Parking Packet Payload with P4

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Abstract

Network Function (NF) deployments suffer from poor link goodput, because popular NFs such as firewalls process only packet headers. As a result, packet payloads limit the potential goodput of the link. Our work, PayloadPark, improves goodput by temporarily parking packet payloads in the stateful memory of dataplane programmable switches. PayloadPark forwards only the packet headers to the NF servers and saves transmit and receive bandwidth between the switch and the NF server. PayloadPark is a transparent in-network optimization that complements existing approaches for optimizing NF performance on end-hosts.

We prototyped PayloadPark on a Barefoot Tofino ASIC using the P4 language. Our prototype, when deployed on a top-of-rack switch, can service up to 8 NF servers using less than 40% of the on-chip memory resources. The prototype improves goodput by 10-36% for Firewall and NAT NFs and by 10-26% for a Firewall → NAT NF chain without harming latency. The prototype also saves 2-58% of the PCIe bandwidth on the NF server thanks to the reduced data transmission between the switch and the NF server. With workloads that have datacenter network traffic characteristics, PayloadPark provides a 13% goodput gain with the Firewall→NAT→LB NF chain without latency penalty. In the same setup, we can further increase the goodput gain to 28% by using packet recirculation.

1 Introduction

Network Functions (NFs) are widely deployed in the enterprise network [42]. NFs, such as firewalls and NATs, typically examine only a small part of each packet. These NFs show poor goodput, because unexamined packet payloads consume valuable link bandwidth. Goodput is the amount of useful information delivered over time and is a measure of how effectively a link is used. In this case, goodput is the amount of data examined by the NF. For instance, NATs and firewalls can achieve throughput that saturates a 40Gbps link when processing 10Mpps with 500 byte (4000 bits) packets. But, NATs and firewalls only examine the 5-tuple in the packet header, approximately only the first 42 bytes1 (336 bits) of the UDP packet. In these cases, the resulting goodput is only 3.36Gbps. To increase goodput, we propose PayloadPark – a header-payload decoupling optimization that temporarily holds packet payloads in switch dataplane memory. PayloadPark forwards only packet headers to NFs, temporarily parks the payload in the switch ASIC memory, and reassembles the packet when returned by the NFs.

While intuitive, PayloadPark has only recently become possible thanks to newly available Reconfigurable Match-Action Table (RMT) switches [3]. RMT switches are equipped with programmable ASICs that add programmability into the switch dataplane. This creates opportunities for implementing in-network optimizations that were impossible with fixed-function ASICs. Prior work proposes offloading application logic to programmable switches (§8), but PayloadPark is a domain-specific optimization, and it is transparent to the application. Our prototype uses RMT switches to temporarily store 160 bytes from each packet’s payload (we expect to be able to increase this with future switch models). In the evaluation (§6), we show that storing this small amount of data per packet is effective in practice.

PayloadPark presents a unique design point as it uses specialized hardware (RMT switches) to improve Network Functions (NFs), without requiring NFs to be adapted to specialized hardware. NFs implement critical network functionality, such as intrusion detection, NAT, and performance optimization (caches, WAN optimizers). NFs are often connected together in an NF chain, such as FW→NAT [30]. Previously, this functionality was implemented by hardware middleboxes that are inflexible and have vendor lock-in problems. NFs address these problems by using software deployed on commodity hardware, but have worse performance [10, 14].

1 Including Ethernet, IPv4, and UDP header.
so research efforts focus on optimizing NFs (§8). Proposals to move NFs to the cloud [42] makes performance even more critical due to additional network hops and encryption overhead. PayloadPark retains the flexibility of running software-based NFs on commodity hardware and simultaneously provides some of the benefits of specialized hardware using RMT switches.

Fig. 1 shows an abstract deployment of PayloadPark. We park the payload by implementing two operations in the switch dataplane: Split and Merge. Split decouples the incoming packet’s header, H, from its payload, P. Header H is forwarded to the shallow NF chain \( F_1, F_2 \ldots F_n \), while payload P is parked (stored) in the switch dataplane. Merge recombines the (potentially modified) header \( H' \) from the NF chain with payload P before forwarding the packet to its destination. Deploying Split and Merge on the same switch uses the bandwidth between the switch and the NF servers for useful information (the headers) rather than unused data (the payload), thereby improving goodput.

**Applicability of PayloadPark.** PayloadPark is appropriate for header-only NFs, i.e., shallow NFs, such as NATs, firewalls, and L4 load balancers. Deep packet inspection, such as intrusion detection, inspects the packet payload, so PayloadPark cannot be applied. Shallow NF processing is widely performed in many enterprise datacenters. A survey of 57 enterprise networks shows that the number of middleboxes is comparable to L2 and L3 routers [42]. A prior survey shows that on average, 44% of datacenter traffic requires at least one of L4 load-balancing and NAT operations [38]. Moreover, with increasingly encrypted traffic [34], many NFs are effectively limited to shallow processing, furthering the applicability of PayloadPark. PayloadPark works seamlessly with encrypted payloads, because it does not inspect payload content.

**Challenges.** The design of PayloadPark and our prototype implementation address the following three challenges to implement this intuitive optimization.

1. **Transparent operation.** Shallow NFs, such as NATs, modify packet headers. PayloadPark must be able to reassemble the packet despite these modifications, without assistance from the NF framework. PayloadPark does not make any assumptions about the NF framework deployed on endhosts, and it can be integrated with popular frameworks, such as OpenNetVM [49], NetBricks [37], and OpenBox [4], without any functional code changes.

2. **Limited memory resources.** PayloadPark needs to temporarily hold payloads, but switch dataplanes have limited storage that is shared across multiple ports. For example, 6.4-Tbps RMT switches have 50-100MB of stateful SRAM [31]. Our insight is that the low latency of NFs significantly limits the payload storage required. Shallow NFs have latency on the order of 10s of \( \mu s \) [37]. Even if the worst case time-delta between Split and Merge operations (including NF operation) is an order of magnitude higher, say 200 \( \mu s \), this requires only 0.8MB of storage to saturate a 40Gbps link, with a 160-byte payload (and a 42-byte UDP header). In addition, PayloadPark works within memory limits by (a) evicting payloads after a predefined expiry threshold, and (b) falling back to non-PayloadPark mode when storage is exhausted.

