Toward building memory-safe network functions with modest performance overhead

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1. INTRODUCTION

For the past few decades network functions have evolved much in variety and complexity. Contributing factors behind are ever-increasing link speeds, novel hardware features, and new network designs (e.g., datacenters), just to name a few [4, 6]. In order to deliver high performance in network I/O, network functions rely heavily on low-level memory management. Yet, such memory management is error-prone. Among the Linux CVEs (Common Vulnerabilities and Exposures) for network functionality with CVSS(Common Vulnerability Scoring System) score 7.5 or higher, more than 30% are due to memory management faults: buffer overflow, null pointer dereferences, use-after-free, and double free. Table 1 shows some examples of critical vulnerabilities from memory-related bugs on the kernel’s network stack. Such bugs often lead system crash, systems being compromised, or leakage of secret information.

In traditional type-safe languages (e.g., ML, Haskell, Scala), memory-safety is preserved by disallowing pointer manipulation; they automatically manage memory resources without explicit `malloc() / free()`, restrict accesses beyond memory bound, and have no null pointer dereferences. There are notable projects of implementing network function using type-safe languages [5, 2, 1]. Yet for performance-critical network functions, intermittent execution of a garbage collector incurs unbearable performance penalty.

Rust [3], a recently developed language for safe system programming, aims to support memory-safety without explicit `malloc() / free()`, restrict accesses beyond memory bound, and have no null pointer dereferences. There are notable projects of implementing network function using type-safe languages [5, 2, 1]. Yet for performance-critical network functions, intermittent execution of a garbage collector incurs unbearable performance penalty.

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Rust developers manipulate low-level memory without garbage collection as in C/C++, while the strongly-typed memory segment and the ownership abstraction enables compile-time verification of memory-safety. In Rust, only a single variable has an ownership of a memory segment, which allows an exclusive update access to it. The ownership linearly moves among variables and multiple immutable borrowing references (read-only) for the memory segment enables high concurrency whenever possible.

This restricted programming model makes certain data structures hard to implement. For example, every element of a doubly-linked list requires at least two writable references and does not fit Rust’s ownership. Therefore, in addition to the default type system, Rust developers need to add unsafe code blocks (e.g., calling native C functions, doing pointer arithmetic) or low-performance abstractions such as reference counting wrappers `Rc<RefCell>` requiring C-like pointer semantics.

We compare the performance of Rust and C implementations of an IPv4 reassembler. It is a simple network function, yet only with per-flow state management. The Rust implementation shows only 17% performance degradation in throughput, while it guarantees memory safety. This performance gap may shrink if we optimize common data structures (e.g., hash table) like C.

2. RUST: ZERO-COST MEMORY-SAFETY

Rust’s [3] type system guarantees memory-safety with- run-time overhead. Rust developers manipulate low-level memory without garbage collection as in C/C++, while the strongly-typed memory segment and the ownership abstraction enables compile-time verification of memory-safety. In Rust, only a single variable has an ownership of a memory segment, which allows an exclusive update access to it. The ownership linearly moves among variables and multiple immutable borrowing references (read-only) for the memory segment enables high concurrency whenever possible.

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3. NETWORK FUNCTION ARCHITECTURE

We argue that the core architecture of network functions fits well with Rust’s type system such that network functions should reap the benefit of zero-cost abstraction for memory safety as shown in Figure 1.

Rust-friendly RW patterns Network functions manage a 5-tuple context of network flows. To exploit the parallelism in the multicore architecture, input packets are evenly distributed to multiple cores preserving flow affinity. Then, network function’s data can be classified into two categories: Per-flow data accessed within a single network flow, and global data accessed across different network flows. The per-flow data is frequently read and updated, but exclusively within a single thread. The ownership of per-flow data is assigned when its flow context is assigned to a thread. The global data is shared among multiple threads. Since it is mostly read and rarely updated, there is enough possibility of parallelism by having read-only references. Such use of sin-
We evaluated our NAT implementation on a 24-core Xeon E5-2670v3 machine connected with two Mellanox ConnextX-3 40G NICs. One NIC is used for the internal network, and the other for the external network. The input workload is 100k UDP flows with 512B packets. Figure 2 shows the performance of our implementation with varying numbers of CPU cores. Our implementation scales well when the number of core increases and almost saturates the 40G link with 16 cores.

5. FUTURE WORK

In this work we have built network functions in Rust with type-safe guarantees and modest performance overhead. We plan to investigate other characteristics of network functions – layered architectures, (de-) multiplexing of data flows – and seek additional optimization opportunities in Rust’s type system.

Acknowledgement

This work was supported by Institute for Information & communications Technology Promotion (IITP) grant funded by the Korea government (MSIT) (No.2017-0-01731, Type-safe networking stack for IoT devices).

6. REFERENCES