5,091
(14) xdp_pktcntr	19*	1,194	19*	260	20	30	20	32	20	44	20	57
(15) xdp_fw	65*	898	66	1,856	65*	245	67	46	66	1,043	66	2,619
(16) xdp_map_access	26*	523	26*	106	26*	30	26*	256	26*	354	26*	78
(17) from-network	30	366	29*	6,871	30	915	30	4,449	30	3,544	30	3,696
(18) recvmsg4	81*	1,170	81*	8,317	84	4,146	85	14,829	85	10,498	87	16,763
# benchmarks where this setting found the best program	16		15		10		8		5		5	
# benchmarks where *only* this setting found the best program	1		2		0		0		0		0	

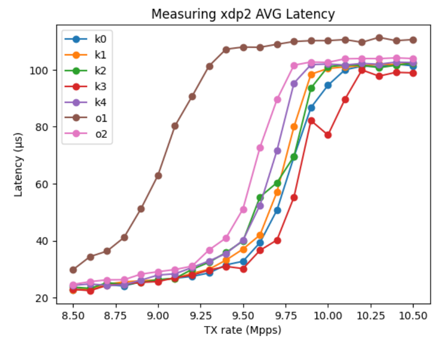
Table 10: Improvements in program compactness under different proposal generation settings (§3.1). We consider turning the following proposal-generation rewrite-rules on or off: MEM_1 implements a type 1 memory exchange, sampling to replace all non-pointer operands, MEM_2 implements a type-2 memory exchange, sampling to replace only the memory operation width, and $CONT$ replaces $k = 2$ contiguous instructions. Instruction counts with the * mark indicate that they are the minimal found among all the proposal generation settings tested.

H PROFILES OF PROGRAM LATENCY *VS.* OFFERED LOAD

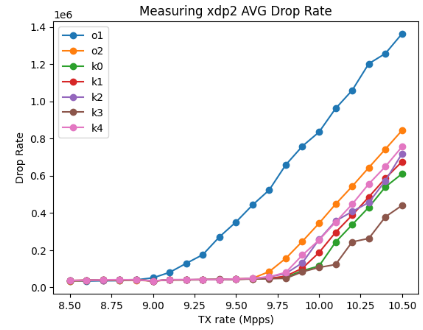
These results supplement the numbers in §8 regarding the latency, throughput, and drop rates of various XDP programs as offered load from the traffic generator increases.



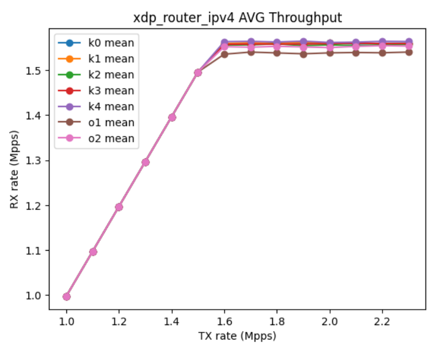
(a) xdp2: Throughput vs. Offered load



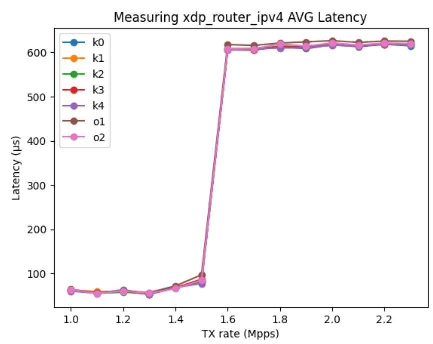
(b) xdp2: Avg. latency vs. Offered load



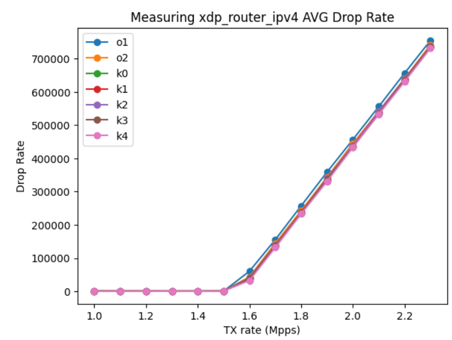
(c) xdp2: Drop rate vs. Offered load



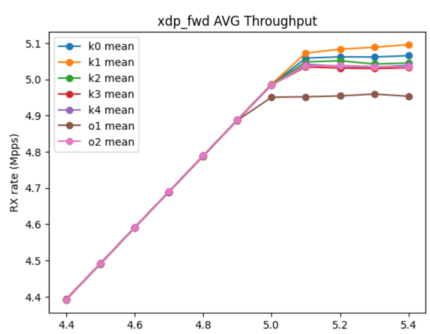
(d) xdp_router_ipv4: Throughput vs. Offered load



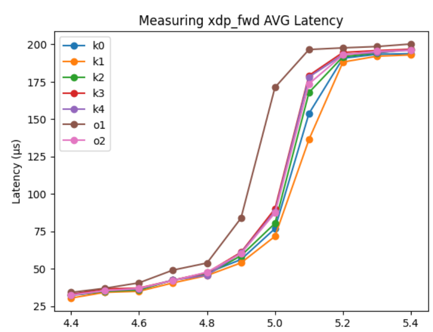
(e) xdp_router_ipv4: Avg. latency vs. Offered load