3. **Limited packet processing time budget.** RMT switches process packets at line rate by imposing an upper-limit on the number of compute and storage operations that can be executed per packet. This means that there is a limited time budget to find empty space in the switch memory. We address this by exploiting the fact that packets are processed by NF frameworks in (mostly) FIFO order and falling back to non-PayloadPark mode in the uncommon case that empty space cannot be found.

To summarize, we make the following contributions:

- We present the design of PayloadPark that uses RMT switches to store payload.
- We implement and evaluate a prototype of PayloadPark using a Barefoot Networks’ Tofino ASIC.
- We quantify the efficacy of PayloadPark to identify under what conditions it provides performance benefits.

## 2 Background: RMT Switches

Commodity switches with fixed-function ASICs use pre-configured header definitions and packet processing logic. This makes it slow, if not impossible, to evolve the network to support new protocols. RMT switches address this shortcoming by providing a programmable dataplane, which puts network engineers in control of header definitions and packet processing logic.

At a high level, RMT switches work by passing each packet through a series of match-action tables (MATs), which perform actions (functions) on packet headers that match criteria. More precisely, the packet processing pipeline consists of three building blocks: a Parser, Match-Action Pipeline, and Deparser. The Parser interprets the packet header using a *user-defined* header and populates the Packet Header Vector (PHV) that makes the parsed fields available to the match-action pipeline. The PHV also includes user-defined metadata fields, used for passing information to subsequent MATs. The maximum PHV size is switch-specific and limits the header size on which the match-action pipeline can operate.

The **Match-Action Pipeline** is composed of stages, where each stage has local ALU, SRAM, and TCAM resources. The match-action pipeline is programmed by writing MAT definitions in P4 [2]. MATs are mapped to stages by the P4 compiler, and independent MATs can be mapped to the same stage. Each MAT contains pairs of *match* rules and *actions*. For each packet, a MAT compares header fields (from the PHV) using user-supplied *match* rules, and executes an *action* based on the comparison result. Action definitions consume hardware resources called Very Large Instruction Word (VLIW)
PayloadPark must give cloud providers the flexibility to enable/disable PayloadPark as needed. To do so, PayloadPark must be functionally equivalent to non-PayloadPark (baseline) deployments and require no changes to the traffic source and the NF framework. Since PayloadPark is agnostic to the NF framework, providers are free to choose NF frameworks that optimize different metrics, such as SLO guarantees (ResQ [45]) or latency (NFP [43], SpeedyBox [19]).

**Operation with limited ASIC resources.** Programmable switch resources are shared across ports, so PayloadPark must work within the limits of the switch and leave enough room for packet processing on other ports. For example, on the 6.4 Tbps switch with Barefoot Networks Tofino ASIC, 16 ports share the compute and storage resources of the same match-action pipeline. Using PayloadPark for a subset of 16 ports sharing the same match-action pipeline must leave sufficient resources to implement packet processing logic for the remainder of the ports.

**Performance.** PayloadPark improves goodput, but NFs are latency sensitive, so PayloadPark must not incur a latency penalty.

### 3.2 PayloadPark Header

PayloadPark is enabled on a per-port basis. When a packet arrives on a PayloadPark-enabled port, the Split operation adds the PayloadPark header (shown in Fig. 2) to track PayloadPark-specific state. The Enable (ENB) bit indicates if the packet payload was successfully stored in the switch. The opcode (OP) bit distinguishes between Merge and Explicit Drop operation (discussed in §6.2.4). The Tag is used to find the payload in the switch dataplane memory; it is composed of three sub-parts: the table index, the generation number, and the CRC. The CRC is used to validate the PayloadPark header before merging the stored payloads with packets returning from the NF server.

### 3.3 High Level Algorithm

PayloadPark implements two primary operations: *Split* and *Merge* as shown in Fig. 3. This section describes their high level implementation and their interaction with auxiliary components.

- **Split** decouples the packet header and payload, by (1) associating a unique tag with the packet, (2) storing the payload in the switch memory, (3) adding the PayloadPark header, and (4) setting the Enable bit (ENB bit in Fig. 2) to one. If there is insufficient memory in the switch to store a payload, the Split operation adds the PayloadPark header but sets the Enable bit to zero.
- **Merge** recombines the payload and the header. When the switch receives the potentially modified header from the NF chain, the Merge operation, (1) uses the tag to locate the stored payload, (2) appends the payload to the packet,
(3) removes the PayloadPark header, and (4) frees the space consumed by the payload.

Split and Merge functionality is composed of three components: packet tagger, lookup table, and payload evictor (Fig. 3).

**Packet tagger.** Every PayloadPark packet must be assigned a unique identifier or tag that is used to index into the register array. The packet header cannot be used for indexing in the register array, because NF chains can modify headers, making it impossible to find the payload.

**Lookup table.** PayloadPark uses a lookup table abstraction on top of the raw register API of P4. The lookup table is composed of two tables – metadata and payload tables – each organized as register arrays indexed using a common table index. The metadata table is conceptually a bitmask indicating which positions in the payload table are occupied. The Split and Merge operations allocate and reclaim memory resources in the lookup table.

**Allocating memory using the Split operation.** Split examines the metadata bitmask to find an unoccupied location. If an unoccupied location is found, Split marks the table entry as occupied, and stores the payload in the payload table at the same index.

**Reclaiming memory using the Merge operation.** Merge examines the Enable bit in the PayloadPark header to determine if the packet’s payload is stored in the lookup table. If so, Merge finds the payload by indexing into the payload table with the tag from the PayloadPark header. Merge adds the payload to the packet, and marks the table entry as empty.

**Payload evictor.** Split packets may get dropped or lost before they return to the switch for merging. Payloads for packets that never return to the switch consume space and, if left unchecked, will exhaust the lookup table. Packet drops may occur when packets are dropped by NFs, such as firewalls, but since the NF framework is unaware of PayloadPark, it will not notify the switch of such packet drops. Packet loss can be caused by lossy links and other components. Dropped or lost packets will never return to the switch, so PayloadPark must be able to evict parked payloads to reclaim space on the switch.

We implement payload eviction by augmenting the metadata table with an expiry threshold. During the Split operation, this threshold is initialized to a predefined constant value. The Split operation decrements the threshold each time it indexes into an occupied location and evicts the payload when the threshold reaches zero. We experiment with different threshold values in §6.2.4.

Payload eviction is necessary to reclaim space, but it can cause packet loss if payloads are evicted prematurely. Eviction also requires the Merge operation to distinguish between evicted and non-evicted payloads. To disambiguate payloads, the metadata table includes generation numbers. When the switch receives a Split-enabled packet from the NF server, the Merge operation checks that the generation number in

![Figure 4. PayloadPark dataplane implementation. Packet processing proceeds from stage 1 to stage N. Packets are first tagged, then looked up in the metadata table, and finally stored in the payload table. The tagger has registers for the table index (TI), which is an index into the metadata and payload tables, and a clock (CLK). The metadata table contains two values at each index, the value of the clock when the index was occupied and an expiry threshold (EXP). If the index is available for storing payload, its EXP value is 0. Payload blocks (P₀, P₁... Pₐ) are striped across MATs. The PayloadPark header matches the one in the metadata table. If they match, the Merge operation proceeds with adding the payload to the packet. Otherwise, Merge concludes that the payload was evicted prematurely and drops the packet and increments the premature eviction counter. The switch uses L2 forwarding to direct packets to their destination, and the NF framework processes the packets through an NF chain. L2 forwarding and the NF framework run independently of the PayloadPark components.

### 4 PayloadPark Switch Dataplane Design

We now map the general purpose design described in §3.3 onto the architecture of the switch dataplane. Recall that RMT switches process packets by passing them through a series of MATs.

**Split operation.** When the switch receives a packet, it executes the Split operation (Alg. 1). In the first stage, we generate two subparts of the tag to probe into the lookup table: (a) an index to find a potential empty location for storing packet payload, and (b) a generation number. We maintain two counters, a table index (TI) and a clock counter (CLK), for indexing into the lookup table. In the first stage, we increment both of these counters (Lines 4 - 7) and roll them over when they reach their assigned maximum values. We update the user-defined metadata fields to make the TI and CLK values available in subsequent stages.

In stage 2, we probe the lookup table to determine if an empty slot is available. The TI is an index into the metadata table. We first read the Expiry value from the slot indicated by the TI. If it is 0 (meaning that the index is available), we write the clock value (CLK) and the Expiry threshold (EXP) into the metadata table at the table index (TI). For example, in Fig. 4, assume that when the Split operation started, the EXP
value at element 0 (the TI) was 0, indicating that the location is available. We then write CLK and EXP into the zeroth entry of the metadata table. The Split operation consumes unoccupied locations by writing the clock value and Expiry threshold (Lines 16 - 17). Stage 2 also adds the PayloadPark header, sets the Enable bit, and adds tag values to the header (Lines 18 - 20). The PayloadPark header fields, including the Enable bit, are set to zero for cases where the lookup table entry at the table index is occupied (Line 23).

Assuming we found an empty location in stage 2, in stage 3..N, we store the packet payload. The payload table is organized as a two dimensional array, where the columns are spread across MATs. To match this memory layout, we break the incoming payload into equal-sized blocks, called payload blocks. The width of a payload block is equal to the width of a single-cell in the 2D array. Following the example in Fig. 4, we store the payload at the zeroth row by striping the payload blocks, $P_0, P_1...P_L$, across all the columns (Lines 28 - 30). A single stage can execute multiple MATs in parallel, in which case, different payload blocks are stored in different MATs in the same stage. For brevity, we show code for a single MAT in each of the 3..N stages in Algorithm 1.

### Payload eviction

The Split operation also reclaims memory in the lookup table by cleaning up long-living payloads. In the metadata table, we keep track of the Expiry threshold for every occupied position in the payload table. If during the Split operation, the TI points to an occupied location (indicated by non-zero value of the Expiry threshold), we decrement the Expiry threshold (Lines 11 - 13 in Alg. 1). When the associated Expiry threshold reaches zero, we evict the stored payload (Lines 14 - 18 in Alg. 1) and reclaim the space for splitting packets.

The value of the Expiry threshold controls how soon payloads are evicted. An Expiry threshold of 1 indicates that the TI will traverse the lookup table once before evicting payloads. Higher Expiry thresholds are more conservative, decreasing the probability of premature payload evictions, but increasing the time for which payloads of lost/dropped packets continue to occupy space in the lookup table. For example, when traffic flows to the NF server but the switch does not receive any packets back from the NF server, the lookup table will fill quickly.

With a modest amount of memory, premature evictions will be rare even with an aggressive Expiry threshold. Consider a worst-case setup where PayloadPark reserves 2MB of switch memory, stores 160 bytes of payload for every packet, uses an Expiry threshold of 1, and packets arrive at line-rate (40Gbps). Assuming there is an average 30 $\mu$s time-delta between Split and Merge operations (including NF processing), payloads will be prematurely evicted after being stored for approximately 520 $\mu$s, or $17.3 \times$ the usual time between Split and Merge operations. A time-delta of 30 $\mu$s aligns with our observations (§6.2.1), so a maximum time of 520 $\mu$s gives NFs ample room to return a packet to the switch.

The maximum number of lookups for finding empty array slots depends on switch-specific constraints: in the presented algorithm, we index into the metadata table once per packet. In the worst case, the Split operation will not be able to find a suitable eviction candidate after exhausting the permitted number of lookups. In such a case, we turn off the Split operation and set the PayloadPark header fields accordingly (Lines 21 - 23 in Alg. 1).
**Merge operation.** When the switch receives a packet from the NF server, we execute the Merge operation (Alg. 2). In the first stage, we process packets for which PayloadPark operation was disabled. This can happen when the lookup table was full, and there were no suitable candidates for payload eviction. For such packets, we remove the PayloadPark header (Line 5). No further PayloadPark processing is required; we simply forward these packets to their destination using L2 forwarding.