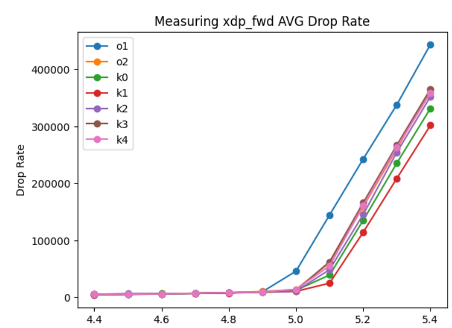
(f) xdp_router_ipv4: Drop rate vs. Offered load



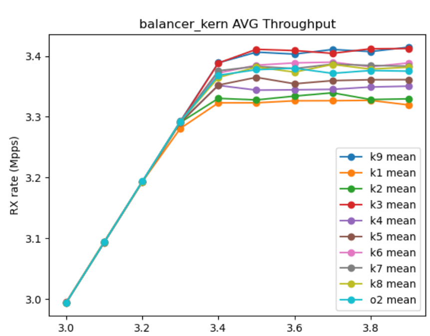
(g) xdp_fwd: Throughput vs. Offered load



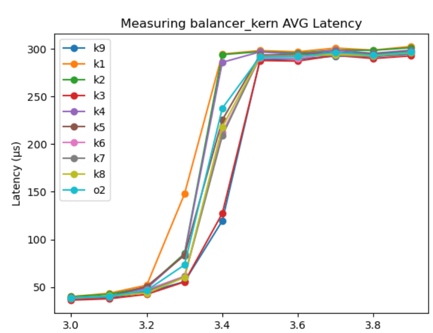
(h) xdp_fwd: Avg. latency vs. Offered load



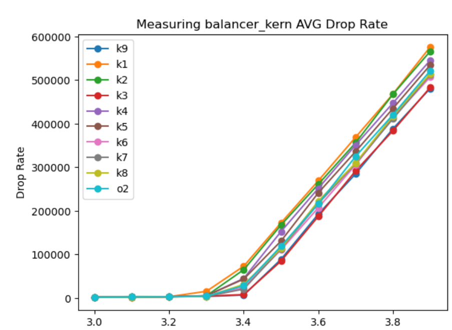
(i) xdp_fwd: Drop rate vs. Offered load



(j) xdp-balancer: Throughput vs. Offered load



(k) xdp-balancer: Avg. latency vs. Offered load



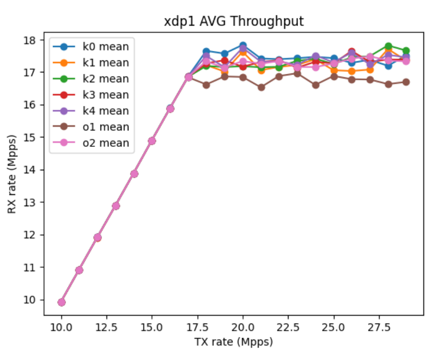
(l) xdp-balancer: Drop rate vs. Offered load

Benchmark	BPF program before optimization	BPF program after optimization	C code	Note

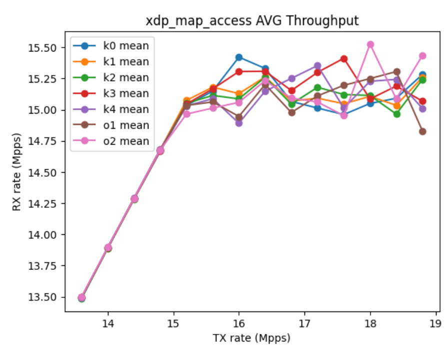
xdp2_kern/xdp1	bpf_load_16 r1 r7 0 // r1 = *(u16*)(r7+0)
	bpf_load_16 r2 r7 6 // r2 = *(u16*)(r7+6)
	bpf_stx_16 r7 0 r2 // *(u16*)(r7+0) = r2
	bpf_load_16 r2 r7 8 // r2 = *(u16*)(r7+8)
	bpf_load_16 r3 r7 2 // r3 = *(u16*)(r7+2)
	bpf_stx_16 r7 8 r3 // *(u16*)(r7+8) = r3
	bpf_stx_16 r7 2 r2 // *(u16*)(r7+2) = r2
	bpf_load_16 r2 r7 10 // r2 = *(u16*)(r7+10)
	bpf_load_16 r3 r7 4 // r3 = *(u16*)(r7+4)
	bpf_stx_16 r7 10 r3 // *(u16*)(r7+10) = r3
	bpf_stx_16 r7 6 r1 // *(u16*)(r7+6) = r1
	bpf_stx_16 r7 4 r2 // *(u16*)(r7+4) = r2
		bpf_load_32 r1 r7 0 // r1 = *(u32*)(r7+0)
		bpf_load_32 r2 r7 6 // r2 = *(u32*)(r7+6)
		bpf_stx_32 r7 0 r2 // *(u32*)(r7+0) = r2
		bpf_load_32 r3 r7 4 // r3 = *(u32*)(r7+4)
		bpf_load_32 r2 r7 10 // r2 = *(u32*)(r7+10)
		bpf_stx_32 r7 10 r3 // *(u16*)(r7+10) = r3
		bpf_stx_32 r7 6 r1 // *(u32*)(r7+6) = r1
		bpf_stx_16 r7 4 r2 // *(u16*)(r7+4) = r2
			dst[0] = p[0];
			dst[1] = p[1];
			dst[2] = p[2];
			p[0] = p[3];
			p[1] = p[4];
			p[2] = p[5];
			p[3] = dst[0];
			p[4] = dst[1];
			p[5] = dst[2];
				This instruction sequence swaps three higher bytes and three lower bytes through six 8-bit loads and stores. K2 coalesced six loads and stores into two 16-bit loads and stores and one 8-bit load and store.