In the second stage, we validate that the packet’s stored payload has not been evicted by comparing the clock values in the PayloadPark header and the metadata table (Line 11). If the validation succeeds, we reclaim the space in the metadata table (Line 13) for subsequent Split operations. We also remove the PayloadPark header (Line 15). If the clock values in the PayloadPark header and the metadata table do not match, we conclude that the payload was prematurely evicted. We drop the packet and record the drop. We omit this code for brevity.

In the subsequent stages, we merge the payload back to the validated Merge packets and remove the stored payload from the lookup table (Lines 21 - 23).

### 5 Implementation

We implemented the PayloadPark prototype on 6.4Tbps switch with Barefoot Tofino ASIC [35]. The chip has 4 pipes, where each pipe is composed of Parsers, Match-action pipeline, and Deparsers. The switch has a total of 64 ports (100Gbps each), divided into four sets of 16. Each set of 16 share a pipe and its resources. In our prototype, we reserve ports for PayloadPark operation. The total number of reserved ports is a matter of policy; we change the policy by changing the configuration in our P4 implementation. The switch ports that process incoming traffic and the NF server must share the same pipe, because pipes do not share stateful memory resources.

We implemented PayloadPark using approximately 900 lines of $P4_{16}$ code [6]. The prototype implements and accesses the lookup table using P4’s register API. In addition, the packet tagger uses two 2-byte registers for the table index and the clock counter (see Fig. 4). Thanks to the atomic nature of action execution in P4, subsequent packets in the match-action pipeline are guaranteed to get different indexes. Therefore, each packet has a unique index in the lookup table. In our design, we can store up to 160 bytes of per-packet payload in the payload table.

We maintain eight counters for monitoring PayloadPark operation. In the first stage, we count the number of packets received from the NF server with Split disabled (i.e., the ENB bit in the PayloadPark header is 0). In the second stage, we measure the number of Splits, Merges, and Explicit Drops (discussed in §6.2.4). In the third stage, we track the total number of evictions and premature payload evictions. In

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**Algorithm 2: Merge operation**

- $M$: Maximum capacity of the lookup table
- $tbl_{idx}$: Register for storing table index value
- $clk$: Register for storing the clock counter
- $meta_{tbl}[M]$: Register array for storing metadata table
- $payload_{tbl}[M]$: MAT-local register array for storing payload block
- $MERGE\_PORT$: Switch port reserved for Merge operation
- $hdr.pp$: PayloadPark header
- $meta$: User-defined struct for intermediate results

1. **stage 1:**
   2. ▷ Remove PayloadPark header when Enable bit is zero
   3. **match** $in\_port == MERGE\_PORT$ and
   4. $hdr.pp.is\_enb == 0$
   5. $hdr.pp.setInvalid()$

2. **stage 2:**
   7. ▷ Validate Merge Requests
   8. **match** $in\_port == MERGE\_PORT$ and
   9. $hdr.pp.is\_enb$ and $hdr.pp.is\_enb == 1$
   10. $meta.is\_pp\_enb == 0$
   11. if $meta.tbl[hdr.pp.tag.tbl_{idx}].clk == hdr.pp.tag.clk$
   12. $meta.is.pp_{enb} == 1$
   13. $meta.tbl[hdr.pp.tag.tbl_{idx}] == 0$
   14. $meta.tbl_{idx} = hdr.pp.tag.tbl_{idx}$
   15. $hdr.pp.setInvalid()$

3. **stage 3..N (idx):**
   17. ▷ Read payload blocks from payload table
   18. **upon receiving** $pkt$
   19. **match** $in\_port == MERGE\_PORT$ and
   20. $meta.is.pp_{enb} == 1$
   21. $hdr.payload_{block}[idx] = payload_{tbl}[meta.tbl_{idx}]$
   22. $hdr.payload_{block}[idx].setValid()$
   23. $payload_{tbl}[meta.tbl_{idx}] == 0$

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addition, for disabled Split operations we count: (a) how many times the payload size was less than 160 bytes, and (b) how many times the next location in metadata table was occupied.

**Implications of ASIC restrictions.** Programmable ASICs (and the Tofino chip) limit the number of compute and stateful operations per MAT to guarantee line-rate packet processing. These limits ensure that PayloadPark meets its design goal of not introducing a latency penalty in NF processing. However, these constraints have significant implications on PayloadPark’s design.

During the Split operation, we do a single lookup in the metadata table. If that index is occupied, we disable the Split operation. It is possible that there are empty slots available elsewhere in the lookup table, but we are not able to find...
them, because MATs are restricted to a single register operation per packet. Laying out stateful memory as arrays, or more accurately, a circular buffer, neatly coexists with this restriction. Usually, Split and Merge process packets in the same (FIFO) order. Thus, if we allocate space in the metadata table sequentially, as the table index works its way through the array, Merge operations reclaim memory at earlier positions in the array. By the time the table index wraps around, it should find empty spots. This access pattern optimizes PayloadPark operation for the common case (FIFO order). In the worst case, where long-living payloads are occupying the lookup table, we disable the Split operation.

We apply the Split operation only when the payload length exceeds the number of per-packet bytes that we can store (160 bytes in our implementation). This decision prevents wasting memory resources. Every stored payload reserves a table index and to fully utilize per-index memory, the payload size must be at least 160 bytes. Turning off Split operation for payloads smaller than 160 bytes prevents this wastage. The PayloadPark header disambiguates between disabled Split packets (payload size < 160 bytes) and packets with small payload size (<160 bytes) after the Split operation.

**NF framework integration.** Our PayloadPark prototype does not require changes to shallow NFs. The PayloadPark header replaces part of the payload, which remains unexamined by shallow NFs. We use switch port numbers to disambiguate between Split and Merge operations, so the NF server does not need to change the Merge opcode.

### 6 Evaluation

The evaluation answers the following research questions:

**Performance.** Does the prototype satisfy the performance goals of providing goodput improvement without hurting latency? What is the performance profile of NFs that benefit from PayloadPark?

**Operation with limited resources.** Does the prototype use the switch resources efficiently? We evaluate the effects of parameters, such as Expiry threshold and percentage of memory reserved, on overall performance.

#### 6.1 Methodology

**Setup.** We deployed PayloadPark on a 6.4Tbps switch with Barefoot Tofino ASIC [35]. For the non-PayloadPark setup (our baseline), the switch uses L2 forwarding to pass traffic between the traffic generator and the NF server.

We use two NF frameworks, OpenNetVM [49] and NetBricks [37], to evaluate our prototype. OpenNetVM is built on top of DPDK and runs NF chains in Docker containers [49]. NetBricks is a DPDK-based framework written in Rust, but does not use containers to isolate memory between NFs. We evaluated PayloadPark using two dual port NICs: an Intel 82599ES 10GE NIC and an Intel XL710 40GE NIC.

We use PktGen, a DPDK-based traffic generator to saturate the NF server with UDP packets. We run PktGen on a dual NUMA node, 2.4 GHz Intel Xeon E5-2407 v2 server with 8 CPU cores and 48GB RAM. Fig. 5 shows the experimental setup. We connect two ports of the traffic generator’s NIC to the switch to saturate the NF server. One port is not sufficient, because PayloadPark reduces data that the switch transmits to the NF server. The NF server is connected to the switch using a single port on the NIC.

The NF server is a four NUMA node, 60 core machine with the 2.3 GHz Intel Xeon E7-4870 v2 processor and 512GB RAM. We reserve 8GB of memory backed by hugepages on each NUMA node. We use two NF chains, Firewall → NAT → LB and Firewall → NAT, to evaluate our prototype. The firewall linearly probes through a list of blacklisted IP addresses. The firewall in the three-NF chain has 20 rules, and the two-NF chain has a single rule in its firewall. The load balancer is based on the Maglev load-balancer [9]. The NAT is based on MazuNAT [13].

**Evaluation metrics.** PayloadPark is a goodput optimization, which we measure from the RMT switch’s perspective. We use a UDP header as the unit of useful information. We also measured average end-to-end packet processing latency from and to the traffic generator to validate our performance goals (§3.1). We also measured PCIe bandwidth utilization on the NF server using Intel’s Processor Counter Monitor [12]. We consider the system to be healthy when the packet drop rate is below 0.1%; we use this threshold to measure peak goodput of PayloadPark and the baseline. Unless mentioned explicitly, all evaluations have no premature payload evictions – a prerequisite for functional equivalence.

**Workloads.** We replay PCAP files to simulate an enterprise datacenter traffic pattern. Our PCAP (shown in Fig. 6) reproduces the packet-size distribution of enterprise datacenters reported by Benson et al. [1]. The packet sizes have a bimodal distribution with an average packet size of 882 bytes. Recall that we do not split packets whose payloads have fewer than 160 bytes. In this workload, 30% of the packets have fewer than 160 bytes for which we add the PayloadPark header

![](image-url)

**Figure 5. Experimental setup.**
and set the ENB bit to zero. We collect performance metrics by replaying UDP packets over a period of 2 minutes. For all experiments, we report the average of three runs. We also evaluate our prototype with fixed-sized packets to determine the range of packet sizes that benefit from the PayloadPark deployment.

**Experiments.** For macro-benchmarks, PayloadPark reserves about 26% of switch memory, and we set the Expiry threshold to 1. We evaluate PayloadPark on our 40 GE NIC using both the datacenter traffic pattern (Fig. 6) and fixed packet sizes for single Firewall and NAT NFs and the NF chain consisting of Firewall $\rightarrow$ NAT. With the 10GE NIC, we evaluate the goodput gain with Firewall $\rightarrow$ NAT $\rightarrow$ LB chain. We also used packet recirculation to increase the number of stored payload bytes and evaluated the Firewall $\rightarrow$ NAT $\rightarrow$ LB chain using the NetBricks framework with a 10GE NIC.

We evaluate PayloadPark when multiple NF servers share the same switch. Each server runs a MAC address swapper. The switch has 4 pipes, and each pipe is connected to two NF servers. Each NF server processes traffic from its dedicated traffic-generator. We use 2.4GHz 8 core Intel Xeon CPUs for both the traffic generator and NF servers. We increase the reserved memory resources on the switch to about 40%, and slice the reserved memory amongst NF servers sharing the same pipe. We use 384-byte packets, because for a fixed link capacity, smaller packets produce a higher packet rate that puts more memory pressure on the switch.

For micro-benchmarks, we vary implementation parameters, such as the reserved memory on the Tofino ASIC and Expiry thresholds. We evaluate PayloadPark using NFs with different computational costs. To create NFs of varying computational cost, we take a MAC address swapper and add a busy loop. We measure per-packet CPU cycles using the RDTSC counter [8].
increase, because we can store more payload bytes on the
switch.
An alternative deployment option is to deploy Payload-
Park on a SmartNIC. However, this approach will not im-
prove goodput on the link. Additionally, prior work showed
that NFs can run directly on SmartNICs [25, 28], in which
case, we could derive the dual benefit of a performance gain
from the SmartNIC and goodput gains from PayloadPark on
the switch.

6.2.2 Goodput Improvement with Fixed Packet Sizes

Fig. 8 and Fig. 9 show PayloadPark’s behavior with differ-
ent packet sizes and NF chains using the 40GE NIC and
OpenNetVM framework. The goodput improvement be-
tween baseline and PayloadPark is 10-36% for 384 to
1492 byte packets. We see a larger goodput gain at smaller
packet sizes, because we truncate a larger proportion of
each packet for small packet sizes. Also, the FW → NAT
chain has lower goodput gain than individual NFs, because
the NF server does more per-packet computation, making
OpenNetVM compute bound sooner. Similarly, for 256 byte
packets, the goodput gain is negligible, because for a fixed
bandwidth, smaller packet sizes put more compute pres-
sure on the NF server and more memory pressure on the
switch than large packet sizes. But, PayloadPark saves
PCIe bandwidth by 58% for 256 byte packets (Fig. 9),
which is important, because PCIe bandwidth is a bottleneck
at small packet sizes [36].