xdp_fwd	bpf_load_16 r1 r10 -2 // r1 = *(u16*)(r10-2) bpf_stx_8 r7 4 r1 // *(u8*)(r7+4) = r1 bpf_rsh64 r1 8 // r1 »= 8 bpf_stx_8 r7 5 r1 // *(u8*)(r7+5) = r1 bpf_load_16 r1 r10 -4 // r1 = *(u16*)(r10-4) bpf_stx_8 r7 2 r1 // *(u8*)(r7+2) = r1 bpf_rsh64 r1 8 // r1 »= 8 bpf_stx_8 r7 3 r1 // *(u8*)(r7+3) = r1 bpf_load_16 r1 r10 -6 // r1 = *(u16*)(r10-6) bpf_stx_8 r7 0 r1 // *(u8*)(r7+0) = r1 bpf_rsh64 r1 8 // r1 »= 8 bpf_stx_8 r7 1 r1 // *(u8*)(r7+1) = r1	bpf_load_32 r1 r10 -4 // r1 = *(u32*)(r10-4) bpf_stx_32 r7 2 r1 // *(u32*)(r7+2) = r1 bpf_load_16 r1 r10 -6 // r1 = *(u16*)(r10-6) bpf_stx_16 r7 0 r1 // *(u16*)(r7+0) = r1	memcpy(eth->h_dest, fib_params.dmac, ETH_ALEN);	This instruction sequence copies 6 bytes from the source address (r10-6) to the destination address r7 by three sets of operations, each involving one 16-bit load and two 8-bit stores. K2 reduced the instruction count by compressing these memory operations into one 32-bit load and store, and one 16-bit load and store.
sys_enter_open	bpf_load_32 r1 r0 0 // r1 = *(u32*)(r0+0) bpf_add64 1 1 // r1 += 1 bpf_stx_32 r0 0 r1 // *(u32*)(r0+0) = r1	bpf_mov64 r1 1 // r1 = 1 bpf_xadd_32 r0 0 r1 // *(u32*)(r0+0) += r1		This instruction sequence increases the memory value by 1. It loads the value from the memory and then performs a register addition, finally stores the register value into the memory. K2 utilized the memory addition to reduce one instruction.
xdp1_kern/xdp1	bpf_mov64 r1 0 // r1 = 0 bpf_stx_32 r10 -4 r1 // *(u32*)(r10-4) = r1	bpf_st_imm32 r10 -4 0 // *(u32*)(r10-4) = 0		This transformation coalesces a register assignment and one register store into a store that writes an immediate value.
recvmsg4	bpf_load_32 r1 r6 24 // r1 = *(u32*)(r6+24) bpf_stx_32 r10 -16 r1 // *(u32*)(r10-16)=r1 bpf_stx_16 r10 -26 r7 // *(u16*)(r10-26)=r7 bpf_load_32 r1 r10 -16 // r1 = *(u32*)(r10-16) bpf_load_16 r10 -28 r1 // *(u16*)(r10-28)=r1	bpf_load_16 r1 r6 24 // r1 = *(u16*)(r6+24) bpf_stx_32 r10 -28 r1 // *(u32*)(r10-28) = r1		This optimization does not hold under all values of r7. In the prefix program, r7 is assigned as 0. Also, the value written in (r10-16) is not read in the postfix program. K2 found this transformation by leveraging both preconditions and postconditions.
xdp_map_access	bpf_mov64 r3 0 // r3 = 0 bpf_stx_8 r10 -8 r3 // *(u8*)(r10-8) = r3	(no instructions)		K2 removed these two instructions by the postconditions where the values set to the register and the memory were not used in the postfix program.

Table 11: A catalog of optimizations found by K2.



(m) xdp1: Throughput vs. Offered load



(n) xdp_map_access: Throughput vs. Offered load

Figure 2: Throughput, average latency and drop rate under different offered loads. We measured the top-k K2 versions ($k = 9$ for xdp-balancer and $k = 5$ for other benchmarks), and two `clang` versions: `-O1` and `-O2`. Note that `-O2` and `-O3` are identical for these benchmarks.