6.2.3 Multiple NF Server Setup

We next examine how PayloadPark can benefit multiple NF
servers, since performance isolation is important in multi-
tenant clouds. We simulate such a setup by connecting the
switch to 8 NF servers. Fig. 10 and Fig. 11 show that all
8 NF servers exhibit consistent performance improve-
ment with an average goodput gain of 31.22% and la-
tency win of 9.4%. These latency savings are on the PCIe
bus, because PayloadPark copies less data between the NIC
and CPU for each packet. This experiment also shows that
PayloadPark efficiently uses the on-chip memory resources,
because it can service traffic for multiple NF servers. Static
slicing of switch resources between NF servers ensures per-
formance isolation in the presence of heavy-hitting traffic
from a subset of customers. This also protects individual
customer’s payloads from being evicted by other customer’s
traffic flowing through the same switch. The goodput gain of
the server is a function of memory reserved for the operation
of that server. We discuss the impact of varying the reserved
memory in §6.3.1.

Instead of static slicing, there is potential to further im-
prove PayloadPark’s memory efficiency by dynamically re-
allocating memory between different NF servers to match
their workload. We leave this optimization as future work.

6.2.4 Payload Eviction and Explicit Payload Drops

In addition to implementing payload eviction in the switch
dataplane, we explored the option of making small code
changes in the NF framework to explicitly notify the switch
when the NF decides to drop a packet. Explicit Drop noti-
fications provide the ground truth to evaluate the payload
eviction policy, because the NF notifies the switch as soon
as a payload can be evicted.

We added 50 lines of code to the NF framework (Open-
NetVM [49]) to send Explicit Drop packets to the switch.
The NF framework marks an incoming packet as dropped by
changing the opcode ("OP" bit in Fig. 2), truncating the
packet payload, and sending the resulting packet back to the
switch. Drop is a special case of Merge that just reclaims
memory after validating the tag. Explicit drops are an op-
tional optimization; the payload evictor already reclaims
memory on the switch.

Fig. 12 compares the goodput with and without explicit
drops to different expiry thresholds. We use the workload
shown in Fig. 6 for the Firewall → NAT chain. The fire-
wall blocks packets using a single rule in its Access Control
List, and we vary the proportion of blacklisted IP addresses
to control the drop rate at the firewall. Unlike the firewall
benchmark recommendations [16], we do consider dropped
packets in our measurement since we measure goodput from
the RMT switch perspective (see §6.1).

Fig. 12 shows that aggressive eviction policy (EXP=2) per-
forms comparably to Explicit Drop notifications. With a more
conservative eviction policy (EXP=10), goodput drops be-
cause more dropped packets occupy space in the lookup table.
Figure 12. (Higher is better) Goodput using Explicit and No Explicit Drop packets for Firewall → NAT. EXP=2 and EXP=10 labels denote Expiry threshold of 2 and 10 respectively. Standard error in goodput measurements is less than 0.26Mbps. The graph shows that PayloadPark has better goodput than baseline.

Figure 13. Goodput and latency improvements of PayloadPark with FW → NAT → LB chain on NetBricks. This is the recirculation-enabled version of the experiment described in Fig. 7.

Overall, the Expiry threshold presents a trade-off between effective memory utilization and protection against premature payload evictions. Explicit Drops in combination with conservative payload eviction balance this trade-off. Fig. 12 shows that a conservative eviction policy when combined with Explicit Drops (Explicit EXP=10) performs comparably to an aggressive eviction policy (No Explicit EXP=2). The benefit of Explicit Drops comes at the cost of small code changes to the NF framework, but this cost is a one-time investment.

6.2.5 Effect of Packet Recirculation

In our prototype, we increase the number of stored payload blocks by recirculating packets in the packet processing pipeline. Recall that we store payload blocks by striping them across Stages 3 to N of a single pipe (see Fig. 4). Using packet recirculation, we stripe payloads in all the stages of a second pipe in addition to payload blocks stored in the first pipe. Recirculation increases the stored payload size from 160 bytes to 384 bytes.

Fig. 13 shows goodput and latency with FW → NAT → LB using the NetBricks framework with the 10GE NIC. The vertical red and blue line highlight the peak send rate that the baseline and our prototype can sustain (without recirculation). We observe a 28% goodput improvement – approximately twice that of the prototype without recirculation. A single packet recirculation induces a latency penalty on the order of 10s of ns [46]. But, we do not observe any end-to-end latency penalty thanks to the reduced PCIe latency caused by the additional payload bytes stored in the switch. We also observe a 23% PCIe bandwidth savings for all send rates before the baseline link gets saturated. With these results, we conclude that goodput improvement and PCIe bandwidth savings increase with an increase in the stored payload size.

6.2.6 Functional Equivalence

We validated functional equivalence by comparing the packets received at the traffic generator upon return from NF chains in the PayloadPark and baseline deployments. We used a single NF that swaps MAC addresses for our evaluation. We used DPDK-pdump to sniff packets at the traffic generator’s NIC. The resulting PCAP files are identical and switch metrics report no premature payload evictions, which gives us confidence that PayloadPark and baseline deployments are functionally equivalent.

6.3 Micro-Benchmark Results

6.3.1 Impact of Reserved Memory

The amount of memory that PayloadPark reserves on the switch presents a trade-off between goodput gain and memory available for implementing additional P4 functionality. We use 384 byte packets with the Firewall → NAT chain to stress the memory resources at the switch. We set the Expiry threshold to 1 and increase the traffic rate until PayloadPark begins to evict packets prematurely. The number of premature payload evictions is an important metric that determines functional equivalence of the PayloadPark deployment. To achieve functional equivalence, there must be zero premature payload evictions. We test with EXP=1, because if there are no premature payload evictions with an aggressive payload eviction policy (EXP=1), the system will...
be functionally equivalent with more conservative (EXP>1) payload eviction policies.

Fig. 14 shows the peak traffic send rate that exhibits no premature payload evictions as we increase the percentage of memory allocated for PayloadPark. First, we see that the PayloadPark optimization provides goodput gain with less than 26% Tofino chip memory. Additionally, with a little more than 17% of switch memory resources, the prototype can sustain at most 3.44Gbps goodput. Beyond this rate, the Expiry threshold is not high enough to prevent premature evictions. For example, at an incoming traffic goodput rate of 3.55Gbps (send rate of 32.45Gbps), we observed that 0.03% of incoming payloads are being prematurely evicted (not shown). Cloud-providers should not use PayloadPark when co-located P4 artifacts are memory-intensive, and there is insufficient memory for PayloadPark operation.

6.3.2 Resource Utilization

Table 1 shows the switch resources used by the PayloadPark prototype (excluding L2 forwarding). Despite being memory-intensive, our average per-stage SRAM utilization is 25.94%, and it is comparable to prior work (SilkRoad [31], BurstRadar [21]). PayloadPark’s SRAM utilization is not uniform across all stages in the Match Action Unit; the peak per-stage memory utilization is 33.75%. This memory is sufficient for supporting 4 NF servers (one on each pipe). To support 8 NF servers, our peak memory utilization is 48.75%.

PayloadPark efficiently uses additional hardware resources such as PHV and VLIW (discussed in §2). We use only 37.65% of the PHV resources, which is comparable to our overall memory consumption and therefore, not a limiting resource. The other resources that PayloadPark uses, including VLIW, TCAM, and crossbars also have less than 20% utilization. Overall, our implementation efficiently uses on-chip memory resources and leaves sufficient resources for implementing additional P4 functionality.

| Resource Name              | PayloadPark Percentage Res. Util. |
|----------------------------|-----------------------------------|
| SRAM (4 NF servers)        | 25.94% (Avg.) / 33.75% (Peak)    |
| SRAM (8 NF servers)        | 38.23% (Avg.) / 48.75% (Peak)    |
| TCAM                       | 0.69%                             |
| VLIW                       | 14.58%                            |
| Exact Match Crossbar       | 16.47%                            |
| Ternary Match Crossbar     | 0.88%                             |
| Packet Header Vector       | 37.65%                            |

Table 1. Resource Utilization on the Tofino chip.

6.3.3 Impact of NF CPU Cycles

We now examine the impact of NF packet processing time on the achievable peak goodput of the PayloadPark prototype. Fig. 15 shows the goodput gain for 4 different packet sizes and 3 different NF computation loads, NF-Light, NF-Medium, and NF-Heavy, with approximately 50, 300, and 570 average CPU cycles per packet, respectively.

With 1492 byte packets, PayloadPark consistently yields better goodput than the baseline, because at large packet size (and smaller packet send rate) OpenNetVM does not become compute bound. However, for smaller packet sizes (<= 1024 bytes), we do not achieve goodput gain with NF-Heavy, because OpenNetVM becomes compute bound when the send rate exceeds 5Mpps (goodput of 1.68Gbps). Sending additional traffic results in packet drops at the NF server NIC in both PayloadPark and baseline deployments.

For 256-byte packets, we see negligible (2.1%) goodput improvement for NF-Light. For small packet sizes, the traffic generator has to send more packets to sustain the requested transmit rate. This puts more memory pressure on the switch, since we store a fixed number of bytes per packet. However, NF-Light is quick enough to free switch memory, thereby avoiding premature payload evictions. For NF-Medium, the baseline has 3.87% better goodput than PayloadPark, because the increased NF computation increases NF latency resulting in premature payload evictions. These results and those presented in §6.2.2 indicate that larger packet sizes (>= 384 bytes) show better goodput improvement than 256-byte packets. We will better utilize switch memory by increasing the minimum payload size threshold of 160 bytes to 384 bytes.

6.3.4 Impact of PayloadPark on NF Frameworks

Overall, section 6.2.1 showed that PayloadPark improved latency with a variety of different packet sizes. In that case, PayloadPark’s latency is better, because large packets dominate the workload with an average packet size of 882 bytes. However, for smaller packet sizes, since PayloadPark causes the NF server to process more packets per second, it adds compute strain on the server and latency can spike. To illustrate this effect, Fig. 16 shows goodput and average latency.
with 512-byte packets. As shown, PayloadPark continues to process packets beyond 33.6Gbps, while the baseline is capped at 33.6Gbps. Before the baseline saturates, PayloadPark results in lower average latency than the baseline, because PayloadPark reduces per-packet bandwidth consumption between the switch and the NF server. But, for both baseline and PayloadPark, latency increases once the send rate exceeds 33.6Gbps. This latency increase is not a fundamental shortcoming of PayloadPark. Optimizations in the NF framework are orthogonal to our work, and this latency increase can be addressed by using PayloadPark with an NF framework that maintains line rate at small packet sizes. It is important to note that this behavior only occurs with small, fixed-size packets. Overall, PayloadPark can improve goodput without latency penalty when packet sizes follow the enterprise traffic pattern.

### 7 Discussion

Overall, our PayloadPark prototype improves goodput on the link between the NF server and the switch for all tested packet sizes, while working within the limitations of the RMT switches, and without impacting latency. These results show that PayloadPark is a promising optimization that is already effective on today’s RMT switches.

**Scalability across switches.** PayloadPark is a general optimization that can be deployed on any switch in the leaf-spine topology: core, aggregate and the ToR switch. In our prototype, goodput gain is achieved by storing payload in a ToR switch. We can further increase the goodput gain, and distribute memory pressure by striping the packet payload across multiple switches in the packet path. When a packet arrives at the cloud-provider’s infrastructure, all switches can perform Split and Merge.

**Decoupling boundary.** In our prototype, we used the UDP header as the header-payload decoupling boundary. We can trivially change this boundary if the NF server needs to inspect more or fewer fields. For example, if the NF chain reads only the first N bytes of the payload, we can store the rest of the payload in the programmable ASIC memory. For example, Fernandes et al. propose Slim-DPI that analyzes a fraction of the payload to classify packets [11]. PayloadPark can be applied to Slim-DPI-like NF chains. The decoupling boundary can also be dictated by the protocol, such as TCP. Our current prototype works with all protocols, but if the NF server needs to inspect protocol-specific headers, the boundary can be extended to include these bits in the header as needed. We leave investigating the impact of different decoupling boundaries to future work.

**Failure scenarios.** The PayloadPark deployment and the baseline setup deal with three failure scenarios:

1. **Link failures:** Both deployments are equally susceptible to link failures and accidental disconnects. All in-flight messages in disconnected link(s) will be lost. Incoming traffic will trigger payload eviction but overall NF processing will stall because of lost connection to the NF server. Once connectivity is restored, the space reclaimed by the payload evictor will resume normal operation.
2. **NF server failures:** All in-flight packets through the NF server will be lost in both deployments. NF chain processing will resume after the NF server recovers. Similar to link failures, the payload evictor will resume normal operation.
3. **Switch failure:** PayloadPark increases the failure-domain of the NF-server to include the switch. Therefore, when the switch fails, all packets in the switch will be lost in both deployments. However, the failure scenario differs for packets that have already reached the NF server. In the baseline deployment, if server connects to another ToR switch, it can route packets through a different ToR. But, this is not applicable to PayloadPark, because the payload resides in the original ToR switch memory. However, the number of lost packets is negligible due to small time-delta between the Split and Merge operations (that includes NF processing). For example, in Fig. 7, we will lose at most 50 packets for a link operating at full capacity (10 Gbps) with an average packet size of 882 bytes and an average latency of 32 μs. With a 40 Gbps link, we will lose at most 200 packets. This packet loss is an overestimate, because we measure latency from the traffic generator and not from the switch.

**Security.** We do not protect the switch and the stored payload against adversarial attacks. We apply PayloadPark in the context of the cloud deployment where both the switch and the NF server are within the cloud provider’s administrative domain. Since the cloud provider owns the infrastructure, we trust all incoming traffic to the switch.

**Adaptive payload eviction policy.** Our prototype tracks premature payload evictions with a counter. In our evaluation, we use this counter to identify the safe operating boundary of PayloadPark. This counter could be used to adaptively change the payload eviction policy and protect against unexpected latency spikes in the NF server. For example, PayloadPark could start with an aggressive payload
eviction policy and dynamically switch to a conservative eviction policy when payload evictions exceed a predefined threshold. We leave this tuning to future work.

8 Related Work

Our work draws inspiration from Cut Payload proposed by Cheng et al. [5]. Cut Payload drops payloads at overloaded switches and generates SACK-style notifications to the sender about the drops. PayloadPark makes a similar observation about not transmitting unnecessary data. Our approach is different because we do not drop the payload. Instead, we store the payload at the switch and later merge it back with the header. In addition, our work broadly spans two areas: in-network computing and NFs.

In-network computing. Prior work has used in-network processors to accelerate applications by offloading application functionality. PayloadPark differs by using the switch to implement a transparent optimization, without modifying application code. For example, NetCache implements an in-network cache for key-value stores [20]. DistCache presents a distributed cache topology to load balance across racks [29]. Silkroad offloads L4 load balancers [31], and NetPaxos [7] offloads some Paxos functions to the switch. NOPaxos (Network Ordered Paxos) uses in-network devices for network sequencing and accelerates data replication [26]. Researchers have also used the switch dataplane to accelerate SQL queries (Jumpgate [33], Cheetah [44]) and string searching (PPS [18]).

Specialized hardware for NFs. Prior work has used specialized hardware to improve NF performance. Wu et al. propose NF acceleration using RMT switches by deploying NF chains directly on the switch [46]. Our work differs in that PayloadPark is a transparent in-network optimization, and the NF chains continue to run on commodity hardware. This retains the flexibility of implementing and upgrading NF chains, while ensuring ease of integration with existing NF frameworks. Researchers have also used other specialized devices for NF acceleration. For example, PacketShader uses GPUs for accelerating software routers [15]. G-NET presents virtualization and isolation approaches for GPU-accelerated NF chains [48]. GEN elastically scales NFs using GPUs [51]. NBA [24] and GPU-NFV [47] use GPUs to accelerate NF performance. Similarly, ClickNP [25] uses FPGAs. Moon et al. offload stateful flow processing to programmable NICS [32]. Metron integrates end-hosts and in-network processing by offloading packet classification and stateless operations of NFs to the switch and programmable NICS, resulting in better latency and throughput [22].

End-host optimizations for NFs. There are several end-host NF frameworks that optimize NF performance, and PayloadPark can be integrated with these frameworks. CoMB consolidates NFs to reduce provisioning and maintenance costs [41]. Sprayer optimizes utilization in multi-core CPUs by using fine-grained packet-to-core allocation [40]. Kat-sikas et al. optimize NF execution by profiling packet processing [23]. TNP optimizes allocation of NFs to multiple cores [27]. mOS provides an API to help develop stateful flow processing programs [17]. SafeBricks protects NFs in untrusted clouds, but at a performance cost [39]. NetBricks uses Rust to eliminate isolation overhead of Docker containers and VMs [37]. NFP [43] and Parabox [50] explore parallel paths in execution of NF chains to reduce packet processing latency. We can seamlessly integrate PayloadPark with existing frameworks. For example, in the combined setup composed of PayloadPark and NFP, PayloadPark would improve goodput and NFP would improve latency.

9 Conclusion

We described PayloadPark, an in-network optimization that decouples packets at the header-payload boundary. PayloadPark improves shallow NF goodput by 2-36% without any latency penalty, saves PCIe bandwidth by 2-58%, and uses less than 40% of Tofino chip resources. Also, PayloadPark preserves the semantics of non-PayloadPark deployments, and can be easily integrated with existing NF frameworks.

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